The Project Physics Course

Reader 2

Motion in the Heavens

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Reader

UNIT 2 Motion in the Heavens

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Project Physics Course

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Directors of Harvard Project Physics
Gerald Holton, Department of Physics, Harvard University
F. James Rutherford, Capuchino High School, San Bruno, California, and Harvard University
Fletcher G. Watson, Harvard Graduate School of Education

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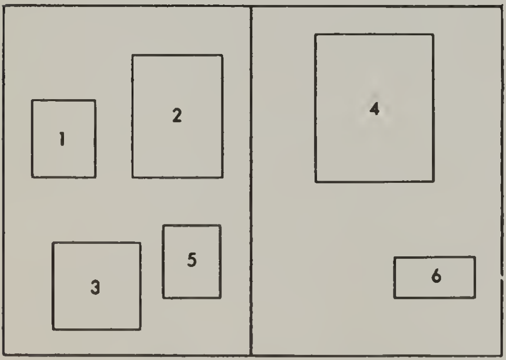

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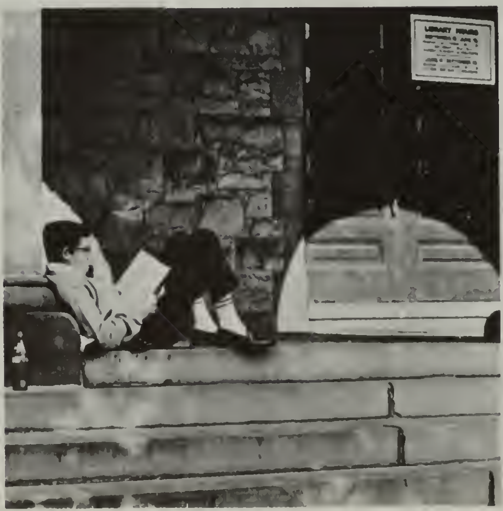
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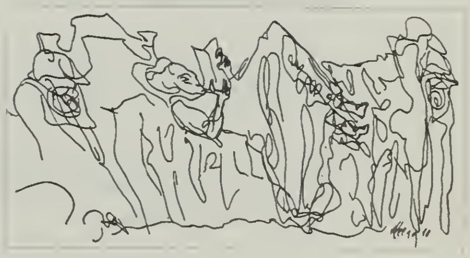
This is not a physics textbook. Rather, it is a physics reader, a collection of some of the best articles and book passages on physics. A few are on historic events in science, others contain some particularly memorable description of what physicists do; still others deal with philosophy of science, or with the impact of scientific thought on the imagination of the artist.

There are old and new classics, and also some little-known publications; many have been suggested for inclusion because some teacher or physicist remembered an article with particular fondness. The majority of articles is not drawn from scientific papers of historic importance themselves, because material from many of these is readily available, either as quotations in the Project Physics text or in special collections.



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Reader 2

Table of Contents

In this introductory chapter to his science fiction novel, *The Black Cloud,* the noted astronomer Fred Hoyle gives a realistic picture of what goes on within an astronomy laboratory. The emphasis is on experimental astronomy.

1 Opening Scenes

Fred Hoyle

A chapter from his book *The Black Cloud,* 1957.

It was eight o'clock along the Greenwich meridian. In England the wintry sun of 7th January, 1964, was just rising. Throughout the length and breadth of the land people were shivering in ill-heated houses as they read the morning papers, ate their breakfasts, and grumbled about the weather, which, truth to tell, had been appalling of late.

The Greenwich meridian southward passes through western France, over the snow-covered Pyrenees and through the eastern corner of Spain. The line then sweeps to the west of the Balearic Islands, where wise people from the north were spending winter holidays—on a beach in Minorca a laughing party might have been seen returning from an early morning bathe. And so to North Africa and the Sahara.

The primary meridian then swings towards the equator through French Sudan, Ashanti, and the Gold Coast, where new aluminium plants were going up along the Volta River. Thence into a vast stretch of ocean, unbroken until Antarctica is reached. Expeditions from a dozen nations were rubbing elbows with each other there.

All the land to the east of this line, as far as New Zealand, was turned towards the Sun. In Australia, evening was approaching. Long shadows were cast across the cricket ground at Sydney. The last overs of the day were being bowled in a match between New South Wales and Queensland. In Java, fishermen were busying themselves in preparation for the coming night's work.

Over much of the huge expanse of the Pacific, over America, and over the Atlantic it was night. It was three a.m. in New York. The city was blazing with light, and there was still a good deal of traffic in spite of recent snow and a cold wind from the north-west. And nowhere on the Earth at that moment was there more activity than in Los Angeles. The evening was still young there, twelve o'clock: the boulevards were crowded, cars raced along the freeways, restaurants were still pretty full.

A hundred and twenty miles to the south the astronomers on Mount Palomar had already begun their night's work. But although the night was clear and stars were sparkling from horizon to zenith, conditions from the point of view of the professional astronomer were poor, the 'seeing' was bad—there was too much wind at high levels. So nobody was sorry to down tools for the midnight snack. Earlier in the evening, when the outlook for the night already looked pretty dubious, they had agreed to meet in the dome of the 48-inch Schmidt.

Paul Rogers walked the four hundred yards or so from the 200-inch telescope to the Schmidt, only to find Bert Emerson was already at work on a bowl of soup. Andy and Jim, the night assistants, were busy at the cooking stove.

"Sorry I got started," said Emerson, "but it looks as though tonight's going to be a complete write-off."

Emerson was working on a special survey of the sky, and only good observing conditions were suitable for his work.

"Bert, you're a lucky fellow. It looks as though you're going to get another early night."

"I'll keep on for another hour or so. Then if there's no improvement I'll turn in."

"Soup, bread and jam, sardines, and coffee," said Andy. "What'll you have?"

"A bowl of soup and cup of coffee, thanks," said Rogers.

"What're you going to do on the 200-inch? Use the jiggle camera?"

"Yes, I can get along tonight pretty well. There's several transfers that I want to get done."

They were interrupted by Knut Jensen, who had walked the somewhat greater distance from the 18-inch Schmidt.

He was greeted by Emerson.

"Hello, Knut, there's soup, bread and jam, sardines, and Andy's coffee."

"I think I'll start with soup and sardines, please."

The young Norwegian, who was a bit of a leg-puller, took a bowl of cream of tomato, and proceeded to empty half a dozen sardines into it. The others looked on in astonishment.

"Judas, the boy must be hungry," said Jim.

Knut looked up, apparently in some surprise.

"You don't eat sardines like this? Ah, then you don't know the real way to eat sardines. Try it, you'll like it."

Then having created something of an effect, he added:

"I thought I smelled a skunk around just before I came in."

"Should go well with that concoction you're eating, Knut," said Rogers.

When the laugh had died away, Jim asked:

"Did you hear about the skunk we had a fortnight ago? He degassed himself near the 200-inch air intake. Before anybody could stop the pump the place was full of the stuff. It sure was some hundred per cent stink. There must have been the best part of two hundred visitors inside the dome at the time."

"Lucky we don't charge for admission," chuckled Emerson, "otherwise the Observatory'd be sunk in for compensation."

"But unlucky for the clothes cleaners," added Rogers.

On the way back to the 18-inch Schmidt, Jensen stood listening to the wind in the trees on the north side of the mountain. Similarities to his native hills set off an irrepressible wave of homesickness, longing to be with his family again, longing to be with Greta. At twenty-four, he was in the United States on a two-year studentship. He walked on, trying to kick himself out of what he felt to be a ridiculous mood. Rationally he had no cause whatsoever to be dispirited. Everyone treated him with great kindness, and he had a job ideally suited to a beginner.

Astronomy is kind in its treatment of the beginner. There are many jobs to be done, jobs that can lead to important results but which do not require great experience. Jensen's was one of these. He was searching for supernovae, stars that explode with uncanny violence.

Within the next year he might reasonably hope to find one or two. Since there was no telling when an outburst might occur, nor where in the sky the exploding star might be situated, the only thing to do was to keep on photographing the whole sky, night after night, month after month. Some day he would strike lucky. It was true that should he find a supernova located not too far away in the depths of space, then more experienced hands than his would take over the work. Instead of the 18-inch Schmidt, the full power of the great 200-inch would then be directed to revealing the spectacular secrets of these strange stars. But at all events he would have the honour of first discovery. And the experience he was gaining in the world's greatest observatory would stand well in his favour when he returned home—there were good hopes of a job. Then he and Greta could get married. So what on earth was he worried about? He cursed himself for a fool to be unnerved by a wind on the mountainside.

By this time he had reached the hut where the little Schmidt was housed. Letting himself in, he first consulted his notebook to find the next section of the sky due to be photographed. Then he set the appropriate direction, south of the constellation of Orion: mid-winter was the only time of the year when this particular region could be reached. The next step was to start the exposure. All that remained was to wait until the alarm clock should signal its end. There was nothing to do except sit waiting in the dark, to let his mind wander where it listed.

Jensen worked through to dawn, following one exposure by another. Even so his work was not at an end. He had still to develop the plates that had accumulated during the night. This needed careful attention. A slip at this stage would lose much hard work, and was not to be thought of.

Normally he would have been spared this last exacting task. Normally he would have retired to the dormitory, slept for five or six hours, breakfasted at noon, and only then would he have tackled the developing job. But this was the end of his 'run.' The moon was now rising in the evening, and this meant the end of observing for a fortnight, since the supernova search could not be carried on during the half of the month when the moon was in the night sky—it was simply that the moon gave so much light that the sensitive plates he was using would have been hopelessly fogged.

So on this particular day he would be returning to the Observatory offices in Pasadena, a hundred and twenty-five miles away. The transport to Pasadena left at half-past eleven, and the developing must be done before then. Jensen decided that it would be best done immediately. Then he would have four hours sleep, a quick breakfast, and be ready for the trip back to town.

It worked out as he had planned, but it was a very tired young man who travelled north that day in the Observatory transport. There were three of them: the driver, Rogers, and Jensen. Emerson's run had still another two nights to go. Jensen's friends in wind-blown, snow-wrapped Norway would have been surprised to learn that he slept as the car sped through the miles of orange groves that flanked the road.

Jensen slept late the following morning and it wasn't until eleven that he reached the Observatory offices. He had about a week's work in front of him, examining the plates taken during the last fortnight. What he had to do was to compare his latest observations with other plates that he had taken in the previous month. And this he had to do separately for each bit of the sky.

So on this late January morning of 8th January, 1964, Jensen was down in the basement of the Observatory buildings setting up an instrument known as the 'blinker.' As its name implies, the 'blinker' was a device that enabled him to look first at one plate, then at the other, then back to the first one again, and so on in fairly rapid succession. When this was done, any star that had changed appreciably during the time interval between the taking of the two plates stood out as an oscillating or 'blinking' point of light, while on the other hand the vast majority of stars that had not changed remained quite steady. In this way it was possible to pick out with comparative ease the one star in ten thousand or so that had changed. Enormous labour was therefore saved because every single star did not have to be examined separately.

Great care was needed in preparing plates for use in the 'blinker.' They must not only be taken with the same instrument, but so far as possible must be shot under identical conditions. They must have the same exposure times and their development must be as similar as the observing astronomer can contrive. This explains why Jensen had been so careful about his exposures and development.

His difficulty now was that exploding stars are not the only sort to show changes. Although the great majority of stars do not change, there are a number of brands of oscillating stars, all of which 'blink' in the manner just described. Such ordinary oscillators had to be checked separately and eliminated from the search. Jensen had estimated that he would probably have to check and eliminate the best part of ten thousand ordinary oscillators before he found one supernova. Mostly he would reject a 'blinker' after a short examination, but sometimes there were doubtful cases. Then he would have to resort to a star catalogue, and this meant measuring up the exact position of the star in question. So all in all there was quite a bit of work to do before he got through his pile of plates—work that was not a little tedious.

By 14th January he had nearly finished the whole pile. In the evening he decided to go back to the Observatory. The afternoon he had spent at the California Institute of Technology, where there had been an interesting seminar on the subject of the spiral arms of the galaxies. There had been quite a discussion after the seminar. Indeed he and his friends had argued throughout dinner about it and during the drive back to the Observatory. He reckoned he would just about get through the last batch of plates, the ones he had taken on the night of 7th January.

He finished the first of the batch. It turned out a finicking job. Once again, every one of the 'possibilities' resolved into an ordinary, known oscillator. He would be glad when the job was done. Better to be on the mountain at the end of a telescope than straining his eyes with this damned instrument, he thought, as he bent down to the eye-piece. He pressed the switch and the second pair flashed up in the field of view. An instant later Jensen was fumbling at the plates, pulling them out of their holders. He took them over to the light, examined them for a long time, then replaced them in the blinker, and switched on again. In a rich star field was a large, almost exactly circular, dark patch. But it was the ring of stars surrounding the patch that he found so astonishing. There they were, oscillating, blinking, all of them. Why? He could think of no satisfactory answer to the question, for he had never seen or heard of anything like this before.

Jensen found himself unable to continue with the job. He was too excited about this singular discovery. He felt he simply must talk to someone about it. The obvious man of course was Dr. Marlowe, one of the senior staff members. Most astronomers specialise on one or other of the many facets of their subject. Marlowe had his specialities too, but he was above all a man of immense general knowledge. Perhaps because of this he made fewer mistakes than most people. He was ready to talk astronomy at all hours of the day and night, and he would talk with intense enthusiasm to anyone, whether a distinguished scientist like himself or a young man at the threshold of his career. It was natural therefore that Jensen should wish to tell Marlowe about his curious find.

He carefully put the two plates in question in a box, switched off the electrical equipment and the lights in the basement, and made his way to the notice board outside the library. The next step was to consult the observing list. He found to his satisfaction that Marlowe was not away either at Palomar or Mount Wilson. But, of course, he might have gone out for the evening. Jensen's luck was in, however, for a phone call soon elicited that Marlowe was at home. When he explained that he wanted to talk to him about something queer that had turned up, Marlowe said:

"Come right over, Knut, I'll be expecting you. No, it's all right. I wasn't doing anything particular."

It says much for Jensen's state of mind that he rang for a taxi to take him to Marlowe's house. A student with an annual emolument of two thousand dollars does not normally travel by taxi. This was particularly so in Jensen's case. Economy was important to him because he wished to travel around the different observatories in the United States before he returned to Norway, and he had presents to buy, too. But on this occasion the matter of money never entered his head. He rode up to Altadena, clutching his box of plates, and wondered whether in some way he'd made a fool of himself. Had he made some stupid mistake?

Marlowe was waiting.

"Come right in," he said. "Have a drink. You take it strong in Norway, don't you?"

Knut smiled.

"Not so strong as you take it, Dr. Marlowe."

Marlowe motioned Jensen to an easy chair by the log fire (so beloved by many who live in centrally heated houses), and after moving a large cat from a second chair, sat down himself.

"Lucky you rang, Knut. My wife's out for the evening, and I was wondering what to do with myself."

Then, typically, he plunged straight to the issue—diplomacy and political finesse were unknown to him.

"Well, what've you got there?" he said, nodding at the yellow box that Jensen had brought.

Somewhat sheepishly, Knut took out the first of his two pictures, one taken on 9th December, 1963, and handed it over without comment. He was soon gratified by the reaction.

"My God!" exclaimed Marlowe. "Taken with the 18-inch, I expect. Yes, I see you've got it marked on the side of the plate."

"Is there anything wrong, do you think?"

"Nothing so far as I can see." Marlowe took a magnifying glass out of his pocket and scanned carefully over the plate.

"Looks perfectly all right. No plate defects."

"Tell me why you're so surprised, Dr. Marlowe."

"Well, isn't this what you wanted me to look at?"

"Not by itself. It's the comparison with a second plate that I took a month later that looks so odd."

"But this first one is singular enough," said Marlowe. "You've had it lying in your drawer for a month! Pity you didn't show it to me right away. But of course, you weren't to know."

"I don't see why you're so surprised by this one plate though."

"Well, look at this dark circular patch. It's obviously a dark cloud obscuring the light from the stars that lie beyond it. Such globules are not uncommon in the Milky Way, but usually they're tiny things. My God, look at this! It's huge, it must be the best part of two and a half degrees across!"

"But, Dr. Marlowe, there are lots of clouds bigger than this, especially in the region of Sagittarius."

"If you look carefully at what seem like very big clouds, you'll find them to be built up of lots of much smaller clouds. This thing you've got here seems, on the other hand, to be just one single spherical cloud. What really surprises me is how I could have missed anything as big as this."

Marlowe looked again at the markings on the plate.

"It is true that it's in the south, and we're not so concerned with the winter sky. Even so, I don't see how I could have missed it when I was working on the Trapezium in Orion. That was only three or four years ago and I wouldn't have forgotten anything like this."

Marlowe's failure to identify the cloud—for this is undoubtedly what it was—came as a surprise to Jensen. Marlowe knew the sky and all the strange objects to be found in it as well as he knew the streets and avenues of Pasadena.

Marlowe went over to the sideboard to renew the drinks. When he came back, Jensen said:

"It was this second plate that puzzled me."

Marlowe had not looked at it for ten seconds before he was back to the first plate. His experienced eye needed no 'blinker' to see that in the first plate the cloud was surrounded by a ring of stars that were either absent or nearly absent in the second plate. He continued to gaze thoughtfully at the two plates.

"There was nothing unusual about the way you took these pictures?"

"Not so far as I know."

"They certainly look all right, but you can never be quite sure."

Marlowe broke off abruptly and stood up. Now, as always when he was excited or agitated, he blew out enormous clouds of aniseed-scented tobacco smoke, a South African variety. Jensen marvelled that the bowl of his pipe did not burst into flames.

"Something crazy may have happened. The best thing we can do is to get another plate shot straight away. I wonder who is on the mountain tonight."

"You mean Mount Wilson or Palomar?"

"Mount Wilson. Palomar's too far."

"Well, as far as I remember one of the visiting astronomers is using the 100-inch. I think Harvey Smith is on the 60-inch."

"Look, it would probably be best if I went up myself. Harvey won't mind letting me have a few moments. I won't be able to get the whole nebulosity of course, but I can get some of the star fields at the edge. Do you know the exact co-ordinates?"

"No. I phoned as soon as I'd tried the plates in the 'blink.' I didn't stop to measure them."

"Well, never mind, we can do that on the way. But there's no real need to keep you out of bed, Knut. Why don't I drop you at your apartment? I'll leave a note for Mary saying I won't be back until sometime tomorrow."

Jensen was excited when Marlowe dropped him at his lodging. Before he turned in that night he wrote letters home, one to his parents telling them very briefly of the unusual discovery, and another to Greta saying that he believed that he'd stumbled on something important.

Marlowe drove to the Observatory offices. His first step was to get Mount Wilson on the phone and to talk to Harvey Smith. When he heard Smith's soft southern accent, he said:

"This is Geoff Marlowe. Look, Harvey, something pretty queer has turned up, so queer that I'm wondering if you'd let me have the 60-inch for tonight. What is it? I don't know what it is. That's just what I want to find out. It's to do with young Jensen's work. Come down here at ten o'clock tomorrow and I'll be able to tell you more about it. If you're bored I'll stand you a bottle of Scotch. That's good enough for you? Fine! Tell the night assistant that I'll be up at about one o'clock, will you?"

Marlowe next put through a call to Bill Barnett of Caltech.

"Bill, this is Geoff Marlowe ringing from the offices. I wanted to tell you that there'll be a pretty important meeting here tomorrow morning at ten o'clock. I'd like you to come along and to bring a few theoreticians along. They don't need to be astronomers. Bring several bright boys. . . . No I can't explain now. I'll know more tomorrow. I'm going on the 60-inch tonight. But I'll tell you what, if you think by lunch-time tomorrow that I've got you out on a wild-goose chase, I'll stand you a crate of Scotch. . . . Fine!"

He hummed with excitement as he hurried down to the basement where Jensen had been working earlier in the evening. He spent some three-quarters of an hour measuring Jensen's plates. When at last he was satisfied that he would know exactly where to point the telescope, he went out, climbed into his car, and drove off towards Mount Wilson.

Dr. Herrick, the Director of the Observatory, was astonished to find Marlowe waiting for him when he reached his office at seven-thirty the following morning. It was the Director's habit to start his day some two hours before the main body of his staff, "in order to get some work done," as he used to say. At the other extreme, Marlowe usually did not put in an appearance until ten-thirty, and sometimes later still. This day, however, Marlowe was sitting at his desk, carefully examining a pile of about a dozen positive prints. Herrick's surprise was not lessened when he heard what Marlowe had to say. The two men spent the next hour and a half in earnest conversation. At about nine o'clock they slipped out for a quick breakfast, and returned in time to make preparations for a meeting to be held in the library at ten o'clock.

When Bill Barnett's party of five arrived they found some dozen members of the Observatory already assembled, including Jensen, Rogers, Emerson and Harvey Smith. A blackboard had been fitted up and a screen and lantern for showing slides. The only member of Barnett's party who had to be introduced round was Dave Weichart. Marlowe, who had heard a number of reports of the abilities of this brilliant twenty-seven-year-old physicist, noted that Barnett had evidently done his best to bring a bright boy along.

"The best thing I can do," began Marlowe, "is to explain things in a chronological way, starting with the plates that Knut Jensen brought to my house last night. When I've shown them you'll see why this emergency meeting was called."

Emerson, who was working the lantern, put in a slide that Marlowe had made up from Jensen's first plate, the one taken on the night of 9th December, 1963.

"The centre of the dark blob," went on Marlowe, "is in Right Ascension 5 hours 49 minutes, Declination minus 30 degrees 16 minutes, as near as I can judge."

"A fine example of a Bok globule," said Barnett.

"How big is it?"

"About two and a half degrees across."

There were gasps from several of the astronomers.

"Geoff, you can keep your bottle of whisky," said Harvey Smith.

"And my crate, too," added Bill Barnett amidst the general laughter.

"I reckon you'll be needing the whisky when you see the next plate. Bert, keep rocking the two backwards and forwards, so that we can get some idea of a comparison," went on Marlowe.

"It's fantastic," burst out Rogers, "it looks as if there's a whole ring of oscillating stars surrounding the cloud. But how could that be?"

"It can't," answered Marlowe. "That's what I saw straight away. Even if we admit the unlikely hypothesis that this cloud is surrounded by a halo of variable stars, it is surely quite inconceivable that they'd all oscillate in phase with each other, all up together as in the first slide, and all down together in the second."

"No, that's preposterous," broke in Barnett. "If we're to take it that there's been no slip-up in the photography, then surely there's only one possible explanation. The cloud is moving towards us. In the second slide it's nearer to us, and therefore it's obscuring more of the distant stars. At what interval apart were the two plates taken?"

"Rather less than a month."

"Then there must be something wrong with the photography."

"That's exactly the way I reasoned last night. But as I couldn't see anything wrong with the plates, the obvious thing was to take some new pictures. If a month made all that difference between Jensen's first plate and his second, then the effect should have been easily detectable in a week—Jensen's last plate was taken on 7th January. Yesterday was 14th January. So I rushed up to Mount Wilson, bullied Harvey off the 60-inch, and spent the night photographing the edges of the cloud. I've got a whole collection of new slides here. They're not of course on the same scale as Jensen's plates, but you'll be able to see pretty well what's happening. Put them through one by one, Bert, and keep referring back to Jensen's plate of 7th January."

There was almost dead silence for the next quarter of an hour, as the star fields on the edge of the cloud were carefully compared by the assembled astronomers. At the end Barnett said:

"I give up. As far as I'm concerned there isn't a shadow of a doubt but that this cloud is travelling towards us."

And it was clear that he had expressed the conviction of the meeting. The stars at the edge of the cloud were being steadily blacked out as it advanced towards the solar system.

"Actually there's no doubt at all about it," went on Marlowe. "When I discussed things with Dr. Herrick earlier this morning he pointed out that we have a photograph taken twenty years ago of this part of the sky."

Herrick produced the photograph.

"We haven't had time to make up a slide," said he, "so you will have to hand it round. You can see the black cloud, but it's small on this picture, no more than a tiny globule. I've marked it with an arrow."

He handed the picture to Emerson who, after passing it to Harvey Smith, said:

"It's certainly grown enormously over the twenty years. I'm a bit apprehensive about what's going to happen in the next twenty. It seems as if it might cover the whole constellation of Orion. Pretty soon astronomers will be out of business."

It was then that Dave Weichart spoke up for the first time.

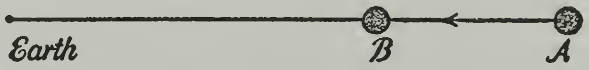
"I've two questions that I'd like to ask. The first is about the position of the cloud. As I understand what you've said, the cloud is growing in its apparent size because it's getting nearer to us. That's clear enough. But what I'd like to know is whether the centre of the cloud is staying in the same position, or does it seem to be moving against the background of the stars?"

"A very good question. The centre seems, over the last twenty years, to have moved very little relative to the star field," answered Herrick.

"Then that means the cloud is coming dead at the solar system."

Weichart was used to thinking more quickly than other people, so when he saw hesitation to accept his conclusion, he went to the blackboard.

"I can make it clear with a picture. Here's the Earth. Let's suppose first that the cloud is moving dead towards us, like this, from A to B. Then at B the cloud will look bigger but its centre will be in the same direction. This is the case that apparently corresponds pretty well to the observed situation."



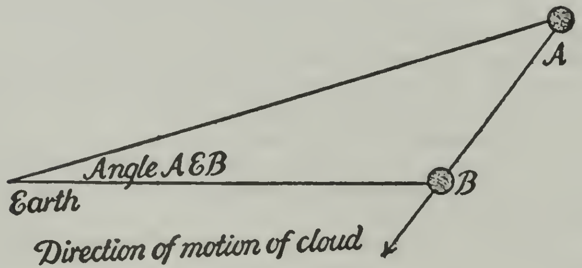
There was a general murmur of assent, so Weichart went on:

"Now let's suppose that the cloud is moving sideways, as well as towards us, and let's suppose that the motion sideways is about as fast as the motion towards us. Then the cloud will move about like this. Now if you consider the motion from A to B you'll see that there are two effects—the cloud will seem bigger at B than it was at A, exactly as in the previous case, but now the centre will have moved. And it will move through the angle AEB which must be something of the order of thirty degrees."

"I don't think the centre has moved through an angle of more than a quarter of a degree," remarked Marlowe.

"Then the sideways motion can't be more than about one per cent of the motion towards us. It looks as though the cloud is heading towards the solar system like a bullet at a target."

"You mean, Dave, that there's no chance of the cloud missing the solar system, of it being a near-miss, let us say?"



"On the facts as they've been given to us that cloud is going to score a bull's eye, plumb in the middle of the target. Remember that it's already two and a half degrees in diameter. The transverse velocity would have to be as much as ten per cent or so of the radial velocity if it were to miss us. And that would imply a far greater angular motion of the centre than Dr. Marlowe says has taken place. The other question I'd like to ask is, why wasn't the cloud detected sooner? I don't want to be rude about it, but it seems very surprising that it wasn't picked up quite a while ago, say ten years ago."

"That of course was the first thing that sprang to my mind," answered Marlowe. "It seemed so astonishing that I could scarcely credit the validity of Jensen's work. But then I saw a number of reasons. If a bright nova or a supernova were to flash out in the sky it would immediately be detected by thousands of ordinary people, let alone by astronomers. But this is not something bright, it's something dark, and that's not so easy to pick up—a dark patch is pretty well camouflaged against the sky Of course if one of the stars that has been hidden by the cloud had happened to be a bright fellow it would have been spotted. The disappearance of a bright star is not so easy to detect as the appearance of a new bright star, but it would nevertheless have been noticed by thousands of professional and amateur astronomers. It happened, however, that all the stars near the cloud are telescopic, none brighter than eighth magnitude. That's the first mischance. Then you must know that in order to get good seeing conditions we prefer to work on objects near the zenith, whereas this cloud lies rather low in our sky. So we would naturally tend to avoid that part of the sky unless it happened to contain some particularly interesting material, which by a second mischance (if we exclude the case of the cloud) it does not. It is true that to observatories in the southern hemisphere the cloud would be high in the sky, but observatories in the southern hemisphere are hard put to it with their small staffs to get through a host of important problems connected with the Magellanic Clouds and the nucleus of the Galaxy. The cloud had to be detected sooner or later. It turned out to be later, but it might have been sooner. That's all I can say."

"It's too late to worry about that now," said the Director. "Our next step must be to measure the speed with which the cloud is moving towards us. Marlowe and I have had a long talk about it, and we think it should be possible. Stars on the fringe of the cloud are partially obscured, as the plates taken by Marlowe last night show. Their spectrum should show absorption lines due to the cloud, and the Doppler shift will give us the speed."

"Then it should be possible to calculate how long the cloud will be before it reaches us," joined in Barnett. "I must say I don't like the look of things. The way the cloud has increased its angular diameter during the last twenty years makes it look as if it'll be on top of us within fifty or sixty years. How long do you think it'll take to get a Doppler shift?"

"Perhaps about a week. It shouldn't be a difficult job."

"Sorry I don't understand all this," broke in Weichart. "I don't see why you need the speed of the cloud. You can calculate straight away how long the cloud is going to take to reach us. Here, let me do it. My guess is that the answer will turn out at much less than fifty years."

For the second time Weichart left his seat, went to the blackboard, and cleaned off his previous drawings.

"Could we have Jensen's two slides again please?"

When Emerson had flashed them up, first one and then the other, Weichart asked: "Could you estimate how much larger the cloud is in the second slide?"

"I would say about five per cent larger. It may be a little more or a little less, but certainly not very far away from that," answered Marlowe.

"Right," Weichart continued, "let's begin by defining a few symbols."

Then followed a somewhat lengthy calculation at the end of which Weichart announced:

"And so you see that the black cloud will be here by August, 1965, or possibly sooner if some of the present estimates have to be corrected."

Then he stood back from the blackboard, checking through his mathematical argument.

"It certainly looks all right—very straightforward in fact," said Marlowe, putting out great volumes of smoke.★

"Yes, it seems unimpeachably correct," answered Weichart.

At the end of Weichart's astonishing calculation, the Director had thought it wise to caution the whole meeting to secrecy. Whether they were right or wrong, no good could come of talking outside the Observatory, not even at home. Once the spark was struck the story would spread like wildfire, and would be in the papers in next to no time. The Director had never had any cause to think highly of newspaper reporters, particularly of their scientific accuracy.

From mid-day to two o'clock he sat alone in his office, wrestling with the most difficult situation he had ever ex-

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★ The details of Weichart's remarks and work while at the blackboard were as follows:

"Write α for the present angular diameter of the cloud, measured in radians,

d for the linear diameter of the cloud,
D for its distance away from us,
V for its velocity of approach,
T for the time required for it to reach the solar system.

To make a start, evidently we have $\alpha = d/D$
Differentiate this equation with respect to time t and we get

$$\frac{d\alpha}{dt} = \frac{-d}{D^2}\frac{dD}{dt}.$$

But $V = -\frac{dD}{dt}$, so that we can write $\frac{d\alpha}{dt} = \frac{d}{D^2}V$.

Also we have $\frac{D}{V} = T$. Hence we can get rid of V, arriving at

$$\frac{d\alpha}{dt} = \frac{d}{DT}.$$

This is turning out easier than I thought. Here's the answer already

$$T = \alpha\frac{dt}{d\alpha}.$$

The last step is to approximate $\frac{dt}{d\alpha}$ by finite intervals, $\frac{\Delta t}{\Delta\alpha}$, where $\Delta t = 1$ month corresponding to the time difference between Dr. Jensen's two plates; and from what Dr. Marlowe has estimated $\Delta\alpha$ is about 5 per cent of α, i.e. $\frac{\alpha}{\Delta\alpha} = 20$. Therefore $T = 20\Delta t = 20$ months."

perienced. It was utterly antipathetic to his nature to announce any result or to take steps on the basis of a result until it had been repeatedly checked and cross-checked. Yet would it be right for him to maintain silence for a fortnight or more? It would be two or three weeks at least before every facet of the matter were fully investigated. Could he afford the time? For perhaps the tenth time he worked through Weichart's argument. He could see no flaw in it.

At length he called in his secretary.

"Please will you ask Caltech to fix me a seat on the night plane to Washington, the one that leaves about nine o'clock. Then get Dr. Ferguson on the phone."

James Ferguson was a big noise in the National Science Foundation, controlling all the activities of the Foundation in physics, astronomy, and mathematics. He had been much surprised at Herrick's phone call of the previous day. It was quite unlike Herrick to fix appointments at one day's notice.

"I can't imagine what can have bitten Herrick," he told his wife at breakfast, "to come chasing over to Washington like this. He was quite insistent about it. Sounded agitated, so I said I'd pick him up at the airport."

"Well, an occasional mystery is good for the system," said his wife. "You'll know soon enough."

On the way from the airport to the city, Herrick would commit himself to nothing but conventional trivialities. It was not until he was in Ferguson's office that he came to the issue.

"There's no danger of us being overheard, I suppose?"

"Goodness, man, is it as serious as that? Wait a minute."

Ferguson lifted the phone.

"Amy, will you please see that I'm not interrupted—no, no phone calls—well, perhaps for an hour, perhaps two, I don't know."

Quietly and logically Herrick then explained the situation. When Ferguson had spent some time looking at the photographs, Herrick said:

"You see the predicament. If we announce the business and we turn out to be wrong then we shall look awful fools. If we spend a month testing all the details and it turns out that we are right then we should be blamed for procrastination and delay."

"You certainly would, like an old hen sitting on a bad egg."

"Well, James, I thought you have had a great deal of experience in dealing with people. I felt you were someone I could turn to for advice. What do you suggest I should do?"

Ferguson was silent for a little while. Then he said:

"I can see that this may turn out to be a grave matter. And I don't like taking grave decisions any more than you do, Dick, certainly not on the spur of the moment. What I suggest is this. Go back to your hotel and sleep through the afternoon—I don't expect you had much sleep last night. We can meet again for an early dinner, and by then I'll have had an opportunity to think things over. I'll try to reach some conclusion."

Ferguson was as good as his word. When he and Herrick had started their evening meal, in a quiet restaurant of his choice, Ferguson began:

"I think I've got things sorted out fairly well. It doesn't seem to me to make sense wasting another month in making sure of your position. The case seems to be very sound as it is, and you can never be quite certain—it would be a matter of converting a ninety-nine per cent certainty into a ninety-nine point nine per cent certainty. And that isn't worth the loss of time. On the other hand you are ill-prepared to go to the White House just at the moment. According to your own account you and your men have spent less than a day on the job so far. Surely there are a good many other things you might get ideas about. More exactly, how long is it going to take the cloud to get here? What will its effects be when it does get here? That sort of question.

"My advice is to go straight back to Pasadena, get your team together, and aim to write a report within a week, setting out the situation as you see it. Get all your men to sign it—so that there's no question of the tale getting round of a mad Director. And then come back to Washington.

"In the meantime I'll get things moving at this end. It isn't a bit of good in a case like this starting at the bottom by whispering into the ear of some Congressman. The only thing to do is to go straight to the President. I'll try to smooth your path there."

This pleasant introduction to the planets and the solar system is by a writer well known as a scientist, a popularizer of science, and a writer of science fiction. Asimov approaches the solar system historically, briefly considering the discovery of some of the planets.

2

Roll Call

Isaac Asimov

A chapter from his book *Of Time and Space and Other Things*, 1963.

When all the world was young (and I was a teen-ager), one way to give a science fiction story a good title was to make use of the name of some heavenly body. Among my own first few science fiction stories, for instance, were such items as "Marooned off Vesta," "Christmas on Ganymede," and "The Callistan Menace." (Real swinging titles, man!)

This has gone out of fashion, alas, but the fact remains that in the 1930's, a whole generation of science fiction fans grew up with the names of the bodies of the Solar System as familiar to them as the names of the American states. Ten to one they didn't know why the names were what they were, or how they came to be applied to the bodies of the Solar System or even, in some cases, how they were pronounced—but who cared? When a tentacled monster came from Umbriel or Io, how much more impressive that was than if it had merely come from Philadelphia.

But ignorance must be battled. Let us, therefore, take up the matter of the names, call the roll of the Solar System in the order (more or less) in which the names were applied, and see what sense can be made of them.

The *Earth* itself should come first, I suppose. Earth is an old Teutonic word, but it is one of the glories of the English language that we always turn to the classic tongues as well. The Greek word for Earth was *Gaia* or, in Latin spelling, *Gaea*. This gives us "geography" ("earth-writing"), "geology" ("earth-discourse"), "geometry" ("earth-measure"), and so on.

The Latin word is *Terra*. In science fiction stories a human being from Earth may be an "Earthling" or an "Earthman," but he is frequently a "Terrestrial," while a creature from another world is almost invariably an "extra-Terrestrial."

The Romans also referred to the Earth as *Tellus Mater* ("Mother Earth" is what it means). The genitive form of *tellus* is *telluris,* so Earthmen are occasionally referred to in s.f. stories as "Tellurians." There is also a chemical element "tellurium," named in honor of this version of the name of our planet.

But putting Earth to one side, the first two heavenly bodies to have been noticed were, undoubtedly and obviously, the *Sun* and the *Moon,* which, like Earth, are old Teutonic words.

To the Greeks the Sun was *Helios,* and to the Romans it was *Sol.* For ourselves, Helios is almost gone, although we have "helium" as the name of an element originally found in the Sun, "heliotrope" ("sun-turn") for the sunflower, and so on.

Sol persists better. The common adjective derived from "sun" may be "sunny," but the scholarly one is "solar." We may speak of a sunny day and a sunny disposition, but never of the "Sunny System." It is always the "Solar System." In science fiction, the Sun is often spoken of as Sol, and the Earth may even be referred to as "Sol III."

The Greek word for the Moon is *Selene*, and the Latin word is *Luna.* The first lingers on in the name of the chemical element "selenium," which was named for the Moon. And the study of the Moon's surface features may be called "selenography." The Latin name appears in the common adjective, however, so that one speaks of a "lunar crescent" or a "lunar eclipse." Also, because of the theory that exposure to the light of the full Moon drove men crazy ("moon-struck"), we obtained the word "lunatic."

I have a theory that the notion of naming the heavenly bodies after mythological characters did not originate with the Greeks, but that it was a deliberate piece of copycattishness.

To be sure, one speaks of *Helios* as the god of the Sun and *Gaea* as the goddess of the Earth, but it seems obvious to me that the words came first, to express the physical objects, and that these were personified into gods and goddesses later on.

The later Greeks did, in fact, feel this lack of mythological character and tried to make Apollo the god of the Sun and Artemis (Diana to the Romans) the goddess of the Moon. This may have taken hold of the Greek scholars but not of the ordinary folk, for whom Sun and Moon remained *Helios* and *Selene*. (Nevertheless, the influence of this Greek attempt on later scholars was such that no other important heavenly body was named for Apollo and Artemis.)

I would like to clinch this theory of mine, now, by taking up another heavenly body.

After the Sun and Moon, the next bodies to be recognized as important individual entities must surely have been the five bright "stars" whose positions with respect to the real stars were not fixed and which therefore, along with the Sun and the Moon, were called planets (see Chapter 4).

The brightest of these "stars" is the one we call Venus, and it must have been the first one noticed—but not necessarily as an individual. Venus sometimes appears in the evening after sunset, and sometimes in the morning before sunrise, depending on which part of its orbit it happens to occupy. It is therefore the "Evening Star" sometimes and the "Morning Star" at other times. To the early Greeks, these seemed two separate objects and each was given a name.

The Evening Star, which always appeared in the west near the setting Sun, was named *Hesperos* ("evening" or "west"). The equivalent Latin name was *Vesper*. The Morning Star was named *Phosphoros* ("light-bringer"), for when the Morning Star appeared the Sun and its light were not far behind. (The chemical element "phosphorus"—Latin spelling—was so named because it glowed in the dark as the result of slow combination with oxygen.) The Latin name for the Morning Star was *Lucifer*, which also means "light-bringer."

Now notice that the Greeks made no use of mythology here. Their words for the Evening Star and Morning Star were logical, descriptive words. But then (during the sixth century B.C.) the Greek scholar, Pythagoras of Samos, arrived back in the Greek world after his travels in Babylonia. He brought with him a skull-full of Babylonian notions.

At the time, Babylonian astronomy was well developed and far in advance of the Greek bare beginnings. The Babylonian interest in astronomy was chiefly astrological in nature and so it seemed natural for them to equate the powerful planets with the powerful gods. (Since both had power over human beings, why not?) The Babylonians knew that the Evening Star and the Morning Star were a single planet—after all, they never appeared on the same day; if one was present, the other was absent, and it was clear from their movements that the Morning Star passed the Sun and became the Evening Star and vice versa. Since the planet representing both was so bright and beautiful, the Babylonians very logically felt it appropriate to equate it with Ishtar, their goddess of beauty and love.

Pythagoras brought back to Greece this Babylonian knowledge of the oneness of the Evening and Morning Star, and Hesperos and Phosphoros vanished from the heavens. Instead, the Babylonian system was copied and the planet was named for the Greek goddess of beauty and love, Aphrodite. To the Romans this was their corresponding goddess *Venus*, and so it is to us.

Thus, the habit of naming heavenly bodies for gods and goddesses was, it seems to me, deliberately copied from the Babylonians (and their predecessors) by the Greeks.

The name "Venus," by the way, represents a problem. Adjectives from these classical words have to be taken from the genitive case and the genitive form of "Venus" is *Veneris*. (Hence, "venerable" for anything worth the respect paid by the Romans to the goddess; and because the Romans respected old age, "venerable" came to be applied to old men rather than young women.)

So we cannot speak of "Venusian atmosphere" or "Venutian atmosphere" as science fiction writers sometimes do. We must say "Venerian atmosphere." Unfortunately, this has uncomfortable associations and it is not used. We might turn back to the Greek name but the genitive form there is *Aphrodisiakos*, and if we speak of the "Aphrodisiac atmosphere" I think we will give a false impression.

But something must be done. We are actually exploring the atmosphere of Venus with space probes and some adjective is needed. Fortunately, there is a way out. The Venus cult was very prominent in early days in a small island south of Greece. It was called Kythera (Cythera in Latin spelling) so that Aphrodite was referred to, poetically, as the "Cytherean goddess." Our poetic astronomers have therefore taken to speaking of the "Cytherean atmosphere."

The other four planets present no problem. The second brightest planet is truly the king planet. Venus may be brighter but it is confined to the near neighborhood of the Sun and is never seen at midnight. The second brightest, however, can shine through all the hours of night and so it should fittingly be named for the chief god. The Babylonians accordingly named it "Marduk." The Greeks followed suit and called it "Zeus," and the Romans named it *Jupiter.* The genitive form of Jupiter is *Jovis,* so that we speak of the "Jovian satellites." A person born under the astrological influence of Jupiter is "jovial."

Then there is a reddish planet and red is obviously the color of blood; that is, of war and conflict. The Babylonians named this planet "Nergal" after their god of war, and the Greeks again followed suit by naming it "Ares" after theirs. Astronomers who study the surface features of the planet are therefore studying "areography." The Latins used their god of war, *Mars,* for the planet. The genitive form is *Martis,* so we can speak of the "Martian canals."

The planet nearest the Sun, appears, like Venus, as both an evening star and morning star. Being smaller and less reflective than Venus, as well as closer to the Sun, it is much harder to see. By the time the Greeks got around to naming it, the mythological notion had taken hold. The evening star manifestation was named "Hermes," and the morning star one "Apollo."

The latter name is obvious enough, since the later Greeks associated Apollo with the Sun, and by the time the planet Apollo was in the sky the Sun was due very shortly. Because the planet was closer to the Sun than any other planet (though, of course, the Greeks did not know this was the reason), it moved more quickly against the stars than any object but the Moon. This made it resemble the wing-footed messenger of the gods, Hermes. But giving the planet two names was a matter of conservatism. With the Venus matter straightened out, Hermes/Apollo was quickly reduced to a single planet and Apollo was dropped. The Romans named it "Mercurius," which was their equivalent of Hermes, and we call it *Mercury*. The quick journey of Mercury across the stars is like the lively behavior of droplets of quicksilver, which came to be called "mercury," too, and we know the type of personality that is described as "mercurial."

There is one planet left. This is the most slowly moving of all the planets known to the ancient Greeks (being the farthest from the Sun) and so they gave it the name of an ancient god, one who would be expected to move in grave and solemn steps. They called it "Cronos," the father of Zeus and ruler of the universe before the successful revolt of the Olympians under Zeus's leadership. The Romans gave it the name of a god they considered the equivalent of Cronos and called it "Saturnus," which to us is *Saturn*. People born under Saturn are supposed to reflect its gravity and are "saturnine."

For two thousand years the Earth, Sun, Moon, Mercury, Venus, Mars, Jupiter, and Saturn remained the only known bodies of the Solar System. Then came 1610 and the Italian astronomer Galileo Galilei, who built himself a telescope and turned it on the heavens. In no time at all he found four subsidiary objects circling the planet Jupiter. (The German astronomer Johann Kepler promptly named such subsidiary bodies "satellites," from a Latin word for the hangers-on of some powerful man.)

There was a question as to what to name the new bodies. The mythological names of the planets had hung on into the Christian era, but I imagine there must have been some natural hesitation about using heathen gods for new bodies. Galileo himself felt it wise to honor Cosimo Medici II, Grand Duke of Tuscany from whom he expected (and later received) a position, and called them *Sidera Medicea* (the Medicean stars). Fortunately this didn't stick. Nowadays we call the four satellites the "Galilean satellites" as a group, but individually we use mythological names after all. A German astronomer, Simon Marius, gave them these names after having discovered the satellites one day later than Galileo.

The names are all in honor of Jupiter's (Zeus's) loves, of which there were many. Working outward from Jupiter, the first is *Io* (two syllables please, eye′oh), a maiden whom Zeus turned into a heifer to hide her from his wife's jealousy. The second is *Europa,* whom Zeus in the form of a bull abducted from the coast of Phoenicia in Asia and carried to Crete (which is how Europe received its name). The third is *Ganymede,* a young Trojan lad (well, the Greeks were liberal about such things) whom Zeus abducted by assuming the guise of an eagle. And the fourth is *Callisto,* a nymph whom Zeus's wife caught and turned into a bear.

As it happens, naming the third satellite for a male rather than for a female turned out to be appropriate, for Ganymede is the largest of the Galilean satellites and, indeed, is the largest of any satellite in the Solar System. (It is even larger than Mercury, the smallest planet.)

The naming of the Galilean satellites established once and for all the convention that bodies of the Solar System were to be named mythologically, and except in highly unusual instances this custom has been followed since.

In 1655 the Dutch astronomer Christian Huygens discovered a satellite of Saturn (now known to be the sixth from the planet). He named it *Titan.* In a way this was appropriate, for Saturn (Cronos) and his brothers and sisters, who ruled the Universe before Zeus took over, were referred to collectively as "Titans." However, since the name refers to a group of beings and not to an individual being, its use is unfortunate. The name was appropriate in a second fashion, too. "Titan" has come to mean "giant" because the Titans and their allies were pictured by the Greeks as being of superhuman size (whence the word "titanic"), and it turned out that Titan was one of the largest satellites in the Solar System.

The Italian-French astronomer Gian Domenico Cassini was a little more precise than Huygens had been. Between 1671 and 1684 he discovered four more satellites of Saturn, and these he named after individual Titans and Titanesses. The satellites now known to be 3rd, 4th, and 5th from Saturn he named *Tethys, Dione,* and *Rhea,* after three sisters of Saturn. Rhea was Saturn's wife as well. The 8th satellite from Saturn he named *Iapetus* after one of Saturn's brothers. (Iapetus is frequently mispronounced. In English it is "eye-ap′ih-tus.") Here finally the Greek names were used, chiefly because there were no Latin equivalents, except for Rhea. There the Latin equivalent is *Ops.* Cassini tried to lump the four satellites he had discovered under the name of "Ludovici" after his patron, Louis XIV–*Ludovicus,* in Latin–but that second attempt to honor royalty also failed.

And so within 75 years after the discovery of the telescope, nine new bodies of the Solar System were discovered, four satellites of Jupiter and five of Saturn. Then something more exciting turned up.

On March 13, 1781, a German-English astronomer, William Herschel, surveying the heavens, found what he thought was a comet. This, however, proved quickly to be no comet at all, but a new planet with an orbit outside that of Saturn.

There arose a serious problem as to what to name the new planet, the first to be discovered in historic times. Herschel himself called it "Georgium Sidus" ("George's star") after his patron, George III of England, but this third attempt to honor royalty failed. Many astronomers felt it should be named for the discoverer and called it "Herschel." Mythology, however, won out.

The German astronomer Johann Bode came up with a truly classical suggestion. He felt the planets ought to make a heavenly family. The three innermost planets (excluding the Earth) were Mercury, Venus, and Mars, who were siblings, and children of Jupiter, whose orbit lay outside theirs. Jupiter in turn was the son of Saturn, whose orbit lay outside his. Since the new planet had an orbit outside Saturn's, why not name it for *Uranus,* god of the sky and father of Saturn? The suggestion was accepted and Uranus* it was. What's more, in 1798 a German chemist, Martin Heinrich Klaproth, discovered a new element he named in its honor as "uranium."

In 1787 Herschel went on to discover Uranus's two largest satellites (the 4th and 5th from the planet, we now know). He named them from mythology, but *not* from Graeco-Roman mythology. Perhaps, as a naturalized Englishman, he felt 200 per cent English (it's that way, sometimes) so he turned to English folktales and named the satellites *Titania* and *Oberon,* after the queen and king of the fairies (who make an appearance, notably, in Shakespeare's *A Midsummer Night's Dream*).

In 1789 he went on to discover two more satellites of Saturn (the two closest to the planet) and here too he disrupted mythological logic. The planet and the five satellites then known were all named for various Titans and Titanesses (plus the collective name, Titan). Herschel named his two *Mimas* and *Enceladus* (en-sel′a-dus) after two of the giants who rose in rebellion against Zeus long after the defeat of the Titans.

After the discovery of Uranus, astronomers climbed hungrily upon the discover-a-planet bandwagon and searched particularly in the unusually large gap between Mars and Jupiter. The first to find a body there was the Italian astronomer Giuseppe Piazzi. From his observatory at Palermo, Sicily he made his first sighting on January 1, 1801.

Although a priest, he adhered to the mythological convention and named the new body *Ceres,* after the tutelary goddess of his native Sicily. She was a sister of Jupiter and the goddess of grain (hence "cereal") and agriculture. This was the second planet to receive a feminine name (Venus was the first, of course) and it set a fashion. Ceres turned out to be a small body (485 miles in diameter), and many more were found in the gap between Mars

* Uranus is pronounced "yoo′ruh-nus." I spent almost all my life accenting the second syllable and no one ever corrected me. I just happened to be reading Webster's Unabridged one day . . .

and Jupiter. For a hundred years, all the bodies so discovered were given feminine names.

Three "planetoids" were discovered in addition to Ceres over the next six years. Two were named *Juno* and *Vesta* after Ceres' two sisters. They were also the sisters of Jupiter, of course, and Juno was his wife as well. The remaining planetoid was named *Pallas,* one of the alternate names for Athena, daughter of Zeus (Jupiter) and therefore a niece of Ceres. (Two chemical elements discovered in that decade were named "cerium" and "palladium" after Ceres and Pallas.)

Later planetoids were named after a variety of minor goddesses, such as *Hebe,* the cupbearer of the gods, *Iris,* their messenger, the various Muses, Graces, Horae, nymphs, and so on. Eventually the list was pretty well exhausted and planetoids began to receive trivial and foolish names. We won't bother with those.

New excitement came in 1846. The motions of Uranus were slightly erratic, and from them the Frenchman Urbain J. J. Leverrier and the Englishman John Couch Adams calculated the position of a planet beyond Uranus, the gravitational attraction of which would account for Uranus's anomalous motion. The planet was discovered in that position.

Once again there was difficulty in the naming. Bode's mythological family concept could not be carried on, for Uranus was the first god to come out of chaos and had no father. Some suggested the planet be named for Leverrier. Wiser council prevailed. The new planet, rather greenish in its appearance, was named *Neptune* after the god of the sea.

(Leverrier also calculated the possible existence of a planet inside the orbit of Mercury and named it *Vulcan,* after the god of fire and the forge, a natural reference to the planet's closeness to the central fire of the Solar System. However, such a planet was never discovered and undoubtedly does not exist.)

As soon as Neptune was discovered, the English astronomer William Lassell turned his telescope upon it and discovered a large satellite which he named *Triton,* appropriately enough, since Triton was a demigod of the sea and a son of Neptune (Poseidon).

In 1851 Lassell discovered two more satellites of Uranus, closer to the planet than Herschel's Oberon and Titania. Lassell, also English, decided to continue Herschel's English folklore bit. He turned to Alexander Pope's *The Rape of the Lock,* wherein were two elfish characters, *Ariel* and *Umbriel,* and these names were given to the satellites.

More satellites were turning up. Saturn was already known to have seven satellites, and in 1848 the American astronomer George P. Bond discovered an eighth; in 1898 the American astronomer William H. Pickering discovered a ninth and completed the list. These were named *Hyperion* and *Phoebe* after a Titan and Titaness. Pickering also thought he had discovered a tenth in 1905, and named it *Themis,* after another Titaness, but this proved to be mistaken.

In 1877 the American astronomer Asaph Hall, waiting for an unusually close approach of Mars, studied its surroundings carefully and discovered two tiny satellites, which he named *Phobos* ("fear") and *Deimos* ("terror"), two sons of Mars (Ares) in Greek legend, though obviously mere personifications of the inevitable consequences of Mars's pastime of war.

In 1892 another American astronomer, Edward E. Barnard, discovered a fifth satellite of Jupiter, closer than the Galilean satellites. For a long time it received no name, being called "Jupiter V" (the fifth to be discovered) or "Barnard's satellite." Mythologically, however, it was given the name *Amalthea* by the French astronomer Camille Flammarion, and this is coming into more common use. I am glad of this. Amalthea was the nurse of Jupiter (Zeus) in his infancy, and it is pleasant to have the nurse of his childhood closer to him than the various girl and boy friends of his maturer years.

In the twentieth century no less than seven more Jovian satellites were discovered, all far out, all quite small, all probably captured planetoids, all nameless. Unofficial names have been proposed. Of these, the three planetoids nearest Jupiter bear the names *Hestia, Hera,* and *Demeter,* after the Greek names of the three sisters of Jupiter (Zeus). Hera, of course, is his wife as well. Under the Roman versions of the names (Vesta, Juno, and Ceres, respectively) all three are planetoids. The two farthest are *Poseidon* and *Hades,* the two brothers of Jupiter (Zeus). The Roman version of Poseidon's name (Neptune) is applied to a planet. Of the remaining satellites, one is *Pan,* a grandson of Jupiter (Zeus), and the other is *Adrastea,* another of the nurses of his infancy.

The name of Jupiter's (Zeus's) wife, Hera, is thus applied to a satellite much farther and smaller than those commemorating four of his extracurricular affairs. I'm not sure that this is right, but I imagine astronomers understand these things better than I do.

In 1898 the German astronomer G. Witt discovered an unusual planetoid, one with an orbit that lay closer to the Sun than did any other of the then-known planetoids. It inched past Mars and came rather close to Earth's orbit. Not counting the Earth, this planetoid might be viewed as passing between Mars and Venus and therefore Witt gave it the name of *Eros,* the god of love, and the son of Mars (Ares) and Venus (Aphrodite).

This started a new convention, that of giving planetoids with odd orbits masculine names. For instance, the planetoids that circle in Jupiter's orbit all received the names of masculine participants in the Trojan war: *Achilles, Hector, Patroclus, Ajax, Diomedes, Agamemnon, Priamus, Nestor, Odysseus, Antilochus, Aeneas, Anchises,* and *Troilus.*

A particularly interesting case arose in 1948, when the German-American astronomer Walter Baade discovered a planetoid that penetrated more closely to the Sun than even Mercury did. He named it *Icarus,* after the mythical character who flew too close to the Sun, so that the wax holding the feathers of his artificial wings melted, with the result that he fell to his death.

Two last satellites were discovered. In 1948 a Dutch-American astronomer, Gerard P. Kuiper, discovered an innermost satellite of Uranus. Since Ariel (the next innermost) is a character in William Shakespeare's *The Tempest* as well as in Pope's *The Rape of the Lock,* free association led Kuiper to the heroine of *The Tempest* and he named the new satellite *Miranda.*

In 1950 he discovered a second satellite of Neptune. The first satellite, Triton, represents not only the name of a particular demigod, but of a whole class of merman-like demigods of the sea. Kuiper named the second, then, after a whole class of mermaid-like nymphs of the sea, *Nereid.*

Meanwhile, during the first decades of the twentieth century, the American astronomer Percival Lowell was searching for a ninth planet beyond Neptune. He died in 1916 without having succeeded but in 1930, from his observatory and in his spirit, Clyde W. Tombaugh made the discovery.

The new planet was named *Pluto,* after the god of the Underworld, as was appropriate since it was the planet farthest removed from the light of the Sun. (And in 1940, when two elements were found beyond uranium, they were named "neptunium" and "plutonium," after Neptune and Pluto, the two planets beyond Uranus.)

Notice, though, that the first two letters of "Pluto" are the initials of Percival Lowell. And so, finally, an astronomer got his name attached to a planet. Where Herschel and Leverrier had failed, Percival Lowell had succeeded, at least by initial, and under cover of the mythological conventions.

Never mind discovering the origin of the universe,
just hanging around the telescope for a night
at Mount Palomar is a pleasant way to pass some relative time

A NIGHT AT THE OBSERVATORY

By HENRY S. F. COOPER, JR.

What is it like to work at a major observatory? A reporter spends a night on Mt. Palomar talking about astronomy with Dr. Jesse L. Greenstein as he photographs star spectra with the 200-inch telescope.

3

A Night at the Observatory

Henry S. F. Cooper, Jr.

An article from *Horizon*, 1967.

A year ago last summer, I was invited out to Mount Palomar, the big observatory in southern California, to spend a night on the two-hundred-inch telescope. A member of the observatory's staff wrote me exuberantly, "The scientists here feel that the last couple of years have been the most exciting in astronomy since Galileo." He was referring to observations of the quasars, most of which had been made at Mount Palomar. Quasars are thought to be tremendously distant objects that may be almost as old as the universe itself; as yet, not a great deal is known about them. "Dr. Jesse L. Greenstein, Executive Officer of the Department of Astronomy at Cal Tech, will be going down to Palomar soon, and he says he will be glad to have you go along," my correspondent continued. "He says to warn you not to expect any great discoveries." That was an acceptable condition. As a final admonition, he added that the telescope is extremely delicate, and before I went out I had to promise to do my best not to break it. This, I thought, would be an easy promise to keep, since the telescope is as big as a small freighter.

On my way to Palomar, I stopped in Pasadena at the California Institute of Technology, which runs the observatory. A smog that made one's eyes smart hung over the city. I found that Dr. Greenstein was already at Palomar, a hundred and thirty-five miles to the south and fifty-six hundred feet up in the clearer, cooler air. I headed south, too. The road wound through ranches and forest up and up a mountain. Soon I saw across a valley, perched on the edge of a plateau, the glistening aluminum dome of the observatory. The huge slit for the telescope to peer through was shut like a closed eyelid.

On top of the plateau, which was dotted with nine sturdy yellow cottages, I headed toward the Monastery, where I expected to find Dr. Greenstein. The Monastery is the dormitory where the astronomers stay when they are using the two-hundred-inch telescope or the smaller forty-eight-inch Schmidt telescope. The Monastery is a solid building fitted out with black leather blinds for daytime sleeping. It was six o'clock in the evening. Dr. Greenstein, who had been up all the night before, was in the dining room having a solitary supper; a stocky, graying man in his mid-fifties who sported a tiny, pencil-thin moustache, he was the only astronomer on the mountain. Dr. Greenstein complained about not being able to sleep. "The first night I'm down here, I can't sleep at all," he said. "It isn't until the fifth day that I get a full night's, or rather morning's, sleep, and then it's time to go back to Pasadena." I asked him how often he had to go through this sleepless state, and he answered that in his case it was about thirty-five nights a year.

"I get up here whenever I can," he went on, planting an elbow next to a half-empty coffee cup. "Time on the telescope is so valuable that you snatch at it whenever you can get it. Just *having* the two-hundred-inch telescope puts Cal Tech in a tough spot. It's a national asset, so we can't do anything trivial. Any reasonably good astronomer would have to try hard in order *not* to make an interesting discovery with it. In practice it is used mainly by the members of the Department of Astronomy, and even with just sixteen of us, we are forever feuding to get time on the telescope. Cloudy time can be a real disaster."

I said I hoped Dr. Greenstein wouldn't be clouded out tonight, and he replied that he didn't think he would be. Since he had some preparations to make for the evening's work, I accompanied him along a path from the Monastery through a dry, prickly field toward the dome. It was partially hidden over the brow of a hill; for all anyone could tell, a big silver balloon had crash-landed there.

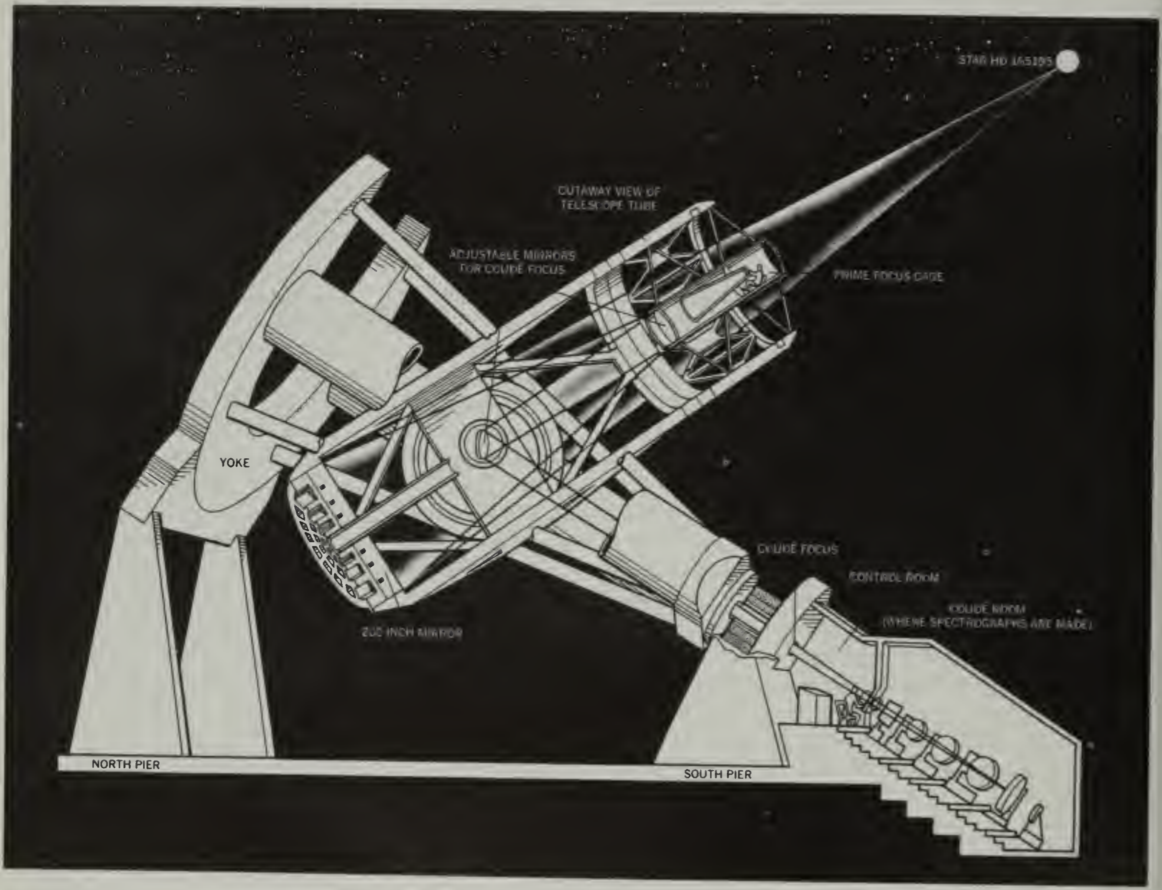
I asked Dr. Greenstein whether he had been involved with quasars lately. He shrugged. "I feel that my work, which is mostly the composition of stars within our galaxy, is more important; and current interpretations of quasars may be obsolete by next week." Although Dr. Greenstein is best known for his studies of the evolution of stars and galaxies, and of the elements within the stars, he is a top quasar man, too, and he has made observations to learn what their composition might be.

Quasars were first noticed in 1960 by radio astronomers as invisible sources of radio waves. One of these sources, 3C-48, was identified with what appeared to be a tiny, sixteenth-magnitude star. Three years later Dr. Maarten Schmidt, at Palomar, managed to concentrate on film enough of the feeble light from a quasar to get a spectrum. It appeared that quasars were not tiny stars within our own galaxy, as had been thought, but instead probably were intense and incredibly distant sources of light and radio waves. Quasar 3C-48 appears to be almost four billion light-years away, and subsequently other quasars have been measured out to almost nine billion light-years away; this is four-fifths of the way back to the "big bang" with which the universe supposedly began.

By studying the quasars, it may be possible to learn whether the universe will expand indefinitely; or whether it will stop some day; or whether it will fall back in upon itself for another big bang—and if so, when these events will take place. But a great deal more information is needed about the quasars, including the answer to why they shine so much more brightly than even the brightest galaxies. This is a problem that Dr. Greenstein is working on.

"As it happens, I don't like working with quasars," Dr. Greenstein continued as we trudged along. "They're tricky little things. I don't even like the word 'quasar.' It was invented by a Chinese astronomer in New York

The huge Hale telescope, seen from the floor of the Palomar observatory in the "fish-eye" photograph opposite, is the largest reflecting telescope in the world. Its 200-inch mirror is at lower left; at right, silhouetted by a patch of sky, is the elevator to the prime-focus cage.



who doesn't speak English well. Chinese is like Hebrew, which has no vowels. He saw the letters QSRS, which stand for quasi-stellar radio source, on a chart, and called them 'quasars.' We shouldn't have a vocabulary for what we don't know, and when we do know what the quasars are, we will have a better word for them. Quasar sounds as if it's short for quasi-star, and that's the one thing we know a quasar isn't." Dr. Greenstein observed that the sky, darkening fast now, was beautifully clear. The moon, about half full, was rising in the east, clear crystal against the dark blue background, which, Dr. Greenstein said, augured well for seeing tonight. The setting sun glinted red on the dome. Dr. Greenstein glanced at the cirrus clouds in the west, which were reddening as the sun sank. "Sunsets are nice," he said, "but you haven't seen anything until you see a sunrise at Palomar."

The dome, which is nine stories tall and as much as that in diameter, rises from a round, yellow, cement drum. Dr. Greenstein fitted a key in a latch, and soon we were blinking our eyes inside a cavernous, pitch-black room three stories below the telescope. Dr. Greenstein said he had some work to do in his darkroom and suggested I go to the third floor and take a look at the telescope.

In operation the Hale telescope resembles nothing so much as a large bucket made to gather light. The mirror collects light and bounces it fifty-five feet up to a focal point where the prime-focus cage is located. For spectrographic analysis, the light is reflected back down and out to the room at lower right.

The inside of the dome was stuffy, dim, mysterious, and silent except for the echo of some approaching footsteps. The telescope loomed in the center of the room, shadowy and intricate, its works mostly exposed, like a fine timepiece under a glass bell. The telescope, Dr. Greenstein had told me, works something like a clock. Its tube has to keep time exactly with the movement of the stars so that a star's light can stay riveted to a photographic plate for several hours at a stretch. The telescope, with its reflecting mirror two hundred inches in diameter, serves as a sort of bucket to catch as much light as possible from a star and concentrate it on film: it could pick up the light of a ten-watt bulb a million miles away. The purpose of the telescope is not to magnify, for no matter how great the magnification, no star would ever show up as more than a point of light.

The footsteps I had heard belonged to the night assistant for the telescope, Gary Tuton, a lean young man with short, wavy hair. Tuton is the technician who runs the telescope for the astronomers. He walked over to a control console and pressed a button. The telescope sprang into life. The big mirror, which weighs almost fifteen tons, rests at the bottom of the telescope tube, an open steel cylinde some sixty feet long. The tube swivels north and south inside a huge frame called the yoke, and the yoke swivels from east to west on two enormous bearings, so that the tube, with the mirror at its bottom, can aim at any point in the sky.

Now the yoke spun to the east and the tube swiveled to the north, only, since both these motions happened simultaneously, the movement was one smooth undulation. The tube can be locked on a star, just as the pencil in a compass can be locked at any given radius. Then the star can be tracked along its path simply by turning the yoke, which is fixed on the North Star as if it were the dot at the center of a circle. The movement of the yoke has to be very delicate. Tuton explained that the huge bearings at either end of the yoke are floated on thin films of oil so that the telescope, which weighs five hundred tons, can be turned by hand. The oil pumps under the enormous bearings whined. The observatory sounded like a very active railroad yard.

Slowly and ponderously the two-hundred-and-twenty-five-ton doors that covered the slit in the dome pulled aside, revealing a widening band of dark blue sky. It was like being inside the eye of an awakening animal. "Sometimes, in winter, when the dome is covered with snow, I have to go up top and sweep the snow off the slit," Tuton said. "One night last winter it got so cold that the gears on the doors that cover the slit in the dome froze. No matter what I did, one shutter would shut and the other wouldn't, and there was a snowstorm coming. But by and large the weather is pretty good up here. Last year we used the telescope on three hundred and ten nights."

A door banged and Dr. Greenstein appeared, struggling under a load of lenses and photographic film. Since it was still too early to begin taking pictures, Dr. Greenstein said that he was going up into the prime-focus cage at the top of the telescope tube and invited me to come along. "I want to take a look at a group of stars, a globular cluster called Messier 13," he said. "There's a peculiar star in it that I want to get a spectrum of later on. It's in with such a mass of other stars that I want to make sure I get my bearings straight."

Dr. Greenstein explained that the prime focus was the simplest and most direct way of looking through the telescope. There are several different ways, and none of them is the conventional one, used with binoculars or refractor telescopes, of holding the telescope up to your eyes. Instead of focusing light through a lens, the big mirror bounces the light back up the tube and concentrates it at a point fifty-five feet above. The exact spot is called the prime focus. The astronomer sits in the prime-focus cage, which is like a balloonist's basket high inside the telescope tube, and from this vantage point he can photograph the image directly.

"I like it in the prime-focus cage," Dr. Greenstein concluded. "You feel closer to the stars." Then he frisked himself and me, removing any hard objects, such as coins and pens, that might fall on the mirror and damage it. It had taken eleven years to polish the mirror into exactly the right configuration; a scratch could mean years more polishing. We climbed to a balcony, boarded the dome elevator, and began a long, hair-raising ascent as the elevator rose upward and outward, following the overhanging contour of the dome. Through the slit we could see the ground several stories below, and several thousand feet below that, the lights of the valley floor. The dome elevator is a peculiar, unenclosed contraption like a long spoon; we stood at the outer end of it where the bowl would be. After a bumpy ride, the elevator deposits the astronomer, like a dollop of medicine, inside the mouth of the telescope. At this point, the astronomer is about seventy feet above the floor of the dome, with very little to hang on to.

"People have gotten killed on telescopes," Dr. Greenstein said with what I thought was poor timing as we lurched unevenly up and out. "Sometimes astronomers get squashed by a telescope slewing about, but that doesn't happen very often."

I gripped the railing of the elevator, fixed my eyes firmly on the top of the dome, and asked Dr. Greenstein to tell me more about the peculiar star in Messier 13. "Globular clusters, like Messier 13, are sort of suburbs of our galaxy which contain some of the oldest stars, and for this reason they might have a bearing on the quasars, which are supposed to be primordial objects, too," he said. "However, the star I want to look at now is blue, a color usually associated with younger stars, so in this case it must represent a peculiar stage of evolution. Although this star—Barnard 29—is blue, it has a peculiar energy distribution. Its spectrum is too much in the red, and one possibility I want to check tonight is whether it couldn't in fact be a close pair, a double star, one blue and one red."

Soon we were directly on top of the telescope tube, and Dr. Greenstein flung open a flimsy gate at the end of the elevator platform. The prime-focus cage—a bucket perhaps five feet in diameter and five feet deep—was about eighteen inches below us. Dr. Greenstein explained that the elevator couldn't go all the way to the cage because of

the danger of collision with the telescope: we would have to travel across the remaining gap ourselves. So saying, he flung himself into the void and disappeared into the mouth of the telescope.

Inside the bucket was a chair and an empty well that looked straight down at the mirror; the astronomer fits his instruments into the well. When Tuton was sure that we were safely installed, and that nothing could drop on the mirror, he opened the diaphragm that covered it. Slowly, like a water lily, the petals of the diaphragm lifted, revealing what looked like a pond of rippling, shimmering water beneath. The stars, which wouldn't stay still, were streaking like meteors; the mirror, it seemed, was popping a few millionths of an inch with the change of temperature. Tuton slewed the telescope off in search of Messier 13 and Barnard 29. As one side of the bucket dipped suddenly down, the chair, which was on rails, moved around and down with gravity, so that the astronomer was always upright; the sensation was like riding very slowly in a Ferris wheel. Stars shot through the big mirror as we sailed along. The telescope came to a smooth halt, moving just fast enough to keep the stars still in spite of the rotation of the earth. Dr. Greenstein peered into the pool of light for a moment. Then he maneuvered a tiny lens that looked like a magnifying glass—it was tied to the well with a string—until he found the exact spot where the image was clearest. This was the prime focus.

"We're right on the beam," Dr. Greenstein said, handing the lens to me. As I looked down, I felt my glasses begin to slide down my nose; I grabbed them just before they dropped down the well toward the mirror. The lens resolved the chaotic splotches of dancing light, and I saw an enormous rash of stars, each one a point of hard, brilliant light. I couldn't make out Barnard 29. Dr. Greenstein was able to converse with Tuton over an intercom, and he asked him to stop the telescope's tracking drive. No sooner had the telescope stopped moving than Messier 13 and Barnard 29 slipped out of the field of vision. Other stars whizzed across the mirror, following Messier 13 into seeming oblivion; a given star crossed the mirror in about ten seconds, before vanishing. That, Dr. Greenstein said, showed how fast the earth, with the telescope, was turning. Tuton's voice crackled through the microphone, asking how I felt. I replied that I was getting a little dizzy. Tuton started up the tracking device; the telescope passed all the stars that had been whipping by, and soon we were safely back with Messier 13.

Dwarfed by the telescope's huge frame, an astronomer stands on the mirror casing prior to its intallation at the observatory in 1948.

"Did Dr. Greenstein tell you about the time I was stuck up there?" Tuton asked; and his voice crackled on, "I was in the prime-focus cage when the power for the telescope shorted out. It was a cold winter night. I had to climb down, which was the hairiest thing I ever did. What made me do it was not the cold so much as what the men who came in the morning would say. I'd never have lived it down."

At last Tuton wafted the telescope toward the elevator platform for us to board. I fixed my eye on the top of the dome again. Dr. Greenstein glanced at his watch and said that he wished the elevator would hurry, because it was already dark enough to start using the spectrograph. He shouted down to Tuton to start setting up the telescope for the coudé focus. The coudé focus is in a room outside the telescope altogether, and the light from a star is deflected to it by a mirror—called the coudé flat—which bounces the starlight in a thin beam down through a hole in the southern foundation of the telescope and into the coudé room one floor below, where the spectrographs are kept. The film to record the spectrum of a star is in this room, which serves something of the purpose of an old Brownie box camera. As we reached the ground, an electronic engine whirred and the coudé flat, weighing a ton and a half, lifted slowly into position just below the prime-focus cage. It glittered like a jewel inside a watch.

Dr. Greenstein fetched the films he had brought with him and disappeared down the steps into the coudé room, a tiny chamber that descends steeply in line with the yoke, pointing at the North Star. It was already after eight o'clock. Barnard 29 was nestled among so many stars that the final zeroing in had to be done by dead reckoning. "There's a sort of triangle of stars," said Dr. Greenstein, who had returned to the control room at the top of the steps. "See it? There ought to be a double star on the upper left. Got it?" He sounded like a man finding his way with a road map. Tuton said he had it. "Do you know what the most difficult object to find is?" Tuton asked as he turned a knob for fine adjustment; I said I didn't. "It's the moon. The moon is so close, and it's moving so fast, that it's like trying to aim a rifle at a moving target close by, instead of at the trees standing behind it."

All of a sudden, Barnard 29 disappeared from view. It was as if the telescope had gone dead. Tuton raced out into the dome and peered up at the sky through the slit; a long, wispy cloud was obstructing the view. "Looks like it's going to-be a cloud-dodging night," he said. Quickly Tuton and Greenstein flipped the telescope to another star, called HD 165195, which was in a cloudless part of the sky.

I asked Dr. Greenstein whether we would see any quasars that night. "The moon is up, so we can't work on anything as dim as quasars," he said. "That's probably just as well. There isn't much you can tell by looking at a quasar anyway. Instead, I will be doing long exposures on some of the oldest stars in the galaxy. The procedure is much the same as with quasars; and in fact part of what we'll be doing is related to quasars. There is a theory that has to be explored that the quasars are a remnant of the first formation of galaxies. According to this theory, during the contraction of the gases that formed the galaxies, some super-massive objects formed within them. These objects may have become extremely dense and pulled themselves together so rapidly that they exploded. Perhaps that is what the quasars are. I don't know. I'm fairly neutral on the subject. There is evidence in our own galaxy of a superexplosion far greater than the explosion of a supernova, but less, I think, than a quasar explosion. In any event, if the quasars represent monumental explosions within galaxies during the half-billion years or so that the galaxies and the stars were condensing out of primeval gas clouds, then you would expect that the oldest stars, the first to condense from the gases, would be heavily contaminated by the elements in the quasars. They would have been loaded with the products of quasar evolution."

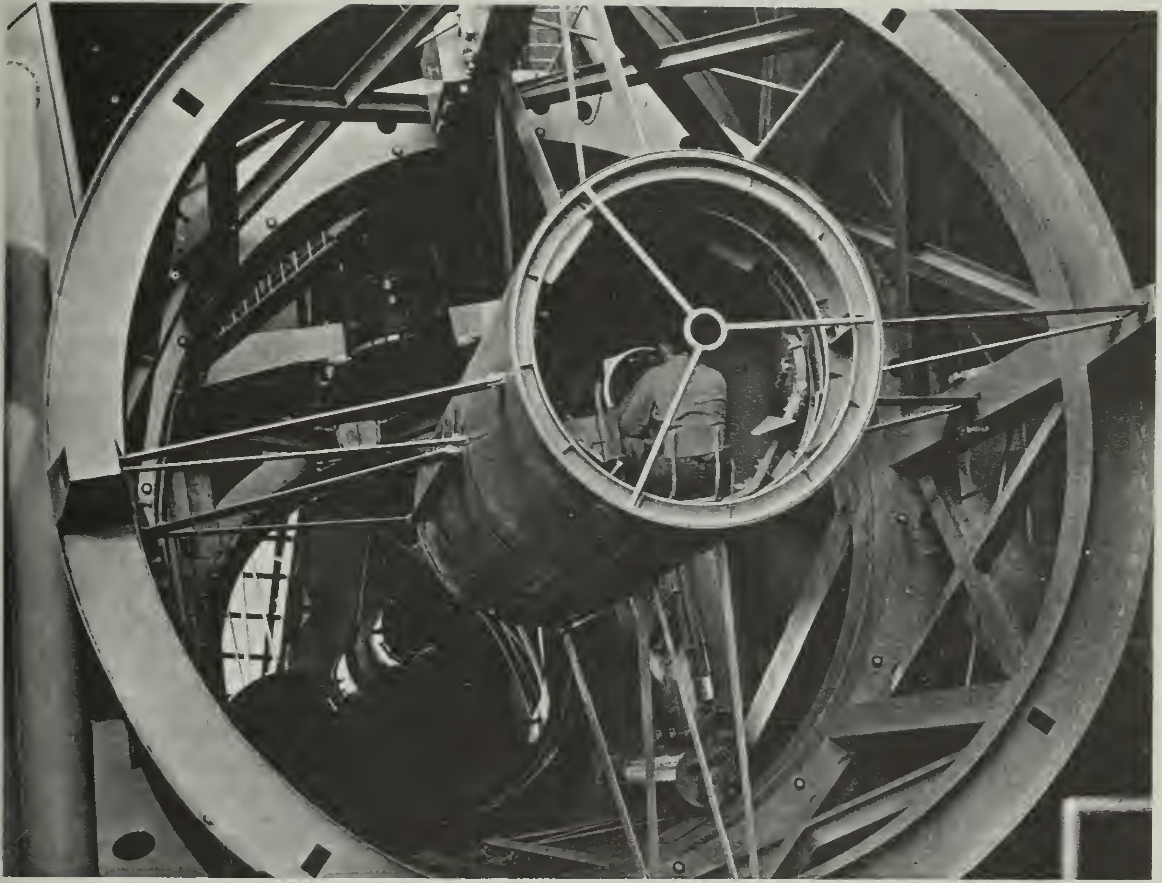
Dr. Greenstein turned out the lights in the control room and pressed a button to start the exposure. The control room was lit only by the soft-green glow of the dials on the control panel, like the cockpit of an airplane at night. "So I will be looking at some of the oldest stars in our galaxy, like this one, to see whether they have the same elements and in roughly the same proportions, as the quasars. We don't know yet the exact composition of the quasars, but we may be able to do something with oxygen or iron. If they have the same elements, it might indicate quasars were the raw material in forming stars. But if there are other elements aside from those found in quasars, it might prove that the quasars are not important in star evolution, for the oldest stars don't seem to have manufactured many new elements after their formation, such as metals. But if I find a trace of metal in HD 165195, I have to decide whether it might have been cooked within the star after all, or whether the metal was part of the original gases of which the star was composed. The chances are we won't know much more after tonight. I'll need this type of information on hundreds of stars before I can begin to get anywhere."

The time was eight-thirty. I found myself standing in the path of the slender stream of light from HD 165195, and Dr. Greenstein asked me to step out of the way, which wasn't easy, since the control room was cramped and narrow. A ticking sound filled the room. Dr. Greenstein said that the ticking came from the photoelectric scaler, which counts the number of photons coming from a star, like a light meter. Each tick meant twenty thousand photons of light. A dial kept count of the ticks, and Dr. Greenstein said that, for this exposure, he wanted about thirty-three hundred.

He invited me to look through the eyepiece of the spectrograph. A spectrograph, an apparatus in the control room that intercepted the light coming from HD 165195, refracts and spreads out the light from a star into its component wave lights, giving a spectrum something like the light from a prism. The lines in a spectrum show the elements in a star. They also show how fast an object is receding from the earth by how much the lines are shifted to the red end of the spectrum. This is called the red shift, and it was in this way that Schmidt first decided the quasars were tremendously distant objects. Through the eyepiece, the star appeared as a fuzzy, bright-green spark; the star's light had been shattered by passing through a slit and some gratings inside the spectrograph. Dr. Greenstein said the light had left the star ten thousand years ago. Tuton darted across to the telescope's control panel and slowed down the telescope's tracking drive by a tiny fraction. "We want to make the star trail along the slit in the spectrograph," he said. "This is what we have to do with faint objects. It's like painting one brush stroke over another, until you get the proper intensity on the plate."

With everything squared away, Tuton settled down by the eyepiece, stretched, yawned, and tuned in a radio to a rock-'n'-roll station in San Bernardino. He kept an ear cocked to make sure the ticking didn't stop, and every once in a while he checked the eyepiece to make sure the star was still there. I asked Dr. Greenstein why he and the other astronomers couldn't stay in Pasadena, and phone down to Tuton whenever they wanted a plate taken of a star. "There are too many things that can go wrong," Dr. Greenstein said. "I wouldn't know whether a plate was any good or not unless I was here." Tuton concurred with him. "I've never been trained in astronomy," he said. "I can run the telescope all right, and find a star, but when it comes to astronomy, I just haven't the foggiest idea what's going on. The astronomer never says what he's doing. Half the time he doesn't know what he's done until he's gotten back to Pasadena. I didn't know anything about quasars until I read about them in the papers." Then Tuton pulled out a magazine, which he squinted at by the light of the dials.

Dr. Greenstein suggested that we go out on the catwalk. Except for a gentle breeze, the plateau was absolutely still. I could see the smaller dome of the Schmidt telescope about half a mile to the east. Dr. Greenstein pointed out a spot between the two domes where an Air Force bomber had crashed four years earlier, killing the crew and two horses that belonged to the superintendent of the observatory but miraculously doing no damage to the telescope. Away to the northwest, the smog over Los Angeles glowed– possibly in something of the way the outer gases of the quasars shine, powered by some mysterious force inside. There was a light mist on the mountain, and the half-moon glowed overhead. "Only spectrograph work can be done in full moonlight, and even that is terribly difficult," Dr. Greenstein said. "You have to be very careful that the moonlight doesn't contaminate your plate. I thought I'd made a great spectro-



Seated in the prime-focus cage, his back to the sky, an astronomer photographs images reflected up from the 200-inch mirror.

graphic discovery once, only to find that it was the light of the moon, and not of the star. There is a gadget called a moon eliminator. I wish we could get rid of the moon for good!"

Dr. Greenstein glanced at his watch. It was eleven o'clock. "The night's young yet," he said energetically. He went inside, bustled into the control room, checked the dial that counted the ticks, and shut down the spectrograph. Tuton slewed the telescope to another star, BD 39°4926, which Dr. Greenstein explained was also very old and might shed light on whether quasars had to do with galaxy formation. Then, since the exposure would last for three hours, Dr. Greenstein went downstairs to his darkroom to develop the plate on HD 165195.

Amid a sloshing of water and the acrid odor of hypo Dr. Greenstein said, "I don't really believe that the older stars are residues of quasars. I don't believe the quasars are a part of galaxies, and therefore I don't happen to believe that they have anything to do with star evolution. There is evidence of giant explosions in galaxies now, but whether these caused quasars or not, we don't know. But what we know of quasars really isn't conducive to the formation of stars. I don't believe quasars come from explosions, though other astronomers do. Speculation is like the stock market. I feel that the quasars instead may be in some kind of balance condition, like a star, and that they are isolated objects, and that they are formed of matter between galaxies. Other people feel they are little things which have been blown out of galaxies. Another group believes that the quasars are extremely dense objects and that their red shifts are caused by gravity, rather than by speed or distance. I don't know. The best we can do is to test the different theories, which is what I'm trying to do now."

Just after midnight, Dr. Greenstein came up from the darkroom. He checked the star, which was ticking away nicely on the slit, and sat on a table. "That's all the developing I do tonight," he said. "It's too risky when you're tired." He had evidently lost his second wind. I asked him if he had been able to tell anything about HD 165195, and he said he hadn't. "It's too late at night for discoveries," he said with a yawn. "There's nothing like making a great discovery that you might absent-mindedly wipe off the plate with a wet finger. I make it a rule never to make great discoveries after midnight."

Dr. Greenstein yawned again. I followed him over to a couple of reclining chairs by the control console under the north bearing. Just visible in the starlight, he lay back with his arms folded behind his head as a pillow and his eyes shut. The moon, for the time being, was obscured, so it was unusually dark inside the dome. As I became more accustomed to the darkness—it was much darker than in the control room, which contained a number of luminous dials—I could make out more and more of the telescope. Dr. Greenstein opened his eyes. "I could look at it forever," he said. "No matter how long you look at it, it always looks different. It looks different now, when you can barely see it in the dim starlight, from what it did a few minutes ago in the light of the half-moon. It's different from whatever side you look at it. Right now, it just sits there and broods. It is a remarkable subordination of brute force for delicate ends. All this mechanism is for is to move one piece of glass; and all the glass is for is to carry one thin layer of aluminum that reflects starlight. I wish it were quieter! We must get rid of those oil pumps."

At last Dr. Greenstein's voice drifted off. He was fast asleep. After a time he sat bolt upright and looked at his watch. It was two fifteen. Above him, the telescope was almost completely on its side, as if it, too, had been asleep. Over the last three hours, its tracking of BD 39°4926 had caused it to assume this position. The ticking ceased abruptly when Dr. Greenstein checked the meter and ended the exposure. After rummaging around in the inky coudé room to change plates, Dr. Greenstein came back to the control room and decided to return to Barnard 29. "We need about three hours, though with this much moon, I doubt if we'll get it," he said briskly as he zeroed in the telescope. As he was talking, the ticking became more and more sporadic, slowing down; finally it stopped altogether. Tuton, who had had no nap, and who looked a little scruffy, went out under the dome and squinted up through the slit. Barnard 29 was obscured by clouds again. "What do we do now?" Tuton asked Greenstein. Tuton said that what he would like to do now would be go home and go to bed.

"We're getting only about ten minutes' exposure time to the hour, but as long as I can get even that much, I can't shut down," Dr. Greenstein said, and added unhappily, "the telescope's time is more valuable than my own." It costs one thousand dollars a night to operate the telescope. Suddenly a great rift appeared in the clouds, and the moon emerged. It was greeted with a terrific burst of ticks. Dr. Greenstein shouted to Tuton to shut off the spectrograph. "We're better off wasting exposure time and not getting contamination," Dr. Greenstein grumbled, exhaling a cloud of cigar smoke that glowed derisively in the moonlight. It was a little after two forty-five, and I had the impression that Dr. Greenstein was about to call it a night.

At three fifteen the sky cleared and Tuton started the exposure once more. Since he was stiff and tired, Dr. Greenstein suggested another spin around the catwalk. There was low-lying mist on the plateau, and not far away a jay woke up raucously. The air was chill and damp. The east was as dark as ever, but Dr. Greenstein said he could see the zodiacal light, which heralds the dawn. "We won't be able to keep the exposure going much longer," he went on. "The sun is already beginning to heat up the atmosphere to the east, which makes it bubble a bit." Groggily, I looked for bubbles in the east, but saw none. A flush of pink appeared and spread rapidly; the stars to the east blinked out, though the ones to the west were, for the time being, as hard and brilliant as they had been for most of the night. Shadows grew where none had been before, and we could begin to see colors—the green of the pines, the pink clay of the road. Dr. Greenstein went back inside and called down to Tuton to turn off the exposure before it was contaminated.

The inside of the dome was suffused with pink; the dome's interior, too, was of brilliant aluminum, and caught the dawn through the slit. The telescope was visible again, like a dinosaur emerging from a misty bog. "This is *my* time on the telescope," Tuton said, "the time after dawn, but before all the stars are washed out. It's useless for spectrography or photography, so I just aim the telescope at what I want to look at. I think Saturn is in a good position for viewing."

He consulted an astronomy book and quickly swung the telescope to a new position. He snapped the eyepiece into place, focusing it. He stepped aside, and I took a look. There was Saturn, as big as a football and, with its rings forming an oval around it, somewhat the same shape. Through the two-hundred-inch telescope, Saturn was so brilliant that it hurt the eyes. Dr. Greenstein squinted through the eyepiece, grunting. "I never particularly liked the solar system," he said, relinquishing the telescope. I looked again; Saturn was less brilliant than before, and it was fading fast in the sunlight. Soon it vanished altogether, like the Cheshire cat, leaving nothing behind but a patch of pale-blue sky.

Henry S. F. Cooper, Jr., a member of the editorial staff of The New Yorker, *writes frequently on scientific subjects.*

Copernicus addresses this preface of his revolutionary book on the solar system to Pope Paul III.

4 Preface to De Revolutionibus

Nicolaus Copernicus

From *Occasional Notes* to the Royal Astronomical Society, No. 10, 1947.

TO THE MOST HOLY LORD, POPE PAUL III.

THE PREFACE OF NICOLAUS COPERNICUS TO THE BOOKS OF THE REVOLUTIONS

I may well presume, most Holy Father, that certain people, as soon as they hear that in this book *On the Revolutions of the Spheres of the Universe* I ascribe movement to the earthly globe, will cry out that, holding such views, I should at once be hissed off the stage. For I am not so pleased with my own work that I should fail duly to weigh the judgment which others may pass thereon; and though I know that the speculations of a philosopher are far removed from the judgment of the multitude—for his aim is to seek truth in all things as far as God has permitted human reason so to do—yet I hold that opinions which are quite erroneous should be avoided.

Thinking therefore within myself that to ascribe movement to the Earth must indeed seem an absurd performance on my part to those who know that many centuries have consented to the establishment of the contrary judgment, namely that the Earth is placed immovably as the central point in the middle of the Universe, I hesitated long whether, on the one hand, I should give to the light these my Commentaries written to prove the Earth's motion, or whether, on the other hand, it were better to follow the example of the Pythagoreans and others who were wont to impart their philosophic mysteries only to intimates and friends, and then not in writing but by word of mouth, as the letter of Lysis to Hipparchus witnesses. In my judgment they did so not, as some would have it, through jealousy of sharing their doctrines, but as fearing lest these so noble and hardly won discoveries of the learned should be despised by such as either care not to study aught save for gain, or—if by the encouragement and example of others they are stimulated to philosophic liberal pursuits—yet by reason of the dulness of their wits are in the company of philosophers as drones among bees. Reflecting thus, the thought of the scorn which I had to fear on account of the novelty and incongruity of my theory, well-nigh induced me to abandon my project.

These misgivings and actual protests have been overcome by my friends. First among these was Nicolaus Schönberg, Cardinal of Capua, a man renowned in every department of learning. Next was one who loved me well, Tiedemann Giese, Bishop of Kulm, a devoted student of sacred and all other good literature, who often urged and even importuned me to publish this work which I had kept in store not for nine years only, but to a fourth period of nine years. The same request was made to me by many other eminent and learned men. They urged that I should not, on account of my fears, refuse any longer to contribute the fruits of my labours to the common advantage of those interested in mathematics. They insisted that, though my theory of the Earth's movement might at first seem strange, yet it would appear admirable and acceptable when the publication of my elucidatory comments should dispel the mists of paradox. Yielding then to their persuasion I at last permitted my friends to publish that work which they have so long demanded.

That I allow the publication of these my studies may surprise your Holiness the less in that, having been at such travail to attain them, I had already not scrupled to commit to writing my thoughts upon the motion of the Earth. How I came to dare to conceive such motion of the Earth, contrary to the received opinion of the Mathematicians and indeed contrary to the impression of the senses, is what your Holiness will rather expect to hear. So I should like your Holiness to know that I was induced to think of a method of computing the motions of the spheres by nothing else than the knowledge that the Mathematicians are inconsistent in these investigations.

For, first, the mathematicians are so unsure of the movements of the Sun and Moon that they cannot even explain or observe the constant length of the seasonal year. Secondly, in determining the motions of these and of the other five planets, they do not even use the same principles and hypotheses as in their proofs of seeming revolutions and motions. So some use only concentric circles, while others eccentrics and epicycles. Yet even by these means they do not completely attain their ends. Those who have relied on concentrics, though they have proven that some different motions can be compounded therefrom, have not thereby been able fully to establish a system which agrees with the phenomena. Those again who have devised eccentric systems, though they appear to have well-nigh established the seeming motions by calculations agreeable to their assumptions, have yet made many admissions which seem to violate the first principle of uniformity in motion. Nor have they been able thereby to discern or deduce the principal thing—namely the shape of the Universe and the unchangeable symmetry of its parts. With them it is as though an artist were to gather the hands, feet, head and other members for his images from divers models, each part excellently drawn, but not related to a single body, and since they in no way match each other, the result would be monster rather than man. So in the course of their exposition, which the mathematicians call their system (μέθοδος) we find that they have either omitted some indispensable detail or introduced something foreign and wholly irrelevant. This would of a surety not have been so had they followed fixed principles; for if their hypotheses were not misleading, all inferences based thereon might be surely verified. Though my present assertions are obscure, they will be made clear in due course.

I pondered long upon this uncertainty of mathematical tradition in establishing the motions of the system of the spheres. At last I began to chafe that philosophers could by no means agree on any one certain theory of the mechanism of the Universe, wrought for us by a supremely good and orderly Creator, though in other respects they investigated with meticulous care the minutest points relating to its orbits. I therefore took pains to read again the works of all the philosophers on whom I could lay hand to seek out whether any of them had ever supposed that the motions of the spheres were other than those demanded by the mathematical schools. I found first in Cicero that Hicetas[*] had realized that the Earth moved. Afterwards I found in Plutarch that certain others had held the like opinion. I think fit here to add Plutarch's own words, to make them accessible to all:—

> "The rest hold the Earth to be stationary, but Philolaus the Pythagorean says that she moves around the (central) fire on an oblique circle like the Sun and Moon. Heraclides of Pontus and Ecphantus the Pythagorean also make the Earth to move, not indeed through space but by rotating round her own centre as a wheel on an axle[†] from West to East."

Taking advantage of this I too began to think of the mobility of the Earth; and though the opinion seemed absurd, yet knowing now that others before me had been granted freedom to imagine such circles as they chose to explain the phenomena of the stars, I considered that I also might easily be allowed to try whether, by assuming some motion of the Earth, sounder explanations than theirs for the revolution of the celestial spheres might so be discovered.

Thus assuming motions, which in my work I ascribe to the Earth, by long and frequent observations I have at last discovered that, if the motions of the rest of the planets be brought into relation with the circulation of the Earth and be reckoned in proportion to the orbit of each planet, not only do their phenomena presently ensue, but the orders and magnitudes of all stars and spheres, nay the heavens themselves, become so bound together that nothing in any part thereof could be moved from its place without producing confusion of all the other parts and of the Universe as a whole.

In the course of the work the order which I have pursued is as here follows. In the first book I describe all positions of the spheres together with such movements as I ascribe to Earth; so that this book contains, as it were, the general system of the Universe. Afterwards, in the remaining books, I relate the motions of the other planets and all the spheres to the mobility of Earth, that we may gather thereby how far the motions and appearances of the rest of the planets and spheres may be preserved, if related to the motions of the Earth.

I doubt not that gifted and learned mathematicians will agree with me if they are willing to comprehend and appreciate, not superficially but thoroughly, according to the demands of this science, such reasoning as I bring to bear in support of my judgment. But that learned and unlearned alike may see that I shrink not from any man's criticism,

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[*] C. writes Nicetas here, as always.

[†] Reading ’ενηξονισμένην.

it is to your Holiness rather than anyone else that I have chosen to dedicate these studies of mine, since in this remote corner of Earth in which I live you are regarded as the most eminent by virtue alike of the dignity of your Office and of your love of letters and science. You by your influence and judgment can readily hold the slanderers from biting, though the proverb hath it that there is no remedy against a sycophant's tooth. It may fall out, too, that idle babblers, ignorant of mathematics, may claim a right to pronounce a judgment on my work, by reason of a certain passage of Scripture basely twisted to suit their purpose. Should any such venture to criticize and carp at my project, I make no account of them; I consider their judgment rash, and utterly despise it. I well know that even Lactantius, a writer in other ways distinguished but in no sense a mathematician, discourses in a most childish fashion touching the shape of the Earth, ridiculing even those who have stated the Earth to be a sphere. Thus my supporters need not be amazed if some people of like sort ridicule me too.

Mathematics are for mathematicians, and they, if I be not wholly deceived, will hold that these my labours contribute somewhat even to the Commonwealth of the Church, of which your Holiness is now Prince. For not long since, under Leo X, the question of correcting the ecclesiastical calendar was debated in the Council of the Lateran. It was left undecided for the sole cause that the lengths of the years and months and the motions of the Sun and Moon were not held to have been yet determined with sufficient exactness. From that time on I have given thought to their more accurate observation, by the advice of that eminent man Paul, Lord Bishop of Sempronia, sometime in charge of that business of the calendar. What results I have achieved therein, I leave to the judgment of learned mathematicians and of your Holiness in particular. And now, not to seem to promise your Holiness more than I can perform with regard to the usefulness of the work, I pass to my appointed task.

The introduction to Galileo's Starry Messenger not only summarizes his discoveries, but also conveys Galileo's excitement about the new use of the telescope for astronomical purposes.

5 The Starry Messenger

Galileo Galilei

An excerpt from *Discoveries and Opinions of Galileo* translated by Stillman Drake, 1957.

ASTRONOMICAL MESSAGE

Which contains and explains recent observations
made with the aid of a new spyglass[3]
concerning the surface of the moon,
the Milky Way, nebulous stars, and
innumerable fixed stars,
as well as four planets never before seen, and
now named
THE MEDICEAN STARS

Great indeed are the things which in this brief treatise I propose for observation and consideration by all students of nature. I say great, because of the excellence of the subject itself, the entirely unexpected and novel character of these things, and finally because of the instrument by means of which they have been revealed to our senses.

Surely it is a great thing to increase the numerous host of fixed stars previously visible to the unaided vision, adding countless more which have never before been seen, exposing these plainly to the eye in numbers ten times exceeding the old and familiar stars.

It is a very beautiful thing, and most gratifying to the sight, to behold the body of the moon, distant from us almost sixty earthly radii,[4] as if it were no farther away than

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[3] The word "telescope" was not coined until 1611. A detailed account of its origin is given by Edward Rosen in *The Naming of the Telescope* (New York, 1947). In the present translation the modern term has been introduced for the sake of dignity and ease of reading, but only after the passage in which Galileo describes the circumstances which led him to construct the instrument (pp. 28–29).

[4] The original text reads "diameters" here and in another place. That this error was Galileo's and not the printer's has been convincingly shown by Edward Rosen (*Isis*, 1952, pp.

two such measures—so that its diameter appears almost thirty times larger, its surface nearly nine hundred times, and its volume twenty-seven thousand times as large as when viewed with the naked eye. In this way one may learn with all the certainty of sense evidence that the moon is not robed in a smooth and polished surface but is in fact rough and uneven, covered everywhere, just like the earth's surface, with huge prominences, deep valleys, and chasms.

Again, it seems to me a matter of no small importance to have ended the dispute about the Milky Way by making its nature manifest to the very senses as well as to the intellect. Similarly it will be a pleasant and elegant thing to demonstrate that the nature of those stars which astronomers have previously called "nebulous" is far different from what has been believed hitherto. But what surpasses all wonders by far, and what particularly moves us to seek the attention of all astronomers and philosophers, is the discovery of four wandering stars not known or observed by any man before us. Like Venus and Mercury, which have their own periods about the sun, these have theirs about a certain star that is conspicuous among those already known, which they sometimes precede and sometimes follow, without ever departing from it beyond certain limits. All these facts were discovered and observed by me not many days ago with the aid of a spyglass which I devised, after first being illuminated by divine grace. Perhaps other things, still more remarkable, will in time be discovered by me or by other observers with the aid of such an instrument, the form and construction of which I shall first briefly explain, as well as the occasion of its having been devised. Afterwards I shall relate the story of the observations I have made.

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344 ff.). The slip was a curious one, as astronomers of all schools had long agreed that the maximum distance of the moon was approximately sixty terrestrial radii. Still more curious is the fact that neither Kepler nor any other correspondent appears to have called Galileo's attention to this error; not even a friend who ventured to criticize the calculations in this very passage.

The end of this summary of Kepler's work in mechanics shows how seriously Kepler took the idea of the harmony of the spheres.

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6 Kepler's Celestial Music

I. Bernard Cohen

An excerpt from his book *The Birth of a New Physics*, 1960.

Since Greek times scientists have insisted that Nature is simple. A familiar maxim of Aristotle is, "Nature does nothing in vain, nothing superfluous." Another expression of this philosophy has come down to us from a fourteenth-century English monk and scholar, William of Occam. Known as his "law of parsimony" or "Occam's razor" (perhaps for its ruthless cutting away of the superfluous), it maintains, "Entities are not to be multiplied without necessity." "It is vain to do with more what can be done with fewer" perhaps sums up this attitude.

We have seen Galileo assume a principle of simplicity in his approach to the problem of accelerated motion, and the literature of modern physical science suggests countless other examples. Indeed, present-day physics is in distress, or at least in an uneasy state, because the recently discovered nuclear "fundamental particles" exhibit a stubborn disinclination to recognize simple laws. Only a few decades ago physicists complacently assumed that the proton and the electron were the only "fundamental particles" they needed to explain the atom. But now one "fundamental particle" after another has crept into the ranks until it appears that there may be as many of them as there are chemical elements. Confronted with this bewildering array, the average physicist is tempted to echo Alfonso the Wise and bemoan the fact that he was not consulted first.

Anyone who examines Fig. 14 on page 58 will see at

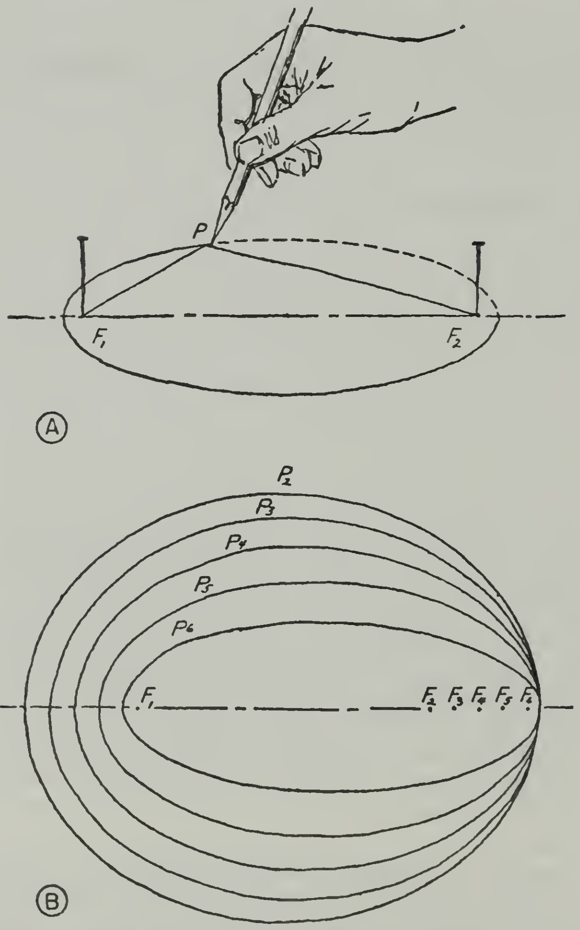

Fig. 22. The ellipse, drawn in the manner shown in (A), can have all the shapes shown in (B) if you use the same string but vary the distance between the pins, as at F_2, F_8, F_4, *etc.*

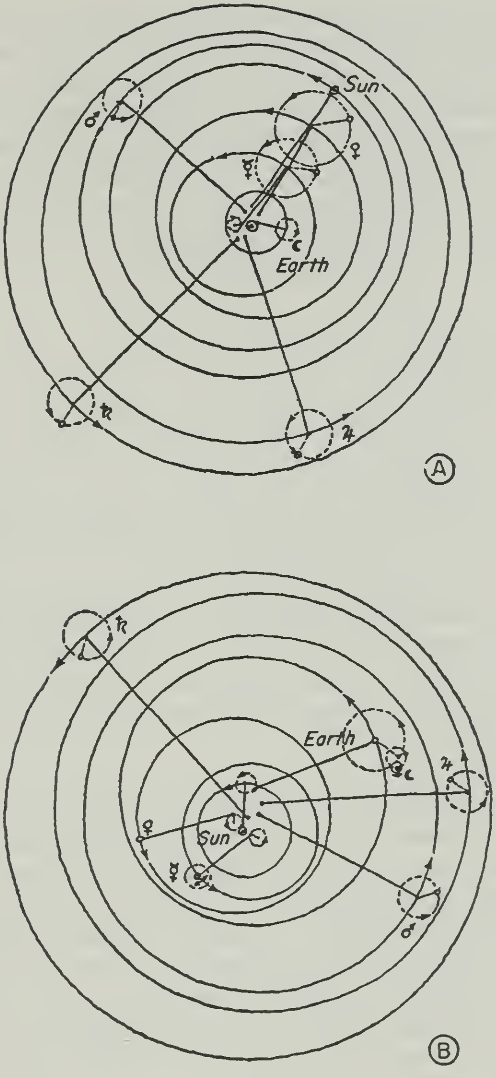

Fig. 14. The Ptolemaic system (A) and the Copernican system (B) were of about equal complexity, as can be

once that neither the Ptolemaic nor Copernican system was, in any sense of the word, "simple." Today we know why these systems lacked simplicity: restricting celestial motion to the circle introduced many otherwise unnecessary curves and centers of motion. If astronomers had used some other curves, notably the ellipse, a smaller number of them would have done the job better. It was one of Kepler's great contributions that he stumbled upon this truth.

The Ellipse and the Keplerian Universe

The ellipse enables us to center the solar system on the true sun rather than some "mean sun" or the center of the earth's orbit as Copernicus did. Thus the Keplerian system displays a universe of stars fixed in space, a fixed sun, and a *single* ellipse for the orbit of each planet, with an additional one for the moon. In actual fact, most of these ellipses, except for Mercury's orbit, look so much like circles that at first glance the Keplerian system seems to be the simplified Copernican system shown on page 58 of Chapter 3: one circle for each planet as it moves around the sun, and another for the moon.

An ellipse (Fig. 22) is not as "simple" a curve as a circle, as will be seen. To draw an ellipse (Fig. 22A), stick two pins or thumbtacks into a board, and to them tie the ends of a piece of thread. Now draw the curve by moving a pencil within the loop of thread so that the thread always remains taut. From the method of drawing the ellipse, the following defining condition is apparent: every point P on the ellipse has the property that the sum of the distances from it to two other points F_1 and F_2, known as the *foci,* is constant. (The sum is equal to the length of the string.) For any pair of foci, the chosen length of the string determines the size and shape of the ellipse, which may also be varied by using one string-length and placing the pins near to, or far from, one another. Thus an ellipse may have a shape (Fig. 22B) with more or less the proportions of an egg, a cigar, or a needle, or may be almost round and like a circle. But unlike the true egg, cigar, or needle, the ellipse must always be symmetrical (Fig. 23) with respect to the axes, one of which (the major axis) is a line drawn across the ellipse through the foci and the other (the minor axis) a line drawn across the ellipse along the perpendicular bisector of the major axis. If the two foci are allowed to coincide, the ellipse becomes a circle; another way of saying this is that the circle is a "degenerate" form of an ellipse.

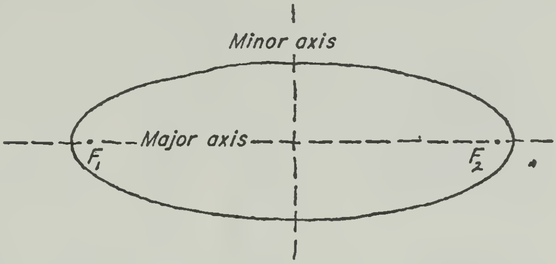

Fig. 23. The ellipse is always symmetrical with respect to its major and minor axes.

The properties of the ellipse were described in antiquity by Apollonius of Perga, the Greek geometer who inaugurated the scheme of epicycles used in Ptolemaic astronomy. Apollonius showed that the ellipse, the parabola (the path of a projectile according to Galilean mechanics), the circle, and another curve called the hyperbola may be formed (Fig. 24) by passing planes at different inclinations through a right cone, or a cone of revolution. But until the time of Kepler and Galileo, no one had ever shown that the conic sections occur in natural phenomena, notably in the phenomena of motion.

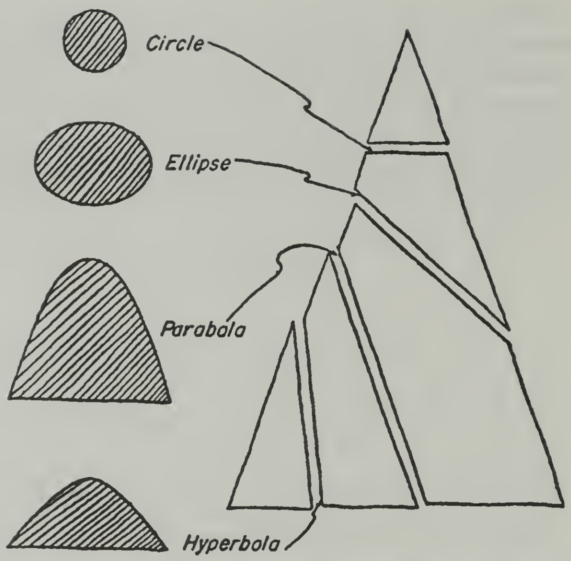

Fig. 24. The conic sections are obtained by cutting a cone in ways shown. Note that the circle is cut parallel to the base of the cone, the parabola parallel to one side.

In this work we shall not discuss the stages whereby Johannes Kepler came to make his discoveries. Not that the subject is devoid of interest. Far from it! But at present we are concerned with the rise of a new physics, as it was related to the writings of antiquity, the Middle Ages, the Renaissance and the seventeenth century. Aristotle's books were read widely, and so were the writings of Galileo and Newton. Men studied Ptolemy's *Almagest* and Copernicus's *De revolutionibus* carefully. But Kepler's writings were not so generally read. Newton, for example, knew the works of Galileo but he probably did not read Kepler's books. He may even have acquired his knowledge of Kepler's laws at secondhand, very likely from Seth Ward's textbook on astronomy. Even today there is no major work of Kepler available in a complete English, French, or Italian translation!

This neglect of Kepler's texts is not hard to understand. The language and style were of unimaginable difficulty and prolixity, which, in contrast with the clarity and vigor of Galileo's every word, seemed formidable beyond endurance. This is to be expected, for writing reflects the personality of the author. Kepler was a tortured mystic, who stumbled onto his great discoveries in a weird groping that has led his most recent biographer,* to call him a "sleepwalker." Trying to prove one thing, he discovered another, and in his calculations he made error after error that canceled each other out. He was utterly unlike Galileo and Newton; never could their purposeful quests for truth conceivably merit the description of sleepwalking. Kepler, who wrote sketches of himself in the third person, said that he became a Copernican as a student and that "There were three things in particular, namely, the number, distances and motions of the heavenly bodies, as to which I [Kepler] searched zealously for reasons why they were as they were and not otherwise." About the sun-centered system of Copernicus, Kepler at another time wrote: "I certainly know that I owe it this duty: that since I have attested it as true in my deepest soul, and since I contemplate its beauty with incredible and ravishing delight, I should also publicly defend it to my readers with all the force at my command." But it was not enough to defend the system; he set out to devote his whole life to finding a law or set of laws that would show how the system held together, why the planets had the particular orbits in which they are found, and why they move as they do.

The first installment in this program, published in 1596, when Kepler was twenty-five years old, was en-

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* Arthur Koestler, *The Sleepwalkers*, Hutchinson & Co., London, 1959.

titled *Forerunner of the Dissertations on the Universe, containing the Mystery of the Universe.* In this book Kepler announced what he considered a great discovery concerning the distances of the planets from the sun. This discovery shows us how rooted Kepler was in the Platonic-Pythagorean tradition, how he sought to find regularities in nature associated with the regularities of mathematics. The Greek geometers had discovered that there are five "regular solids," which are shown in Fig. 25. In the Copernican system there are six planets: Mercury, Venus, Earth, Mars, Jupiter, Saturn. Hence it occurred to Kepler that five regular solids might separate six planetary orbits.

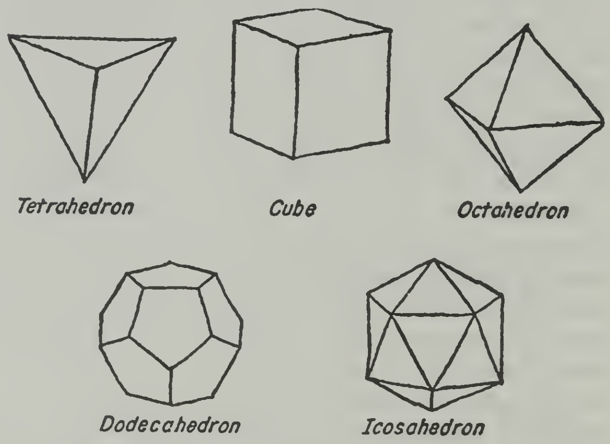

Fig. 25. The "regular" polyhedra. Tetrahedron has four faces, each an equilateral triangle. The cube has six faces, each a square. The octahedron has eight faces, each an equilateral triangle. Each of the dodecahedron's twelve faces is an equilateral pentagon. The twenty faces of the icosahedron are all equilateral triangles.

He started with the simplest of these solids, the cube.

A cube can be circumscribed by one and only one sphere, just as one and only one sphere can be inscribed in a cube. Hence we may have a cube that is circumscribed by sphere No. 1 and contains sphere No. 2. This sphere No. 2 just contains the next regular solid, the tetrahedron, which in turn contains sphere No. 3. This sphere No. 3 contains the dodecahedron, which in turn contains sphere No. 4. Now it happens that in this scheme the radii of the successive spheres are in more or less the same proportion as the mean distances of the planets in the Copernican system except for Jupiter—which isn't surprising, said Kepler, considering how far Jupiter is from the sun. The first Keplerian scheme (Fig. 26), then, was this:

Sphere of Saturn
Cube
Sphere of Jupiter
Tetrahedron
Sphere of Mars
Dodecahedron
Sphere of Earth
Icosahedron
Sphere of Venus
Octahedron
Sphere of Mercury.

"I undertake," he said, "to prove that God, in creating the universe and regulating the order of the cosmos, had in view the five regular bodies of geometry as known since the days of Pythagoras and Plato, and that He has fixed, according to those dimensions, the number of heavens, their proportions, and the relations of their movements." Even though this book fell short of unqualified success, it established Kepler's reputation as a clever mathematician and as a man who really knew something about astronomy. On the basis of this performance, Tycho Brahe offered him a job.

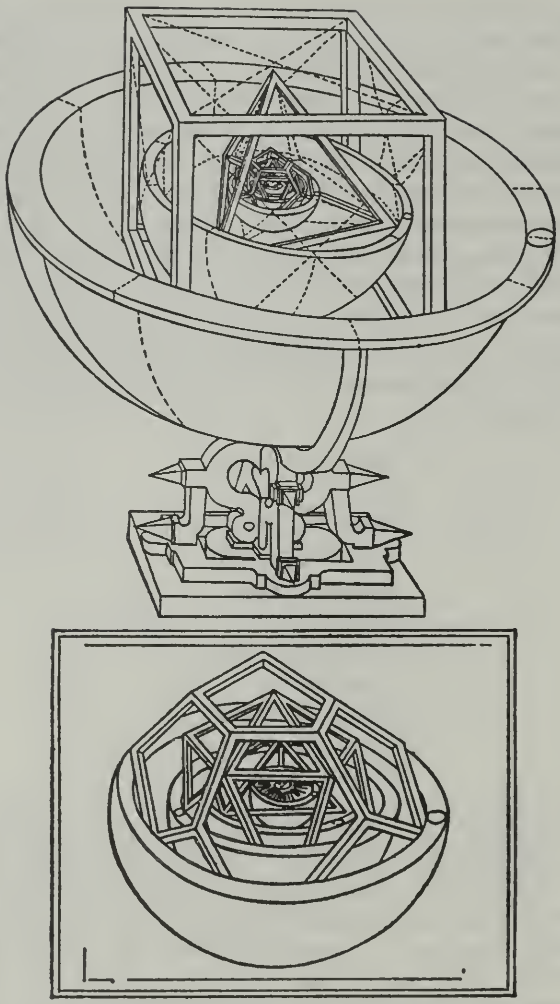

Fig. 26. Kepler's model of the universe. This weird contraption, consisting of the five regular solids fitted together, was dearer to his heart than the three laws on which his fame rests. From Christophorus Leibfried (1597).

The Keplerian Achievement

Galileo particularly disliked the idea that solar emanations or mysterious forces acting at-a-distance could affect the earth or any part of the earth. He not only rejected Kepler's suggestion that the sun might be the origin of an attractive force moving the earth and planets (on which the first two laws of Kepler were based), but he especially rejected Kepler's suggestion that a lunar force or emanation might cause the tides. Thus he wrote:

> "But among all the great men who have philosophized about this remarkable effect, I am more astonished at Kepler than at any other. Despite his open and acute mind, and though he has at his fingertips the motions attributed to the earth, he has nevertheless lent his ear and his assent to the moon's dominion over the waters, and to occult properties, and to such puerilities."

As to the harmonic law, or third law, we may ask with the voice of Galileo and his contemporaries, Is this science or numerology? Kepler already had committed himself in print to the belief that the telescope should reveal not only the four satellites of Jupiter discovered by Galileo, but two of Mars and eight of Saturn. The reason for these particular numbers was that then the number of satellites per planet would increase according to a regular geometric sequence: 1 (for the earth), 2 (for Mars), 4 (for Jupiter), 8 (for Saturn). Was not Kepler's distance-period relation something of the same pure number-juggling rather than true science? And was not evidence for the generally nonscientific aspect of Kepler's whole book to be found in the way he tried to fit the numerical aspects of the planets' motions and locations into the questions posed in the table of contents for Book Five of his *Harmony of the World?*

"1. Concerning the five regular solid figures.
2. On the kinship between them and the harmonic ratios.
3. Summary of astronomical doctrine necessary for speculation into the celestial harmonies.
4. In what things pertaining to the planetary movements the simple consonances have been expressed and that all those consonances which are present in song are found in the heavens.
5. That the clefs of the musical scale, or pitches of the system, and the genera of consonances, the major and the minor, are expressed in certain movements.
6. That the single musical Tones or Modes are somehow expressed by the single planets.
7. That the counterpoints or universal harmonies of all the planets can exist and be different from one another.
8. That the four kinds of voice are expressed in the planets; soprano, contralto, tenor, and bass.
9. Demonstration that in order to secure this harmonic arrangement, those very planetary eccentricities which any planet has as its own, and no others, had to be set up.
10. Epilogue concerning the sun, by way of very fertile conjectures."

Below are shown the "tunes" played by the planets in the Keplerian scheme.

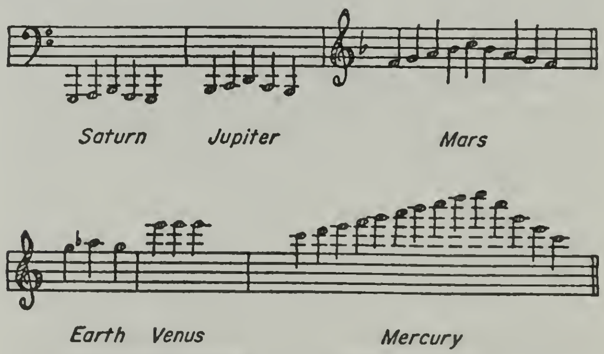

Fig. 29. Kepler's music of the planets, from his book Harmony of the World. *Small wonder a man of Galileo's stamp never bothered to read it!*

Surely a man of Galileo's stamp would find it hard to consider such a book a serious contribution to celestial physics.

Kepler's last major book was an *Epitome of Copernican Astronomy,* completed for publication nine years before his death in 1630. In it he defended his departures from the original Copernican system. But what is of the most interest to us is that in this book, as in the *Harmony of the World* (1619), Kepler again proudly presented his earliest discovery concerning the five regular solids and the six planets. It was, he still maintained, the reason for the number of planets being six.

It must have been almost as much work to disentangle the three laws of Kepler from the rest of his writings as to remake the discoveries. Kepler deserves credit for having been the first scientist to recognize that the Copernican concept of the earth as a planet and Galileo's discoveries demanded that there be one physics–applying equally to the celestial objects and ordinary terrestrial bodies. But, alas, Kepler remained so enmeshed in Aristotelian physics that when he attempted to project a terrestrial physics into the heavens, the basis still came from Aristotle. Thus the major aim of Keplerian physics remained unachieved, and the first workable physics for heaven and earth derived not from Kepler but from Galileo and attained its form under the magistral guidance of Isaac Newton.

This brief sketch of Johannes Kepler's life and work was initially written as a review of Max Caspar's definitive biography of Kepler.

7 Kepler

Gerald Holton

An article from the *Scientific American*, 1960.

The early part of the 17th century was the hinge on which the world view of the West, which had been dominated by scholasticism, turned toward science. In this period of transition the center of gravity of intellectual life shifted from the Scriptures to the Book of Nature. The stage for the later triumph of Newtonianism was being prepared by men working on problems that sprawled across the then indistinctly separated disciplines of mathematics, physics, astronomy, cosmology, philosophy and theology. It was, in short, the time of Kepler, Galileo and Descartes.

Of the three Johannes Kepler is perhaps the most interesting, both as a scientist and as a personality. He is also the least known. Until now there has been no serious biography of him in English. This neglect has at last been remedied: The definitive biography by Max Caspar has been translated from the German by C. Doris Hellman of the Pratt Institute in New York.

As Caspar warns the reader, "No one who has once entered the magic sphere that surrounds [Kepler] can ever escape from it." Caspar devoted his whole life to Kepler; at the time of Caspar's recent death his monumental 13-volume edition of Kepler's collected works, his translation of Kepler's letters and his biography had already become a gold mine for scholars—and for popular writers. The more meritorious passages of Arthur Koestler's *The Sleepwalkers*, for example, are little more than a paraphrase of Caspar.

Albert Einstein, who felt a deep kinship with Kepler (and who, like Kepler, was born in Swabia), said of him: "He belonged to those few who cannot do otherwise than openly acknowledge their convictions on every subject." Caspar's dedication and erudition consequently found an enormous amount of material on which to feed. This book is not merely a detailed portrait of Kepler. It is also an account of the intellectual ferment from which modern science arose, and of the historical context: the tragic and turbulent age of the Counter Reformation and the Thirty Years' War.

From the beginning Kepler's personal life was unfortunate. His father Heinrich, as characterized by Kepler himself, was an immoral, rough and quarrelsome soldier; his mother Katharina, a querulous and unpleasant woman, did not waste much love on her son. Too weak and sickly for agricultural labor, the boy was sent through a school system leading to theological studies at the Protestant seminary in Tübingen. One of his teachers, Michael Maestlin, introduced him privately to the Copernican system, which Maestlin was prohibited from teaching in his public lectures. This was the spark that set the youthful mind afire.

At the age of 23, a few months before attaining the goal of his studies (the pulpit), Kepler was directed by his seminary to leave in order to serve as teacher of mathematics and astronomy at the seminary in Graz. He was a wretched teacher, and he had few students. This enabled him, however, to devote that much more time to other work. Although he spurned astrology as it was then practiced, he began to write horoscopes and prognostications. He had good reasons to do so: It was part of his official duties as district mathematician and calendar-maker; he believed that he could "separate some precious stones from the dung"; he was convinced that the harmonious arrangement of planets and stars could impart special qualities to the soul; he loved to spread his opinions among the noblemen and prelates who read these writings; he needed the money; and, last but not least, he found that his predictions were often accurate.

At this time he also began a work that combined a little of each of his previous studies: of Plato, Aristotle, Euclid, Augustine, Copernicus, Nicholas of Cusa and Luther. This was not merely astronomy; his aim was nothing less than to discover the plan of the Creator, "to think the thoughts of God over again," and to show that His plan was Copernican. In 1597 Kepler published the *Mysterium Cosmographicum*, in which he hoped to show the reasons for the number of planets, the size of their orbits and their specific motions. His method was to search for geometrical regularities with which to "explain" physical observation. His immense ingenuity, coupled with his unparalleled persistence, enabled him to uncover geometrical coincidences which satisfied him that his prejudices were correct. The key was his famous discovery that the relative radii of the planetary orbits in the heliocentric system correspond fairly well to the relative radii of thin spherical shells that may be thought to separate a nested arrangement of the five Platonic solids. (The agreement is surprisingly good; the discrepancy between the radii of the shells and those of the orbits according to Copernicus was within about 5 per cent, except for the single case of Jupiter—"at which," Kepler said, "nobody will wonder, considering the great distance.")

Kepler soon saw that this was an incomplete effort at best, and changed his method of work. Still, the fundamental motivation behind the *Mysterium Cosmographicum,* namely the search for harmonies, remained strong throughout the remaining 33 years of his life. In 1597 he could feel the elation of the young man who, in Max Weber's phrase, "finds and obeys the demon who holds the fibers of his very life."

But in that same year the dark clouds that seemed always to hover over him sent down some lightning bolts. He married a young widow whom he described later as "simple-minded and fat, confused and perplexed." In 1600, the Counter Reformation having begun in earnest, all Protestants who did not choose to abandon their faith were banished from Graz. Kepler found an uncertain refuge in Prague with the aging and difficult Tycho Brahe, the foremost astronomer of his time, himself in exile from Denmark at the court of Emperor Rudolph.

Brahe lived for only one more year. When he died, however, he left Kepler two great treasures: a healthy respect for accurate measurement, and a set of the best observations of planetary positions that had ever been made. Out of this raw material came Kepler's second great work, the *Astronomia Nova*, famous because it contained his first two laws of planetary motion. During this period Kepler also did fundamental work in optics.

In 1612 he was obliged to leave Prague. His protector, the Emperor, had been forced to abdicate; Bohemia had been devastated by warfare among the contenders for the throne; his wife had died of a disease sweeping the capital. Kepler fled to Linz, where for 14 years he worked as a schoolteacher and district mathematician. At first this was the most tranquil time of his life. He brought out his *Epitome*, an account of the Copernican system which was more persuasive than Galileo's, but which was neglected by contemporary scholars, including Galileo. He chose a new wife in a comically careful way from 11 candidates (the choice turned out rather well), and fought in his Lutheran congregation for the right to interpret the concept of transubstantiation as he saw fit (he was deeply hurt when, as a result, his pastor excluded him from communion).

This was also the time when Kepler's aged and feeble-minded mother was tried as a witch. It was a miserable affair, involving the full spectrum of human fears and stupidities. Kepler devoted a full year to her defense. He did not claim that witches did not exist, but only that his mother was not one. He barely managed to keep her from the rack and gallows. When one of his children died, he turned for solace to his work on the *Harmonice Mundi,* which contained his third law of planetary motion and was his last major book. He wrote: "I set the *Tables* [the Rudolphine tables] aside, since they require peace, and turned my mind to the contemplation of the *Harmony*."

Kepler discovered the third law in May, 1618; the month also marked the beginning of the Thirty Years' War, which devastated Germany. Within a year the published part of his *Epitome* was placed on the Index of forbidden books. By 1626 his stay in Linz had become intolerable; his library had been sealed up by the Counter Reformation Commission; the countryside was swept by bloody peasant uprisings; the city of Linz was besieged; the press that had been printing the Rudolphine tables had gone up in flames. It seemed that he had no place to go. He was received splendidly in Prague by Emperor Ferdinand II, but he refused employment at the court because he would have had to embrace Catholicism. For a time he found refuge in the retinue of the Austrian duke Wallenstein, partly because of Wallenstein's interest in astrology. Then in 1630, as he was passing through Regensburg on a fruitless journey to collect some money that was owed him, he was seized by a fever and died. Soon afterward the churchyard in which he was buried was destroyed by one of the battles of the time. Caspar writes: "It is as though the fate which in life gave him no peace continued to pursue him even after death."

But Kepler had left something more durable than a headstone: the three laws of planetary motion. During his lifetime they attracted little attention. For a generation they slept quietly; then they awoke as the key inspiration for Newton's theory of universal gravitation.

These three empirical rules for which Kepler is remembered are scattered through his voluminous work. They are almost submerged in a flood of other ideas: from a means of calculating the optimum size for wine casks to an attempt to fix the year of Christ's birth, from an excellent discussion of lens optics to an attempt to connect the position of planets with the local weather. (For 20 years Kepler faithfully made weather observations for this purpose; and at the end he bravely confessed that no connection was provable.)

His whole work is characterized by this search for an arena of fruitful study in disciplines that, from our point of view, are incongruously mixed: physics and metaphysics, astronomy and astrology, geometry and theology, mathematics and music. But this was the time when the sciences were emerging from the matrix of general intellectual activity and assuming more specific forms. It fell to Kepler to show, through his successes and through his failures, where the fruitful ground for science lay. It was ground that he himself could not reach.

If we look into Kepler's turbulent life and work for those brief moments that best illuminate the man and the time, I would select passages from two letters. One, written to Guldin in 1626, described Kepler's life during the long siege of Linz. His house was situated at the city wall around which the fighting was raging, and a whole company of soldiers was stationed in it. "One had to keep all doors open for the soldiers, who through their continual coming day and night kept us from sleep and study." Here we find Kepler deep at work in technical chronology: "I set to work against Joseph Scaliger—one thought followed the next, and I did not even notice how time was passing."

The other revealing view of Kepler is provided by a letter to Herwart von Hohenburg in 1605. Here we come as close as we can to putting the finger on the moment when the modern mechanical-mathematical conception of science breaks out of its earlier mold. Kepler wrote: "I am much occupied with the investigation of the physical causes. My aim in this is to show that the celestial machine is to be likened not to a divine organism but rather to a clockwork . . . , insofar as nearly all the manifold movements are carried out by means of a single, quite simple magnetic force; as in the case of a clockwork all motions [are caused] by a simple weight. Moreover, I show how this physical conception is to be presented through calculation and geometry."

The celestial machine, driven by a single *terrestrial* force, in the image of a clockwork! This was indeed a prophetic goal. When the *Astronomia Nova* (on which Kepler was working at the time) was published four years later, it significantly bore the subtitle *Physica Coelestis.* Here we find the search for one universal force-law to explain terrestrial gravity and the oceanic tides as well as the motion of the planets. It is a conception of unity that is perhaps even more striking than Newton's, for the simple reason that Kepler did not have a predecessor.

Kepler did not, of course, succeed in his aim to find the physics that explains astronomical observations in terms of mechanics. The Achilles heel of his celestial physics was his Aristotelian conception of the law of inertia, which identified inertia with a tendency to come to rest: "Outside the field of force of another related body, every bodily substance, insofar as it is corporeal, by nature tends to remain at the same place at which it finds itself." (The quotation is from the *Astronomia Nova.*) This axiom deprived him of the concepts of mass and force in useful form, and without them his world machine was doomed.

And yet, perhaps precisely because of the failure of his physics, he still had to see the world in one piece, holding before him an image in which there were three components: the universe as a physical machine, the universe as mathematical harmony and the universe as a central theological order. Taken by itself, any one of the three was incomplete and insufficient. It was Kepler's vision of all three together that makes him so interesting to us when we compare his view of the world to ours, so much more successful in each detail but — perhaps necessarily and irretrievably — so much more fragmented.

Kepler's description of how he came to take up the study of Mars, from his greatest book, The New Astronomy. Kepler records in a personal way everything as it occurred to him, not merely the final results.

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8 Kepler on Mars

Johannes Kepler

Written in 1609 and translated by Owen Gingerich, 1967.

Johannes Kepler

(Translated by Owen Gingerich)

Astronomia Nova, Chapter 7, first part

On the Occasion When I Took up the Theory of Mars

The divine voice that calls men to learn astronomy is, in truth, expressed in the universe itself, not by words or syllables, but by things themselves and by the agreement of the human intellect and senses with the ensemble of celestial bodies and phenomena. Nevertheless, there is a certain destiny which secretly drives men toward different arts and gives them the assurance that just as they are part of the works of creation, so also they participate in the divine Providence.

Thus when I was old enough to taste the sweetness of philosophy, I embraced it all with an extreme passion, without taking a particular interest in astronomy. I have for it, certainly, a sufficient intelligence, and I understood without difficulty the geometry and astronomy imposed by the program of studies, which depends on figures, numbers and proportions. But these were the prescribed studies, and nothing indicated to me a particular inclination for astronomy.

Since I was supported by a scholarship from the Duke of Württemberg and when I saw that my fellow students would excuse themselves when the Prince was soliciting for foreign countries, although in face they simply refused for love of their native land, I decided very quickly, being of a tougher nature, to go immediately where I might be sent.

The first place offered to me was an astronomical position into which, frankly, I was pushed only because of the authority of my teachers, not that I was frightened by the distance of the place—a fear I had condemned in the others (as I have said)—but because of the unexpected character and lowness of the position as well as the weakness of my knowledge in this part of philosophy. I accepted, therefore, being richer in ingenuity than in knowledge, and protesting highly that I would by no means abandon my right to another kind of life and ecclesiastical position that appeared to me much better. What was the success of my studies during the first two years appears in my Mysterium Cosmographicum. Moreover, what stimulus my teacher Maestlin applied to me for taking up astronomy, you will read in the same little book and in his letter prefixed to the Narratio of Rheticus. I have esteemed my discovery very high, and much more so when I saw that it was approved so highly by Maestlin. But he did not stimulate me as much by the untimely promise made by him to the readers, of a general astronomical work by me (Uranicum vel Cosmicum Opus, as it was called), inasmuch as I was eager to inquire into the restoration of astronomy and to see if my discovery could be exposed to the discrimination of observations. Indeed it was demonstrated in the book itself that it agreed within the precision of common astronomy.

Therefore at this time I began to think seriously of comparing it with observations. And when, in 1597, I wrote to Tycho Brahe asking him to tell me what he thought of my little work, in his answer he mentioned, among other things, his observations, he fired me with an enormous desire to see them. Moreover, Tycho Brahe, himself an important part in my destiny, did not cease from then on to urge that I come to visit him. But since the distance of the two places would have deterred me, I ascribe it to divine Providence that he came to Bohemia. I thus arrived there just before the beginning of the year 1600, with the hope of obtaining the correct eccentricities of the planetary orbits. When, in the first week, I learned that he himself along with Ptolemy and Copernicus employed the mean motion of the sun, but in fact the apparent motion agreed more with my little book, (as shown by the book itself), I was authorized to use the observations in my manner. Now at that time, his personal aide, Christian Severinus Longomontanus had taken up the theory of Mars, which was placed in his hands so that they might study the observation of the acronycal place, or opposition of Mars, with the sun in nine degrees of Leo. Had Christian been occupied with another planet, I would have started with that same one.

This is why I consider it again an effect of divine Providence that I arrived at Benatek at the time when he was directed toward Mars; because for us to arrive at the secret knowledge of astronomy, it is absolutely necessary to use the motion of Mars; otherwise it would remain eternally hidden.

This article describes briefly the events which transpired immediately before the writing of the Principia.

9

Newton and the *Principia*

C. C. Gillispie

An excerpt from his book *The Edge of Objectivity*, 1960.

AFTER 1676 Newton gave over contending for his theory of colors and withdrew into his alternate posture of renunciation. "I had for some years past," he wrote in 1679, "been endeavouring to bend myself from philosophy to other studies in so much that I have long grutched the time spent in that study unless it be perhaps at idle hours sometimes for a diversion." It is not known in detail how he spent those years. On theology and biblical antiquities certainly, on mathematics probably, on chemistry and on perfecting his optics perhaps, for it is in character that he should have nursed his disenchantment in public and continued his work in private. In 1679 he was recalled to science, but to dynamics this time, by a further letter from Hooke, now become Secretary of the Royal Society. Hooke approached him on two levels. Privately, the letter was an olive branch. Officially, it was the new secretary bespeaking the renewed collaboration of the most potent of his younger colleagues, sulking in his tent.

Newton answered, correctly enough in form, but not very frankly, not at all cordially, affecting ignorance of an "hypothesis of springynesse" (Hooke's law of elasticity) on which Hooke had invited his opinion. So as to disguise without taking the edge off his snub, he threw in as a crumb "a fancy of my own," the solution of a curious problem he had toyed with in one of those idle hours. It concerned the trajectory of a body falling freely from a high tower, supposing the earth permeable and considering only the diurnal rotation. This was in fact a famous puzzle suggested by the Copernician theory, the same problem which Galileo had so curiously and erroneously answered with a semi-circle to the center of the earth. Since then it had been much discussed in obscure and learned places. And having brought it up himself, as if to flex a mental muscle in Hooke's face, Newton gave an answer as wrong as Galileo's. The trajectory, he casually said and drew it, will be a spiral to the center of the earth.

Now, Hooke did not know the right answer. The forces are in fact complex: the force of gravity increases by the inverse square relationship as far as the surface of the earth and thereafter as the first power of the distance. Hooke, along with many others, surmised the former (though he was too feeble a mathematician to handle gravity other than as constant) but was ignorant—as Newton then was—of the latter fact. He did have the happy thought of eliminating Coriolis forces by putting his tower on the equator. But Hooke did not need to solve the problem correctly to perceive that the initial tangential component of motion will not only, as Newton pointed out with an air of correcting vulgar errors, carry the body east of the foot of the tower, but by the same reasoning will insure that one point which the body can never traverse, either on a spiral or on any other path, is the center of the earth. Hooke was not the man to resist this opportunity. He had invited Newton to a private correspondence. He communicated Newton's reply to the Royal Society, and corrected his error publicly.

It would be tedious to follow the ensuing correspondence: the outward forms of courtesy, the philosophical tributes to truth as the goal, the underlying venom, the angry jottings in the margin. Newton "grutched" admitting error far more than the time spent on philosophy. He never did solve the problem. But he left it as the most important unsolved problem in the history of science. For it drew his mind back to dynamics and gravity, back to where he had left those questions thirteen years before. And in the course of these geometrical investigations, he solved the force law of planetary motion: "I found the Proposition that by a centrifugal force reciprocally as the square of the distance a Planet must revolve in an Ellipsis about the center of the force placed in the lower umbilicus of the Ellipsis and with a radius drawn to that center describe areas proportional to the times." He would prove the point mass theorem only after 1685. But he had proved the law of gravity on the celestial scale, not just approximately for circular orbits as in 1666, but as a rigorous geometric deduction combining Kepler's laws with Huygens' law of centrifugal force. And he told no one, "but threw the calculations by, being upon other studies."

It is one of the ironies attending the genesis of Newton's *Principia* that no one knew beforehand of his work on celestial mechanics. In inviting Newton's correspondence, Hooke may even have thought that he was taking his rival onto his own ground. For the problem of gravity was constantly under discussion. Hooke had certainly surmised that a gravitating force of attraction was involved in the celestial motions, and that it varied in power inversely as the square of the distance. So, too, had Christopher Wren, then one of the most active of the virtuosi, and the young astronomer, Edmund Halley. But none of them was mathematician enough to deduce the planetary motions from a force law.

Far more than Boyle, Hooke was the complete Baconian. The only plausible explanation of his later conduct is that he truly did not understand the necessity for mathematical demonstration. He relied uniquely upon experiment to sort out the good from the bad ideas that crowded out of his fertile imagination. He seems to have been prepared to build even celestial mechanics out of experiments on falling bodies like those improvised to test out

Newton's spiral. Nor could he see that the rigorous geometrical demonstrations of the *Principia* added anything to his own idea. They gave the same result. Once again, thought Hooke on seeing the manuscript, Newton had wrapped his intellectual property in figures and stolen it away.

Halley was more sophisticated. He was also an attractive and sympathetic young man. In August 1684 he went up from London to consult Newton. An account of this visit by John Conduitt, who later married Newton's niece, is generally accepted.

> Without mentioning either his own speculations, or those of Hooke and Wren, he at once indicated the object of his visit by asking Newton what would be the curve described by the planets on the supposition that gravity diminished as the square of the distance. Newton immediately answered, *an Ellipse.* Struck with joy and amazement, Halley asked him how he knew it? Why, replied he, I have calculated it; and being asked for the calculation, he could not find it, but promised to send it to him.

While others were looking for the law of gravity, Newton had lost it. And yielding to Halley's urging, Newton sat down to rework his calculations and to relate them to certain propositions *On Motion* (actually Newton's laws) on which he was lecturing that term. He had at first no notion of the magnitude of what he was beginning. But as he warmed to the task, the materials which he had been turning over in his mind in his twenty-five years at Cambridge moved into place in an array as orderly and planned as some perfect dance of figures. Besides proving Halley's theorem for him, he wrote the *Mathematical Principles of Natural Philosophy*. The *Principia,* it is always called, as if there were no other principles. And in a sense there are none. For that book contains all that is classical in classical physics. There is no work in science with which it may be compared.

"I wrote it," said Newton, "in seventeen or eighteen months." He employed an amanuensis who has left an account of his working habits.

> I never knew him to take any recreation or pasttime either in riding out to take the air, walking, bowling, or any other exercise whatever, thinking all hours lost that was not spent in his studies, to which he kept so close that he seldom left his chamber except at term time, when he read in the schools as being Lucasianus Professor. . . . He very rarely went to dine in the hall, except on some public days, and then if he has not been minded, would go very carelessly, with shoes down at heels, stockings untied, surplice on, and his head scarcely combed. At some seldom times when he designed to dine in the hall, [he] would turn to the left hand and go out into the street, when making a stop when he found his mistake, would hastily turn back, and then sometimes instead of going into the hall, would return to his chamber again.

Mostly Newton would have meals sent to his rooms and forget them. His secretary would ask whether he had eaten. "Have I?" Newton would reply.

The Royal Society accepted the dedication, undertook to print the work, and like a true learned organization found itself without funds. The expense, therefore, as well as the editing came upon Halley. He was not a rich man, but he bore both burdens cheerfully, with devotion and tact. He had the disagreeable task of informing Newton that upon receipt of the manuscript Hooke had said of the inverse square law, "you had the notion from him," and demanded acknowledgment in a preface. Upon this Newton threatened to suppress the third book, the climax of the argument, which applied the laws of motion to the system of the world. He was dissuaded, as no doubt he meant to be, but one can understand how his feeling for Hooke turned from irritable dislike to scornful hatred:

> Now is not this very fine? Mathematicians, that find out, settle, and do all the business, must content themselves with being nothing but dry calculators and drudges; and another that does nothing but pretend and grasp at all things, must carry away all the invention, as well of those that were to follow him, as of those that went before. Much after the same manner were his letters writ to me, telling me that gravity, in descent from hence to the centre of the earth, was reciprocally in a duplicate ratio of the altitude, that the figure described by projectiles in this region would be an ellipsis, and that all the motions of the heavens were thus to be accounted for; and this he did in such a way, as if he had found out all, and knew it most certainly. And, upon this information, I must now acknowledge, in print, I had all from him, and so did nothing myself but drudge in calculating, demonstrating, and writing, upon the inventions of this great man. And yet, after all, the first of those three things he told me of is false, and very unphilosophical; the second is as false; and the third was more than he knew, or could affirm me ignorant of by any thing that past between us in our letters.

The provocation was great, as was the strain under which it was given. A few years after completing the *Principia* Newton suffered a nervous collapse. He wrote very strange letters. One of them accused Locke of trying to embroil him with women—Newton, who was as oblivious to women as if they were occult qualities. Alarmed, his friends had arranged a move to London, to bring him more into company. He gave up solitude in Cambridge with no regrets, became after a few years Master of the Mint, then President of the Royal Society which once he had held at such a haughty distance. Knighted in 1705 he lived out his years until 1727, the incarnation of science in the eyes of his countrymen, a legend in his own lifetime.

But he did very little more science.

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The Latin original of Newton's statement of the three Laws of Motion and the proof of Proposition One is followed here by the English translation by Andrew Motte and Florian Cajori.

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10 The Laws of Motion, and Proposition One

Isaac Newton

From his *Mathematical Principles of Natural Philosophy* translated by Florian Cajori, 1962.

AXIOMATA,

SIVE

LEGES MOTUS.

LEX I.

Corpus omne perseverare in statu suo quiescendi vel movendi uniformiter in directum, nisi quatenus illud a viribus impressis cogitur statum suum mutare.

PROJECTILIA perseverant in motibus suis, nisi quatenus a resistentia aëris retardantur, & vi gravitatis impelluntur deorsum. Trochus, cujus partes cohærendo perpetuo retrahunt sese a motibus rectilineis, non cessat rotari, nisi quatenus ab aëre retardatur. Majora autem planetarum & cometarum corpora motus suos & progressivos & circulares in spatiis minus resistentibus factos conservant diutius.

LEX II.

Mutationem motus proportionalem esse vi motrici impressæ, & fieri secundum lineam rectam qua vis illa imprimitur.

Si vis aliqua motum quemvis generet; dupla duplum, tripla triplum generabit, sive simul & semel, sive gradatim & successive impressa fuerit. Et hic motus (quoniam in eandem semper plagam cum vi generatrice determinatur) si corpus antea movebatur, motui ejus vel conspiranti additur, vel contrario subducitur, vel obliquo oblique adjicitur, & cum eo secundum utriusque determinationem componitur.

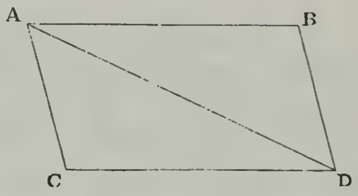
LEX III.

Actioni contrariam semper & æqualem esse reactionem: sive corporum duorum actiones in se mutuo semper esse æquales & in partes contrarias dirigi.

Quicquid premit vel trahit alterum, tantundem ab eo premitur vel trahitur. Si quis lapidem digito premit, premitur & hujus digitus a lapide. Si equus lapidem funi alligatum trahit, retrahetur etiam & equus (ut ita dicam) æqualiter in lapidem: nam funis utrinque distentus eodem relaxandi se conatu urgebit equum versus lapidem, ac lapidem versus equum; tantumque impediet progressum unius quantum promovet progressum alterius. Si corpus aliquod in corpus aliud impingens, motum ejus vi sua quomodocunque mutaverit, idem quoque vicissim in motu proprio eandem mutationem in partem contrariam vi alterius (ob æqualitatem pressionis mutuæ) subibit. His actionibus æquales fiunt mutationes, non velocitatum, sed motuum; scilicet in corporibus non aliunde impeditis. Mutationes enim velocitatum, in contrarias itidem partes factæ, quia motus æqualiter mutantur, sunt corporibus reciproce proportionales. Obtinet etiam hæc lex in attractionibus, ut in scholio proximo probabitur.

COROLLARIUM I.

Corpus viribus conjunctis diagonalem parallelogrammi eodem tempore describere, quo latera separatis.



Si corpus dato tempore, vi sola M in loco A impressa, ferretur uniformi cum motu ab A ad B; & vi sola N in eodem loco impressa, ferretur ab A ad C: compleatur parallelogrammum $ABDC$, & vi utraque feretur corpus illud eodem tempore in diagonali ab A ad D. Nam quoniam vis N agit secundum lineam AC ipsi BD parallelam, hæc vis per legem II nihil mutabit velocitatem accedendi ad lineam illam BD a vi altera genitam. Accedet igitur corpus eodem tempore ad lineam BD, sive vis N imprimatur, sive non; atque ideo in fine illius temporis reperietur alicubi in linea illa BD. Eodem argumento in fine temporis ejusdem reperietur alicubi in linea CD, & idcirco in utriusque lineæ concursu D reperiri necesse est. Perget autem motu rectilineo ab A ad D per legem I.

SECTIO II.

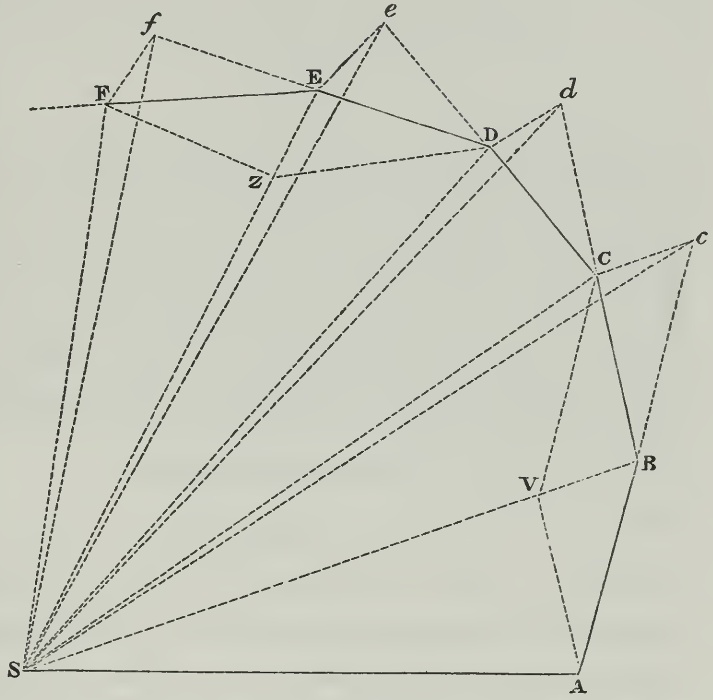
De inventione virium centripetarum.

PROPOSITIO I. THEOREMA I.

Areas, quas corpora in gyros acta radiis ad immobile centrum virium ductis describunt, & in planis immobilibus consistere, & esse temporibus proportionales.

Dividatur tempus in partes æquales, & prima temporis parte describat corpus vi insita rectam AB. Idem secunda temporis parte, si nil impediret, recta pergeret ad c, (per leg. I.) describens lineam Bc

æqualem ipsi *AB*; adeo ut radiis *AS*, *BS*, *cS* ad centrum actis, confectæ forent æquales areæ *ASB*, *BSc*. Verum ubi corpus venit ad *B*, agat vis centripeta impulsu unico sed magno, efficiatque ut corpus de recta *Bc* declinet & pergat in recta *BC*. Ipsi *BS* parallela agatur *cC*, occurrens *BC* in *C*; & completa secunda temporis parte, corpus (per legum corol. I.) reperietur in *C*, in eodem plano cum triangulo *ASB*. Junge *SC*; & triangulum *SBC*, ob parallelas *SB*, *Cc*, æquale erit triangulo *SBc*, atque ideo etiam triangulo *SAB*. Simili argumento si vis centripeta successive agat in *C*, *D*, *E*, &c. faciens ut corpus singulis temporis particulis singulas describat rectas *CD*, *DE*, *EF*, &c. jacebunt hæ omnes in eodem plano; & triangulum *SCD* triangulo *SBC*, & *SDE* ipsi *SCD*, & *SEF* ipsi *SDE* æquale erit. Æqualibus igitur temporibus æquales areæ in plano immoto describuntur: & componendo, sunt arearum summæ quævis *SADS*, *SAFS* inter se, ut sunt tempora descriptionum. Augeatur jam numerus & minuatur latitudo triangulorum in infinitum; & eorum ultima perimeter *ADF*, (per corollarium quartum lemmatis tertii) erit linea curva: ideoque vis centripeta, qua corpus a tangente hujus curvæ perpetuo retrahitur, aget indesinenter; areæ vero quævis descriptæ *SADS*, *SAFS* temporibus descriptionum semper proportionales, erunt iisdem temporibus in hoc casu proportionales. *Q. E. D.*



AXIOMS, OR LAWS OF MOTION[1]

LAW I

Every body continues in its state of rest, or of uniform motion in a right line, unless it is compelled to change that state by forces impressed upon it.

PROJECTILES continue in their motions, so far as they are not retarded by the resistance of the air, or impelled downwards by the force of gravity. A top, whose parts by their cohesion are continually drawn aside from rectilinear motions, does not cease its rotation, otherwise than as it is retarded by the air. The greater bodies of the planets and comets, meeting with less resistance in freer spaces, preserve their motions both progressive and circular for a much longer time.

LAW II[2]

The change of motion is proportional to the motive force impressed; and is made in the direction of the right line in which that force is impressed.

If any force generates a motion, a double force will generate double the motion, a triple force triple the motion, whether that force be impressed altogether and at once, or gradually and successively. And this motion (being always directed the same way with the generating force), if the body moved before, is added to or subtracted from the former motion, according as they directly conspire with or are directly contrary to each other; or obliquely joined, when they are oblique, so as to produce a new motion compounded from the determination of both.

LAW III

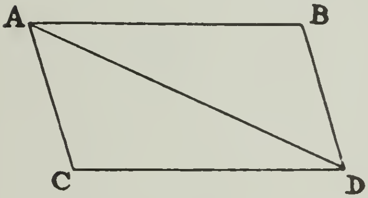
To every action there is always opposed an equal reaction: or, the mutual actions of two bodies upon each other are always equal, and directed to contrary parts.

Whatever draws or presses another is as much drawn or pressed by that other. If you press a stone with your finger, the finger is also pressed by the stone. If a horse draws a stone tied to a rope, the horse (if I may so say) will be equally drawn back towards the stone; for the distended rope, by the same endeavor to relax or unbend itself, will draw the horse as much towards the stone as it does the stone towards the horse, and will obstruct the progress of the one as much as it advances that of the other. If a body impinge upon another, and by its force change the motion of the other, that body also (because of the equality of the mutual pressure) will undergo an equal change, in its own motion, towards the contrary part. The changes made by these actions are equal, not in the velocities but in the motions of bodies; that is to say, if the bodies are not hindered by any other impediments. For, because the motions are equally changed, the changes of the velocities made towards contrary parts are inversely proportional to the bodies. This law takes place also in attractions, as will be proved in the next Scholium.

COROLLARY I

A body, acted on by two forces simultaneously, will describe the diagonal of a parallelogram in the same time as it would describe the sides by those forces separately.

If a body in a given time, by the force M impressed apart in the place A, should with an uniform motion be carried from A to B, and by the force N impressed apart in the same place, should be carried from A to C, let the parallelogram ABCD be completed, and, by both forces acting together, it will in the same time be carried in the diagonal from A to D. For since the force N acts in the direction of the line AC, parallel to BD, this force (by the second Law) will not at all alter the velocity generated by the other force M, by which the body is carried towards the line BD. The body therefore will arrive at the line BD in the same time, whether the force N be impressed or not; and therefore at the end of that time it will be found somewhere in the line BD. By the same argument, at the end of the same time it will be found somewhere in the line CD. Therefore it will be found in the point D, where both lines meet. But it will move in a right line from A to D, by Law 1.



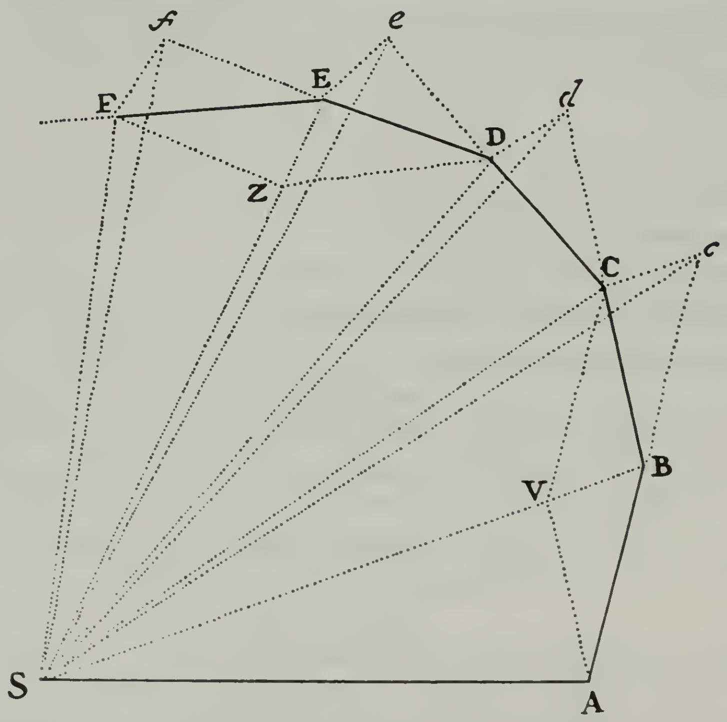
SECTION II

The determination of centripetal forces.

PROPOSITION I. THEOREM I

The areas which revolving bodies describe by radii drawn to an immovable centre of force do lie in the same immovable planes, and are proportional to the times in which they are described.

For suppose the time to be divided into equal parts, and in the first part of that time let the body by its innate force describe the right line AB. In the second part of that time, the same would (by Law 1), if not hindered, proceed directly to *c*, along the line B*c* equal to AB; so that by the radii AS, BS, *c*S, drawn to the centre, the equal areas ASB, BS*c*, would be described. But when the body is arrived at B, suppose that a centripetal force acts at once with a great impulse, and, turning aside the body from the right line B*c*, compels it afterwards to continue its motion along the right line BC.



Draw *c*C parallel to BS, meeting BC in C; and at the end of the second part of the time, the body (by Cor. I of the Laws) will be found in C, in the same plane with the triangle ASB. Join SC, and, because SB and C*c* are parallel, the triangle SBC will be equal to the triangle SB*c*, and therefore also to the triangle SAB. By the like argument, if the centripetal force acts successively in C, D, E, &c., and makes the body, in each single particle of time, to describe the right lines CD, DE, EF, &c., they will all lie in the same plane; and the triangle SCD will be equal to the triangle SBC, and SDE to SCD, and SEF to SDE. And therefore, in equal times, equal areas are described in one immovable plane: and, by composition, any sums SADS, SAFS, of those areas, are to each other as the times in which they are described. Now let the number of those triangles be augmented, and their breadth diminished *in infinitum;* and (by Cor. IV, Lem. III) their ultimate perimeter ADF will be a curved line: and therefore the centripetal force, by which the body is continually drawn back from the tangent of this curve, will act continually; and any described areas SADS, SAFS, which are always proportional to the times of description, will, in this case also, be proportional to those times. Q.E.D.

Anatole France is best known as the writer of novels such as Penguin Island. This brief passage shows that he, along with many writers, is interested in science.

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11 The Garden of Epicurus

Anatole France

An essay written in 1920.

WE find it hard to picture to ourselves the state of mind of a man of older days who firmly believed that the Earth was the center of the Universe, and that all the heavenly bodies revolved round it. He could feel beneath his feet the writhings of the damned amid the flames; very likely he had seen with his own eyes and smelt with his own nostrils the sulphurous fumes of Hell escaping from some fissure in the rocks. Looking upwards, he beheld the twelve spheres, —first that of the elements, comprising air and fire, then the sphere of the Moon, of Mercury, of Venus, which Dante visited on Good Friday of the year 1300, then those of the Sun, of Mars, of Jupiter, and of Saturn, then the incorruptible firmament, wherein the stars hung fixed like so many lamps. Imagination carried his gaze further still, and his mind's eye discerned in a remoter distance the Ninth Heaven, whither the Saints were translated to glory, the *primum mobile* or crystalline, and finally the Empyrean, abode of the Blessed, to which, after death, two angels robed in white (as he steadfastly hoped) would bear his soul, as it were a little child, washed by baptism and perfumed with the oil of the last sacraments. In those times God had no other children but mankind, and all His creation was administered after a fashion at once puerile and poetical, like the routine of a vast cathedral. Thus conceived, the Universe was so simple that it was fully and adequately represented, with its true shape and proper motion, in sundry great clocks compacted and painted by the craftsmen of the Middle Ages.

We are done now with the twelve spheres and the planets under which men were born happy or unhappy, jovial or saturnine. The solid vault of the firmament is cleft asunder. Our eyes and thoughts plunge into the infinite abysses of the heavens. Beyond the planets, we discover, instead of the Empyrean of the elect and the angels, a hundred millions of suns rolling through space, escorted each by its own procession of dim satellites, invisible to us. Amidst this infinitude of systems *our* Sun is but a bubble of gas and the Earth a drop of mud. The imagination is vexed and startled when the astronomers tell us that the luminous ray which reaches us from the pole-star has been half a century on the road ; and yet that noble star is our next neighbour, and with Sirius and Arcturus, one of the least remote of the suns that are sisters of our own. There are stars we still see in the field of our telescopes which ceased to shine, it may be, three thousand years ago.

Worlds die,—for are they not born? Birth and death are unceasingly at work. Creation is never complete and perfect; it goes on for ever under incessant changes and modifications. The stars go out, but we cannot say if these daughters of light, when they die down into darkness, do not enter on a new and fecund existence as planets,—if the planets themselves do not melt away and become stars again. All we know is this; there is no more repose in the spaces of the sky than on earth, and the same law of strife and struggle governs the infinitude of the cosmic universe.

There are stars that have gone out under our eyes, while others are even now flickering like the dying flame of a taper. The heavens, which men deemed incorruptible, know of no eternity but the eternal flux of things.

That organic life is diffused through all parts of the Universe can hardly be doubted,—unless indeed organic life is a mere accident, an unhappy chance, a deplorable something that has inexplicably arisen in the particular drop of mud inhabited by ourselves.

But it is more natural to suppose that life has developed in the planets of our solar system, the

Earth's sisters and like her, daughters of the Sun, and that it arose there under conditions analogous in the main to those in which it manifests itself with us,—under animal and vegetable forms. A meteoric stone has actually reached us from the heavens containing carbon. To convince us in more gracious fashion, the Angels that brought St. Dorothy garlands of flowers from Paradise would have to come again with their celestial blossoms. Mars to all appearance is habitable for living things of kinds comparable to our terrestrial animals and plants. It seems likely that, being habitable, it is inhabited. Rest assured, there too species is devouring species, and individual individual, at this present moment.

The uniformity of composition of the stars is now proved by spectrum analysis. Hence we are bound to suppose that the same causes that have produced life from the nebulous nucleus we call the Earth engender it in all the others.

When we say life, we mean the activity of organized matter under the conditions in which we see it manifested in our own world. But it is equally possible that life may be developed in a totally different environment, at extremely high or extremely low temperatures, and under forms unthinkable by us. It may even be developed under an ethereal form, close beside us, in our atmosphere ; and it is possible that in this way we are surrounded by angels,—beings we shall never know, because to know them implies a point of common contact, a mutual relation, such as there can never be between them and us.

Again, it is possible that these millions of suns, along with thousands of millions more we cannot see, make up altogether but a globule of blood or lymph in the veins of an animal, of a minute insect, hatched in a world of whose vastness we can frame no conception, but which nevertheless would itself, in proportion to some other world, be no more than a speck of dust.

Nor is there anything absurd in supposing that centuries of thought and intelligence may live and die before us in the space of a minute of time, in the confines of an atom of matter. In themselves things are neither great nor small, and when we say the Universe is vast we speak purely from a human standpoint. If it were suddenly reduced to the dimensions of a hazel-nut, all things keeping their relative proportions, we should know nothing of the change. The pole-star, included together with ourselves in the nut, would still take fifty years to transmit its light to us as before. And the Earth, though grown smaller than an atom, would be watered with tears and blood just as copiously as it is to-day. The wonder is, not that the field of the stars is so vast, but that man has measured it.

A physical concept, such as gravitation, can be a powerful tool, illuminating many areas outside of that in which it was initially developed. As these authors show, physicists can be deeply involved when writing about their field.

12

Universal Gravitation

Richard P. Feynman, Robert B. Leighton, and Matthew Sands

An excerpt from their book *The Feynman Lectures on Physics, Volume 1,* 1963.

What else can we understand when we understand gravity? Everyone knows the earth is round. Why is the earth round? That is easy; it is due to gravitation. The earth can be understood to be round merely because everything attracts everything else and so it has attracted itself together as far as it can! If we go even further, the earth is not *exactly* a sphere because it is rotating, and this brings in centrifugal effects which tend to oppose gravity near the equator. It turns out that the earth should be elliptical, and we even get the right shape for the ellipse. We can thus deduce that the sun, the moon, and the earth should be (nearly) spheres, just from the law of gravitation.

What else can you do with the law of gravitation? If we look at the moons of Jupiter we can understand everything about the way they move around that planet. Incidentally, there was once a certain difficulty with the moons of Jupiter that is worth remarking on. These satellites were studied very carefully by Roemer, who noticed that the moons sometimes seemed to be ahead of schedule, and sometimes behind. (One can find their schedules by waiting a very long time and finding out how long it takes on the average for the moons to go around.) Now they were *ahead* when Jupiter was particularly *close* to the earth and they were *behind* when Jupiter was *farther* from the earth. This would have been a very difficult thing to explain according to the law of gravitation—it would have been, in fact, the death of this wonderful theory if there were no other explanation. If a law does not work even in *one place* where it ought to, it is just wrong. But the reason for this discrepancy was very simple and beautiful: it takes a little while to *see* the moons of Jupiter because of the time it takes light to travel from Jupiter to the earth. When Jupiter is closer to the earth the time is a little less, and when it is farther from the earth, the time is more. This is why moons appear to be, on the average, a little ahead or a little behind, depending on whether they are closer to or farther from the earth. This phenomenon showed that light does not travel instantaneously, and furnished the first estimate of the speed of light. This was done in 1656.

If all of the planets push and pull on each other, the force which controls, let us say, Jupiter in going around the sun is not just the force from the sun; there is also a pull from, say, Saturn. This force is not really strong, since the sun is much more massive than Saturn, but there is *some* pull, so the orbit of Jupiter should not be a perfect ellipse, and it is not; it is slightly off, and "wobbles" around the correct elliptical orbit. Such a motion is a little more complicated. Attempts were made to analyze the motions of Jupiter, Saturn, and Uranus on the basis of the law of gravitation. The effects of each of these planets on each other were calculated to see whether or not the tiny deviations and irregularities in these motions could be completely understood from this one law. Lo and behold, for Jupiter and Saturn, all was well, but Uranus was "weird." It behaved in a very peculiar manner. It was not travelling in an exact ellipse, but that was understandable, because of the attractions of Jupiter and Saturn. But even if allowance were made for these attractions, Uranus *still* was not going right, so the laws of gravitation were in danger of being overturned, a possibility that could not be ruled out. Two men, Adams and Leverrier, in England and France, independently,

Fig. 7–6. A double-star system.

arrived at another possibility: perhaps there is *another* planet, dark and invisible, which men had not seen. This planet, *N*, could pull on Uranus. They calculated where such a planet would have to be in order to cause the observed perturbations. They sent messages to the respective observatories, saying, "Gentlemen, point your telescope to such and such a place, and you will see a new planet." It often depends on with whom you are working as to whether they pay any attention to you or not. They did pay attention to Leverrier; they looked, and there planet *N* was! The other observatory then also looked very quickly in the next few days and saw it too.

This discovery shows that Newton's laws are absolutely right in the solar system; but do they extend beyond the relatively small distances of the nearest planets? The first test lies in the question, do *stars* attract *each other* as well as planets? We have definite evidence that they do in the *double stars*. Figure 7–6 shows a double star—two stars very close together (there is also a third star in the picture so that we will know that the photograph was not turned). The stars are also shown as they appeared several years later. We see that, relative to the "fixed" star, the axis of the pair has rotated, i.e., the two stars are going around each other. Do they rotate according to Newton's laws? Careful measurements of the relative positions of one such double star system are shown in Fig. 7–7. There we see a beautiful ellipse, the measures starting in 1862 and going all the way around to 1904 (by now it must have gone around once more). Everything coincides with Newton's laws, except that the star Sirius A is *not at the focus*. Why should that be? Because the plane of the ellipse is not in the "plane of the sky." We are not looking at right angles to the orbit plane, and when an ellipse is viewed at a tilt, it remains an ellipse but the focus is no longer at the same place. Thus we can analyze double stars, moving about each other, according to the requirements of the gravitational law.

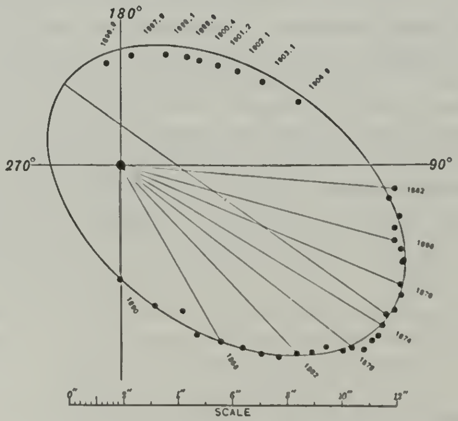

Fig. 7–7. Orbit of Sirius B with respect to Sirius A.

Fig. 7–8. A globular star cluster.

That the law of gravitation is true at even bigger distances is indicated in Fig. 7–8. If one cannot see gravitation acting here, he has no soul. This figure shows one of the most beautiful things in the sky—a globular star cluster. All of the dots are stars. Although they look as if they are packed solid toward the center, that is due to the fallibility of our instruments. Actually, the distances between even the centermost stars are very great and they very rarely collide. There are more stars in the interior than farther out, and as we move outward there are fewer and fewer. It is obvious that there is an attraction among these stars. It is clear that gravitation exists at these enormous dimensions, perhaps 100,000 times the size of the solar system. Let us now go further, and look at an *entire galaxy*, shown in Fig. 7–9. The shape of this galaxy indicates an obvious tendency for its matter to agglomerate. Of course we cannot prove that the law here is precisely inverse square, only that there is still an attraction, at this enormous dimension, that holds the whole thing together. One may say, "Well, that is all very clever but why is it not just a ball?" Because it is *spinning* and has *angular momentum* which it cannot give up as it contracts; it must contract mostly in a plane. (Incidentally, if you are looking for a good problem, the exact details of how the arms are formed and what determines the shapes of these galaxies has not been worked out.) It is, however, clear that the shape of the galaxy is due to gravitation even though the complexities of its structure have not yet allowed

Fig. 7–9. A galaxy.

us to analyze it completely. In a galaxy we have a scale of perhaps 50,000 to 100,000 light years. The earth's distance from the sun is $8\frac{1}{3}$ light *minutes*, so you can see how large these dimensions are.

Gravity appears to exist at even bigger dimensions, as indicated by Fig. 7–10, which shows many "little" things clustered together. This is a *cluster of galaxies*, just like a star cluster. Thus galaxies attract each other at such distances that they too are agglomerated into clusters. Perhaps gravitation exists even over distances of *tens of millions* of light years; so far as we now know, gravity seems to go out forever inversely as the square of the distance.

Not only can we understand the nebulae, but from the law of gravitation we can even get some ideas about the origin of the stars. If we have a big cloud of dust and gas, as indicated in Fig. 7-11, the gravitational attractions of the pieces of dust for one another might make them form little lumps. Barely visible in the figure are "little" black spots which may be the beginning of the accumulations of dust and gases which, due to their gravitation, begin to form stars. Whether we have ever seen a star form or not is still debatable. Figure 7–12 shows the one piece of evidence which suggests that we have. At the left is a picture of a region of gas with some stars in it taken in 1947, and at the right is another picture, taken only 7 years later, which shows two new bright spots. Has gas accumulated, has gravity acted hard enough and collected it into a ball big enough that the stellar nuclear reaction starts in the interior and turns it into a star? Perhaps, and perhaps not. It is unreasonable that in only seven years we should be so lucky as to see a star change itself into visible form; it is much less probable that we should see *two!*

Fig. 7–10. A cluster of galaxies.

Fig. 7–11. An interstellar dust cloud.

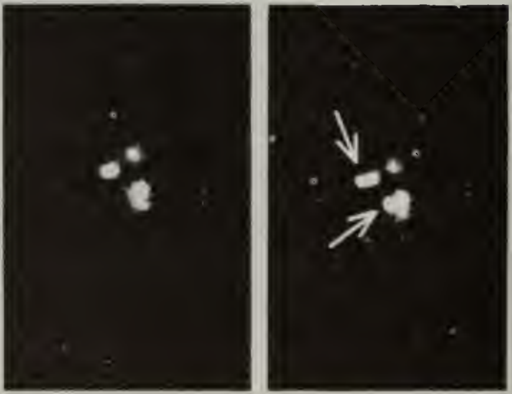

Fig. 7–12. The formation of new stars?

The earth, with all its faults, is a rather pleasant habitation for man. If things were only slightly different, our planet might not suit man nearly as well as it now does.

13 An Appreciation of the Earth

Stephen H. Dole

An excerpt from his book *Habitable Planets for Man*, 1964.

We take our home for granted most of the time. We complain about the weather, ignore the splendor of our sunsets, the scenery, and the natural beauties of the lands and seas around us, and cease to be impressed by the diversity of living species that the Earth supports. This is natural, of course, since we are all products of the Earth and have evolved in conformity with the existing environment. It is our natural habitat, and all of it seems very commonplace and normal. Yet how different our world would be if some of the astronomical parameters were changed even slightly.

Suppose that, with everything else being the same, the Earth had started out with twice its present mass, giving a surface gravity of 1.38 times Earth normal. Would the progression of animal life from sea to land have been so rapid? While the evolution of marine life would not have been greatly changed, land forms would have to be more sturdily constructed, with a lower center of mass. Trees would tend to be shorter and to have strongly buttressed trunks. Land animals would tend to develop heavier leg bones and heavier musculature. The development of flying forms would certainly have been different, to conform with the denser air (more aerodynamic drag at a given velocity) and the higher gravity (more lifting surface necessary to support a given mass). A number of opposing forces would have changed the face of the land. Mountain-forming activity might be increased, but mountains could not thrust so high and still have the structural strength to support their own weight; raindrop and stream erosion would be magnified, but the steeper density gradient in the atmosphere would change the weather patterns; wave heights in the oceans would be lower, and spray trajectories would be shortened, resulting in less evaporation and a drier atmosphere; and cloud decks would tend to be lower. The land-sea ratio would probably be smaller. The length of the sidereal month would shorten from 27.3 to 19.4 days (if the Moon's distance remained the same). There would be differences in the Earth's magnetic field, the thickness of its crust, the size of its core, the distribution of mineral deposits in the crust, the level of radioactivity in the rocks, and the size of the ice caps on islands in the polar regions. Certainly man's counterpart (assuming that such a species would have evolved in this environment) would be quite different in appearance and have quite different cultural patterns.

Conversely, suppose that the Earth had started out with half its present mass, resulting in a surface gravity of 0.73 times Earth normal. Again the course of evolution and geological history would have changed under the influences of the lower gravity, the thinner atmosphere, the reduced erosion by falling water, and the probably increased level of background radiation due to more crustal radioactivity and solar cosmic particles. Would evolution have proceeded more rapidly? Would the progression from sea to land and the entry of animal forms into the ecological niches open to airborne species have occurred earlier? Undoubtedly animal skeletons would be lighter, and trees would be generally taller and more spindly; and again, man's counterpart, evolved on such a planet, would be different in many ways.

What if the inclination of the Earth's equator initially had been 60 degrees instead of 23.5 degrees? Seasonal weather changes would then be all but intolerable, and the only climatic region suitable for life as we know it would be in a narrow belt within about 5 degrees of the equator. The rest of the planet would be either too hot or too cold during most of the year, and with such a narrow habitable range, it is probable that life would have had difficulty getting started and, once started, would have tended to evolve but slowly.

Starting out with an inclination of 0 degrees would have influenced the course of development of the Earth's life forms in only a minor way. Seasons would be an unknown phenomenon; weather would undoubtedly be far more predictable and constant from day to day. All latitudes would enjoy a constant spring. The region within 12 degrees of the equator would become too hot for habitability but, in partial compensation, some regions closer to the poles would become more habitable than they are now.

Suppose the Earth's mean distance from the Sun were 10 per cent less than it is at present. Less than 20 per cent of the surface area (that between latitudes 45 degrees and 64 degrees) would then be habitable. Thus there would be two narrow land regions favorable to life separated by a wide and intolerably hot barrier. Land life could evolve independently in these two regions. The polar ice would not be present, so the ocean level would be higher than it is now, thus decreasing the land area.

If the Earth were 10 per cent farther away from the Sun than it is, the habitable regions would be those within 47 degrees of the equator. (The present limit of habitability is assumed to be, on an average, within 60 degrees of the equator.)

If the Earth's rotation rate were increased so as to make the day 3 hours long instead of 24 hours, the oblateness would be pronounced, and changes of gravity as a function of latitude would be a common part of a traveler's experience. Day-to-night temperature differences would become small.

On the other hand, if the Earth's rotation rate were slowed to make the day 100 hours in length, day-to-night temperature changes would be extreme; weather cycles would have a more pronounced diurnal pattern. The Sun would seem to crawl across the sky, and few life forms on land could tolerate either the heat of the long day or the cold of the long night.

The effects of reducing the eccentricity of the Earth's orbit to 0 (from its present value of 0.0167) would be scarcely noticeable. If orbital eccentricity were increased to 0.2 without altering the length of the semimajor axis (making perihelion coincide with summer solstice in the Northern Hemisphere to accentuate the effects), the habitability apparently would not be affected in any significant manner.

Increasing the mass of the Sun by 20 per cent (and moving the Earth's orbit out to 1.408 astronomical units to keep the solar constant at its present level) would increase the period of revolution to 1.54 years and decrease the Sun's apparent angular diameter to 26 minutes of arc (from its present 32 minutes of arc). Our primary would then be a class F5 star with a total main-sequence lifetime of about 5.4 billion years. If the age of the solar system were 4.5 billion years, then the Earth, under these conditions, could look forward to another billion years of history. Since neither of these numbers is known to the implied accuracy, however, a 10 per cent error in each in the wrong direction could mean that the end was very near indeed. An F5 star may well be more "active" than our Sun, thus producing a higher exosphere temperature in the planetary atmosphere; but this subject is so little understood at present that no conclusions can be drawn. Presumably, apart from the longer year, the smaller apparent size of the Sun, its more pronounced whiteness, and the "imminence" of doom, life could be much the same.

If the mass of the Sun were reduced by 20 per cent (this time decreasing the Earth's orbital dimensions to compensate), the new orbital distance would be 0.654 astronomical unit. The year's length would then become 0.59 year (215 days), and the Sun's apparent angular diameter, 41 minutes of arc. The primary would be of spectral type G8 (slightly yellower than our Sun is now) with a main-sequence lifetime in excess of 20 billion years. The ocean tides due to the primary would be about equal to those due to the Moon; thus spring tides would be somewhat higher and neap tides lower than they are at present.

What if the Moon had been located much closer to the Earth than it is, say, about 95,000 miles away instead of 239,000 miles? The tidal braking force would probably have been sufficient to halt the rotation of the Earth with respect to the Moon, and the Earth's day would equal its month, now 6.9 days in length (sidereal). Consequently, the Earth would be uninhabitable.

Moving the Moon farther away than it is would have much less profound results: the month would merely be longer and the tides lower. Beyond a radius of about 446,000 miles, the Earth can not hold a satellite on a circular orbit.

Increasing the mass of the Moon by a factor of 10 at its present distance would have an effect similar to that of reducing its distance. However, the Earth's day and month would then be equal to 26 days. Decreasing the Moon's mass would affect only the tides.

What if the properties of some of the other planets of the solar system were changed? Suppose the mass of Jupiter were increased by a factor of 1050, making it essentially a replica of the Sun. The Earth could still occupy its present orbit around the Sun, but our sky would be enriched by the presence of an extremely bright star, or second sun, of magnitude −23.7, which would supply at most only 6 per cent as much heat as the Sun. Mercury and Venus could also keep their present orbits; the remaining planets could not, although those exterior to Saturn could take up new orbits around the new center of mass.

All in all, the Earth is a wonderful planet to live on, just the way it is. Almost any change in its physical properties, position, or orientation would be for the worse. We are not likely to find a planet that suits us better, although at some future time there may be men who prefer to live on other planets. At the present time, however, the Earth is the only home we have; we would do well to conserve its treasures and to use its resources intelligently.

Close-up television photographs of Mars reveal craters like those on the moon, but also other unexpected features.

14 Mariners 6 and 7 Television Pictures; Preliminary Analysis.

R. B. Leighton and others*

An article from *Science*, 1969.

Before the space era, Mars was thought to be like the earth; after Mariner 4, Mars seemed to be like the moon; Mariners 6 and 7 have shown Mars to have its own distinctive features, unknown elsewhere within the solar system.

The successful flyby of Mariner 4 past Mars in July 1965 opened a new era in the close-range study of planetary surfaces with imaging techniques. In spite of the limited return of data, Mariner 4 established the basic workability of one such technique, which involved use of a vidicon image tube, on-board digitization of the video signal, storage of the data on magnetic tape, transmission to the earth at reduced bit rate by way of a directional antenna, and reconstruction into a picture under computer control. Even though the Mariner 4 pictures covered only about 1 percent of Mars's area, they contributed significantly to our knowledge of that planet's surface and history (*1, 2, 19, 21*).

The objectives of the Mariner 6 and 7 television experiment were to apply the successful techniques of Mariner 4 to further explore the surface and atmosphere of Mars, both at long range and at close range, in order to determine the basic character of features familiar from ground-based telescopic studies: to discover possible further clues as to the internal state and past history of the planet; and to provide information germane to the search for extraterrestrial life.

The Mariner 6 and 7 spacecraft successfully flew past Mars on 31 July and 5 August 1969, respectively: first results of the television experiment, based upon qualitative study of the uncalibrated pictures, have been reported (*3, 4*). The purpose of this article is to draw together the preliminary television results from the two spacecraft: to present tentative data concerning crater size distributions, wall slopes, and geographic distribution: to discuss evidences of haze or clouds; to describe new, distinctive types of topography seen in the pictures; and to discuss the implications of the results with respect to the present state, past history, and possible biological status of Mars.

The data presented here and in the two earlier reports were obtained from inspection and measurement of a partial sample of pictures in various stages of processing. As such, the results must be regarded as tentative, subject to considerable expansion and possible modification as more complete sets, and better-quality versions, of the pictures become available over a period of several months. They are offered at this

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* Drs. Leighton, Horowitz, Murray, and Sharp are affiliated with the California Institute of Technology, Pasadena; Mr. Herriman and Dr. Young, with the Jet Propulsion Laboratory, Pasadena; Mr. Smith, with New Mexico State University, Las Cruces; Dr. Davies, with the RAND Corporation, Santa Monica, California; and Dr. Leovy, with the University of Washington, Seattle.

time because of their unique nature, their wide interest, and their obvious relevance to the forthcoming Mariner 1971 (orbiter) and Viking 1973 (lander) missions.

Television System Design

The experience and results of Mariner 4 strongly influenced the basic design of the Mariner 6 and 7 television experiment. The earlier pictures showed Mars to be heavily cratered, but to have subdued surface relief and low photographic contrast, and possibly to have a hazy atmosphere. It was also found that a vidicon-type camera tube has a most important property: the "target noise," analogous to photographic grain, is less than that of a photographic emulsion by perhaps a factor of 10 (*2*) and is the same from picture to picture. Thus the 64-level (6-bit) encoding scheme of Mariner 4 was able to cope with the extremely low contrast conditions because intensity calibration and contrast enhancement by computer techniques could be effectively applied to the data to produce pictures of useful quality.

Early design studies for Mariner 6 and 7 centered around 256-level (8-bit) encoding—at least a tenfold increase in data return over that from Mariner 4; overlapping two-color coverage along the picture track (similar to that of Mariner 4); use of two cameras of different focal lengths to provide higher-resolution views of areas nested within overlapping, wider-angle frames; and use of the camera of longer focal length to obtain a few full-disk photographs showing all sides of Mars as the spacecraft approached the planet. A third filter color, "blue," was added to the "red" and "green" of Mariner 4 for the purpose of studying atmospheric effects.

Limitations of volume, money, and schedule prevented use of a suitable digital recorder system with the necessary data storage capacity, but, through a hybrid system which uses both digital and analog tape recorders, it appeared possible to achieve sufficient data storage capacity, albeit at the expense of complexity.

In its final form, the television experiment employed a two-camera system in which the picture formats and electronic circuits of the cameras were identical (for economy and for efficient use of the tape recorders); a digital tape recorder to store the six lowest-order bits of an 8-bit encoded word for every seventh picture element ("pixel") along each TV picture line (referred to as 1/7 digital data; see *5*); and a second, similar tape recorder to store analog data for all pixels (*6*). . . .

Some technical data relating to the camera system are given in Leighton *et al.* (*3*), and more complete data will be given elsewhere (*6*). Briefly, one camera, called camera A, has a field of view 11° × 14° and a rotary shutter which carries four colored filters in the sequence red, green, blue, green, and so on. Alternating exposures with camera A is camera B, which has a focal length 10 times as great and a field of view 1°.1 × 1.°4. Camera B carries only a minus-blue haze filter. . . .

To illustrate the nature of the picture restoration process, we list some of the steps in the computer reduction: Restore the two highest-order bits to the digital data (*7*); remove effects of AGC and "cuber" in the analog data; combine digital and analog data; measure and remove electronic "pickup" noise (*7*); measure pixel locations of reseau marks on flight pictures and calibration pictures (*8*); bring pictorial calibration and flight data, by interpolation, into agreement with the known reseau pattern; measure and correct for optical distortions; measure and remove effects of residual image from calibration and flight data; evaluate the sensitometric response of each pixel from calibration data and deduce the true photometric exposure for each flight pixel (*9*); correct for the effects of shutter-speed variations and light leakage (camera B); and evaluate and correct for the modulation-transfer function of the camera system. . . .

Mission Design and Television Data Return

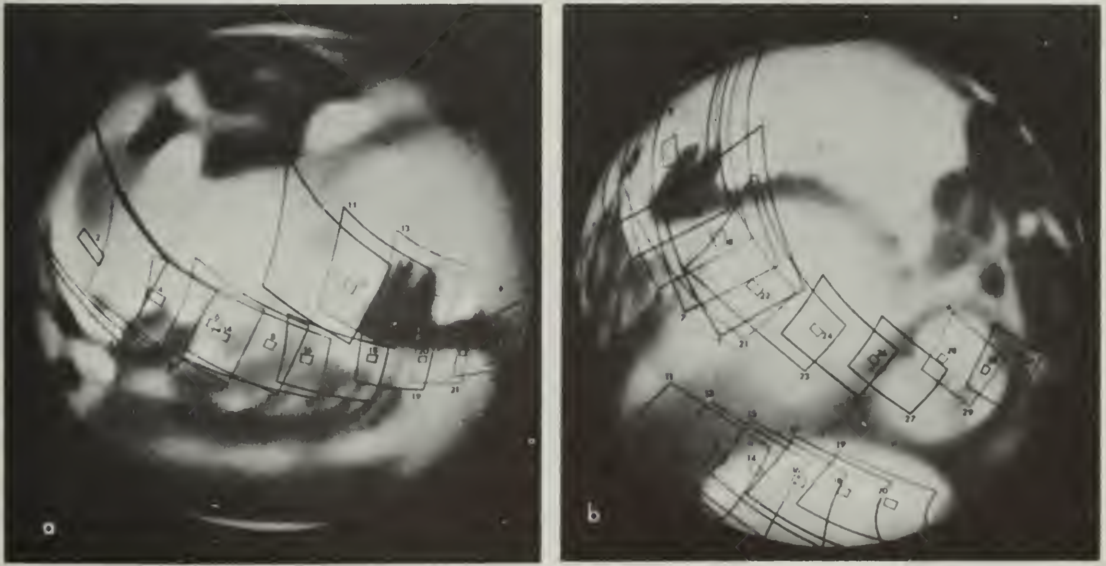
As was described in Leighton *et al.* (*3*), the planetary encounter period for each spacecraft was divided into two parts: a far-encounter (FE) period beginning 2 or 3 days prior to, and extending to within a few hours of, closest approach, and a near-encounter (NE) period bracketing the time of closest approach. . . .

In all, 50 FE pictures, 26 NE pictures, and 428 useful (*10*) real-time 1/7 digital pictures were returned from Mariner 6, and 93 FE pictures, 33 NE pictures, and 749 useful real-time digital pictures were returned from Mariner 7. This further ninefold increase in the number of FE pictures and 18 percent increase in the number of NE pictures over the original plan represents a total data return 200 times that of Mariner 4, not counting the real-time digital frames.

The pictures are designated by spacecraft, camera mode, and frame number. Thus "6N17' means Mariner 6 NE frame 17; "7F77" means Mariner 7 FE frame 77; and so on. The first NE picture from each spacecraft was a camera-A, blue-filter picture. Thus, in near-encounter, all odd-numbered frames are camera-A (wide-angle, low-resolution) frames. . . .

The approximate near-encounter picture locations for the two spacecraft are shown in Fig. 3, and the relevant data are given in Tables 1 and 2. The picture tracks were chosen, in concert with investigators for other on-board experiments, on the basis of several considerations and constraints. First, the choice of possible arrival dates was limited by engineering considerations to the interval 31 July to 15 August 1969. Second, on any given arrival date, the time of closest approach was limited to an interval of about 1 hour by the requirement that the spacecraft be in radio view of Goldstone tracking station during a period of several hours which bracketed the time of closest approach. These two constraints and the approximate 24-hour rotation period of Mars

Fig. 3. (a) Mariner 6 NE picture locations, plotted on a painted globe of Mars. The first picture is taken with a blue filter. The camera-A filter sequence is blue, green, red, green, and so on. Wide-angle (camera A) frames and narrow-angle (camera B) frames alternate. (b) Mariner 7 NE picture locations. The filter sequence is the same as for Mariner 6.



considerably limited the possible longitudes of Mars that could effectively be viewed; in particular, the most prominent dark area, Syrtis Major, could not be seen under optimum conditions. Fortunately, Meridiani Sinus, a prominent dark area almost as strong and permanent as Syrtis Major, and various other important features well known from Earth observation, were easily accessible. . . .

The cameras and other instruments were mounted on a two-axis "scan platform" which could be programmed to point the instruments in as many as five successive directions during the near-encounter. The particular orbit and platform-pointing strategy adopted for each spacecraft was designed to achieve the best possible return of scientific data within a context of substantial commonality but with some divergence of needs of the various experiments. The television experimenters placed great weight upon viewing a wide variety of classical features, including the polar cap; continuity of picture coverage; substantial two-color overlap and some three-color overlap if possible; stereoscopic overlap; viewing the planet limb in blue light; viewing the same area at two different phase angles; and seeing the same area under different viewing conditions at nearly the same phase angle. . . .

The Mariner 6 picture track was chosen to cover a broad longitude range at low latitudes in order to bring into view a number of well-studied transitional zones between light and dark areas, two "oases" (Juventae Fons and Oxia Palus), and a variable light region (Deucalionis Regio). The picture track of Mariner 7 was selected so that it would cross that of Mariner 6 on the dark area Meridiani Sinus, thereby providing views of that important region under different lighting conditions. The track was also specifically arranged to include the south polar cap and cap edge, to intersect the "wave-of-darkening" feature Hellespontus, and to cross the classical bright circular desert Hellas. . . .

Camera Operation and Picture Appearance

The first impression of Mars conveyed by the pictures is that the surface is generally visible and is not obscured by clouds or haze except perhaps in the polar regions and in a few areas marked by the appearance of afternoon "clouds." The classical martian features stand out clearly in the far-encounter pictures, and, as the image grows, these features transform into areas having recognizable relationships to the numerous craters which mark the surface. The near-encounter pictures seem to show a Moon-like terrain. However, one must bear in mind the fact that the camera system was designed to enhance the contrast of local brightness fluctuations by a factor of 3, and that the contrast of the pictures is often further enhanced in printing. Actually, although the surface is generally visible, its contrast is much less than that of the moon under similar lighting conditions. Fewer shadows are seen near the terminator.

The determination of true surface contrast depends critically upon the amount of haze or veiling glare in the picture field. Although the pictures appear to be free of such effects, more refined photometric measurements may well reveal the presence of veiling glare or a general atmospheric haze. Definite conclusions must await completion of the photometric reduction of the pictures, including corrections for vidicon dark current, residual images, shutter light leaks, and possible instrumental scattering.

Observed Atmospheric Features

Aerosol scattering. Clear-cut evidence for scattering layers in the atmosphere is provided by the pictures of the northeastern limb of Mariner 7. The limb appears in frames 7N1, 2, 3, 5, and 7, and in a few real-time digital A-camera frames received immediately prior to frame 7N1 . . . .

The real-time digital data reveal an apparent limb haze near the south polar cap, and over the regions of Mare Hadriaticum and Ausonia just east of Hellas. The haze over these regions is not as bright as the haze discussed above, so it is unlikely that it is sufficiently dense to obscure surface features seen at NE viewing angles. A faint limb haze may also be present in the Mariner 6 limb frames.

The "blue haze." Despite these evidences of very thin aerosol hazes, visible tangentially on the limb, there is no obscuring "blue haze" sufficient to account for the normally poor visibility of dark surface features seen or photographed in blue light and for their occasional better visibility—the so-called "blue-clearing" phenomenon (*11, 12*).

The suitability of the Mariner blue pictures for "blue haze" observations was tested by photographing Mars through one of the Mariner blue filters on Eastman III-G plates, whose response in this spectral region is similar to that of the vidicons used in the Mariner camera. Conventional blue photographs on unsensitized emulsions and green photographs were taken for comparison. A typical result is shown in Fig. 5; the simulated T-V blue picture is very similar to the conventional blue photographs. . . . .

The blue pictures taken by Mariners 6 and 7 clearly show craters and other surface features, even near the limb and terminator, where atmospheric effects are strong. Polar cap frame 7N17 shows sharp surface detail very near the terminator. The blue limb frame 6N1 shows surface detail corresponding to that seen in the subsequent overlapping green frame 6N3. Figure 6 includes blue, green, and red pictures in the region of Sinus Meridiani. Although craters show clearly in all three colors, albedo variations, associated both with craters and with larger-scale features, are much more pronounced in green and red than in blue. Blue photographs obtained from the earth during the Mariner encounters show the normal "obscured" appearance of Mars.

South polar cap shading. Another possible indication of atmospheric haze is the remarkable darkening of the south polar cap near both limb and terminator in the FE pictures (Fig. 7). This darkening is plainly *not* due to cloud or thick haze since, during near-encounter, surface features are clearly visible everywhere over the polar cap. It may be related to darkening seen in NE Mariner 7 frames near the polar cap terminator, and to the decrease in contrast with increasing viewing angle between the cap and the adjacent mare seen in frame 7N11 (Fig. 8b). The darkening may be due to optically thin aerosol scattering over the polar cap, or possibly to unusual photometric behavior of the cap itself. In either case,

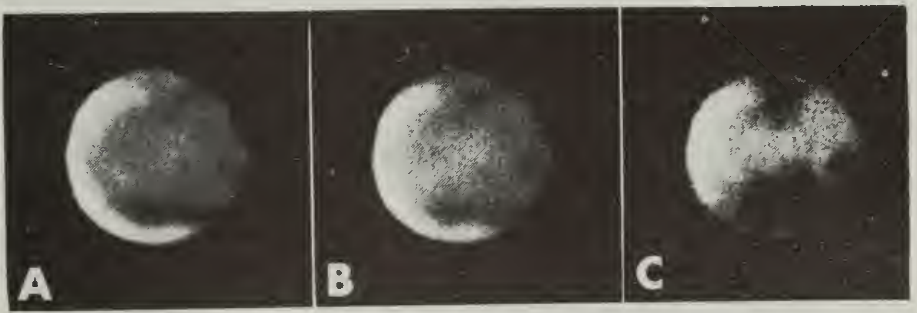


Fig. 5. Photographs of Mars from the earth, taken to compare Mariner-type blue-filter pictures with "standard" green and blue pictures of Mars. The pictures were taken 24 May 1969 at New Mexico State University Observatory. (A) "Standard" blue (0915 U.T.); (B) Mariner blue (0905 U.T.); (C) standard green (0844 U.T.). North is at the top.

it may be complicated by systematic diurnal or latitudinal effects.

North polar phenomena. Marked changes seem to have occurred, between the flybys of Mariners 6 and 7, in the appearance of high northern latitudes. Some of these changes are revealed by a comparison of frames 6F34 and 7F73, which correspond to approximately the same central meridian and distance from Mars (Fig. 7). A large bright tongue (point 1 in frame 73) and a larger bright region near the limb (point 2) appear smaller and fainter in the Mariner 7 picture, despite the generally higher contrast of Mariner 7 FE frames. Much of the brightening near point 2 has disappeared entirely between the two flybys; in fact, it was not visible at all on pictures taken by Mariner 7 during the previous Mars rotation, although it was clearly visible in several Mariner 6 frames taken over the same range of distances. The bright tongue (point 1) increases in size and brightness during the martian day, as may be clearly seen from a comparison of frames 7F73 and 7F76 (Fig. 7).

The widespread, diffuse brightening covering much of the north polar cap region (point 3) apparently corresponds to the "polar hood" which has been observed from the earth at this martian season (northern early autumn). The extent of this hood is smaller in Mariner 7 than in Mariner 6 pictures; the region between, and just north of, points 1 and 2 appears to be covered by the hood in the Mariner 6 frames, but shows no brightening in the Mariner 7 frames.

The different behaviors of the discrete bright regions and the hood suggest different origins for these features, although both apparently are either atmospheric phenomena or else result from the interaction of the atmosphere and the surface. The discrete bright regions have fixed locations suggesting either surface frost or orographically

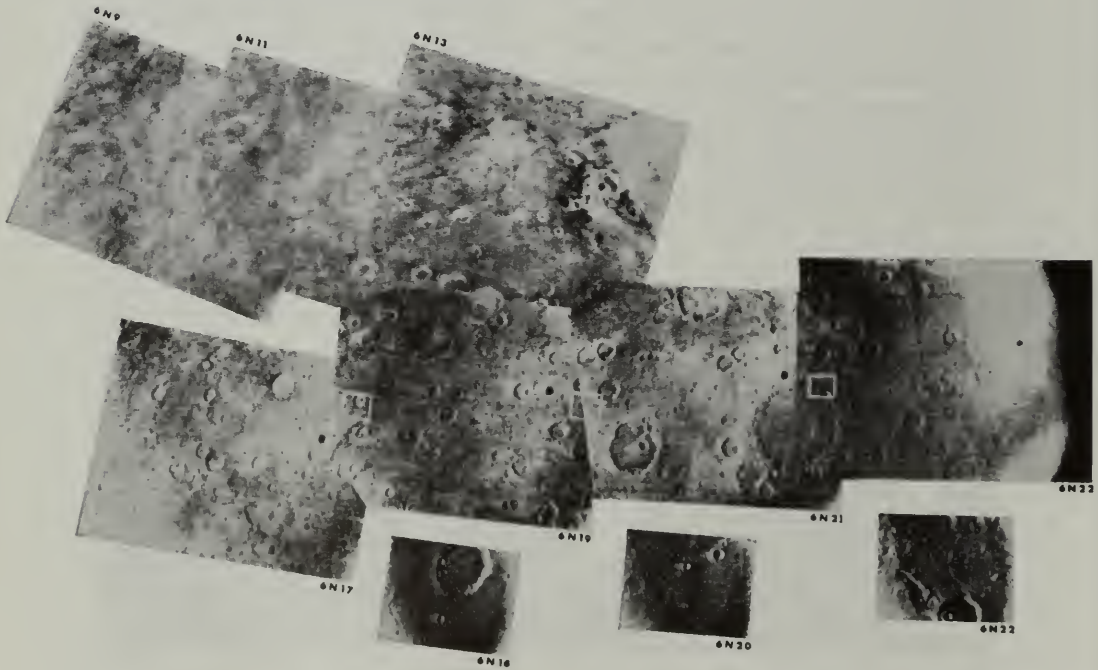


Fig. 6. Composite of ten Mariner 6 pictures showing cratered terrain in the areas of Margaritifer Sinus (top left), Meridiani Sinus (top center), and Deucalionis Regio (lower strip). Large-scale contrasts are suppressed by AGC and small-scale contrast is enhanced (see text). Craters are clearly visible in blue frames 6N9 and 6N17, but albedo variations are subdued. Locations of three camera-B frames are marked by rectangles. North is approximately toward the top, and the sunset terminator lies near the right edge of 6N23.

fixed clouds. The fluctuation in the areal extent of the diffuse hood suggests cloud or haze. An extensive cloud or haze composed of either CO_2 or CO_2 and H_2O ice would be consistent with the atmospheric temperature structure revealed by the Mariner 6 occultation experiment (*13*)....

Search for local clouds and fog. All NE frames from both spacecraft were carefully examined for evidences of clouds or fog. Away from the south polar cap there are no evidences of such atmospheric phenomena. Over the polar cap and near its edge a number of bright features which may be atmospheric can be seen, although no detectable shadows are present and no local differences in height can be detected by stereoscopic viewing of overlapping regions whose stereo angles lie between 5° and 12°. Little or no illumination is evident near and beyond the polar cap terminator. On the other hand, frames 7N11, 12, and 13 (Fig. 8) show several diffuse bright patches suggestive of clouds near the polar cap edge. Also, on the cap itself a few local diffuse bright patches are present in frames 7N15 (green) and 7N17 (blue). Unlike most polar cap craters, which appear sharp and clear, a few crater rims and other topographic forms appear diffuse (frames 7N17, 18, and 19). In frames 7N17 (blue) and 7N19 (green), remarkable curved, quasi-parallel bright streaks are visible near the south pole itself. While these show indications

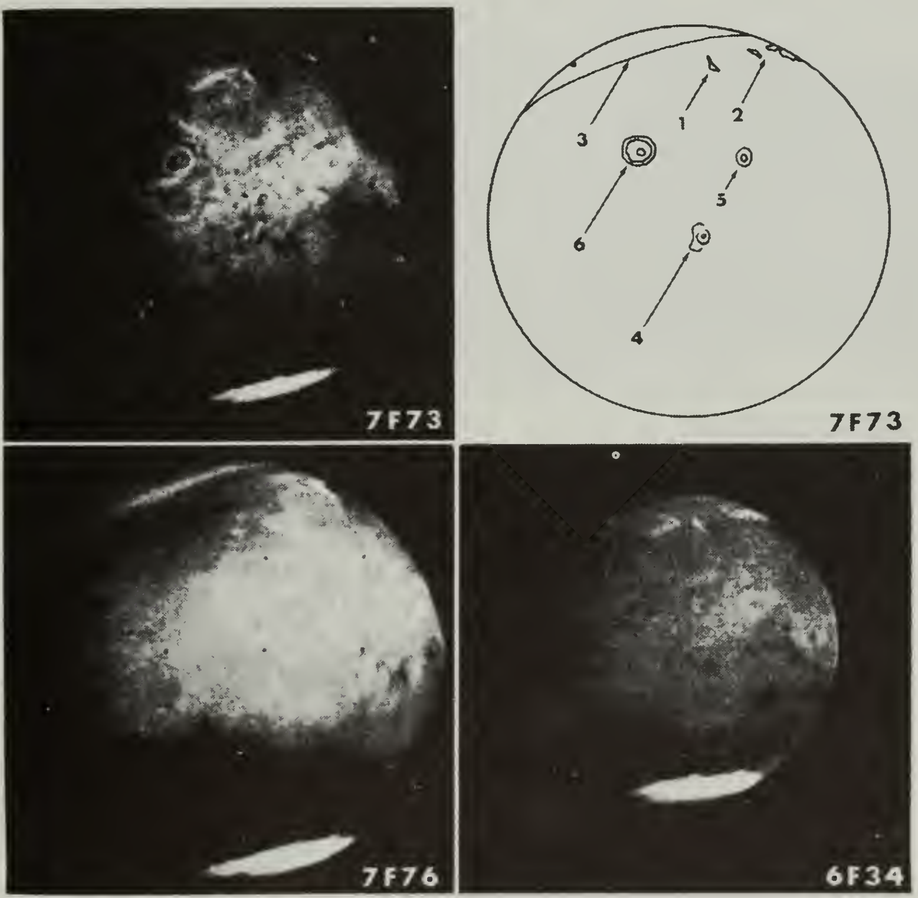


Fig. 7. Far-encounter pictures showing atmospheric and atmosphere-surface effects. Picture shutter times were as follows: 6F34, 30 July 0732 U.T.; 7F73, 4 August 1115 U.T.; 7F76, 4 August 1336 U.T.

of topographic form or control, including some crater-like shapes, their possible cloud-like nature is suggested by lack of shading....

Observed Surface Features

A primary objective of the Mariner 6 and 7 television experiment was to examine, at close range, the principal types of martian surface features seen from the earth.

Mariners 6 and 7, while confirming the earlier evidence of a Moon-like cratered appearance for much of the martian surface, have also revealed significantly different terrains suggestive of more active, and more recent, surface processes than were previously evident. Preliminary analyses indicate that at least three distinctive terrains are represented in the pictures, as well as a mixture of permanent and transitory surface features displayed at the edge of, and within, the south polar cap; these terrains do not exhibit any simple correlation with the light and dark markings observed from the earth.

Cratered terrains. Cratered terrains are those parts of the martian surface upon which craters are the dominant topographic form (Fig. 6). Pictures from Mariners 4, 6, and 7 all suggest that cratered terrains are widespread in the southern hemisphere.

Knowledge of cratered terrains in the northern hemisphere is less complete. Cratered areas appear in some Mariner frames as far north as latitude 20°. Nix Olympica, which in far-encounter photographs appears to be an unusually large crater, lies at 18°N. Numerous craters are visible in the closer-range FE frames. These are almost exclusively seen in the dark areas lying in the southern hemisphere, few being visible in the northern hemisphere. This difference may result from an enhancement of crater visibility by reflectivity variations in dark areas. However, poor photographic coverage, highly oblique views, and unfavorable sun angles combine to limit our knowledge of the northern portion of the planet.

Preliminary measurements of the diameter-frequency distribution of martian craters in the region Deucalionis Regio were made on frames 6N19 to 6N22 and are shown in Fig. 9a. The curves are based upon 104 craters more than 0.7 kilometer in diameter seen on frames 6N20 and 22, and upon 256 craters more than 7 kilometers in diameter seen on frames 6N19 and 21. The most significant result is the existence of two different crater distributions, a dichotomy also apparent in morphology. The two morphological crater types are (i) large and flat-bottomed and (ii) small and bowl-shaped. Flat-bottomed craters are most evident on frames 6N19 and 6N21. The diameters range from a few kilometers to a few hundred kilometers, with estimated diameter-to-depth ratios on the order of 100 to 1. The smaller, bowl-shaped craters are best observed in frames 6N20 and 6N22 and resemble lunar primary-impact craters. Some of them appear to have interior slopes steeper than 20 degrees....

On frame 6N20 there are low irregular ridges similar to those seen on the lunar maria. However, no straight or sinuous rills have been identified with confidence. Similarly, no Earth-like tectonic forms possibly associated with mountain building, island-arc formation, or compressional deformation have been recognized.

Chaotic terrains. Mariner frames 6N6, 14, and 8 (Fig. 10a) show two types of terrain—a relatively smooth cratered surface that gives way abruptly to irregularly shaped, apparently lower areas of chaotically jumbled ridges. This chaotic terrain seems characteristically to display higher albedo than its surroundings. On that basis, we infer that significant parts of the overlapping frames 6N5, 7, and 15 may contain similar terrain, although their resolution is not great enough to reveal the general morphological characteristics. As shown in Fig. 10a, frames 6N6, 14, and 8 all lie within frame 6N7, for which an interpretive map of possible chaotic terrain extent has been prepared (Fig. 11).

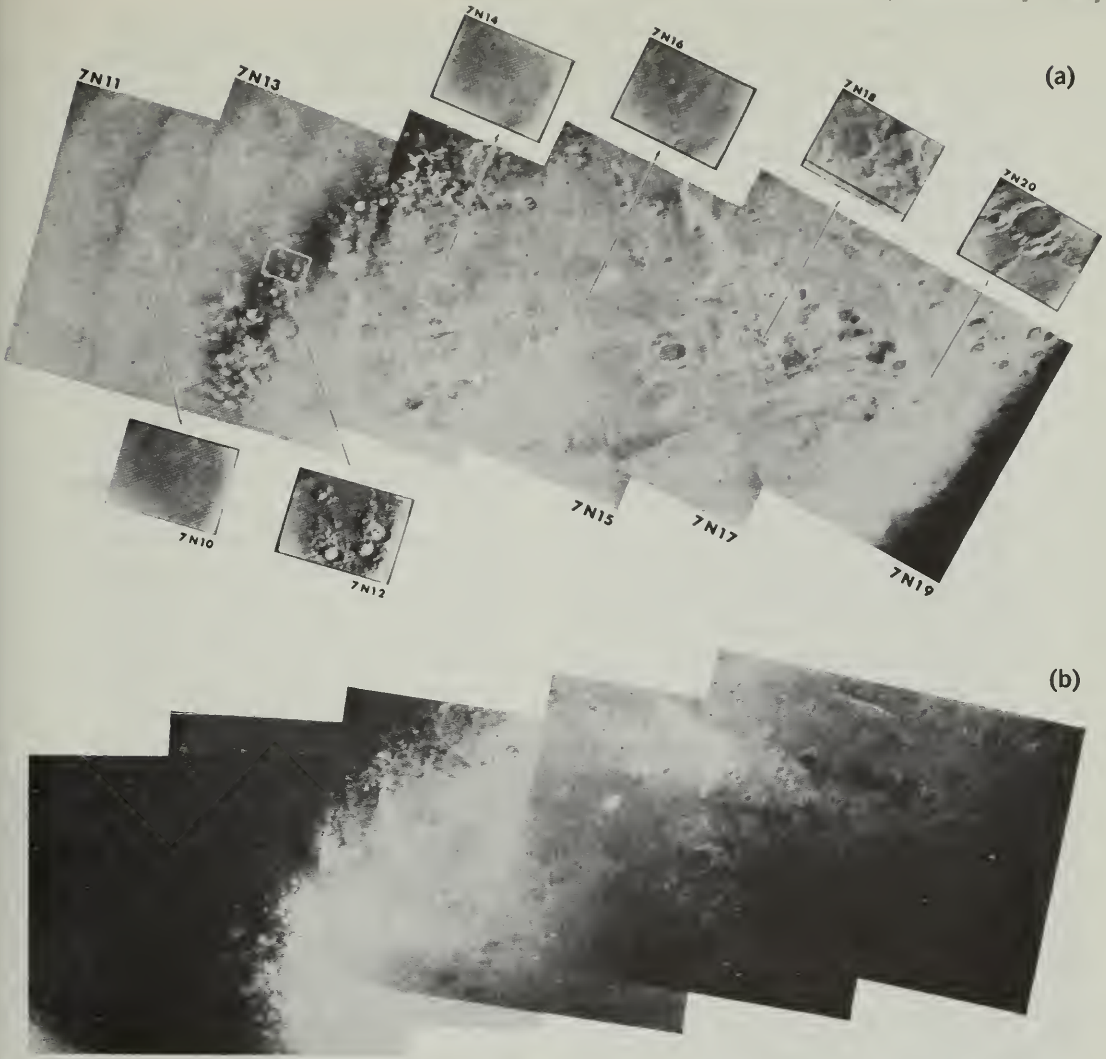


Fig. 8. (a) Composite of polar cap frames 7N10 to 7N20. Effects of AGC are clearly evident near the terminator (right) and at cap edge. (b) Composite of poplar cap camera-A frames 7N11 to 7N19. The effects of AGC have been partially corrected, but contrast is enhanced. The south pole lies near the parallel streaks in the lower right corner of frame 7N17.

About 10^6 square kilometers of chaotic terrain may lie within the strip, 1000 kilometers wide and 2000 kilometers long, covered by these Mariner 6 wide-angle frames. Frames 6N9 and 10 contain faint suggestions of similar features. This belt lies at about 20°S, principally within the poorly defined, mixed light-and-dark area between the dark areas Aurorae Sinus and Margaritifer Sinus.

Chaotic terrain consists of a highly irregular plexus of short ridges and depressions, 1 to 3 kilometers wide and 2 to 10 kilometers long, best seen in frame 6N6 (Fig. 10a). Although irregularly jumbled, this terrain is different in setting and pattern from crater ejecta sheets. Chaotic terrain is practically uncratered; only three faint possible craters are recognized in the 10^6-square-kilometer area. The patches of chaotic terrain are not all integrated, but they constitute an irregular pattern with an apparent N to N 30°E grain.

Featureless terrains. The floor of the bright circular "desert," Hellas, centered at about 40°S, is the largest area of featureless terrain so far identified. Even under very low solar illumination the area appears devoid of craters down to the resolution limit of about 300 meters. No area of comparable size and smoothness is known on the moon. It may be that all bright circular "deserts" of Mars have smooth featureless floors; however, in the present state of our knowledge it is not possible to define any significant geographic relationship for featureless terrains. . . .

South polar cap features. The edge of the martian south polar cap was visible at close range over a 90° span of longitude, from 290°E to 20°E, and the cap itself was seen over a latitude range from its edge, at −60°, southward to, and perhaps beyond, the pole itself. Solar zenith angles ranged from 51° to 90° and more; the terminator is clearly visible in one picture. The phase angle for the picture centers was 35°. The superficial appearance is that of a clearly visible, moderately cratered surface covered with a varying thickness of "snow." The viewing angle and the unfamiliar surface conditions make quantitative comparison with other areas of Mars difficult with respect to the number and size distributions of craters. Discussion here is therefore confined to those qualitative aspects of the polar cap which seem distinctive to that region.

The edge of the cap was observed in the FE pictures to be very nearly at 60°S, as predicted from Lowell Observatory measurements (*15*); this lends confidence to Earth-based observations concerning the past behavior of the polar caps.

The principal effect seen at the cap edge is a spectacular enhancement of crater visibility and the subtle appearance of other topographic forms. In frames 7N11 to 7N13, where the local solar zenith angle was about 53°, craters are visible both on and off the cap. However, in the transition zone, about 2 degrees of latitude in width, the population density of visible craters is several times greater, and may equal any so far seen on Mars. This enhancement of crater visibility results mostly from the tendency, noted in Mariner 4 pictures 14 and 15, for snow to lie preferentially on poleward-facing slopes.

In frame 7N12 the cap edge is seen in finer detail. The tendency mentioned above is here so marked as to cause confusion concerning the direction of the illumination. There are several tiny craters as small as 0.7 kilometer in diameter, and areas of fine mottling and sinuous lineations are seen near the larger craters. The largest crater shows interesting grooved structure, near its center and on its west inner wall, which appears similar to that in frame 6N18.

On the cap itself, the wide-angle views show many distinct reflectivity variations, mostly related to moderately large craters but not necessarily resulting from slope-illumination effects. Often a crater appears to have a darkened floor and a bright rim, and in some craters having central peaks the peaks seem unusually prominent. In frames 7N17 and 7N19 several large craters seem to have quite dark floors.

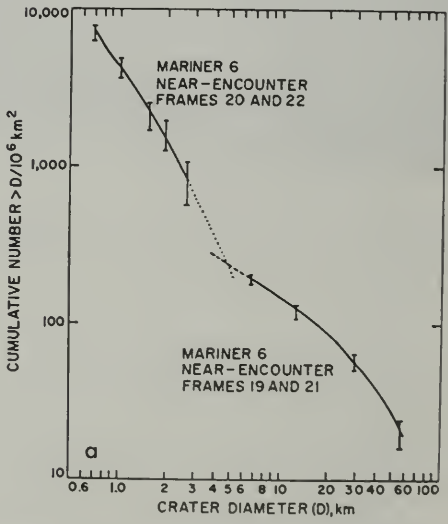


Fig. 9. (a) Preliminary cumulative distribution of crater diameters. Solid curve at right is based upon 256 counted craters in frames 6N19 and 6N21 having diameters $\geqslant$ 7 kilometers. The solid curve at left is based upon 104 counted craters in frames 6N20 and 6N22. The error bars are from counting statistics only $(N^{1/2})$.

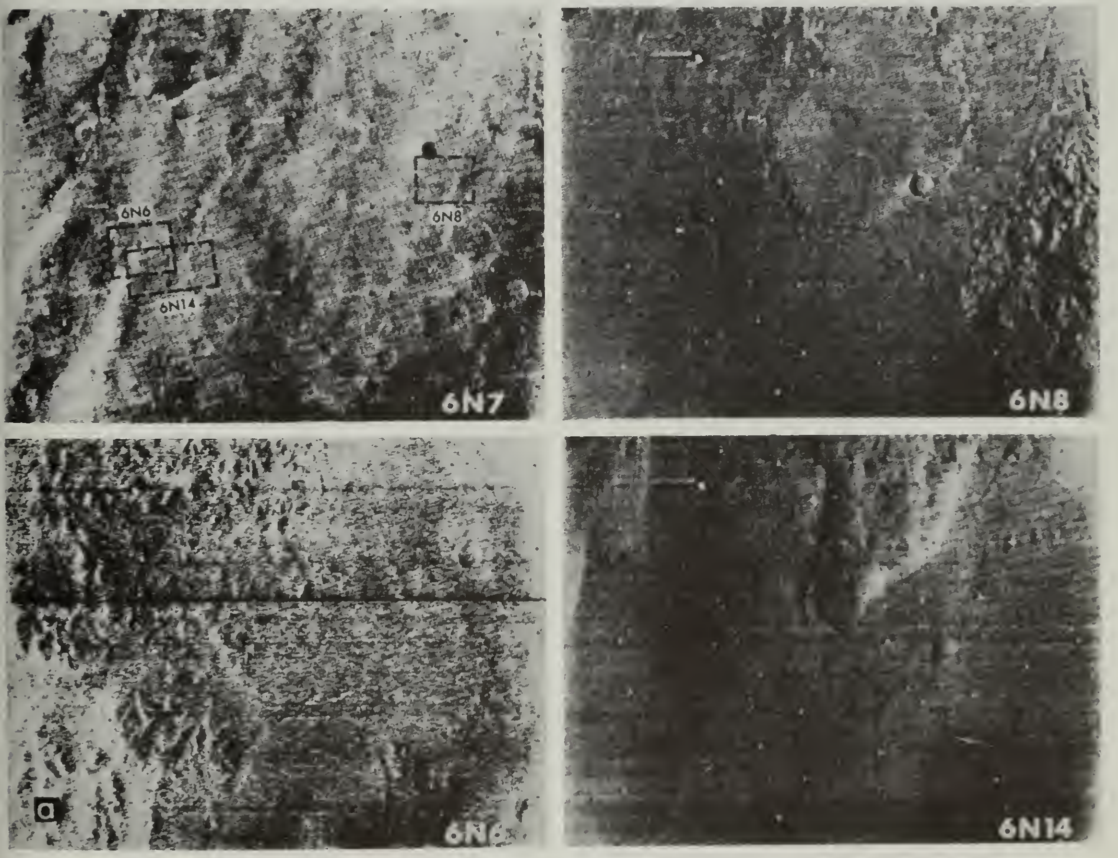
In contrast, the high-resolution polar cap frames 7N14 to 7N20 suggest a more uniformly coated surface whose brightness variations are mostly due to the effects of illumination upon local relief. . . .

Some of the classical "oases" observed from the earth have now been identified with single, large, dark-floored craters (such as Juventae Fons, see *4* and Fig. 4) or groups of such craters (such as Oxia Palus, frame 7N5). At least two classical "canals" (Cantabras and Gehon) have been found to coincide with quasi-linear alignment of several dark-floored craters, shown also in frame 7N5 (Fig. 13). As reported elsewhere (*4*), other canals are composed of irregular dark patches. It is probable that most canals will, upon closer inspection, prove to be associated with a variety of physiographic features, and that eventually they will be considered less distinctive as a class. . . .

Inferences concerning Processes and Surface History

The features observed in the Mariner 6 and 7 pictures are the result of both present and past processes; therefore, they provide the basis of at least limited conjecture about those processes and their variations through time. In this section we consider the implications of (i) the absence of Earth-like tectonic features; (ii) the erosion, blanketing, and secondary modification evidenced in the three principal terrains; and (iii) the probable role of equilibrium between CO$_2$ solid and vapor in the formation of features of the south polar cap. We also consider the possible role of equilibrium between H$_2$O solid and vapor as an explanation of the diurnal brightenings observed in the FE photographs and biological implications.

Significance of the absence of Earth-like forms. The absence of Earth-like



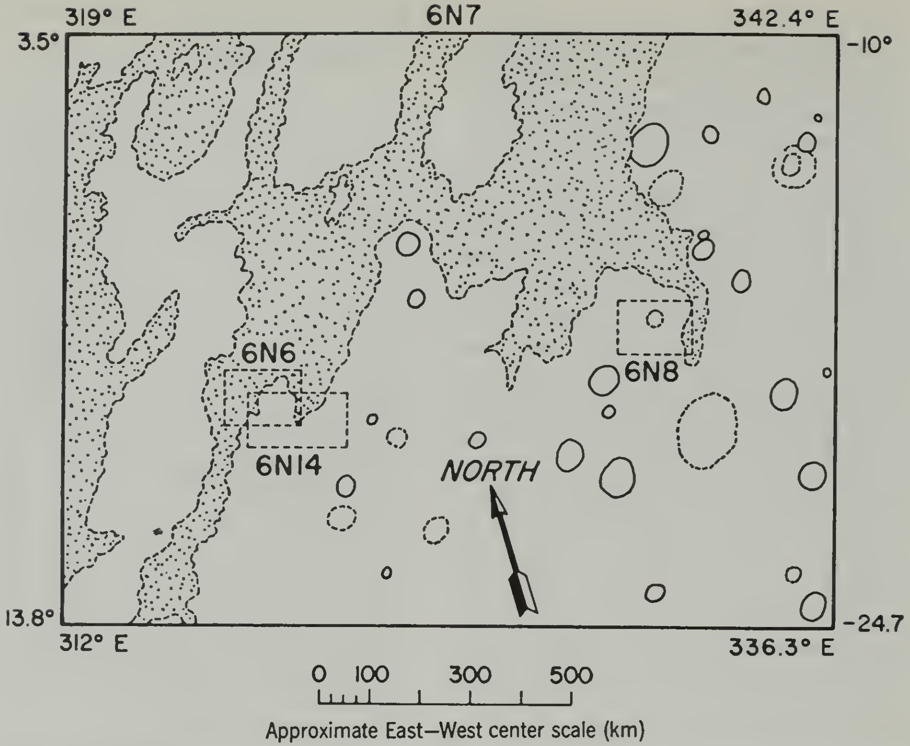


Fig. 11. Interpretive drawing showing the possible extent of chaotic terrain in frame 6N7.

tectonic features on Mars indicates that, for the time period represented by the present large martian topographic forms, the crust of Mars has not been subjected to the kinds of internal forces that have modified, and continue to modify, the surface of the earth.

Inasmuch as the larger craters probably have survived from a very early time in the planet's history, it is inferred that Mars's interior is, and probably has always been, much less active than the earth's (*19*). Furthermore, a currently held view (*20*) is that the earth's dense, aqueous atmosphere may have formed early, in a singular event associated with planetary differentiation and the origin of the core. To the extent, therefore, that surface tectonic features may be related in origin to the formation of a dense atmosphere, their absence on Mars independently suggests that Mars never had an Earth-like atmosphere.

Age implications of cratered terrains. At present, the ages of martian topographic forms can be discussed only by comparison with the moon. Both the moon and Mars exhibit heavily cratered and lightly cratered areas, which evidently reflect in each case regional differences in the history of, or the response to, meteoroidal bombardment over the total life-span of the surfaces. The existence of a thin atmosphere on Mars may have produced recognizable secondary effects in the form and size distribution of craters, by contrast with the moon, where a significant atmosphere has presumably never been present. To the extent that relative fluxes of large objects impinging upon the two bodies can be determined, or a common episodic history established, a valid age comparison may be hoped for, except in the extreme case of a saturated cratered surface, where only a lower limit to an age can be found.

It is a generally accepted view that the present crater density on the lunar uplands could not have been produced within the 4.5-billion-year age of the solar system had the bombardment rate been no greater than the estimated present rate; that is, the inferred minimum age is already much greater than is considered possible. Indeed, it is found that even the sparsely cratered lunar maria would have required about a billion years to attain their present crater density. Unless this discrepancy is somehow removed by direct measurements of the crystallization ages of returned samples of lunar upland and mare materials, the previously accepted implication of an early era of high bombardment followed by a long period of bombardment at a drastically reduced rate will presumably stand.

In the case of Mars, a bombardment rate per unit area as much as 25 times that on the moon has been estimated (*21*). However, even this would still seem to require at least several billion years to produce the density of large craters that is seen on Mars in the more heavily cratered areas (*19*). Thus these areas *could also be primordial.* Further, were these areas to have actually been bombarded at a constant rate for such a time, at least a few very recent, large craters should be visible, including secondary craters and other local effects. Instead, the most heavily cratered areas seem relatively uniform with respect to the degree of preservation of large craters, with no martian Tycho or Copernicus standing out from the rest. This again suggests an early episodic history rather than a continuous history for cratered martian terrain, and increases the likelihood that cratered terrain is primordial.

If areas of primordial terrain do exist on Mars, an important conclusion follows: these areas have never been subject to erosion by water. This in turn reduces the likelihood that a dense, Earth-like atmosphere and large, open bodies of water were ever present on the planet, because these would almost surely have produced high rates of planet-wide erosion. On the earth, no topographic form survives as long as 10^8 years unless it is renewed by uplift or other tectonic activity.

Implications of modification of terrain. Although erosional and blanketing processes on Mars have not been strong enough to obliterate large craters within the cratered terrains, their effects are easily seen. On frames 6N19 and 6N21 (Fig. 6), even craters as large as 20 to 50 kilometers in diameter appear scarce by comparison with the lunar uplands [a feature originally noted by Hartmann (*19*) on the basis of the Mariner 4 data], and the scarcity of smaller craters is marked. The latter have a relatively fresh appearance, however, which suggests an episodic history of formation, modification, or both. Such a history seems particularly indicated by the apparently bimodal crater frequency distribution of Fig. 9.

Marked erosion, blanketing, and other surface processes must have been operating almost up to the present in the areas of featureless and chaotic terrains; only this could account for the absence of even small craters there. These processes may not be the same as those at work on the cratered terrains, because large craters have also been erased. The cratered terrains obviously have *never been* affected by such processes; this indicates an enduring geographic dependence of these extraordinary surface processes.

The chaotic terrain gives a general impression of collapse structures, suggesting the possibility of large-scale withdrawal of substances from the underlying layers. The possibility of permafrost some kilometers thick, and of its localized withdrawal, may deserve further consideration. Magmatic withdrawal or other near-surface disturbance associated with regional volcanism might be another possibility, but the apparent absence of extensive volcanic terrains on the surface would seem to be a serious obstacle to such an interpretation. It may also be that chaotic terrain is the product either of some unknown intense and localized ero-

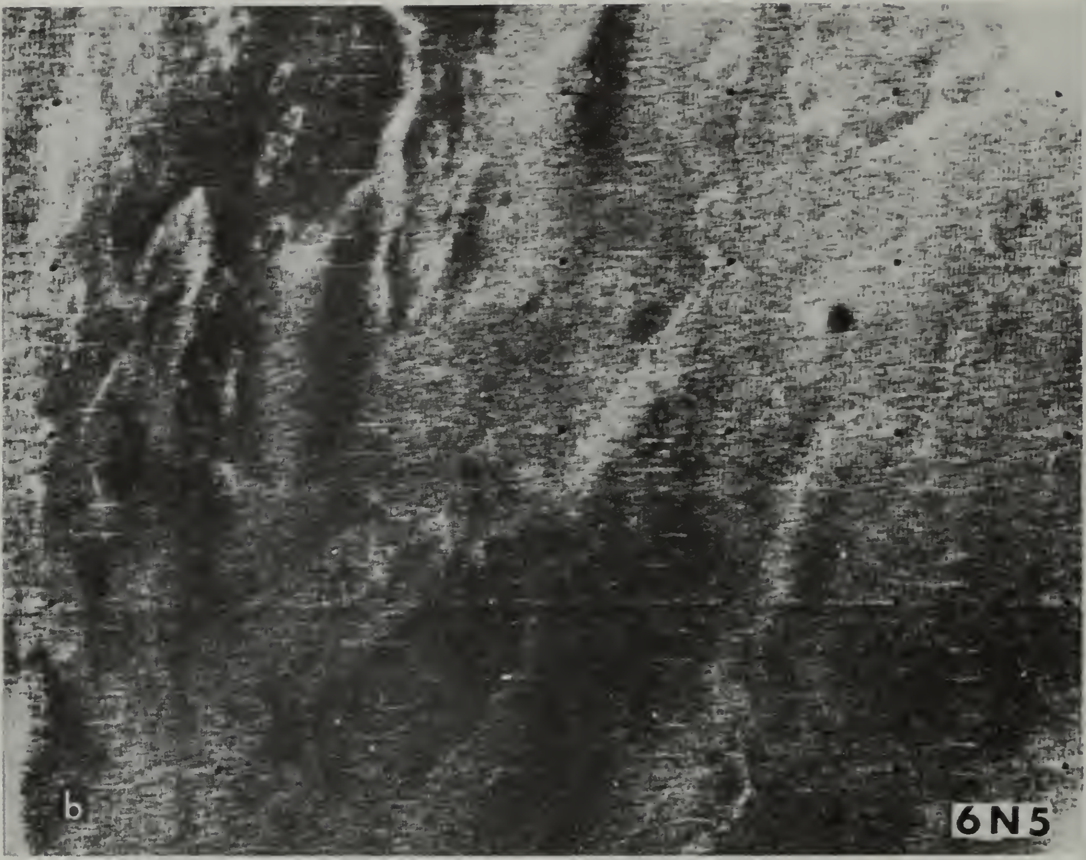
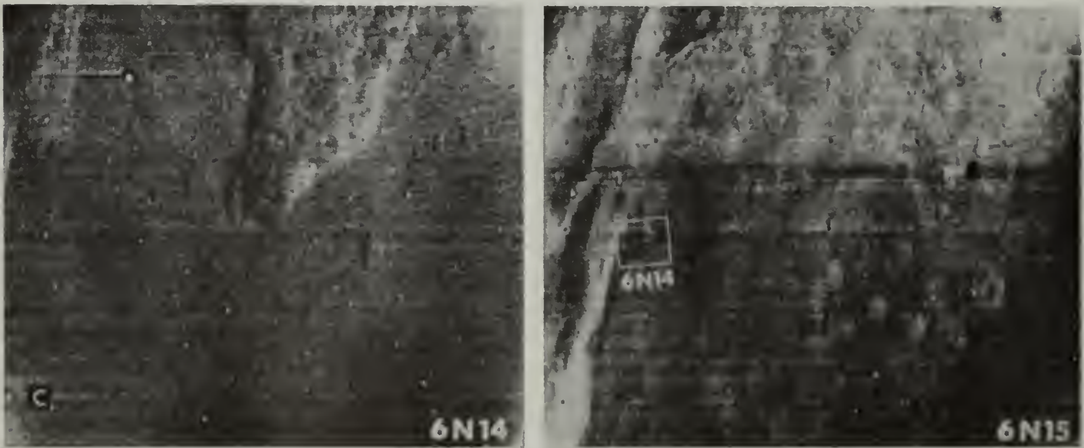


Fig. 10. (a) Examples of chaotic terrain. The approximate locations of the camera-B views inside camera-A frame 6N7 are shown by the dashed rectangles. North is approximately at the top. (b) Example of possible chaotic terrain. The lighter color and the absence of craters suggest that large parts of the right-hand half of this camera-A view may consist of chaotic terrain. (c) Example of chaotic terrain. The location of frame 6N14 inside frame 6N15 is shown by the solid rectangle.



sional process or of unsuspected local sensitivity to a widespread process.

Carbon dioxide condensation effects. The Mariner 7 NE pictures of the polar cap give no direct information concerning the material or the thickness of the polar snow deposit, since the observed brightness could be produced by a very few milligrams per square centimeter of any white, powdery material. However, they do provide important indirect evidence as to the thickness of the deposit and, together with other known factors, may help to establish its composition.

The relatively normal appearance of craters on the polar cap in the high-resolution frames, and the existence on these same frames of topographic relief unlike that so far recognized elsewhere on the planet, suggest that some of the apparent relief may be due to variable thicknesses of snow, perhaps drifted by wind. If it is, local thicknesses of at least several meters are indicated.

The structure of the polar cap edge shows that evaporation of the snow is strongly influenced by local slopes—that is, by insolation effects rather than by wind. On the assumption that the evaporation is entirely determined by the midday radiation balance, when the absorbed solar power exceeds the radiation loss at the appropriate frost-point temperature, one may estimate the daily evaporation loss from the cap. We find the net daily loss to be about 0.8 gram per square centimeter in the case of CO_2, although the loss is reduced by overnight recondensation. In the case of H_2O, the loss would be about 0.08 gram per square centimeter, and it would be essentially irreversible because H_2O is a minor constituent whose deposition is limited by diffusion.

Since the complete evaporation of the cap at a given latitude requires many days, we may multiply the above rates by a factor between 10 and 100, obtaining estimates for total cap thickness of tens of grams per square centimeter for CO_2 and several grams per square centimeter for H_2O, on the assumption that the cap is composed of one or the other of these materials. The estimate for CO_2 is quite acceptable, but that for H_2O is unacceptable because of the problem of transporting such quantities annually from one pole to the other at the observed vapor density (*22*). For the remainder of this discussion we assume the polar cap to be composed of CO_2, with a few milligrams of H_2O per square centimeter deposited throughout the layer.

Several formations have been observed which suggest a tendency for snow to be preferentially removed from low areas and deposited on high areas, contrary to what might be expected under quiescent conditions (*23*). These formations include craters with dark floors and bright rims, prominent central peaks in some craters, and irregular depressed areas (frames 7N14, 15, and 17). While such effects might result simply from wind transport of solid material, it is also possible that interchange of solid and vapor plays a role. . . .

Water: processes suggested by brightening phenomena. Several of the brightening and haze phenomena described above could be related either to formation of H_2O frost on the surface or to formation of H_2O ice clouds in the atmosphere. In most of these instances, however, the phenomena could equally well be explained by condensation of CO_2. This is true of the bright tongues and polar hood in the north polar region, of the cloud-like features observed over and near the south polar cap, and of the limb hazes observed in tropical latitudes and over the Mare Hadriaticum and Ausonia regions.

On the other hand, the brightenings in the Nix Olympica, Tharsis, Candor, and Tractus Albus regions cannot be explained by CO_2 condensation because their complete topographic control requires that they be on or near the surfaces where temperatures are well above the CO_2 frost point. An explanation of these phenomena in terms of H_2O condensation processes also faces serious difficulties, however. Most of the region is observed to brighten during the forenoon, when the surface is hotter than either the material below or the atmosphere above, so that water vapor could not diffuse toward the surface and condense on it, either from above or below. Thus a surface ice-frost is very unlikely. A few features in the area, parts of the "W-cloud," for example, are observed to brighten markedly during the late afternoon, where H_2O frost could form on the surface if the air were sufficiently saturated. These features are not observed, from the earth, to be bright in the early morning, but a thin layer of H_2O frost persisting through the night would evaporate almost immediately when illuminated by the early morning sun, provided the air were then sufficiently dry. Under these conditions, the behavior of the "W-cloud" could be due to frost.

The diurnal behavior of the bright regions throughout this part of Mars is consistent with a theory of convective H_2O ice clouds, but the absence of any cloud-like morphology and the clear topographic detail observed at the highest resolution available (frame 7F76) render this explanation questionable. Even very light winds of 5 meters per second would produce easily observable displacements of the order of 100 kilometers in the course of the more than one-fourth of the Mars day during which these regions were continuously observed by each spacecraft. Since condensation and evaporation processes are slow at Mars temperatures and pressures, some observable distortion and streakiness due to these displacements should be seen in clouds, even if they are orographically produced. No such distortions or streakiness are observed.

An additional difficulty with an explanation of these phenomena in terms of H_2O condensation lies in the relatively rapid removal of water from the local surface. Water vapor evolved from the surface during the daytime would quickly be transported upward through a deep atmospheric layer by thermal convection, and most of it would be removed from the source region. Local permafrost sources should be effectively exhausted by this mechanism within a few hundred years at most, unless somehow replenished. Since most of this region lies near the equator, where seasonal temperature variations are small, it is difficult to see how any significant seasonal replenishment from the atmosphere could take place. The possibility of replenishment from a subsurface source of liquid water is not considered here.

In summary, in our examination of the data thus far, we see no strong indications of H_2O processes involving vapor and ice. The brightenings seen in the tropics and subtropics at far-encounter are not easily explained by a mechanism involving H_2O. On the other hand, we have no satisfactory alternative explanation for these phenomena. Perhaps detailed exploration of these regions by the Mariner '71 orbiters will provide the answer.

Biological inferences. No direct evidence suggesting the presence of life on Mars has been found in the pictures. This is not surprising, since martian life, if any, would probably be microbial and undetectable at a resolution of 300 meters. Although inconclusive on the question of martian life, the photographs are informative on at least three subjects of biological interest: the general nature of the martian maria, the present availability of water, and the availability of water in the past.

One of the most surprising results so far of the TV experiment is that nothing in the pictures suggests that the dark areas, the sites of the seasonal darkening wave, are more favorable for life than other parts of the planet. On the contrary, it would now appear that the large-scale surface processes implied by the chaotic and featureless terrains may be of greater biological interest than the wave of darkening. We reiterate that these are preliminary conclusions: it may be that subtle physiographic differences between dark and bright regions will become evident when photometrically corrected pictures are examined.

With regard to the availability of water, the pictures so far have not revealed any evidence of geothermal areas. We would expect such areas to be permanently covered with clouds and frost, and these ought to be visible on the morning terminator: no such areas have been seen. A classically described feature of the polar cap which has been interpreted as wet ground—the dark collar—has likewise not been found. Other locales which have been considered to be sites of higher-than-average moisture content are those which show diurnal brightening. A number of such places have been observed in the pictures, but on close inspection the brightening appears not to be readily interpretable in terms of water frosts or clouds. Pending their definite identification, however, the brightenings should be considered possible indications of water.

The results thus reinforce the conclusion, drawn from Mariner 4 and ground-based observations, that scarcity of water is the most serious limiting factor for life on Mars. No terrestrial species known to us could live in the dry martian environment. If there is a permafrost layer near the surface, or if the small amount of atmospheric water vapor condenses as frost in favorable sites, it is conceivable that, by evolutionary adaptation, life as we know it could use this water and survive on the planet. In any case, the continued search for regions of water condensation on Mars will be an important task for the 1971 orbiter.

The past history of water on Mars is a matter of much biological interest. According to current views, the chemical reactions which led to the origin of life on the earth were initiated in the reducing atmosphere of the primitive earth. These reactions produced simple organic compounds which were precipitated into the ocean, where they underwent further reactions that eventually yielded living matter. The pictorial evidence raises the question of whether Mars ever had enough water to sustain an origin of life. If the proportion of water outgassed relative to CO_2 is the same for Mars as for the earth, then, from the mass of CO_2 now in the martian atmosphere, it can be estimated that Mars has produced sufficient water to cover the planet to a depth of a few meters. The question is whether anything approaching this quantity of water was ever present on Mars in the liquid state.

The existence of cratered terrains and the absence of Earth-like tectonic forms on Mars clearly implies that the planet has not had oceans of terrestrial magnitude for a very long time, possibly never. However, we have only very rough ideas of how much ocean is required for an origin of life, and of how long such an ocean must last. An upper limit on the required time, based on terrestrial experience, can be derived from the age of the oldest fossils, $>3.2 \times 10^9$ years (*24*). Since these fossils are the remains of what were apparently highly evolved microorganisms, the origin of life must have taken place at a much earlier time, probably during the first few hundred million years of the earth's history. While one cannot rule out, on the basis of the TV data, the possibility that a comparably brief, aqueous epoch occurred during the early history of the planet, it must be said that the effect of the TV results so far is to diminish the a priori likelihood of finding life on Mars. However, it should be noted that if Mars is to be a testing ground for our notions about the origin of life, we must avoid using these same notions to disprove in advance the possibility of life on that planet.

Potentialities of the Data

Careful computer restoration of the pictures, starting with data recovered from six sequential playbacks of the near-encounter analog tapes, will be carried out over the next several months. This further processing will greatly enhance the completeness, appearance, and quantitative usefulness of the pictures. While it is not yet certain whether the desired 8-bit relative photometric accuracy can be attained, there are reasonable grounds for thinking that much new information bearing on the physiography, meteorology, geography, and other aspects of Mars will ultimately be obtained from the pictures. Some of the planned uses of the processed data are as follows.

Stereoscopy. Most of the NE wide-angle pictures contain regions of two-picture overlap, and a few contain regions of three-picture overlap. These areas can be viewed in stereoscopic vision in the conventional manner of aerial photography. Preliminary tests on pictures of the south polar cap (frames 7N17 and 7N19) indicate that measurement of crater depth, central-peak height, and crater-rim height is possible. However, accuracy can be estimated for the elevation determinations at this time.

Planetary radii. Geometric correction of the FE photographs should make it possible to determine the radius of Mars as a function of latitude, and possibly of longitude. The geometric figure of Mars has been historically troublesome because of inconsistencies between the optical and the dynamical oblateness, a discrepancy amounting to some 18 kilometers in the value for the difference of the equatorial and polar radii. It is possible that the darkening of the polar limb observed by Mariners 6 and 7, if it is a persistent phenomenon, might have systematically affected the earlier telescopic measurements of the polar diameter more than irradiation has, giving too large a value for the optical flattening. However, this cannot explain the large flattening obtained from surface-feature geodesy (*25*). Although a fairly reliable figure for the polar flattening may be obtained from the Mariner data, it is unlikely that the actual radii will be determined with an accuracy greater than several kilometers because of the relatively low picture-element resolution in these frames and the difficulty in locating the limb.

Cartography. The large number of craters found on the surface of Mars makes it feasible to establish a control net which uses topographic features as control points, instead of surface markings based on albedo differences. This net should provide the basic locations for compiling a new series of Mars charts. The NE pictures, which cover 10 to 20 percent of the area of the planet, will constitute the basic material for detailed maps of these areas.

Satellites. We hope to detect the larger of Mars's satellites, Phobos, in two of the Mariner 6 FE pictures taken when Phobos was just beyond the limb of the planet. The satellite should have moved between the two frames by about ten picture elements, and should appear as a "defect" that has moved by this amount between the two pictures. If Phobos itself is not visible, its shadow (again detectable by its motion) should be. The shadow will be some five picture elements across and will have a photometric depth of about 10 percent. If the photometric depth of the shadow can be measured accurately, we can determine the projected area (and hence the diameter) of the satellite. A similar method has been used to measure the diameter of Mercury during solar transits.

Photometric studies. We expect to derive the photometric function for each color, combining data from the two spacecraft. Observations by the current Mariners were made near 25°, 35°, 45°, and 80° phase. Since data obtained from the earth can be used to establish the absolute calibration at the smaller phase angles, we will also be able to relate the 80°-phase data to Earth-based observations, thus doubling the range over which the phase function is determined. This information should then make possible the determination of crater slopes. Agreement for areas of overlap between different filters and between A-camera and B-camera frames can be used to check the validity of the results and possibly to measure and correct for atmospheric scattering.

The reciprocity principle may be useful in testing quantitatively for diurnal changes in the FE pictures. Such changes might include dissipation of frost or haze near the morning terminator and formation of afternoon clouds near the limb.

Overlap areas in NE pictures can be used to obtain approximate colors, even though these areas are seen at different phase angles in each color. In addition, color-difference or color-ratio pictures may be useful in identifying local areas of anomalous photometric or colorimetric behavior. Camera-A digital pictures obtained by Mariner 7 in late far-encounter will be very useful for making color measurements.

Comparison of pictures with radar-scattering and height data. The reflection coefficient of the martian surface for radar waves of decimeter wavelength shows marked variations at a given latitude as a function of longitude. Even though few of the areas of Mars so far observed by radar are visible at close range, some correlation of topography with radar reflectivity may become apparent upon careful study. Clearly, the Mariner pictures will become steadily more valuable in this connection as more radar results and other height data become available.

Effects on Mariner '71

The distinctive new terrains revealed in the Mariner 6 and 7 pictures, the relatively small fraction (10 to 20 percent) of the surface so far viewed even at moderate (A-camera) resolution, and the tantalizing new evidence of afternoon-brightening phenomena all emphasize the importance of an exploratory, adaptive strategy in 1971 as opposed to a routine mapping of geographic features. The fact that each of three successive Mariner spacecraft has revealed a new and unexpected topography strongly suggests that more surprises (perhaps the most important ones) are still to appear.

A primary objective should be to view nearly all of the visible surface at A-camera resolution (1-kilometer pixel spacing), and to inspect selected typical areas at higher resolution, very early in the 90-day orbiting period. The true extent and character of cratered, chaotic, and featureless terrains, and of any new kinds of terrain, can thus be determined and correlated with classical light and dark areas, with regional height data, and so on.

A second objective should be to search for and examine, in both spatial and temporal detail, those areas which suggest the local presence of water, through the afternoon-brightening phenomena, morning frosts or fogs, or other behavior not now recognized. Certainly the known "W-cloud" areas, Nix Olympica, and other, similar areas known from Earth observation take on a new interest by virtue of the Mariner 6 and 7 results.

The complex structure found in the south polar cap calls for further examination, particularly with respect to separation of its more permanent features from diurnally or seasonally varying ones. The sublimation of the cap should be carefully followed, so as to detect evidence of variations in thickness of the deposit and especially evidence of the possible existence of permanent deposits. Study of the north polar cap at close range should also be exceedingly interesting.

Effects on Viking '73

If the effects of the Mariner 6 and 7 results on Mariner '71 are substantial, they at least do not require a change of instrumentation, only one of mission strategy. This may not be true of the effects on Viking '73. The discovery of so many new, unexpected properties of the martian surface and atmosphere adds a new dimension to the problem of selecting the most suitable landing site and may make Viking even more dependent on the success of Mariner '71 than has been supposed. Furthermore, since so much new information is revealed through the tenfold step in resolution afforded by the B-camera frames, a further substantial increase in resolution, not available to Mariner '71, may have to be incorporated in Viking in order to examine even more closely the fine-scale characteristics of various terrain types before a landing site is chosen.

Summary and Conclusions

Even in relatively unprocessed form, the Mariner 6 and 7 pictures provide fundamental new insights concerning the surface and atmosphere of Mars. Several unexpected results emphasize the importance of versatility in instrument design, flexibility in mission design, and use of an adaptive strategy in exploring planetary surfaces at high resolution.

The surface is clearly visible in all wavelengths used, including the blue. No blue-absorbing haze is found.

Thin, patchy, aerosol-scattering layers are present in the atmosphere at heights of from 15 to 40 kilometers, at several latitudes.

Diurnal brightening in the "W-cloud" area is seen repeatedly and is associated with specific topographic features. No fully satisfactory explanation for the effect is found.

Darkening of the polar cap in a band near the limb is clearly seen in FE pictures and is less distinctly visible in one or two NE frames. Localized, diffuse bright patches are seen in several places on and near the polar cap; these may be small, low clouds.

Widespread cratered terrain is seen, especially in dark areas of the southern hemisphere. Details of light-dark transitions are often related to local crater forms. Asymmetric markings are characteristic of craters in many dark areas; locally, these asymmetries often appear related, as if defined by a prevailing wind direction.

Two distinct populations of primary craters are present, distinguished on the basis of size, morphology, and age. An episodic surface history is indicated.

In addition to the cratered terrain anticipated from Mariner 4 results, at least two new, distinctive topographic forms are seen: chaotic terrains and featureless terrains. The cratered terrain is indicative of extreme age; the two new terrains both seem to require the present-day operation of especially active modifying processes in these areas. When seen at closer range, the very bright, streaked complex found in the Tharsis-Candor region may reveal yet another distinctive topographic character. Because of the afternoon-brightening phenomena long known here, this area provides a fascinating prospect for further exploration in 1971.

No tectonic and topographic forms similar to terrestrial forms are observed.

Evidences of both atmosphere-surface effects and topographic effects are seen on the south polar cap. At the cap edge, where the "snow" is thinnest, strong control by solar heating, as affected by local slopes, is indicated. Crater visibility is greatly enhanced in this area.

On the cap itself, intensity variations suggestive of variable "snow" thickness are seen. These may be caused by wind-drifting of the snow or by differential exchange of solid and vapor, or by both.

Snow thicknesses here of several grams or several tens of grams per square centimeter are inferred if the snow material is H_2O or CO_2, respectively. The possibility that the material is H_2O seems strongly ruled out on several grounds.

Variable atmospheric, and atmosphere-surface, effects are seen at high northern latitudes; these effects include the polar "hood" and bright, diurnally variable circumpolar patches.

Several classical features have been successfully identified with specific topographic forms, mostly craters or crater remnants.

The findings are inconclusive on the question of life on Mars, but they are relevant in several ways. They support earlier evidence that scarcity of water, past and present, is a serious limiting factor for life on the planet. Nothing so far seen in the pictures suggests that the dark regions are more favorable for life than other parts of Mars.

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A dramatized account of the boyhood of the Japanese astronomer who discovered a recent comet. This same comet, Ikeya-Seki, is described also in the following article.

15

The Boy Who Redeemed His Father's Name

Terry Morris

An article from *Redbook*, 1965.

With a homemade telescope that cost only $22.32, Kaoru Ikeya searched the skies for 109 nights, until he made a discovery that brought honor to his family

As she had done many times, Mrs. Ikeya woke when her son Kaoru did and, unnoticed by him, saw him preparing for sky-watching. All the other children, stretched out beside her on the *tatami* matting, slept soundly under their quilts. Only her eldest son, mainstay of this fatherless house, refused to take his full rest before going to work the next morning. Winter nights are cold in Japan. Moving quietly, Kaoru drew on his leather windbreaker, heavy work pants, wool scarf and gloves. Carrying his bed quilt with him, he left the house to climb an outside ladder to his rooftop perch beside his telescope.

Mrs. Ikeya closed her eyes and tried to go back to sleep, but couldn't. Instead, she lay listening to the bitter wind as it swept in from the Pacific and blew across Lake Hamana, just outside the door.

No matter how bizarre his behavior might seem to others, Mrs. Ikeya felt that she owed her son understanding and acceptance. Yet when she saw him, pale, too thin, and haggard from lack of sleep, she often had to stifle a protest.

By this night of January 2, 1963, 19-year-old Kaoru Ikeya had logged a total of 335 hours and 30 minutes of observing the sky in a period of 109 nights; and there had been countless nights before he began his official log. Yet each time he peered through the eyepiece of the telescope he had made with his own hands, his pulse quickened in expectation. Kaoru had set himself a goal. More than anything else, he wanted to be the discovered of a new comet.

Kaoru adjusted the eyepiece and almost at once sighted in the sky a misty object he had never noticed before. He consulted his sky maps. They showed nothing in that location. Thoroughly roused, he rechecked its position meticulously, then remained glued to his telescope, half-convinced that what he was seeing must be a delusion. But the small, round, diffuse glow remained in the sky, and observing its gradual movement among the stars, Kaoru positively identified it not as a faint star cluster but a coma, the head of a comet.

But was it *his* comet? Or was he witnessing the return of a comet already recorded? Only when the Tokyo Astronomical Observatory had checked out his data would he know whether he had made a discovery.

Next morning Kaoru waited outside the telegraph office before it opened to dispatch a wire to the observatory reporting the comet's position three degree southwest of star Pi in the constellation Hydra, its 12th-magnitude brightness and its direction of movement. Then, mounting his bicycle, he pedaled off to work.

Before the whistle blew at 8 A.M., hundreds of workers from surrounding towns had parked their bicycles within the gates of the huge plant of the Kawai Gakki Company, manufacturers of

ILLUSTRATED BY ED YOUNG

pianos. In visored cap and factory coveralls, Kaoru Ikeya, a slight figure standing five feet four inches and weighing a bit under 125 pounds, was at once absorbed into the anonymity of the assembly line, where as an ungraded, or unskilled, worker he polished the white celluloid sheaths for piano keyboards at a salary of 13,000 yen, or about $35, per month.

But Kaoru's thoughts were not on factory work. He had refused special training to upgrade himself at the piano company, and once again he was grateful that his job demanded so little of him. Polishing celluloid was mechanical; he could think of other things.

"A steady fellow," his personnel card read. "Reliable. Quiet. Middle school education only. Nonparticipant in company sports or hobby clubs. . . . Lacks ambition and initiative."

Within a few days after Kaoru received his reply wire from the Tokyo Observatory, the international news services were flashing quite another profile:

"Self-taught 19-year-old amateur astronomer Kaoru Ikeya, using a reflector telescope he constructed by himself at a cost of $22.32, has discovered the New Year's first comet, officially designated Comet Ikeya 1963a and now the subject of observation and tracking by astronomers in both hemispheres."

A spate of publicity greeted Kaoru's discovery. His home was invaded by news photographers; he was led before TV cameras and radio hookups; he received more than 700 letters from amateur astronomers seeking his advice; he was awarded a gold medal by the Tokyo Observatory; and he watched in polite silence a professional actor portray him in a hackneyed, melodramatic version of his life story, an "inspirational" 40-minute movie short called *Watching the Stars,* which was to be shown to the school children of Japan.

Aglow with pride at the honors heaped on her son, Mrs. Ikeya saw the film through rose-colored glasses.

But Kaoru did not share her bias. "This movie is a novel, a fiction about me," he commented wryly. "Why isn't the truth good enough?"

The truth was neither hackneyed nor melodramatic. To begin with, if his father had not moved the family from the large industrial city of Nagoya to the town of Bentenjima when Kaoru was six years old, Kaoru would probably have acquired a city boy's indifference to the sky, observing it only in bits and patches between buildings. But their house fronted on Lake Hamana, a salt-water lake fed by the Pacific, and the flat roof offered a perfect platform for observing a far-flung canopy of the heavens. As the family grew and Kaoru sought to escape from the noisy clamor of three younger brothers and a sister, he often mounted to the quiet rooftop to look at the stars.

In addition, there were Japanese holidays that had stimulated his interest in the stars. For as long as he could remember, he had joined with other boys and girls in hanging strips of colored papers bearing poems and pictures on stalks of bamboo that had been set up outdoors. These were directed to the two celestial lovers, the Weaver Star and the Cowherd Star, who, so the story goes, live on either side of the Milky Way and meet only once a year, on the night of the festival. In the middle of or in late September of each year there was also *Tsukimi,* a special holiday when all Japan makes offerings of trays of rice dumplings and clusters of seven autumn flowers to the new full moon.

By the time he was 11 years old Kaoru was highly "sky conscious." He was so enthralled with the mystery of the heavens that he had begun to look for books in his school library that would tell him more about the stars, and to trace maps and diagrams of the skies into his school notebook. Tentatively at first, then with deepening familiarity, he began to distinguish among the galaxies and constellations and to wish to see more than he could with his naked eye. What fascinated him most were comets, those ghostly celestial bodies so nebulous as to be commonly described in his books as "the nearest thing to nothing that anything can be and still be something." Kaoru made up his mind. It was a new comet that he longed to discover—a comet of his own, with its fuzzy head surrounding a bright nucleus, its long, ephemeral tail pointing away from the sun and its journey through the skies lasting from three to thousands of years.

There was still another holiday that made an impression on Kaoru during his early years. Every May 5th, on the national holiday known as Boys' Day, the Ikeya family, along with others among their neighbors who were fortunate enough to have sons, held a special celebration. On tall poles next to their houses they displayed cloth streamers in five colors made in the image of Japan's favorite fish, the river carp. Proudly the Ikeya pole flew six carp, one for each son of the house and one for each parent. Poor Fumiko, the sole daughter of the house, was given new dolls to placate her. Then Mr. Ikeya lined up his sons and exhorted them to grow up to be good citizens. In emulation of the carp's brave, vigorous struggle upstream, he said, they must aspire ever higher in their own lives.

By the time Kaoru was 12 and had had the six years of elementary school, he had determined to build his own telescope. Although his father's fish market was prospering, Kaoru was reluctant to ask him to buy one. Already there was tension between them. Instead of applying himself to learning the family's business, his father complained, Kaoru's head was "always in the stars."

Mr. Ikeya was still moored to the old, prewar attitudes. "Sound sense should show you, my son," he insisted, "that astronomy does not belong to our station in life."

How, Kaoru wondered silently, did his father's annual Boys' Day message square with this contention? How much higher could one aspire than to the stars? In contrast to his father, Kaoru was growing up in a postwar Japan heavily influenced by the Americans who occupied the country. In response to reforms enacted in the New Education Law of 1947, his teachers from first grade on rejected the old emphasis on passive, rote learning and memorizing. Instead, they encouraged questions and discussions and created projects that his father called a foolish waste of time.

The new way also widened Kaoru's horizons outside the classroom. In the spring and fall he was among the hundreds of thousands of school children who took off on excursions to parks, monuments, temples and shrines. The Get-To-Know-Japan program, under which the participants were chaperoned by teachers and billeted at hostels and inexpensive inns, was so inexpensive that by contributing pennies into the class travel fund each week, Kaoru could afford to take advantage of it.

In middle school, where he completed the nine years of compulsory education, Kaoru was a good student, ranking fifth in a class of 50 students. But he had no favorite subjects. "Except, of course, the one I thought about and worked at by myself," he says.

Astronomy was not taught in middle school, but Kaoru haunted the school library, reading texts on astronomy and studying the principles of optics, physics and chemistry involved in telescope-making. With his meager savings he also managed to buy a number of do-it-yourself manuals on how to build a telescope. He was barely 14 when, reading an astronomy journal, he came across the name of Dr. Hideo Honda, an ophthalmologist in Nagoya who held monthly meetings for amateur astronomers in his clinic.

Kaoru wrote to Dr. Honda that he was planning to construct a Newtonian reflector telescope with a 20-cm. or 8-inch mirror—the most popular and feasible for do-it-yourself amateurs. Noting that his young correspondent was only 14, Dr. Honda didn't think the boy would have either the skill or the stamina to see his project through. On the other hand, he was reluctant to discourage Kaoru.

"I think," he replied cautiously, "that you are very likely too young to make a 20-cm. mirror. Your idea presents many difficulties and I shall tell you all I know about them. But so many young men in Japan after the war are impatient, especially with regard to making observations. Although many have high-priced telescopes, they rarely observe the stars. They use their fine instruments only to watch an eclipse of the sun or some other show in the heavens. Few of them would be able to take the pains to construct their own instruments."

Kaoru reflected that Dr. Honda could not possibly understand how prepared he really was—at least to take infinite pains. He continued with his studies and gradually began to acquire the materials needed for making his telescope. It was at about this time that misfortune struck the Ikeya family.

For some time Mr. Ikeya's fish market had been failing. The reasons he ascribed to this were "price-fixing by ignorant and officious Japanese and American policy makers," but also, he pointed out, it was retribution by the gods, who were angered by the way Shinto beliefs were being shunted aside.

Discouraged and embittered, Mr. Ikeya began to lounge about the cafés, drinking sake, increasingly reluctant to face his family or five young children. Early in 1958 he resolved his dilemma by disappearing, abandoning them all.

Perhaps nowhere else in the world does a father's desertion so cruelly punish those he leaves behind as in Japan, where the concept of *on* heavily influences individual behavior. *On* refers to the obligations each person incurs through contact with others by the mere fact of his existence. The most basic form of *on* is *ko*, the obligation to one's parents for the daily care and trouble to which they are put; even by offering unwavering loyalty, obedience and reverence, no more than one ten-thousandth of this debt can ever be paid. This particular duty, *ko*, also imparts the same obligations to descendants. A Japanese proverb says: "Only after a person is himself a parent does he know how indebted he is to his own parents." It follows, then, that a significant part of *ko* is to one's own parents in giving as good or better care to one's children.

In deserting his family, Mr. Ikeya not only failed utterly in his duty as a parent but violated his most sacred *on* of filial duty to his own parents. He placed an oppressive burden of shame on them all and tarnished the family name, perhaps for generations.

"We could think of nothing else, my mother and I," Kaoru says, "but that our family was disgraced, our house destroyed."

The first and hardest impact of the disaster was on Mrs. Ikeya. Sadly Kaoru watched his mother go to work at the hotel near the Bentenjima railroad station, cooking and cleaning for strangers instead of in the seclusion of her own house and family. But, as she observed to him, at least the older children were safe in school during the day and she could keep the baby, four-year-old Yasutoshi, with her on the job. Although she was under five feet tall and even in her bulky, padded house jacket, trousers and coverall apron looked slight as a sparrow, her strength and fortitude in dealing with this family crisis were immense. What she told herself was that the money she earned, around 17,000 yen a month, or about $47, ensured food for her children.

Kaoru felt the weight of his love and duty toward his mother. But until he completed the compulsory third year of middle school he could do no more to lighten her burden than to take a part-time job, rising at five A.M. to deliver morning newspapers before school, then returning after classes to deliver the evening edition. Of course, attendance at high school was barred to him. The family could not afford either the time or the fees, which amounted to about $25 for registration and about $8 per month.

Mrs. Ikeya's and Kaoru's combined efforts were inadequate to keep up payments on their comfortable, roomy house. The bank foreclosed and permitted them to move, virtually rent-free, into a far less adequate house a few doors away.

This house provided a narrow entry-way, an all-purpose eating-sleeping-living room, a tiny kitchen, a catchall cubicle and a lavatory at the back. But in common with most Japanese houses it was orderly and simple to keep clean, since shoes, which might track up the *tatami* on which families bed down at night, are never worn inside Japanese houses. In the Ikeya home the furniture consisted of a bureau, a square low table with floor cushions, Kaoru's worktable, and two rough shelves that he constructed to hold his small collection of books and manuals. No Japanese houses have central heating, and the Ikeyas relied on a large porcelain jar filled with heated charcoal briquets. Even well-to-do families have nothing more than a *hibachi*, a pit in the floor filled with charcoal.

The feature of the house that most concerned Kaoru was the flat roof, which provided as good a platform and as good a sky to view as before. On his shoulders rested the responsibility not only of replacing his father as breadwinner and head of the house, but of somehow removing from the family name the stigma his father had attached to it. More than ever he thought about his comet. What if one day he could attach the dishonored name to the tail of a new comet and write that name across the sky? New comets were generally named after their discoverers. "Comet Ikeya!" The name had a fine, proud ring to it!

In June, 1959, when he graduated from middle school, Kaoru was deeply immersed in his thoughts about telescope building, but he paused long enough to get a job at the Kawai Gakki piano factory, a few miles from home. Since degree of education is directly and, on the whole, inflexibly related to earning power in the Japanese economic scale, Kaoru was classified as an ungraded or unskilled worker at base pay.

Kaoru wasn't disturbed. "It's a simple job," he reported to his mother. "It will not bother me."

Mrs. Ikeya also was content. Although the Japanese are now more concerned with money-making and worldly success than before World War II, with its postwar Western influences, many still place greater emphasis on the reflective life and spiritual values. On the practical side of her ledger, Kaoru's base pay and regular annual raises, together with her own earnings, were enough for the necessities of life. Soon, too, Tadashi, her second son, only two years younger than Kaoru, would also become a wage earner. She didn't attempt, though, to budget the spiritual side of the ledger. She would be a poor mother indeed if she offered Kaoru anything but encouragement and the greatest freedom, within the confines imposed on him by necessity, to follow his own pursuits. Who knew? Perhaps he would even attain Buddhahood through the ordeals he imposed on himself.

Kaoru set to work grinding the high-precision surface for the main mirror that would go into his telescope. Shopping around in secondhand supply stores, he obtained the last-minute materials he needed. Bit by bit, and after trial and error, Kaoru, still thinking for himself and going it alone, completed the preliminary work, and then began the final process of assembling and mounting his telescope on the roof. In August, 1961, he was ready to begin once more to search the skies. Since starting work at the factory he had put nearly two years of off-work hours of labor into achieving his telescope, at a total out-of-pocket cost of 8,000 yen, or about $22.

In Japan, the best hours for viewing are from 3 A.M. to 5 A.M., but of course, not every sky is fit for observation. On cloudy mornings Kaoru caught up on the sleep he lost during clear mornings, when the predawn spectacles thrilled him. He logged his watches meticulously and checked back with his sky maps, but six months after he had begun to search regularly, Kaoru felt deeply discouraged. The search for a new comet seemed futile. More and more often he began to fall into a mood of profound depression.

"My son," Mrs. Ikeya said, "you are too much alone with your thoughts. Is there no one you could talk to who would give you advice?"

Perhaps she was right. Kaoru broke out of his solitude to establish communication with someone who had known not only the trials of comet-seeking but also the rewards. He wrote to the astronomer Minoru Honda, discoverer of nine comets, about his lack of success, pleading between the lines for a word of encouragement.

At first the reply seemed to him almost a rebuff. Then, pondering it, Kaoru seized eagerly on its meaning.

"To observe the skies solely to seek a new comet is a hopeless task which demands a great deal of time and hard labor," Minoru Honda wrote. "But to observe the brilliant heavens for their own sake without thought of a discovery may bring good luck to your comet-seeking. You must have humility and not be too ambitious, for, after all, you are quite young and only an amateur."

Kaoru returned to his sky watches. He tried to maintain a humbler and more relaxed attitude. He still had a great deal to learn about the heavens, and instead of searching for a comet in particular, he concentrated on the whole sky, trying to become as familiar with its plan as he was with the streets and byways of Bentenjima.

On December 31, 1962, Mrs. Ikeya counted a total of 16 months since Kaoru had begun his night vigils with his new telescope.

"Surely, Kaoru," she pleaded, "this first night of the holidays you will take your full rest. It is *Omisoka,* after all, the Grand Last Day of the year! Both of us have worked hard. We have honorably settled all our debts, and can start the new year with a clean record. Let us stay awake until midnight, listening to the temple bells, and then sleep late in the morning."

To please her, Kaoru didn't climb to the roof that night, and all through New Year's Day he remained with the family, enjoying his mother's holiday meal of *ozoni* (rice cake soup), playing her favorite game of cards, *karuta,* and then joining her for a visit to a nearby shrine to pray for good luck in 1963.

It was on the following night of January 2, 1963, while he was still in a relaxed, holiday mood, that Kaoru made his 109th search and discovered his comet.

At the Harvard Observatory, the western hemisphere's clearinghouse for astronomic information, all the data on Comet Ikeya 1963a, together with a projection of its orbit, were placed on announcement cards and sent to observatories, journals of astronomy and a network of professional and amateur astronomers around the world.

The comet changed its form and brightness nightly as it reached its maximum visibility at perihelion, or closest passage to the sun, calculated to take place on March 21st. At this point Comet Ikeya would be 59 million miles distant from the sun and some 93 million miles from the earth. Then the celestial spectacle it offered would be over until late spring, when it would become visible again in the morning sky, a considerably fainter object on the far side of the sun. Finally, traveling in an elliptical orbit out beyond the farthest planets, it would disappear, to return anywhere from 100 to 10,000 years hence.

Comet Ikeya 1963a was at first described as dim, but a few weeks after Kaoru sighted it, reports from Tokyo, the Yerkes Observatory, in Wisconsin, and the U.S. Naval Observatory's station at Flagstaff, Arizona, indicated that it was moving rapidly southward and brightening.

By February and early March, 1963, Comet Ikeya was providing an exciting spectacle for southern hemisphere watchers. In four weeks, beginning February 13th, it had traveled northward a quarter of the way around the sky and become an object visible to the naked eye.

An American physicist then working in Sydney, Australia, wrote to the journal *Sky and Telescope* of his experience with the comet:

"On February 14th I had my children in the back yard to show them 47 Tucani, a very beautiful globular cluster. My daughter Judy was looking through binoculars and remarked that what she saw was between the Magellanic Clouds. When I looked, I realized that she had not been viewing 47 at all, but a new comet—actually Ikeya's."

Kaoru kept in touch with his comet through a widening circle of fellow observers, but his most immediate source was the Tokyo Observatory and its staff members, notably Dr. Masahisa Tarao, distinguished astronomer and vice-president of the Japanese Astronomical Society, on whose behalf he presented Kaoru with the gold medal for achievement.

"We professional astronomers cannot watch the heavens all the time," Dr. Tarao said. "We need the assistance of amateurs in the observation of artificial satellites, solar explosions, meteors, comets and other phenomena of our universe. You, Kaoru Ikeya, by your patience and diligence, have added to our knowledge of the solar system."

All this while, Kaoru reported for his job at the piano factory, quietly and reliably. Only when the press requested interviews with Kaoru did the company learn of his achievement. The company's response was to initiate a collection among the workers to help Ikeya continue his work. A certificate lauding Kaoru's on-the-job zeal and dedication together with a check for about $300, a lordly sum in Japan, were presented to him at a ceremony at the plant. The company also financed the movie short about Kaoru's life, and paid him 30,000 yen, or about $80, for permission to make the film.

Kaoru made no effort to capitalize on his publicity. To have achieved a magnificent "first" in comet-hunting was all the reward he needed, and his appreciation of it deepened when he learned of other amateur astronomers such as Dr. Floyd L. Waters, of Hugo, Oklahoma, who very nearly made it, but did not quite.

"On the morning of January 26th," Dr. Waters wrote Kaoru, "at about 5 A.M., temperature 10 above zero, I discovered this object in the south. I became quite excited, wired my finding to Harvard Observatory, and found out later that day that what I had reported was the Comet Ikeya that had been discovered by a boy in Japan on January 2nd. All amateur astronomers would be very thrilled to discover a comet but of course do not have the perseverance to spend 335 hours trying to find one!"

But Comet Ikeya was not the last of Kaoru's discoveries. As if especially favored by the gods, Kaoru made a second discovery in June, 1964. Working with a new, improved telescope with a 17.5-cm. mirror, which he had made at a cost of 5,000 yen, or about $13, he discovered a second comet—Comet 1964f.

Still in the same job at the factory, Kaoru has neither sought after nor been offered the reward of advancement. For him the greatest advancement, according to his Buddhist faith, would be to find that "limitless, ever-expanding path, an eternal path to tranquility." For the rest, his richest reward has been that in the span of his 21 years he has made partial payment on his *ko*, or primary duty to his mother and to his family, by taking a dishonored name and writing it across the skies.

The director of the Central Bureau for Astronomical Telegrams describes the excitement generated by a recent comet, and reviews current knowledge of comets.

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The Great Comet of 1965

Owen Gingerich

An article from *The Atlantic Monthly*, 1966.

Of all the memorable comets that have excited astronomers and stirred men's imaginations, not one had more impact on our concepts of the universe than the Great Comet of 1577. Discovered in November of that year, the comet stood like a bent red flame in the western sky just after sunset. The celebrated Danish astronomer Tycho Brahe was among the early observers: he caught sight of the brilliant nucleus while he was fishing, even before the sun had set. As darkness fell, a splendid twenty-two-degree tail revealed itself. Tycho's precise observations over the ten-week span before the comet faded away were to deal the deathblow to ancient cosmogonies and pave the way for modern astronomy.

In the sixteenth century nearly everyone accepted Aristotle's idea that comets were meteorological phenomena, fiery condensations in the upper atmosphere. Or, if not that, they were burning impurities on the lower fringe of the celestial ether, far below the orbit of the moon. In 1577 most astronomers still subscribed to the ancient belief that the moon and planets were carried around the earth on concentric shells of purest ether. Tycho, by comparing his careful measurements of the comet's position with data from distant observers, proved that it sped through space far beyond the moon. The Comet of 1577 completely shattered the immutable crystalline spheres, thereby contributing to the breakdown of Aristotelian physics and the acceptance of the Copernican system.

But the most renowned and most thoroughly studied of all comets is the one associated with Edmund Halley. It was the first to have a periodic orbit assigned, thus securing for comets their place as members of the solar system. Halley had matched the Comet of 1682, which he had observed, with those of 1531 and 1607. Assuming these to be different appearances of the same celestial object, he predicted another return in 1758. Although he was ridiculed for setting the date beyond his expected lifetime, the comet indeed returned, and Halley's name has been linked with it ever since.

On its latest return, in 1910, Halley's comet put on a magnificent display, reaching its climax several weeks after perihelion passage in mid-April. During the early part of May it increased until the brilliance of its head equaled the brightest stars and its tail extended sixty degrees across the sky. Later in May, the earth grazed the edge of the tail. The thin vacuous tail caused no observable effect on earth, except for such human aberrations as the spirited sale of asbestos suits. That no terrestrial consequences were detected is not surprising when we learn that 2000 cubic miles of the tail contained less material than a single cubic inch of ordinary air.

If prizes were offered for cometary distinctions, then last year's Comet Ikeya-Seki would win a medal as the most photographed of all time, and it might win again for the range of astrophysical observations carried out. As it swung around the sun, its brilliancy outshone that of the full moon, and within ten days its tail extended almost as far as the distance from the earth to the sun. The behavior of the comet was neatly explained by the "dirty snowball" theory. According to this widely accepted picture, a comet's nucleus is a huge block of frozen gases generously sprinkled with dark earthy materials. Occasionally the gravitational attraction of nearby passing stars can perturb a comet from its cosmic deep freeze in the distant fringes of the planetary system beyond Neptune; the comet then can penetrate the inner circles of the solar system, where it develops a shining gaseous shroud as its surface vaporizes under the sun's warming rays. Hence, the closer a comet approaches the sun, the more it vaporizes and the larger and brighter it becomes. Comet Ikeya-Seki passed unusually close to the sun, becoming possibly the brightest comet of the century; the resulting tail was the fourth longest ever recorded.

Today I look back with a wry smile to the Sunday morning last September when I decoded the telegram bringing the first word of the new comet. Early that morning in Benten Jima, Japan, a youthful comet hunter, Kaoru Ikeya, had discovered a fuzzy glow not charted on his sky maps. At the same time, another young amateur 250 miles away, Tsutomu Seki, had independently detected the new celestial visitor. Both men had used simple, homemade telescopes for their discovery, and both had sent urgent messages of their find to the Tokyo Astronomical Observatory.

News of the comet's appearance was quickly relayed from Tokyo to my office at the Smithsonian Astrophysical Observatory. Here the name "Comet Ikeya-Seki" was officially assigned, as well as the astronomical designation 1965 f. Throughout that day, September 19, the communications center at Smithsonian alerted observatories and astronomical groups all over the world — Flagstaff, Rio de Janeiro, Johannesburg, Prague, Peking, Canberra — in all, more than 120. Included were the twelve astrophysical observing stations of the Smithsonian Observatory, whose specially designed satellite-tracking cameras are ideal for comet photography. Within hours a confirmation of Ikeya-Seki arrived from the Woomera, Australia, station.

By Tuesday afternoon, half a dozen approximate positions were in hand, more than enough for us to try for a crude preliminary solution of the comet's orbit. Unfortunately, the positions from the observing stations were only approximate "eyeball" measurements obtained by laying the film onto a standard star chart with marked coordinates. Furthermore, the observatory's computer program had not been fully checked out. When the rough observations were used in different combinations, the computer produced two orbits in wild disagreement. Nevertheless, Professor Fred L. Whipple, director of the Smithsonian Astrophysical Observatory and author of the "dirty snowball" comet theory, noted that the second of the preliminary orbits closely resembled the path of a famous family of sun-grazing comets. The agreement was too close to be coincidence, he reasoned, and therefore the second solution must be correct.

Professor Whipple's astute suggestion provided the first hint of the excitement that was to come. Several of the previous sun-grazers had been spectacular objects. Notable among them was the Great Comet of 1843, whose seventy-degree tail stretched 200 million miles into space, setting an all-time record, and whose brilliance induced the citizenry of Cambridge to build a fifteen-inch telescope for Harvard equal to the largest in the world. And the second comet of 1882 achieved such brilliancy as it rounded the sun that it could be seen in broad daylight with the naked eye.

In the few days following the first computer solutions three "precise" positions were reported to the Central Telegram Bureau, one from Steward Observatory in Tucson, Arizona, and two from the Skalnate Pleso Observatory in Czechoslovakia. When these new positions were fed by themselves into the computer, the result indicated an ordinary comet, and not a sun-grazer at all. But our programmers noticed that something was seriously wrong. When positions from the satellite-tracking cameras were included in the calculations, the computer gave different answers. Among them was the interesting possibility that Comet Ikeya-

Seki might die by fire, plunging directly into the sun.

Then, suddenly, the mystery vanished. Six accurate positions from veteran comet observer Elizabeth Roemer at the Flagstaff, Arizona, station of the U.S. Naval Observatory established the path with great precision. One of the earlier "precise" observations had been faulty, and with its elimination, the others fell into place. Comet Ikeya-Seki was accelerating along a course that would carry it within a solar radius of the sun's surface. And since a comet's brightness depends on its closeness to the sun, there was every indication that Comet Ikeya-Seki would become a brilliant object.

Armed with predictions of Comet Ikeya-Seki's sun-grazing path, the Smithsonian staff set out to forewarn space scientists and radio astronomers whose attention does not normally encompass comets. We called a press conference to describe the magnificent view hoped for as the comet swung around perihelion, its nearest approach to the sun. First discovered in the morning sky, the comet would cross into the evening sky for only a few hours on October 21. If a tail of this comet were to appear in the evening, it would sweep across the western sky after sunset on that evening. Afterward it would reappear in the morning twilight. Such a prediction was hazardous, because although the comet's trajectory was well established, its brightness and tail length resisted astronomical forecasting since no one knew just how much material would be activated as it sped past the sun.

Had we examined more carefully the historical records of Comet 1882 II, we might have been more cautious in telling the public to look for the tail of Comet Ikeya-Seki sweeping across the western sky after sunset on October 21. Each new observation of the 1965 comet confirmed that it was a virtual twin of the Great Comet of 1882; thus, by looking at the observations from the last century, we should have guessed that the comet's enormous velocity as it rounded the sun — one million miles per hour — would dissipate the tail so widely that it could not be seen in the dark sky. On the other hand, we hardly dared publicize what the computer's brightness predictions showed: that Comet Ikeya-Seki would be visible in full daylight within a few degrees of the sun!

AND thus it happened that thousands of would-be observers in the eastern United States maintained a cold and fruitless search in the early morning hours of October 21. Thousands of others, especially in the American Southwest, had the view of a lifetime — a bright comet with its short silvery tail visible next to the sun in broad daylight. Simply by holding up their hands to block out the sunlight, they could glimpse the comet shining with the brilliance of the full moon. Hazy, milky skies blocked the naked-eye view for observers in the eastern United States and much of the rest of the world; even in New England, however, telescopes revealed the comet with a sharp edge facing the sun and the beginnings of a fuzzy tail on the other side. Professional astronomers were excited by the opportunity to photograph the object at high noon. For the first time, the daylight brilliance of a comet permitted analysis from solar coronagraphs. Airborne and rocket-borne ultraviolet detectors examined features never before studied in comets.

The spectrum observations ended eight decades of controversy. In most comets, the reflected spectrum of sunlight is seen, combined with the more interesting bright molecular spectrum from carbon and carbon compounds. The molecules are excited by the ultraviolet light from the sun, and glow in much the same way that certain minerals fluoresce under an ultraviolet lamp. But back in 1882, when spectroscopy was in its infancy, the great sun-grazing comet yielded an entirely different spectrum. Scientists at the Dunecht Observatory in Scotland thought they saw emission lines from metal atoms such as iron, titanium, or calcium, but a similar spectrum was never found in subsequent comets. Some observers expressed their disbelief in this unique record.

Astronomers did not get another chance to examine a comet so close to the sun until October 20, 1965. On that morning at the Radcliffe Observatory in South Africa, Dr. A. D. Thackeray obtained spectrograms of the nucleus of Comet Ikeya-Seki, then only 8 million miles from the sun. These showed bright lines of both iron and calcium. The telegraphic announcement, again relayed by the Central Bureau, set other spectroscopists into action. Within days, there were reports of nickel, chromium, sodium, and copper.

Though fully expected from a theoretical point of view, these observations confirmed that the impurities in comets had a chemical composition similar to that of meteors. The connection is not fortuitous; for many years astronomers recognized that those ephemeral streaks of light in the night sky, the meteors, were fragile cometary debris plunging through the earth's atmosphere. As the gases boil out of a cometary nucleus, myriads of dirty, dusty fragments are lost in space. In time, they can be distributed throughout a comet's entire orbit, and if that path comes close to the earth's own trajectory, a meteor shower results.

The Leonid meteors are a splendid example of "falling stars" closely related to a comet. A meteor swarm follows close to Comet Tempel-Tuttle. Every thirty-three years, as the comet nears the earth's orbit, a particularly good display of Leonids appears around November 16. The recovery of this same comet in 1965 was followed by a November shower in which hundreds of brilliant meteors flashed through the sky within a period of a few hours. Nonetheless, the 1965 Leonids provided a sparse show compared with the hundreds of thousands seen in 1833 and 1866. In 1899, astronomers predicted yet another fireworks spectacular. The prognostication proved to be a great fiasco, for gravitational attraction from the planet Jupiter had slightly shifted the orbit of the comet and its associated meteor swarm. Ever since, astronomers have been wary of alerting the public to meteors or comets. Our enthusiasm in predicting the greatness of Comet Ikeya-Seki on October 21 was indeed risky.

Nevertheless, the daylight apparition of Comet Ikeya-Seki was but a prelude to a more spectacular show. Its surface thoroughly heated by its passage through the solar corona, the comet developed a surrounding coma of gas and dust some thousands of miles in diameter as it left the sun. As it slowed its course and receded from the hearth of our planetary system, the solar wind drove particles from that coma into a long stream preceding the comet.

As soon as Comet Ikeya-Seki could once again be seen in the early morning sky, its long twisted tail caused a sensation. Standing like a wispy searchlight beam above the eastern horizon, the tail could be traced for at least twenty-five degrees. Its maximum length corresponded to 70 million miles, ranking it as the fourth longest ever recorded. Only the great comets of 1843, 1680, and 1811 had tails stretching farther through space. (Quite a few comets have spanned greater arcs of the sky because they were much closer to the earth. Their actual lengths in space could not compare with that of the Great Comet of 1965.) At its peak brightness, Comet Ikeya-Seki was about equal to the sun-grazers of 1843 and 1882. Even after it receded from the sun, its nucleus shone brilliantly through the morning twilight. By all accounts, Comet Ikeya-Seki compared favorably with the great comets of the past. Those portentous sights, compared to giant swords by many a bygone observer, had little competition from city lights, smog, and horizon-blocking apartment buildings.

Comet Ikeya-Seki surprised most astronomers by developing a strikingly brilliant tail on its outward path from the sun, especially when compared with the poor show on its incoming trajectory. Had they looked in Book III of Newton's *Principia*, however, they would have seen another sun-grazing comet neatly diagrammed with a short, stubby tail before perihelion passage and the great flowing streamlike tail afterward. Newton spent many pages describing that Great Comet of 1680. Especially interesting to American readers is the generous sprinkling of observations reported from New England and "at the river Patuxent, near Hunting Creek, in Maryland, in the confines of Virginia."

In the new world not only astronomers were interested in the comet. From the Massachusetts pulpit of Increase Mather came the warning,

> As for the SIGN in Heaven now appearing, what Calamityes may be portended thereby? . . . As *Vespasian* the Emperour, when There was a long *hairy Comet* seen, he did but deride at it, and make a Joke of it, saying, That it concerned the Parthians that wore long hair, and not him, who was bald: but within a Year, Vespasian himself (and not the Parthian) dyed. There is no doubt to be made of it, but that God by this *Blazing-star* is speaking to other Places, and not to *New England* onely. And it may be, He is declaring to the generation of hairy Scalps, who go on still in their Trespasses, that the day of Calamity is at hand.

Superstitions concerning comets reached their highest development and received their sharpest attacks at this time. For centuries comets had been considered fearsome omens of bloody catastrophe, and Increase Mather must have been among the great majority who considered the Comet of 1680 as a symbol fraught with dark meanings. The terrors of the superstitious were compounded when a report came that a hen had laid an egg marked with a comet. Pamphlets were circulated in France and Germany with wood blocks of the comet, the hen, and the egg. Even the French Academy of Sciences felt obliged to comment:

> Last Monday night, about eight o'clock, a hen which had never before laid an egg, after having cackled in an extraordinarily loud manner, laid an egg of an uncommon size. It was not marked with a comet as many have believed, but with several stars as our engraving indicates.

In a further analysis of this comet, Newton's *Principia* reported that a remarkable comet had appeared four times at equal intervals of 575 years beginning with the month of September in the year Julius Caesar was killed. Newton and his colleague Halley believed that the Great Comet of 1680 had been the same one as seen in 1106, 531, and in 44 B.C. This conclusion was in fact false, and the Great Comet of 1680 had a much longer period. Within a few years, however, Halley correctly analyzed the periodicity of the famous comet that now bears his name.

Is Comet Ikeya-Seki periodic like Halley's? If so, can it be identified with any of the previous sun-grazers? The resemblance of Comet Ikeya-Seki to Comet 1882 II has led many people to suppose that these objects were identical. The orbits of both of these comets take the form of greatly elongated ellipses, extending away from the sun in virtually identical directions. Nevertheless, even the earliest orbit calculations scuttled the possibility that the comets were one and the same, since at least several hundred years must have passed since Comet Ikeya-Seki made a previous appearance in the inner realms of the solar system. On the other hand, it is unlikely that Comet Ikeya-Seki, Comet 1882 II, and a half dozen others would share the same celestial traffic pattern and remain unrelated. The only reasonable explanation is to suppose that some single giant comet must have fissioned into many parts hundreds of years ago.

Indeed, the Great Comet of 1882 did just that. Before perihelion passage, it showed a single nucleus; a few weeks afterward, astronomers detected four parts, which gradually separated along the line of the orbit. The periods for the individual pieces are calculated as 671, 772, 875, and 955 years. Consequently, this comet will return as *four* great comets, about a century apart.

It was, therefore, not at all unexpected when the Central Bureau was able to relay the message on November 5 that Comet Ikeya-Seki had likewise broken into pieces. The first report suggested the possibility of three fragments, but later observers were able to pinpoint only two. One of these was almost starlike, the other fuzzy and diffuse. Though first observed two weeks after perihelion passage, the breakup was probably caused by unequal heating of the icy comet as it neared the sun.

If the Great Comet of 1965 was itself merely a fragment, what a superb sight the original sun-grazer must have been. Appearances of comets with known orbits total 870, beginning with Halley's in 240 B.C., but the earliest known sun-grazer of this family is the Comet of 1668. In medieval chronicles and Chinese annals, and on cuneiform tablets, hundreds of other comets have been recorded, but the observations are inadequate for orbit determinations. Undoubtedly, that original superspectacular sun-grazer was observed, but whether it was recorded and whether such records can be found and interpreted are at present unanswerable questions.

A similar search of historical records, which holds more promise of success, is now under way at the Smithsonian Astrophysical Observatory. The comet with the shortest known period, Encke, cycles around the sun every three and a third years. Inexorably, each close approach to the sun further erodes Comet Encke. The size of its snowball has never been directly observed, but a shrewd guess based on the known excrescence of gaseous material places it in the order of a few miles. By calculating ahead, Professor Whipple has predicted the final demise of Comet Encke in the last decade of this century. By calculating backward in time, he has concluded that it might once have been a brilliant object. Its three-and-a-third-year period would bring a close approach to the earth every third revolution, so that a spectacular comet might appear in the records at ten-year intervals. In the centuries before Christ, the Chinese and Babylonian records show remarkable agreement, but the register is too sketchy, and so far, Comet Encke's appearances in antiquity have not been identified.

In addition to Encke there are nearly 100 comets whose periods are less than 200 years. Like Comet Encke, they face a slow death, giving up more of their substance on each perihelion passage. On an astronomical time scale, the solar system's corps of short-period comets would be rapidly depleted if a fresh supply were unavailable. On the other hand, there is apparently an unlimited abundance of long-period comets that spend most of their lifetime far beyond the planetary system. Astronomers now envision an extensive cloud of hundreds of thousands of comets encircling the sun at distances well beyond Pluto. Originally there may only have been a ring of cometary material lying in the same plane as the earth's orbit — the leftover flotsam from the solar system's primordial times. Perhaps the density of material was insufficient to coalesce into planetary objects, or perhaps at those great distances from the sun the snowballs were too cold to stick together easily.

Gravitational attractions from passing stars presumably threw many of the comets out of their original orbits into the present cometary cloud. These gravitational perturbations still continue, and a few comets from the cloud reach the earth's orbit every year. Their appearances are entirely unexpected, and their discoveries are fair game for professional and amateur alike. But since most professional astronomers are busily engaged in more reliable pursuits, persistent amateurs manage to catch the majority of bright long-period comets. Devotees such as Ikeya and Seki have spent literally hundreds of hours sweeping the sky with their telescopes in the hope of catching a small nebulous wisp that might be a new comet. The great sun-grazer was the third cometary find for each man. Within a week of its discovery, a British schoolteacher, G. E. D. Alcock, also found a new comet — his fourth. Alcock started his comet-finding career in 1959 by uncovering *two* new comets within a few days.

How does an amateur, or a professional, recognize a new comet when he finds one? Most new-found comets are as diffuse and formless as a squashed star, completely devoid of any tail. In this respect they resemble hundreds of faint nebulae that speckle the sky, with this difference: nebulae are fixed, but a comet will inevitably move. Consequently, a second observation made a few hours later will generally reveal a motion if the nebulous wisp is indeed a comet. However, most comet hunters compare the position of their suspected comet with a sky map that charts faint nebulae and clusters. Then the discovery is quickly reported to a nearby observatory or directly to the Central Bureau.

Today the chief reward for a comet find lies in the tradition of attaching the discoverer's name to the object, but in times past there have been other compensations. Jean Louis Pons, who discovered thirty-seven comets during the first quarter of the nineteenth century, rose from observatory doorkeeper to observatory director largely as a result of his international reputation for comet finding. And the Tennessee astronomer E. E. Barnard paid for his Nashville house with cash awards offered by a wealthy patron of astronomy for comet discoveries in the 1880s. Barnard has recorded a remarkable incident relating to the great sun-grazing comet of 1882:

> My thoughts must have run strongly on comets during that time, for one night when thoroughly worn out I set my alarm clock and lay down for a short sleep. Possibly it was the noise of the clock that set my wits to work, or perhaps it was the presence of that wonderful comet which was then gracing the morning skies, or perhaps, it was the worry over the mortgage in the hopes of finding another comet or two to wipe it out. Whatever the cause, I had a most wonderful dream. I thought I was looking at the sky which was filled with comets, long-tailed and short-tailed and with no tails at all. It was a marvelous sight, and I had just begun to gather in the crop when the alarm clock went off and the blessed vision of comets vanished. I took my telescope out in the yard and began sweeping the heavens to the southwest of the Great Comet in the search for comets. Presently I ran upon a very cometary-looking object where there was no known nebula. Looking more carefully I saw several others in the field of view. Moving the telescope about I found that there must have been ten or fifteen comets at this point within the space of a few degrees. Before dawn killed them out I located six or eight of them.

Undoubtedly Barnard's observations referred to ephemeral fragments disrupted from the Comet 1882 II then in view.

A great majority of the comets reaching the earth's orbit go back to the vast comet cloud, never to be identified again. Occasionally, however, a comet swings so close to the great planet Jupiter that its orbit is bent, and it is "captured" into a much shorter period. A "Jupiter capture" has never been directly observed, because most comets are still too faint when they reach Jupiter's orbit. Nevertheless, about a year ago, astronomers came almost as close as they ever will to witnessing the aftermath of this remarkable phenomenon.

In January, 1965, the press reported the discovery of two new comets by the Chinese, a rather unexpected claim inasmuch as it has been centuries since the Chinese discovered even one comet, not to mention two. To everyone's astonishment a pair of telegrams eventually reached our Central Bureau via England, confirming the existence of the objects. At the same time, the Chinese managed to flout the centuries-old tradition of naming comets after their discoverer. In the absence of the discoverer's name, our bureau assigned to both comets the label Tsuchinshan, which translated means "Purple Mountain Observatory."

Tsuchinshan 1 and Tsuchinshan 2 have remarkably similar orbits, whose greatest distances from the sun fall near the orbit of Jupiter. As these faint comets swung around that distant point in 1961, Jupiter was passing in close proximity. Quite possibly the gravitational attraction from Jupiter secured the capture of a long-period comet in that year, simultaneously disrupting it into the two Tsuchinshan fragments. However, it is more likely that the capture occurred at a somewhat earlier pass, a point that will eventually be established by a computer investigation. In any event, the observation of a comet pair with such a close approach to Jupiter is without precedence in the annals of comet history.

The complete roster of comets for 1965 included not only the Tsuchinshan pair, Comet Alcock, and the once-in-thirty-three-years visit of Tempel-Tuttle, but the recoveries of four other faint periodic comets and another new one, Comet Klemola, which was accidently picked up during a search for faint satellites of Saturn. Of this rich harvest, Comet Ikeya-Seki received more attention than all the others combined. Day after day, the Smithsonian observing stations around the world kept a continual photographic watch as the long twisted tail developed and faded. These thousands of frames — an all-time pictorial record — may eventually be combined in a film to illustrate in motion the details of cometary tail formation.

By now the Great Comet of 1965 has faded beyond the range of either Ikeya's or Seki's small telescope, and has apparently vanished from the larger instruments of professional astronomers as well. Perhaps in a millennium hence an unsuspecting amateur, never imagining that he has caught a sun-grazer, will find it on its next return.

"When discovered, the comet was only a white spot in the moonlit sky," Seki recently wrote to us. "I did not even dream that it would later come so close to the sun and become so famous."

The delicate modern version of the Eötvös experiment described here shows that the values of inertial mass and gravitational mass of an object are equal to within one ten-billionth of a percent. Such precision is seldom attainable in any area of science.

17

Gravity Experiments

R. H. Dicke, P. G. Roll, and J. Weber

An article from *International Science and Technology* and *Modern Science and Technology*, 1965.

In Brief: *Meaningful experiments concerning the nature of gravity are few and far between—for two reasons: gravitational forces are woefully weak, so data sufficiently precise to be meaningful are hard to come by; and the essential nature of gravity lies hidden in the theoretical labyrinth of relativity, in which it's easy to lose your way, assuming you have the courage to enter in the first place. But to the intrepid, three experimental paths lie open.*

The first is in null checks of extreme precision—accuracies of 1 part in 10^{11} and a few parts in 10^{23} are involved in two such experiments discussed here—which seek to balance against each other two quantities that are expected from existing theory to be equal. The magnitude of any inequality discovered sets clear limits to theory. A second kind of experiment seeks more accurate checks than are presently available for the three famous predictions of Einstein's theory of general relativity which ties gravitation to curved space—the gravity-induced red shift, bending of light, and precession of Mercury's orbit. The third experimental approach has generated most industrial interest lately, because it seems to point to the possibilities—remote ones—of communication by gravity and of shielding against gravity. This approach assumes the existence of gravity waves analogous to electromagnetic radiation, as predicted by Einstein, and seeks to find them.—S.T.

■ There has been until recently what we might term a psychological lull in matters gravitational. Perhaps this was only to be expected after the early great labors in the long history of gravity studies. Our present ideas about it are most completely crystallized in Newton's law of universal gravitation and his three laws of motion, and in Einstein's theory of general relativity and its modern extensions (see "The Dynamics of Space-Time," page 11). Yet this lull would be easier for us to understand if the field really was "cleaned up" by these theoretical achievements. It is not, of course. In many fundamental respects gravitation still offers all the exploratory challenges of a field that's just beginning.

The feeble force called gravity

The nature of the challenge and the main barrier to possible rewards arises from the fact that gravity is the weakest force now known. The ratio of the gravitational force to the electrostatic force between a proton and an electron in an average atom is only about 5×10^{-40}. If the diminutive size of this number is hard to comprehend, here's another analogy that may help. The electrostatic force of repulsion between two electrons 5 meters apart—a scant 10^{-24} dynes—approximately equals the gravitational force exerted by the *entire* earth on one of the electrons. The extremely small magnitude of gravitational forces has led many technical people to feel that, while gravitation may be interesting from a philosophical standpoint, it's unimportant either theoretically or experimentally in work concerned with everyday phenomena. This feeling may be justified, of course. In fact, on a slightly more sophisticated level, application of the strong principle of equivalence seems at first to reinforce this point of view.

This principle tells us that the effects of gravitational forces on observations can be transformed away by making the observations in a laboratory framework that is properly accelerated. The best concrete example of this still is Einstein's original freely falling elevator in a gravity field, in which an experimenter and all his apparatus are placed. Since he and his apparatus fall with the same acceleration, gravitational effects apparently disappear from phenomena observed in the elevator. Gravitational forces, in other words, sometimes simulate inertial ones. From this it's easy to conclude that gravitation is of little or no concern.

This is probably too provincial a point of view. Our little laboratories are embedded in a large universe and thinking scientists can hardly ignore this external reality. The universal character of gravitation shows that it affects all matter, in ways we have yet fully to comprehend. For all we know now, gravitation may play a dominant role in determining ultimate particle structure. And our laboratories—freely falling or otherwise—may be tossing about on "gravitational waves" without our knowing it.

Gravitational waves represent the energy which should be radiated from a source—any source—composed of masses undergoing accelerated motion with respect to each other. Such waves—if they exist as called for in Einstein's theory of general relativity—should exert forces on objects with mass, just as elastic waves do in passing through an elastic medium, or as ocean waves do when striking the shore. An athlete exercising with dumbbells or riding a bicycle, however, would radiate away an incredibly small amount of such energy. A pair of white dwarf stars, on the other hand, with a total mass roughly equal to that of the sun, and with each star rotating at enormous speed with respect to the other in a binary or double-star system, might radiate about 2×10^{37} ergs/sec of energy as gravitational waves. This is 5000 times the amount of energy contained in the sun's optical luminosity, and far from negligible if it occurs, but in order to decide whether gravity and gravitational waves are significant or not we must learn more about them. And to do this we must subject our most profound physical theories concerning them to critical scrutiny. The moment we do we find that these theories rest upon an exceedingly small number of significant experimental measurements, and that many of these measurements are of dubious precision.

Profound theories with shaky foundations

Einstein's theory of general relativity (usually abbreviated by physicists as GTR, to distinguish it from many other relativistic theories of gravitation) is, of course, the prime example. The key idea expressed by the theory, relating gravitation to a curvature of space, is an elegant one despite the tensor language which makes it difficult for many to understand. It reduces to the more generally comprehended Newtonian form in most cases where measurements can be made. And further contributions to its tacit acceptance by most present-day physicists have come from the experimental checks of Einstein's three famous predictions made on the basis of it: the gravitational redshift of light, the gravitational bending of light, and the precession of the perihelion of the orbit of the planet Mercury. We have in GTR a widely accepted theory, elegant beyond most others, based on very little *critical* evidence.

Strategy and tactics in experimentation

How can we remedy this lack? What can the earth-bound experimenter do to investigate the nature of gravitation? Most often, in view of the extreme weakness of the force, he will need to use as his power source astronomical bodies which have sufficiently strong gravitational fields. Instead of a laboratory experiment in which all of the significant variables are under his control, some or all of the effects he seeks may be associated with planetary systems, stars, galaxies, or the universe as a whole. Two examples of this approach (to which we'll return) are the Princeton group's recent refinement of the classic Eötvös experiment, which used the sun as a source of a gravitational field, and Weber's suggested study of elastic oscillations in the earth, on the idea that they may be caused by gravitational waves coming, perhaps, from an exploding supernova.

There are roughly three categories into which experiments on gravitation may be placed. First and most important are highly precise null experiments, such as the classic experiment devised by the Hungarian nobleman and physicist Baron von Eötvös. By balancing on a torsion balance the inertial forces arising from the earth's rotation against gravitational forces due to the earth's mass (Fig. 1-1) he was able to show to a precision of a few parts in 10^9 that all materials and masses fell with the same acceleration. This was an amazing accuracy for his day, and one that two of us (Roll and Dicke) have had to work hard for several years to improve by just two orders of magnitude! Null checks of this sort seek to balance against each other two quantities, which are expected from GTR to be equal or almost equal, in order to obtain an upper limit on the magnitude of any inequality and thus place clear limits on the applicability of the theory.

The second experimental category seeks to improve the accuracy of the three experimental verifications of the predictions of GTR mentioned above. These values can and should be improved as we'll show later. But limited as they are, they do provide valuable insights into the kind and number of fields associated with the all-pervading force called gravity.

The third class of experiments deals with gravitational radiation. In 1916 Einstein studied the approximate solutions of his gravitational-field equations and concluded that gravity waves ought to exist. But only recently has it become technologically possible even to attempt to detect the minute effects of such waves in the laboratory, as is being done by the Maryland group with equipment like that shown in Fig. 1-2.

What we've said so far suggests that experimental programs in gravity and relativity exist at only two places—Princeton and Maryland. That very nearly is the case. Miscellaneous experiments, some highly important, have of course been carried out elsewhere; we'll mention one of them later on. And the air in recent years has turned thick with glamorous proposals for "critical" one-shot experiments. But—to our knowledge—no other institutions in the world are following a consistent and continuing *experimental* program guided by the rigorous theoretical framework which guides our efforts.

The null-experiment program at Princeton, for instance, considers Einstein's GTR as only *one* theory in a large class of relativistic theories, any one of which can account for gravitational effects equally well with the limited, low-quality experimental evidence presently available. Our program aims at narrowing down possibilities in this large class.

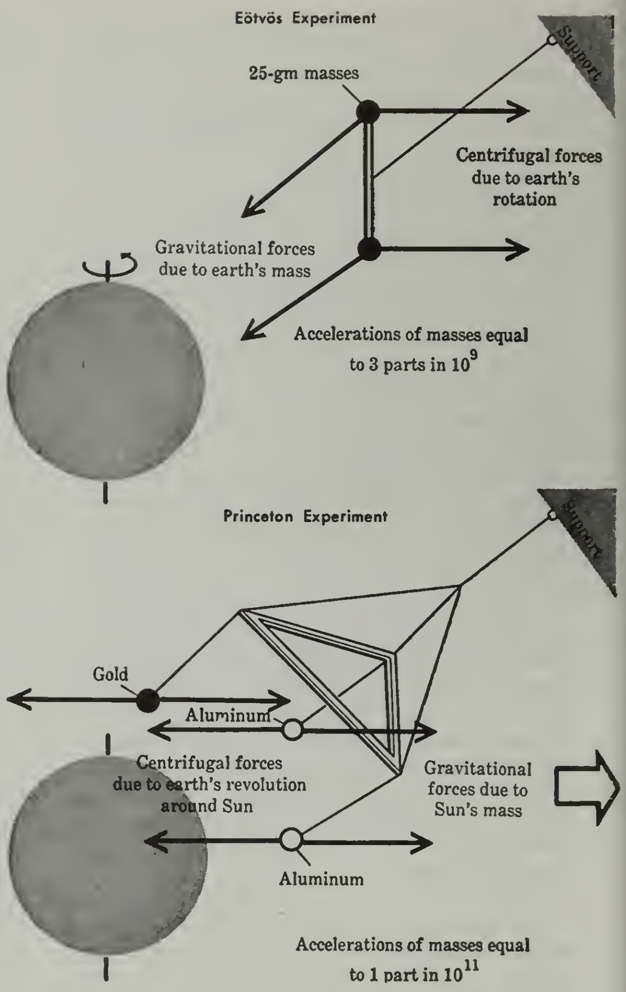

Fig. 1-1. The classic Eötvös experiment and the recent Princeton version of it that raised its accuracy two orders of magnitude, both shown above, prove that all masses fall with the same acceleration to within the accuracies achieved. This result is necessary—but not sufficient by itself—to validate the theory of general relativity which ascribes gravitational interactions to tensor field interactions in curved space.

What gravity seems to be

All relativistic requirements suggest that gravitational effects—like electromagnetic ones—are due to the interaction of matter with one or more of three kinds of classical field. (1) Matter could interact with a *scalar* field. Perhaps the most familiar such field is the sound field associated with fluctuations in air pressure. The air pressure itself is a scalar quantity, a number whose value at any point is independent of the coordinates used to label the point. (2) Matter could interact with a *vector* field. A familiar three-dimensional example of this is a flowing fluid, in which the streaming velocity at each point is a vector quantity. (3) Matter could interact with one or more *tensor* fields. The stress distribution in an elastic body is one example of a simple three-dimensional tensor field. The stress at any point in the body has no single value, but varies with the direction considered. For this reason we must specify six quantities to characterize the stress at each point. More exactly, the scalar, vector, and tensor fields which concern us are all in *four*-dimensional space, and

Fig. 1-2. Group at the University of Maryland hopes to detect oscillations in the gravitational field reaching earth—gravity waves—with the solid 1½-ton aluminum cylinder shown mounted in the hollow cylindrical vacuum chamber. Detection cylinder is 2 ft in diameter × 6 ft long, and is suspended on acoustic bricks to null out extraneous vibration. Wiring leads to piezo-electric quartz sensors embedded in detector, that convert its oscillations to voltages. The hope is that if gravity waves with frequencies near the natural frequency of the detector (1657 cps) impinge upon it, its natural frequency will be reinforced.

they cannot be as readily visualized as in these three-dimensional examples.

In the experimental effort at Princeton we hope to eliminate one or more of these four-dimensional fields—scalar, vector, and tensor—as possible contributors to gravitation. If we could demonstrate, for example, that all fields could be eliminated except a single tensor field with suitable properties, Einstein's GTR would receive strong support. As of this writing, null experiments which have been performed at Princeton and other places do seem to drastically narrow down the number of possible combinations of fields permitted by relativistic theories—and hence the possible theories themselves—to a smaller class which still includes the GTR. Vector fields of any appreciable strength, for example, can be excluded from the gravitational interaction by the Princeton Eötvös experiment. And the same experiment appears to exclude more than one scalar field from gravitational interactions. Arguments based upon another experiment, performed by Vernon Hughes and collaborators at Yale University, appear to exclude more than one tensor field from contributing to gravitational interactions.

Thus, by this unspectacular process of experimental elimination, gravitation is being increasingly revealed as primarily due to a single tensor field, as the GTR requires, although a substantial contribution from a scalar field, which some other relativistic theories permit, cannot yet be excluded.

Null experiments don't prove "nothin"

Of the various null experiments, perhaps the most important is the Eötvös experiment confirming that all masses and all materials have the same gravitational acceleration. A null result is necessary (but not sufficient) for GTR (and Newton's law of universal gravitation) to be valid. The most precise version of this experiment, completed recently at Princeton University (Figs. 1-1 and 1-3), showed that the acceleration toward the sun of test masses of gold and aluminum differs by no more than 1 part in 10^{11}, an improvement of two orders of magnitude over Eötvös' original experimental precision of 3 parts in 10^9.

The results of this experiment are highly significant for ascertaining that various forms of *energy* (which are related to the inertial mass of a body via Einstein's well-known formula $E = Mc^2$) are indeed equivalent to the gravitational *mass* of the body. (The gravitational mass is defined as that property of matter on which gravity acts.) To see this, consider the energy associated with the strong nuclear forces which bind the atomic nuclei of our gold and aluminum test masses against the disruptive effects of electrostatic repulsive forces. Nuclear binding energy makes up 11.0×10^{-3} of the total mass of a gold atom and 9.7×10^{-3} of the total mass of an aluminum atom. Hence, recalling the accuracy of 1 part in 10^{11} of the new Eötvös experiment, its result says that—to within about 1.3 parts in 10^8—the gravitational acceleration of the inertial mass (which is equivalent to nuclear binding energy) is the same as the gravitational acceleration of *all* the other mass-energy contributions to the total masses of gold and aluminum. The other contributions come from neutrons, protons, electrons, electrostatic energy, and other still smaller contributors to the total mass of an atom. Moreover, since gold and aluminum atoms differ not only in nuclear binding energy and total mass, but also in many other significant respects—such as total electron mass, electron binding energy, nuclear electrostatic energy, and energies concentrated in the electron-positron pair field surrounding the nucleus—similar arguments may be advanced to set small upper limits on any nonequivalence among *all* of these different forms of energy in their gravitational interactions.

So the Eötvös experiment establishes with considerable precision a different form of the principle of equivalence than the strong one we discussed earlier; it establishes a *weak* form which states that gravitational acceleration is the same for all important contributions to the mass-energy of a small body like an atomic nucleus.

But what of the strong version of this same principle, upon which GTR is founded? This requires that the form and numerical content of *all* physical laws be the same in all freely falling, nonrotating laboratories. The more precise null result of our Eötvös experiment verifies the *strong* principle of equivalence, too, for *strongly interacting* particles and fields such as the electro-magnetic and nuclear-force fields and their associated particles, positron-electron pairs, and pi mesons. But the experiment *fails* to verify the strong equivalence principle for interactions as weak as the universal Fermi interaction (involved in the beta decay of atomic nuclei) or the gravitational interaction itself.

Tactics of the Eötvös experiment

One of the fundamental differences between the Princeton experiment and that of Eötvös was our use of the gravitational acceleration toward the sun, balanced by the corresponding centrifugal acceleration due to revolution of the earth in orbit about the sun (Fig. 1-1, bottom). Although these accelerations are somewhat less than those which Eötvös used—his were due to the earth's mass and its rotation on its axis, remember—ours had the great advantage of appearing with a 24-hour period because, in effect, the sun moves around the earth once each day. Thus any gravitational anomalies on our torsion balance would have appeared with a sinusoidal 24-hour periodicity. By recording the rotation or torque on our balance remotely and continuously, then using a digital computer to analyze the record for a 24-hour periodicity with the proper phase, all of the extraneous effects which can produce small torques with other periods or the wrong phase could be discarded.

One additional difficulty with which Eötvös had to contend was the sensitivity of his torsion balance to gradients in the gravitational field, such as those produced by the good Baron himself sitting at the telescope. The Princeton experiment minimized such problems not only by remote observation (Fig. 1-3) but by making the torsion balance triangular in shape, with the two aluminum weights and one gold weight suspended from the corners of a triangular quartz frame. This threefold symmetry made it insensitive to nonuniformities in the gravitational field.

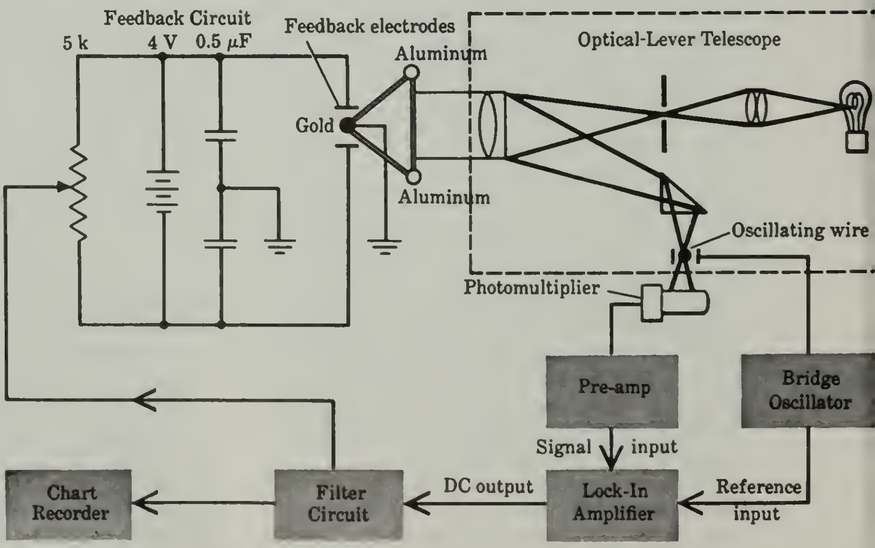

Fig. 1-3. The optical-lever system shown here was used to detect rotation of the triangular torsion balance used in Princeton version of the Eötvös experiment, shown in Fig. 1-1. Output of the detector had to be fed back to the torsion balance, through an appropriate filter network, in order to damp out long-period non-gravitational disturbances of the torsion balance caused by ground vibrations. Because balance was suspended in high-vacuum chamber (10^{-8} mm) there were no natural mechanisms to damp such extraneous oscillations in periods of time less than several months.

Our torsion balance evolved to its final form over a period of several years, and the final data were obtained between July 1962 and April 1963 in some 39 runs, lasting from 38 to 86 hours each. We could detect angular rotations of about 10^{-9} radians, corresponding to a torque of about 2.5×10^{-10} dyne cm, which in turn was 1×10^{-11} times the gravitational torque of the sun on one of the balance weights. As you may have discerned, we're rather proud of our results. They were not easy to get; but they buttress our fragile theoretical edifice a bit more firmly.

Arthur Clarke began to think seriously about space travel before almost anyone else. His conclusions, as seen in the article's very first sentence, are somewhat more pessimistic than are now fashionable.

18

Space The Unconquerable

Arthur C. Clarke

An excerpt from his book *Profiles on the Future—An Inquiry into the Limits of the Possible,* 1958.

Man will never conquer space. After all that has been said in the last two chapters, this statement sounds ludicrous. Yet it expresses a truth which our forefathers knew, which we have forgotten—and which our descendants must learn again, in heartbreak and loneliness.

Our age is in many ways unique, full of events and phenomena which never occurred before and can never happen again. They distort our thinking, making us believe that what is true now will be true forever, though perhaps on a larger scale. Because we have annihilated distance on this planet, we imagine that we can do it once again. The facts are far otherwise, and we will see them more clearly if we forget the present and turn our minds toward the past.

To our ancestors, the vastness of the Earth was a dominant fact controlling their thoughts and lives. In all earlier ages than ours, the world was wide indeed and no man could ever see more than a tiny fraction of its immensity. A few hundred miles—a thousand, at the most—was infinity. Great empires and cultures could flourish on the same continent, knowing nothing of each other's existence save fables and rumors faint as from a distant planet. When the pioneers and adventurers of the past left their homes in search of new lands, they said good-by forever to the places of their birth and the companions of their youth. Only a lifetime ago, parents waved farewell to their emigrating children in the virtual certainty that they would never meet again.

And now, within one incredible generation, all this has changed. Over the seas where Odysseus wandered for a decade, the Rome-Beirut *Comet* whispers its way within the hour. And above that, the closer satellites span the distance between Troy and Ithaca in less than a minute.

Psychologically as well as physically, there are no longer any remote places on Earth. When a friend leaves for what was once a far country, even if he has no intention of returning, we cannot feel that same sense of irrevocable separation that saddened our forefathers. We know that he is only hours away by jet liner, and that we have merely to reach for the telephone to hear his voice. And in a very few years, when the satellite communication network is established, we will be able to see friends on the far side of the Earth as easily as we talk to them on the other side of the town. Then the world will shrink no more, for it will have become a dimensionless point.

But the new stage that is opening up for the human drama will never shrink as the old one has done. We have abolished space here on the little Earth; we can never abolish the space that yawns between the stars. Once again, as in the days when Homer sang, we are face to face with immensity and must accept its grandeur and terror, its inspiring possibilities and its dreadful restraints. From a world that has become too small, we are moving out into one that will be forever too large, whose frontiers will recede from us always more swiftly than we can reach out toward them.

Consider first the fairly modest solar, or planetary, distances which we are now preparing to assault. The very first Lunik made a substantial impression upon them, traveling more than two hundred million miles from Earth—six times the distance to Mars. When we have harnessed nuclear energy for space flight, the solar system will contract until it is little larger than the

Earth today. The remotest of the planets will be perhaps no more than a week's travel from Earth, while Mars and Venus will be only a few hours away.

This achievement, which will be witnessed within a century, might appear to make even the solar system a comfortable, homely place, with such giant planets as Saturn and Jupiter playing much the same role in our thoughts as do Africa or Asia today. (Their qualitative differences of climate, atmosphere, and gravity, fundamental though they are, do not concern us at the moment.) To some extent this may be true, yet as soon as we pass beyond the orbit of the Moon, a mere quarter-million miles away, we will meet the first of the barriers that will sunder Earth from her scattered children.

The marvelous telephone and television network that will soon enmesh the whole world, making all men neighbors, cannot be extended into space. *It will never be possible to converse with anyone on another planet.*

Do not misunderstand this statement. Even with today's radio equipment, the problem of sending speech to the other planets is almost trivial. But the messages will take minutes—sometimes hours—on their journey, because radio and light waves travel at the same limited speed of 186,000 miles a second. Twenty years from now you will be able to listen to a friend on Mars, but the words you hear will have left his mouth at least three minutes earlier, and your reply will take a corresponding time to reach him. In such circumstances, an exchange of verbal messages is possible—but *not* a conversation. Even in the case of the nearby Moon, the two-and-a-half second time lag will be annoying. At distances of more than a million miles, it will be intolerable.

To a culture which has come to take instantaneous communication for granted, as part of the very structure of civilized life, this "time barrier" may have a profound psychological impact. It will be a perpetual reminder of universal laws and limitations against which not all our technology can ever prevail. For it seems as certain as anything can be that no signal—still less any material object—can ever travel faster than light.

The velocity of light is the ultimate speed limit, being part of the very structure of space and time. Within the narrow confines of the solar system, it will not handicap us too severely, once we have accepted the delays in communication which it involves. At the worst, these will amount to eleven hours—the time it takes a radio signal to span the orbit of Pluto, the outermost planet. Between the three inner worlds Earth, Mars, and Venus, it will never be more than twenty minutes—not enough to interfere seriously with commerce or administration, but more than sufficient to shatter those personal links of sound or vision that can give us a sense of direct contact with friends on Earth, wherever they may be.

It is when we move out beyond the confines of the solar system that we come face to face with an altogether new order of cosmic reality. Even today, many otherwise educated men—like those savages who can count to three but lump together all numbers beyond four—cannot grasp the profound distinction between *solar* and *stellar* space. The first is the space enclosing our neighboring worlds, the planets; the second is that which embraces those distant suns, the stars. *And it is literally millions of times greater.*

There is no such abrupt change of scale in terrestrial affairs. To obtain a mental picture of the distance to the nearest star, as compared with the distance to the nearest planet, you must imagine a world in which the closest object to you is only five feet away—and then there is nothing else to see until you have traveled a thousand miles.

Many conservative scientists, appalled by these cosmic gulfs, have denied that they can ever be crossed. Some people never learn; those who sixty years ago scoffed at the possibility of flight, and ten (even five!) years ago laughed at the idea of travel to the planets, are now quite sure that the stars will always be beyond our reach. And again they are wrong, for they have failed to grasp the great lesson of our age—that if something is possible in theory, and no fundamental scientific laws oppose its realization, then sooner or later it will be achieved.

One day—it may be in this century, or it may be a thousand years from now—we shall discover a really efficient means of propelling our space vehicles. Every technical device is always developed to its limit (unless it is superseded by something better) and the ultimate speed for spaceships is the velocity of light. They will never reach that goal, but they will get very close to it. And then the nearest star will be less than five years' voyaging from Earth.

Our exploring ships will spread outward from their home over an ever-expanding sphere of space. It is a sphere which will grow at almost—but never quite—the speed of light. Five years to the triple system of Alpha Centauri, ten to that strangely matched doublet Sirius A and B, eleven to the tantalizing enigma of 61 Cygni, the first star suspected of possessing a planet. These journeys are long, but they are not impossible. Man has always accepted whatever price was necessary for his explorations and discoveries, and the price of space is time.

Even voyages which may last for centuries or millenniums will one day be attempted. Suspended animation, an undoubted possibility, may be the key to interstellar travel. Self-contained cosmic arks which will be tiny traveling worlds in their own right may be another solution, for they would make possible journeys of unlimited extent, lasting generation after generation. The famous time dilation effect predicted by the theory of relativity, whereby time appears to pass more slowly for a traveler moving at almost the speed of light, may be yet a third.[1] And there are others.

With so many theoretical possibilities for interstellar flight, we can be sure that at least one will be realized in practice. Remember the history of the atomic bomb; there were three different ways in which it could be made, and no one knew which was best. So they were all tried—and they all worked.

Looking far into the future, therefore, we must picture a slow (little more than half a billion miles an hour!) expansion of human activities outward from the solar system, among the suns scattered across the region of the Galaxy in which we now find ourselves. These suns are on the average five light-years apart; in other words, we can never get from one to the next in less than five years.

To bring home what this means, let us use a down-to-earth analogy. Imagine a vast ocean, sprinkled with islands—some desert, others perhaps inhabited. On one of these islands an energetic race has just discovered the art of building ships. It is preparing to explore the ocean, but must face the fact that the very nearest island is five years' voyaging away, and that no possible improvement in the technique of shipbuilding will ever reduce this time.

In these circumstances (which are those in which we will soon find ourselves) what could the islanders achieve? After a few centuries, they might have established colonies on many of the nearby islands, and have briefly explored many others. The daughter colonies might themselves have sent out further pioneers, and so a kind of chain reaction would spread the original culture over a steadily expanding area of the ocean.

But now consider the effects of the inevitable, unavoidable time lag. There could be only the most tenuous contact between the home island and its offspring. Returning messengers could report what had happened on the nearest colony—five years ago. They could never bring information more up to date than that, and dispatches from the more distant parts of the ocean would be from still further in the past—perhaps centuries behind the times. There would never be news from the other islands, but only history.

No oceanic Alexander or Caesar could ever establish an empire beyond his own coral reef; he would be dead before his orders reached his governors. Any form of control or administration over other islands would be utterly impossible, and all parallels from our own history thus cease to have any meaning. It is for this reason that the popular science-fiction stories of interstellar empires and intrigues become pure fantasies, with no basis in reality. Try to imagine how the War of Independence would have gone if news of Bunker Hill had not arrived in England until Disraeli was Victoria's prime minister, and his urgent instructions on how to deal with the situation had reached America during President Eisenhower's second term. Stated in this way, the whole concept of interstellar administration or culture is seen to be an absurdity.

All the star-borne colonies of the future will be independent, whether they wish it or not. Their liberty will be inviolably protected by time as well as space. They must go their own way and achieve their own destiny, with no help or hindrance from Mother Earth.

At this point, we will move the discussion on to a new level and deal with an obvious objection. Can we be *sure* that the velocity of light is indeed a limiting factor? So many "impassable" barriers have been shattered in the past; perhaps this one may go the way of all the others.

We will not argue the point, or give the reasons scientists believe that light can never be outraced by any form of radiation or any material object. Instead, let us assume the contrary and see just where it gets us. We will even take the most optimistic possible case, and imagine that the speed of transportation may eventually become infinite.

Picture a time when, by the development of techniques as far beyond our present engineering as a transistor is beyond a stone ax, we can reach anywhere we please *instantaneously*, with no more effort than by dialing a number. This would indeed cut the universe down to size, and reduce its physical immensity to nothingness. What would be left?

Everything that really matters. For the universe has two aspects—its scale, and its overwhelming, mind-numbing complexity. Having abolished the first, we are now face-to-face with the second.

What we must now try to visualize is not size, but quantity. Most people today are familiar with the simple notation which scientists use to describe large numbers; it consists merely of counting zeros, so that a hundred becomes 10^2, a million, 10^6; a billion, 10^9 and so on. This useful trick enables us to work with quantities of any magnitude, and even defense budget totals look modest when expressed as $\$5.76 \times 10^9$ instead of \$5,760,000,000.

The number of other suns in our own Galaxy (that is, the whirlpool of stars and cosmic dust of which our Sun is an out-of-town member, lying in one of the remoter spiral arms) is estimated at about 10^{11}—or written in full, 100,000,000,000. Our present telescopes can observe something like 10^9 other galaxies, and they show no sign of thinning out even at the extreme limit of vision. There are probably at least as many galaxies in the whole of creation as there are stars in our own Galaxy, but let us confine ourselves to those we can see. They must contain a total of about 10^{11} times 10^9 stars, or 10^{20} stars altogether.

One followed by twenty other digits is, of course, a number beyond all understanding. There is no hope of ever coming to grips with it, but there are ways of hinting at its implications.

Just now we assumed that the time might come when we could dial ourselves, by some miracle of matter transmission, effortlessly and instantly round the cosmos, as today we call a number in our local exchange. What would the cosmic telephone directory look like if its contents were restricted to suns and it made no effort to list individual planets, still less the millions of places on each planet?

The directories for such cities as London and New York are already getting somewhat out of hand, but they list only about a million—10^6—numbers. The cosmic directory would be 10^{14}

times bigger, to hold its 10^{20} numbers. It would contain more pages than all the books *that have ever been produced since the invention of the printing press.*

To continue our fantasy a little further, here is another consequence of twenty-digit telephone numbers. Think of the possibilities of cosmic chaos, if dialing 27945015423811986385 instead of 27945015243811986385 could put you at the wrong end of Creation. . . . This is no trifling example; look well and carefully at these arrays of digits, savoring their weight and meaning, remembering that we may need every one of them to count the total tally of the stars, and even more to number their planets.

Before such numbers, even spirits brave enough to face the challenge of the light-years must quail. The detailed examination of all the grains of sand on all the beaches of the world is a far smaller task than the exploration of the universe.

And so we return to our opening statement. Space can be mapped and crossed and occupied without definable limit; but it can never be conquered. When our race has reached its ultimate achievements, and the stars themselves are scattered no more widely than the seed of Adam, even then we shall still be like ants crawling on the face of the Earth. The ants have covered the world, but have they conquered it—for what do their countless colonies know of it, or of each other?

So it will be with us as we spread outward from Mother Earth, loosening the bonds of kinship and understanding, hearing faint and belated rumors at second—or third—or thousandth-hand of an ever-dwindling fraction of the entire human race. Though Earth will try to keep in touch with her children, in the end all the efforts of her archivists and historians will be defeated by time and distance, and the sheer bulk of material. For the number of distinct societies or nations, when our race is twice its present age, may be far greater than the total number of all the men who have ever lived up to the present time.

We have left the realm of comprehension in our vain effort to grasp the scale of the universe; so it must always be, sooner rather than later.

When you are next out of doors on a summer night, turn your head toward the zenith. Almost vertically above you will be shining the brightest star of the northern skies—Vega of the Lyre, twenty-six years away at the speed of light, near enough the point-of-no-return for us short-lived creatures. Past this blue-white beacon, fifty times as brilliant as our sun, we may send our minds and bodies, but never our hearts.

For no man will ever turn homeward from beyond Vega to greet again those he knew and loved on Earth.

Many scientists have argued recently that intelligent life may be quite common in the universe. This work was originally written by Shklovskii, in Russian, and the "Annotations, additions, and discussions" which Sagan has added are bracketed by the symbols ▽ and △ .

19

Is There Intelligent Life Beyond the Earth?

I. S. Shklovskii and Carl Sagan

An excerpt from *Intelligent Life in the Universe,* 1966.

▽ In the last two chapters, we have seen that the prospects for interstellar communication over distances of some tens of light years seem reasonable; over hundreds of light years, more difficult; and over thousands of light years, only possibly by civilizations in substantial advance of our own. If it seemed likely that technical civilizations existed on planets only 10 or 20 light years away, or civilizations greatly in advance of our own, at larger distances, a serious effort to establish contact might be justified. On the other hand, if we can only reasonably expect civilizations at about our level of technical advance thousands of light years away, attempts at communication would not seem profitable, at least at the present time. In the present chapter, we shall make some effort to compute the number of extant technical civilizations in the Galaxy, which will permit us to estimate the average distances between civilizations. To perform such estimates, we must select numerical values for quantities which are extremely poorly known, such as the average lifetime of a technical civilization. The reliability of our answers will reflect this uncertainty. △ The analysis will have an exclusively probabilistic character, ▽ and the reader is invited to make his own estimate of the numerical values involved, and to draw his own conclusions on the numbers of advanced technical civilizations in the Galaxy. △ However, these analyses are of undoubted methodological interest and illustrate very well the potentialities and limitations of this type of investigation.

▽ We shall be concerned with two general approaches: first, a simple discussion due essentially to Frank Drake, and then a more elaborate treatment due to the German astronomer Sebastian von Hoerner, when he was working at the National Radio Astronomy Observatory, Green Bank, West Virginia.

▽ We desire to compute the number of extant Galactic communities which have attained a technical capability substantially in advance of our own. At the present rate of technological progress, we might picture this capability as several hundred years or more beyond our own stage of development. A simple method of computing this number, N, was discussed extensively at a conference on intelligent extraterrestrial life, held at the National Radio Astronomy Observatory in November, 1961, and sponsored by the Space Science Board of the National Academy of Sciences. Attending this meeting were D. W. Atchley, Melvin Calvin, Giuseppe Cocconi, Frank Drake, Su-Shu Huang, John C. Lilley, Philip M. Morrison, Bernard M. Oliver, J. P. T. Pearman, Carl Sagan, and Otto Struve. While the details differ in several respects, the following discussion is in substantial agreement with the conclusions of the conference.

▽ The number of extant advanced technical civilizations possessing both the interest and the capability for interstellar communication can be expressed as

$$N = R_* f_p n_e f_l f_i f_c L$$

R_* is the mean rate of star formation, averaged over the lifetime of the Galaxy; f_p is the fraction of stars with planetary systems; n_e is the mean number of planets in each planetary system with environments favorable for the origin of life; f_l is the fraction of such favorable planets on which life does develop; f_i is the fraction of such inhabited planets on which intelligent life with manipulative abilities arises during the lifetime of the local sun; f_c is the fraction of planets populated by intelligent beings on which an advanced technical civilization in the sense previously defined arises, during the lifetime of the local sun; and L is the lifetime of the technical civilization. We now proceed to discuss each parameter in turn.

▽ Since stars of solar mass or less have lifetimes on the main sequence comparable to the age of the Galaxy, it is not the present rate of star formation, but the mean rate of star formation during the age of the Galaxy which concerns us here. The number of known stars in the Galaxy is $\sim 10^{11}$, most of which have masses equal to or less than that of the Sun. The age of the Galaxy is $\sim 10^{10}$ years. Consequently, a first estimate for the mean rate of star formation would be ~ 10 stars yr^{-1}. The present rate of star formation is at least an order of magnitude less than this figure, and according to the Dutch-American astronomer Maarten Schmidt, of Mt. Wilson and Palomar Observatories, the rate of star formation in early Galactic history is possibly several orders of magnitude greater. According to present views of element synthesis in stars, discussed in Chapter 8, those stars and planets formed in the early history of the Galaxy must have been extremely poor in heavy elements. Technical civilizations developed on such ancient planets would of necessity be extremely different from our own. But in the flurry of early star formation, when the Galaxy was young, heavy elements must have been generated rapidly, and later generations of stars and planets would have had adequate endowments of the heavy elements. These very early systems should be subtracted, from our estimate of R_*. On the other hand, there are probably vast numbers of undetected low-mass stars whose inclusion will tend to increase our estimate of R_*. For present purposes, we adopt $R_* \sim 10$ stars yr^{-1}.

▽ From the frequencies of dark companions of nearby stars, from the argument on stellar rotation, and from contemporary theories of the origin of the solar system [see Chapters 11–13], we have seen that planets seem to be a very common, if not invariable, accompaniment to main sequence stars. We therefore adopt $f_p \sim 1$.

▽ In Chapter 11, we saw that even many multiple star systems may have planets in sufficiently stable orbits for the origin and development of life. In our own solar system, the number of planets which are favorably situated for the origin of life at some time or another is at least one, probably two, and possibly three or more [see Chapters 16, 19, 20, and 23]. We expect main sequence stars of approximately solar spectral type—say, between F2 and K5—to have a similar distribution of planets, and for such stars, we adopt $n_e \sim 1$. However, the bulk of the main sequence stars—well over 60 percent—are M stars; as we mentioned in

Chapter 24, if the planets of these suns are distributed with just the same spacings as the planets of our Sun, even the innermost will be too far from its local sun to be heated directly to temperatures which we would consider clement for the origin and evolution of life. However, it is entirely possible that such lower-luminosity stars were less able to clear their inner solar systems of nebular material from which the planets were formed early in their history. Further, the greenhouse effect in Jovian-type planets of M stars should produce quite reasonable temperatures. We therefore tentatively adopt for main sequence stars in general $n_e \sim 1$.

▽ In Chapters 14–17, we discussed the most recent work on the origin of life on Earth, which suggests that life arose very rapidly during the early history of the Earth. We discussed the hypothesis that the production of self-replicating molecular systems is a forced process which is bound to occur because of the physics and chemistry of primitive planetary environments. Such self-replicating systems, with some minimal control of their environments and situated in a medium filled with replication precursors, satisfy all the requirements for natural selection and biological evolution. Given sufficient time and an environment which is not entirely static, the evolution of complex organisms is, in this view, inevitable. The finding of even relatively simple life forms on Mars or other planets within our solar system would tend to confirm this hypothesis. In our own solar system, the origin of life has occurred at least once, and possibly two or more times. We adopt $f_l \sim 1$.

▽ The question of the evolution of intelligence is a difficult one. This is not a field which lends itself to laboratory experimentation, and the number of intelligent species available for study on Earth is limited. In Chapter 25, we alluded to some of the difficulties of this problem. Our technical civilization has been present for only a few billionths of geological time; yet it has arrived about midway in the lifetime of our Sun on the main sequence. The evolution of intelligence and manipulative abilities has resulted from the product of a large number of individually unlikely events. On the other hand, the adaptive value of intelligence and of manipulative ability is so great—at least until technical civilizations are developed—that if it is genetically feasible, natural selection seems likely to bring it forth.

▽ The American physiologist John C. Lilley, of the Communication Research Institute, Coral Gables, Florida, has argued that the dolphins and other cetacea have surprisingly high levels of intelligence. Their brains are almost as large as those of human beings. These brains are as convoluted as our brains, and their neural anatomy is remarkably similar to that of the primates, although the most recent common ancestor of the two groups lived more than 100 million years ago. Dolphins are capable of making a large number of sounds of great complexity, which are almost certainly used for communication with other dolphins. The most recent evidence suggests that they are capable of counting, and can mimic human speech. Large numbers of anecdotes supposedly illustrating great intelligence in the dolphins have been recorded, from the time of Pliny to the present. The detailed study of dolphin behavior and serious attempts to communicate with them are just beginning and hold out the possibility that some day we will be able to communicate, at least at a low level, with another intelligent species on our planet. Dolphins have very limited manipulative abilities, and despite their apparent level of intelligence, could not have developed a technical civilization. But their intelligence and communicativeness strongly suggest that these traits are not limited to the human species. With the expectation that the Earth is not unique as the abode of creatures with intelligence and manipulative abilities, but also allowing for the fact that apparently only one such species has developed so far in its history, and this only recently, we adopt $f_i \sim 10^{-1}$.

▽ The present technical civilization of the planet Earth can be traced from Mesopotamia to Southeastern Europe, to Western and Central Europe, and then to Eastern Europe and North America. Suppose that somewhere along the tortuous path of cultural history, an event had differed. Suppose Charles Martel had not stopped the Moors at Tours in 732 A.D. Suppose Ogdai had not died at Karakorum at the moment that Subutai's Mongol armies were entering Hungary and Austria, and that the Mongol invasion had swept through the non-forested regions of western Europe. Suppose the classical writings of Greek and Roman antiquity had not been preserved through the Middle Ages in African mosques and Irish monasteries. There are a thousand "supposes." Would Chinese civilization have developed a technical civilization if entirely insulated from the West? Would Aztec civilization have developed a technical phase had there been no *conquistadores?* Recorded history, even in mythological guise, covers less than 10^{-2} of the period in which the Earth has been inhabited by hominids, and less than about 10^{-5} of geological time. The same considerations are involved here as in the determination of f_i. The development of a technical civilization has high survival value at least up to a point; but in any given case, it depends on the concatenation of many improbable events, and it has occurred only recently in terrestrial history. It is unlikely that the Earth is very extraordinary in possessing a technical civilization, among planets already inhabited by intelligent beings. As before, over stellar evolutionary timescales, we adopt $f_c \sim 10^{-1}$.

▽ The multiplication of the preceding factors gives $N = 10 \times 1 \times 1 \times 1 \times 10^{-1} \times 10^{-1} \times L = 10^{-1} \times L$. L is the mean lifetime in years of a technical civilization possessing both the interest and the capability for interstellar communication. For the evaluation of L there is—fortunately for us, but unfortunately for the discussion—not even one known terrestrial example. The present technical civilization on Earth has reached the communicative phase (in the sense of high-gain directional antennas for the reception of extraterrestrial radio signals) only within the last few years. There is a sober possibility that L for Earth will be measured in decades. On the other hand, it is possible that international political differences will be permanently settled, and that L may be measured in geological time. It is conceivable that on other worlds, the resolution of national conflicts and the establishment of planetary governments are accomplished before weapons of mass destruction become available. We can imagine two extreme alternatives for the evaluation of L: (a) a technical civilization destroys itself soon after reaching the communicative phase (L less than 10^2 years); or (b) a technical civilization learns to live with itself soon after reaching the communicative phase. If it survives more than 10^2 years, it will be unlikely to destroy itself afterwards. In the latter case, its lifetime may be measured on a stellar evolutionary timescale (L much greater than 10^8 years). Such a society will exercise self-selection on its members. The slow, otherwise inexorable genetic changes which might in one of many ways make the individuals unsuited for a technical civilization could be controlled. The technology of such a society will certainly be adequate to cope with geological changes, although its origin is sensitively dependent on geology. Even the evolution of the local sun through the red giant and white dwarf evolutionary stages may not pose insuperable problems for the survival of an extremely advanced community.

▽ It seems improbable that surrounded by large numbers of flourishing and diverse galactic communities, a given advanced planetary civilization will retreat from the communicative phase. This is one reason that L itself depends on N. Von Hoerner has suggested another reason: He feels that the means of avoiding self-destruction will be among the primary contents of initial interstellar communications. If N is large, the values of f_l, f_i, and f_c may also be larger as a result. In Chapter 15, we mentioned the possibility of the conscious introduction of life into an otherwise sterile planet by interstellar space travelers. In Chapter 33, below, we shall discuss the possibility that such interstellar space travelers might also affect the value of f_c.

▽ Our two choices for L— $< 10^2$ years, and $>> 10^8$ years—lead to two values for N: less than ten communicative civilizations in the Galaxy; or many more than 10^7. In the former case, we might be the only extant civilization; in the latter case, the Galaxy is filled with them. The value of N depends very critically on our expectation for the lifetime of an average advanced community. It seems reasonable to me that at least a few percent of the advanced technical civilizations in the Galaxy do not destroy themselves, nor lose interest in interstellar communication, nor suffer insuperable biological or geological catastrophes, and that their lifetimes, therefore, are measured on stellar evolutionary timescales. As an average for all technical civilizations, both short-lived and long-lived, I adopt $L \sim 10^7$ years. This then yields as the average number of extant advanced technical civilizations in the Galaxy

$$N \sim 10^6.$$

Thus, approximately 0.001 percent of the stars in the sky will have a planet upon which an advanced civilization resides. The most probable distance to the nearest such community is then several hundred light years. (In the Space Science Board Conference on Intelligent Extraterrestrial Life, previously mentioned, the individual values of N selected lay between 10^4 and 10^9 civilizations. The corresponding range of distances to the nearest advanced community is then between ten and several thousands of light years.) △

The table on the facing page lists only those stars within twenty-two light years of the earth that have probabilities for the existence of planets which could support human life. The reader with astronomical interests should scan books on astronomy for a detailed explanation of most of the terminology used in this table.

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The Stars Within Twenty-Two Light Years That Could Have Habitable Planets

Stephen H. Dole

An excerpt from his book *Habitable Planets for Man,* 1964.

Name of star	Other designations	Right ascension, RA, 1900		Declination, 1900		Apparent visual magnitude		Parallax, π (sec)		Spectral class, Allen	Distance (light-years), Allen	Absolute visual magnitude, M_v, Allen	Adopted mass	Probability of habitable planet, P_{HP}
		(hours)	(minutes)	(degrees)	(minutes)	Allen	Boss	Allen	Boss					
α Centauri A	Rigel Kentaurus	14	32.8	−60	25	0.02[a]	0.33	0.754	0.756	G4	4.3	4.5	1.08	0.054 } 0.107
α Centauri B		14	32.8	−60	25	1.39[a]	1.70	0.754	0.760	K1	4.3	5.9	0.88	0.057
Lal 21185 (A)	BD + 36° 2147	10	57.9	+36	38	7.54	7.60	0.398	0.388	M2	8.2	10.51	0.37	(b)
ε Eridani		3	28.2	−9	48	4.2	3.81	0.303	0.305	K2	10.8	6.2	0.80	0.033
61 Cygni A		21	2.4	+38	15	5.29	5.57	0.293	0.299	K5	11.1	7.65	0.63	(b)
61 Cygni B		21	2.4	+38	15	6.06	6.28	0.293	0.299	K8	11.1	8.42	0.51	(b)
ε Indi		21	55.8	−57	12	4.7	4.74	0.288	0.288	K5	11.3	7.0	0.71	(b)
Grm 34 A	BD + 43° 44	0	12.7	+43	27	8.18	8.1	0.278	0.284	M2	11.7	10.44	0.38	(b)
Lac 9352	CD − 36° 15693	22	59.4	−36	26	7.2	7.44	0.273	0.278	M1	12.0	9.4	0.47	(b)
τ Ceti		1	39.4	−16	28	3.65	3.65	0.268	0.301	G8	12.2	6.02	0.82	0.036
Lac 8760	CD − 39° 14192	21	11.4	−39	15	6.65	6.65	0.258	0.257	M0	12.6	8.7	0.54	(b)
Cin 3161	CD − 37° 15492	23	59.5	−37	51	8.6	8.57	0.219	0.222	M3	14.9	10.3	0.39	(b)
Grm 1618	BD + 50° 1725	10	5.3	+49	57	6.75	6.82	0.219	0.218	K8	14.9	8.45	0.56	(b)
CC 1290	− 49° 13515	21	26.9	−49	26	8.6	. . .	0.212	. . .	M3	15.4	10.5	0.37	(b)
Cin 18,2354	+ 68° 946	17	37.0	+68	26	9.15	9.5	0.203	0.212	M3	16.1	10.75	0.35	(b)
+15° 2620	HD 119850	13	40.7	+15	26	8.58	8.5	0.193	0.191	M1	16.9	10.0	0.42	(b)
70 Ophiuchi A		18	0.4	+2	31	4.19	4.23	0.188	0.196	K1	17.3	5.7	0.90	0.057
70 Ophiuchi B		18	0.4	+2	31	5.87	6.23	0.188	0.196	K5	17.3	7.3	0.65	(b)
η Cassiopeiae A		0	43.0	+57	17	3.54	3.64	0.181	0.182	F9	18.0	4.87	0.94	0.057
η Cassiopeiae B		0	43.0	+57	17	7.4	. . .	0.181	. . .	K6	18.0	8.7	0.58	(b)
σ Draconis		19	32.6	+69	29	4.72	4.78	0.179	0.181	G9	18.2	6.01	0.82	0.036
36 Ophiuchi A		17	9.2	−26	27	5.17	. . .	0.179	0.178	K2	18.2	6.4	0.77	0.023 } 0.042
36 Ophiuchi B		17	9.2	−26	27	5.20	. . .	0.179	0.178	K1	18.2	6.5	0.76	0.0195
36 Ophiuchi C		17	9.2	−26	27	6.53	. . .	0.179	0.178	K6	18.2	7.8	0.63	(b)
HR 7703 A	HD 191408	20	4.6	−36	21	5.24	5.34	0.175	0.178	K2	18.6	6.5	0.76	0.0195
HR 5568 A	HD 131977	14	51.6	−20	58	5.90	5.76	0.174	0.172	K4	18.8	7.1	0.70	(b)
HR 5568 B	HD 131976	14	51.6	−20	58	8.08	8.87	0.174	0.172	M0	18.8	9.2	0.50	(b)
δ Pavonis		19	58.9	−66	26	3.67	3.64	0.170	0.155	G7	19.2	4.9	0.98	0.057
−21° 1377		6	6.4	−21	49	8.3	. . .	0.170	. . .	M0	19.2	9.6	0.455	(b)
+44° 2051 A	Lal 21258	11	0.5	+44	2	8.7	8.8	0.170	0.175	M0	19.2	9.9	0.43	(b)
+4° 4048 (A)		19	12.1	+5	2	9.18	. . .	0.168	. . .	M3	19.4	10.33	0.39	(b)
HD 36395	−3° 1123	5	26.4	−3	42	7.96	8.4	0.163	0.168	M1	20.0	9.06	0.51	(b)
+1° 4774	Lal 46650	23	44.0	+1	52	9.05	8.8	0.161	0.164	M2	20.2	10.18	0.40	(b)
+53° 1320		9	7.6	+53	7	7.90	. . .	0.161	. . .	K7	20.2	8.9	0.52	(b)
+53° 1321		9	7.6	+53	7	8.01	. . .	0.161	. . .	K9	20.2	9.0	0.51	(b)
−45° 13677		20	6.7	−45	28	8.4	. . .	0.158	. . .	M0	20.6	9.4	0.48	(b)
82 Eridani		3	15.9	−43	27	4.3	4.30	0.156	0.159	G5	20.9	5.3	0.91	0.057
β Hydri		0	20.5	−77	49	2.9	2.90	0.153	0.144	G1	21.3	3.8	1.23	0.037
HR 8832		23	8.5	+56	37	5.67	5.65	0.152	0.146	K3	21.4	6.69	0.74	0.011
+15° 4733		22	51.8	+16	2	8.69	. . .	0.150	. . .	M2	21.8	9.72	0.445	(b)
p Eridani A		1	36.0	−56	42	6.1	6.00	0.148	0.163	K2	22.0	7.0	0.71	(b)
p Eridani B		1	36.0	−56	42	6.1	6.03	0.148	0.163	K2	22.0	7.1	0.70	(b)
HR 753 A		2	30.6	+6	25	5.94	5.92	0.148	0.144	K3	22.0	6.79	0.725	0.004
														Net 0.434

Note: Lal—*Lalande's Star Catalogue* (1837); BD—*Bonner Durchmusterung*; Grm—*Groombridge's Catalogue of Circumpolar Stars*; Lac—*Lacaille's Catalogue* (1847); CD—*Cordoba Durchmusterung* (1886); HD—*Henry Draper Catalogue* (1918–1924); HR—*Revised Harvard Photometry* (1908).

[a] van de Kamp (1958) gives $m_{v_A} = 0.09$, $m_{v_B} = 1.38$.

[b] Very small; less than 0.001.

The evidence concerning Unidentified Flying Objects is carefully examined in this government-sponsored study.

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Scientific Study of Unidentified Flying Objects

Edward U. Condon and Walter Sullivan

An excerpt from this title based on the work of a government-sponsored research project, 1969.

INTRODUCTION

If, as many people suspect, our planet is being visited clandestinely by spacecraft, manned or controlled by intelligent creatures from another world, it is the most momentous development in human history.

Opinion surveys indicate that several million Americans believe they have seen objects that could be described as unidentified flying objects (UFOs), or "flying saucers." What, in fact, have they seen?

It appears that the Central Intelligence Agency, in 1953, was party to a scheme to "debunk" the UFOs. (The previously-secret document relating to this proposal is Appendix U in this book.) Has the government, in fact, been aware for some years that earth was under surveillance and has there been an effort to avoid panic by concealing the fact?

Or has the Air Force, in fulfilling its responsibility to deny our skies to hostile vehicles, been too lax to recognize the threat? Project Blue Book, the Air Force office responsible for assembling UFO reports at Wright-Patterson Air Force Base near Dayton, Ohio, is a low-priority operation, long manned by one officer, a sergeant and secretary.

In 1966 rumblings of discontent, both on Capitol Hill and among the public at large, led the Air Force to seek an independent assessment of the situation. It was a remarkable fact that, despite the enormous public interest in UFOs, the big guns of science had never been brought to bear on the problem.

Now for the first time a full-fledged scientific study has been carried out. Over a two-year period hundreds of cases were investigated. Case studies on 59 of the most important or most representative are presented in this report. Of these, ten relate to incidents that occurred before the project but were sufficiently well documented to merit pursuit.

A number of alleged UFO photographs have been analyzed in depth, with measurements being made at the scenes where the photographs were taken and of the film itself. Some have been explained, but at least one, showing a disk-shaped object in flight over Oregon, (plates 23 through 26), is classed as difficult to explain in a conventional way.

The study, at a cost of about half a million dollars, was carried out by the University of Colorado under the direction of Dr. Edward U. Condon. He was clearly chosen, not only because of his scientific eminence, but because of his unquestionable independence. He has served as President of the American Association for the Advancement of Science, the American Physical Society and as head of the National Bureau of Standards. The latter operated a complex of laboratories in Boulder, home of the University of Colorado. They now come under the recently-created Environmental Science Services Administration. Also in Boulder, on a mesa overlooking the town, is the National Center for Atmospheric Research. These centers offered Dr. Condon a wide range of experts in many fields of science.

Dr. Condon has the build of a football halfback. In his mid-sixties, he is a bit old for the game. Nevertheless, as the reader will see in this report, he has a tendency in scientific matters to lower his knowledgeable head and charge the line.

His independence has been many times demonstrated in his support of liberal (and sometimes unpopular) causes. He was one of the few who tangled with the House Committee on Un-American Activities and, to all intents and purposes, came out on top. Richard M. Nixon was associated with attempts to challenge his security clearance, and early in 1969 the Air Force, mindful that little love was lost between the two men, clearly wanted to get the Condon Report out of the way before Nixon became President.

The report concludes that there is no evidence to justify a belief that extraterrestrial visitors have penetrated our skies and not enough evidence to warrant any further scientific investigation. As Condon himself anticipated, this will not gladden UFO enthusiasts. There is no question but that a great many people want to believe the extraterrestrial hypothesis.

Why they do so is beyond the scope of the report—or this introduction. The feeling has been attributed to a hope that some sort of superior beings are watching over our world, prepared to intervene if things get too bad. Some people, too, are suspicious of "The Establishment" or resentful of what seems to them arrogant disregard by scientists of "evidence" for the existence of UFOs.

Although people have been reporting "flying saucers" for more than 20 years, there has been no machinery for bringing to bear on such sightings the many techniques for objective analysis available to modern science. When a citizen saw a UFO he tended to call the police who, in many cases, had no idea what to do about it. Those who knew that the nearest Air Force base was responsible for investigating such reported intrusions into American air space often found that the man at the base assigned to such duty was preoccupied with other tasks.

Some private organizations of concerned citizens, notably the National Investigations Committee for Aerial Phenomena (NICAP) and the Aerial Phenomena Research Organization (APRO) did the best they could. However, their resources were limited and they were handicapped, particularly in their dealings with government agencies, by their unofficial status and the fact that their membership consisted largely of people sympathetic to the view that UFOs may be controlled by an alien civilization (the so-called ETI, or Extra-Terrestrial Intelligence, hypothesis).

For the University of Colorado study, experts in radar, in plasma physics, in mirages, in photographic analysis and problems of perception were called in. Upon receipt of a promising UFO report scientists armed with a variety of observational tools flew to the scene, in some cases to witness the phenomena themselves.

The result has been a series of case histories that reads like a modern, real-life collection of Sherlock Holmes episodes. The cases range from the eerily perplexing to the preposterously naive. The reader is given a taste of the scientific method, even though the cases are often such that they defy anything approaching deductive analysis.

The reader can also exercise his own judgment by comparing this report with efforts to dispute it. For example a book has been published by a former member of the University of Colorado project who was dismissed. He and his co-author argue that the project may have been organized—without the knowledge of most of its staff—as a cover to divert attention from the real nature of UFOs.

He supports this conspiracy hypothesis with what he considers evidence that two members of a panel of top scientists convened by the government in 1953 to assess the UFO situation refused to sign the resulting report. That report found there was no threat to the nation in the UFOs and urged that they be stripped of their "aura of mystery." The panel feared that an enemy could exploit the tendency of the public toward hysterical behavior through "clogging of channels of communication by irrelevant reports." Real indications of hostile action would then be ignored.

The chairman of the panel was Dr. H. P. Robertson of the California Institute of Technology. According to surviving members of the panel no one dissented from its findings, although the name of one member was deleted before the report was declassified in 1966. The time was one of sensitivity about involvement of the Central Intelligence Agency in activities beyond its intelligence-gathering role and all references to the CIA's role in the panel's work, as well as names of its employees and others involved in intelligence work, were deleted.

Apart from these deletions, this document (Appendix U), like all other aspects of this report, is uncensored. Some of the documents presented here, as well as many of the UFO episodes, are offered to the public for the first time.

Despite the efforts of some UFO enthusiasts to discredit the report in advance, a panel of the nation's most eminent scientists, chosen by the prestigious National Academy of Sciences, has examined it, chapter by chapter, and given it "straight As," so to speak.

This "grading" of the report was performed at the request of the Air Force, which foresaw charges of "whitewash" if—as it earnestly expected—the Colorado study echoed earlier findings that even the most mysterious UFOs have not been shown to be of exotic origin.

Concurrence by the Academy, representing the nation's most distinguished scientists, would help divert such criticism. It was understood originally that the Academy panel would be asked merely to assess the working methods of the Colorado team, rather than to endorse its conclusions, but the panel went further than that. It expressed clear-cut agreement with the findings.

"We are unanimous in the opinion," the panel said, "that this has been a very creditable effort to apply objectively the relevant techniques of science to the solution of the UFO problem. The report recognizes that there remain UFO sightings that are not easily explained. The report does suggest, however, so many reasonable and possible directions in which an explanation may eventually be found, that there seems to be no reason to attribute them to an extraterrestrial source without evidence that is much more convincing. The report also shows how difficult it is to apply scientific methods to the occasional transient sightings with any chance of success. While further study of particular aspects of the topic (e.g., atmospheric phenomena) may be useful, a study of UFOs in general is not a promising way to expand scientific understanding of the phenomena. On the basis of present knowledge the least likely explanation of UFOs is the hypothesis of extraterrestrial visitations by intelligent beings."

The Chairman of this panel was Dr. Gerald M. Clemence of Yale University, former Scientific Director of the United States Naval Observatory. The others included leading specialists in fields relevant to the UFO problem—astronomy, atmospheric physics, meteorology and psychology. They were:

Dr. Horace R. Crane, Professor of Physics, University of Michigan.

Dr. David M. Dennison, Professor of Physics, University of Michigan.

Dr. Wallace O. Fenn, physiologist and former Director of the Space Science Center at the University of Rochester.

Dr. H. Keffer Hartline, biophysicist, Professor at Rockefeller University and 1967 co-winner of the Nobel Prize in medicine and physiology.

Dr. Ernest R. Hilgard, Professor of Psychology at Stanford University.

Dr. Mark Kac, mathematician, Professor at Rockefeller University.

Dr. Francis W. Reichelderfer, former head of the United States Weather Bureau.

Dr. William W. Rubey, Professor of Geology and Geophysics at the University of California at Los Angeles.

Dr. Charles D. Shane, Emeritus Astronomer at the Lick Observatory in California.

Dr. Oswald G. Villard, Jr., Director of the Radio Science Laboratory, Stanford University.

The panel did a certain amount of homework, in addition to reviewing the Colorado report. It read scientific papers prepared by outspoken scientific protagonists on both sides of the controversy. Two of these, Dr. William Markowitz, former head of the time service at the Naval Observatory, and Dr. Donald H. Menzel, former director of the Harvard College Observatory, have scoffed at the extraterrestrial hypothesis. Another author, Dr. James E. McDonald of the University of Arizona, has argued that UFOs are one of the biggest scientific puzzles of our time and that visitations from afar are the best explanation for UFOs that cannot otherwise be explained.

In forwarding the panel's assessment to the Air Force Dr. Frederick Seitz, President of the Academy, said: "Substantial questions have been raised as to the adequacy of our research and investigation programs to explain or to determine the nature of these sometimes puzzling reports of observed phenomena. It is my hope that the Colorado report, together with our panel review, will be helpful to you and other responsible officials in determining the nature and scope of any continuing research effort in this area."

The panel report was copyrighted to prevent its appearance in unauthorized publications. The review was done, Dr. Seitz said, "for the sole purpose of assisting the government in reaching a decision on its future course of action. Its use in whole or in part for any other purpose would be incompatible with the purpose of the review and the conditions under which it was conducted."

Apparently the Academy and its panel members did not want their review to appear between the covers of some of the more far-out UFO books. However, the review was distributed to the press on January 8, 1969, with the Colorado report itself, for release the next day.

The report is a memorable document. While the case histories read like detective stories, it is also a scientific study. There are sections here and there that most readers will find technical and difficult to follow. They are easily skipped. However, in the technical sections there are also nuggets that no one will want to miss. For example in Chapter 7, on atmospheric electricity and plasma interpretations of UFOs, there are accounts of collisions of Soviet and American aircraft with a peculiar phenomenon known as ball lightning, as well as a description of the extraordinary behavior of lightning inside a tornado. Also of special interest is the section describing UFOs observed by astronauts (all presumably man-made objects in earth orbit).

Efforts have been made by UFO enthusiasts to blunt the effect of this report by arguing that Dr. Condon and his colleagues were too biased for a meaningful finding. These attempts to discredit the report have concentrated in large measure on an episode that occurred when much of the on-the-spot investigation had been done.

Early in the project things seemed to be going smoothly. The two largest quasi-scientific organizations of UFO "buffs" cooperated by tipping off the Colorado project to new sightings. They also made available samples from their files of interviews, photographs and the like.

Then, however, a certain amount of infighting developed. One of the UFO groups, NICAP, is headed by Donald Keyhoe who, as author of *Flying Saucers Are Real,* has a vested interest in the confirmation of his thesis. Various statements attributed to Dr. Condon suggested to NICAP that he did not take very seriously the possibility that UFOs come from another civilization.

In this respect it should be pointed out that Dr. Condon is a somewhat garrulous soul who loves to spin a good yarn. The inquiry into UFOs was a rich source of such material and he found it hard, on various occasions, not to recount some of the sillier episodes.

This infuriated those, like Dr. McDonald at the University of Arizona, who believed in the possibility of an extraterrestrial origin. They charged that the Colorado project was wasting its time on crackpot reports and turning its back on the more solid evidence. Anyone who reads the following pages will see that this is untrue. It is obvious that the project concentrated on the best documented and most substantial cases and it did not hesitate to conclude that, on the basis of available evidence, some are difficult to explain by conventional means.

The most severe blow to the project came when one of its staff members, going through the files, came across a memorandum written by Robert J. Low before the University undertook the project. Low, who was serving as project coordinator, had been an assistant dean in the graduate school. His memo, to University officials, sought to analyze the pros and cons of the Air Force proposal. Could the University undertake the project in a manner that would satisfy public concern, yet not subject the University to ridicule by the academic community? He argued that the study would perforce be done almost entirely by nonbelievers and, while the project could never "prove" that no UFOs have ever come from another world, it could contribute impressive evidence for such a conclusion. "The trick," he wrote, "would be, I think, to describe the project so that, to the public, it would appear a totally objective study but, to the scientific community, would present the image of a group of nonbelievers trying their best to be objective, but having an almost zero expectation of finding a saucer."

He proposed, to this end, that the emphasis be on the psychological and sociological investigation of those reporting UFOs, rather than on checking out the physical evidence for alleged visitations.

Condon apparently never saw this memo at the time it was written and, in fact, rejected suggestions that the emphasis be on the psychology of UFO witnesses. As the case histories in this report show, the stress was on the search for physical evidence and physical explanations. However, the Low memo fell into the hands of Dr. McDonald and of NICAP. It was brought to the attention of John G. Fuller, author of two books *(Incident at Exeter* and *Interrupted Journey)* supporting the extraterrestrial explanation for UFOs. In an article in *Look* magazine, which had published parts of his two books, Fuller quoted the memo and reported dissension among staff members of the Colorado project. His article was entitled "Flying Saucer Fiasco," with the subtitle: "The Extraordinary Story of the Half-Million-Dollar 'Trick' to Make Americans Believe the Condon Committee Was Conducting an Objective Investigation."

Two men whom Condon considered responsible for leaking the memo to disgruntled UFO believers were discharged from the project.

In exploring possible roots of this controversy the journal *Science* quoted a statement by James and Coral Lorenzen, who run the Aerial Phenomena Research Organization (APRO) in Tucson, Arizona, which rivals NICAP as a comparatively sober association of UFO buffs. They suggested that there was "a strong attempt by the NICAP group (McDonald and Saunders are both close to NICAP) to control the study. When they found they couldn't control it, they attempted to scuttle it."

Whatever the merits of this analysis, the Condon Report and the challenges to it must stand or fall on their own merits —not on the degree of squabbling that may, or may not have occurred in its preparation. That Condon, an old scientific pro, was well aware of this shines forth from the pages of this document.

There is probably no such thing as a scientific researcher without bias. It is rare indeed for someone to undertake an experiment with no inkling as to its outcome. More commonly the scientist has formulated a hypothesis and he carries out a series of experiments that, he hopes, will convince himself— and all the world—of its correctness. Those experiments, to assure him of a place in scientific history, must, insofar as possible, be such that any other scientist can confirm his results.

The extent to which such tests can be applied to UFOs is limited. More often, as the case histories show, the judgement must be based on common sense. If, for example, it can be shown that a UFO photograph could have been faked, and if the story told by the person who took the picture displays suspicious inconsistencies, then Condon and his colleagues have tended to reject the picture as evidence. Those inclined to be believers might be more willing to accept the picture as genuine, but they could not use it as "proof" of the extraterrestrial hypothesis.

A reading of the case histories in this report forces on the reader a certain humility regarding human perception. We do not see only with our eyes and hear only with our ears. We see and hear with that complex and little-understood organ, the brain, crammed with memories and earlier impressions.

It is the ingenuity of this brain that enables us to read fast or recognize a friend at a glance. If we had to read every letter of every word, or had to scrutinize the entire physiognomy of a person to recognize him, the pace of our lives would be slow indeed. Instead we have learned to deduce entire words or phrases and entire people from a limited number of observed clues.

However, when the circumstances are unusual we can easily be fooled by misleading clues. Nicolaas Tinbergen, Professor of Animal Behavior at Oxford and a founder of the young science of ethology (the study of animal behavior in the wild), told me of a personal experience that illustrates this.

In east Greenland he was once atop a mountain a number of miles inland. Offshore wind had blown the pack ice beyond the horizon some days earlier and now, to his horror, he saw the distant sea in violent motion. Giant waves were racing toward shore. "We must get down off the mountain," he told his Eskimo companion excitedly. "That gale could hit any minute and blow us off the mountain!"

Then suddenly the motion of the sea stopped as though a moving picture had been brought to a halt. This occurred at the moment when his mind realized that he was looking at pack ice that had blown back onshore, not at waves. The motion was a fiction of his brain.

It was not many generations ago that ghosts seemed plausible, and night visions, be they wisps of luminous gas rising from a swamp, or play of moonlight on a blowing curtain, could raise palpitations in the most stalwart heart. Today, if one hears a creak in the night or sees a peculiar glow, the usual reaction is to investigate, rather than duck under the covers. However, UFOs are often too far away for such intimate checking.

This report, in showing the fallibility of even such sober observers as policemen, airline pilots and radar operators, raises questions as to the role of conditioning in many other fields of human activity. The purveyors of advertising are well versed in the techniques of conditioning, but one wonders to what extent this phenomenon affects such basic attitudes as our nationalism, our theological point of view and our moral standards.

Are they really founded on logic and the ultimate truth?

One cannot help but view our points of view on a great many things with new skepticism.

Anyone who reads this study will, I believe, lay it down with a new perspective on human values and limitations.

Walter Sullivan

Section I

CONCLUSIONS AND RECOMMENDATIONS

Edward U. Condon

We believe that the existing record and the results of the Scientific Study of Unidentified Flying Objects of the University of Colorado, which are presented in detail in subsequent sections of this report, support the conclusions and recommendations which follow.

As indicated by its title, the emphasis of this study has been on attempting to learn from UFO reports anything that could be considered as adding to scientific knowledge. Our general conclusion is that nothing has come from the study of UFOs in the past 21 years that has added to scientific knowledge. Careful consideration of the record as it is available to us leads us to conclude that further extensive study of UFOs probably cannot be justified in the expectation that science will be advanced thereby.

It has been argued that this lack of contribution to science is due to the fact that very little scientific effort has been put on the subject. We do not agree. We feel that the reason that there has been very little scientific study of the subject is that those scientists who are most directly concerned, astronomers, atmospheric physicists, chemists, and psychologists, having had ample opportunity to look into the matter, have individually decided that UFO phenomena do not offer a fruitful field in which to look for major scientific discoveries.

This conclusion is so important, and the public seems in general to have so little understanding of how scientists work, that some more comment on it seems desirable. Each person who sets out to make a career of scientific research, chooses a general field of broad specialization in which to acquire proficiency. Within that field he looks for specific fields in which to work. To do this he keeps abreast of the published scientific literature, attends scientific meetings, where reports on current progress are given, and energetically discusses his interests and those of his colleagues both face-to-face and by correspondence with them. He is motivated by an active curiosity about nature and by a personal desire to make a contribution to science. He is constantly probing for error and incompleteness in the efforts that have been made in his fields of interest, and looking for new ideas about new ways to attack new problems. From this effort he arrives at personal decisions as to where his own effort can be most fruitful. These decisions are personal in the sense that he must estimate his own intellectual limitations, and the limitations inherent in the working situation in which he finds himself, including limits on the support of his work, or his involvement with other pre-existing scientific commitments. While individual errors of judgment may arise, it is generally not true that all of the scientists who are actively cultivating a given field of science are wrong for very long.

Even conceding that the entire body of "official" science might be in error for a time, we believe that there is no better way to correct error than to give free reign to the ideas of individual scientists to make decisions as to the directions in which scientific progress is most likely to be made. For legal work sensible people seek an attorney, and for medical treatment sensible people seek a qualified physician. The nation's surest guarantee of scientific excellence is to leave the decision-making process to the individual and collective judgment of its scientists.

Scientists are no respecters of authority. Our conclusion that study of UFO reports is not likely to advance science will not be uncritically accepted by them. Nor should it be, nor do we wish it to be. For scientists, it is our hope that the detailed analytical presentation of what we were able to do, and of what we were unable to do, will assist them in deciding whether or not they agree with our conclusions. Our hope is that the details of this report will help other scientists in seeing what the problems are and the difficulties of coping with them.

If they agree with our conclusions, they will turn their valuable attention and talents elsewhere. If they disagree it will be because our report has helped them reach a clear picture of wherein existing studies are faulty or incomplete and thereby will have stimulated ideas for more accurate studies. If they do get such ideas and can formulate them clearly, we have no doubt that support will be forthcoming to carry on with such clearly-defined, specific studies. We think that such ideas for work should be supported.

Some readers may think that we have now wandered into a contradiction. Earlier we said that we do not think study of UFO reports is likely to be a fruitful direction of scientific advance; now we have just said that persons with good ideas for specific studies in this field should be supported. This is no contradiction. Although we conclude after nearly two years of intensive study, that we do not see any fruitful lines of advance from the study of UFO reports, we believe that any scientist with adequate training and credentials who does come up with a clearly defined, specific proposal for study should be supported.

What we are saying here was said in a more general context nearly a century ago by William Kingdon Clifford, a great English mathematical physicist. In his "Aims and Instruments of Scientific Thought" he expressed himself this way:

> Remember, then, that [scientific thought] is the guide of action; that the truth which it arrives at is not that which we can ideally contemplate without error, but that which we may act upon without fear; and you cannot fail to see that scientific thought is not an accompaniment or condition of human progress, but human progress itself.

Just as individual scientists may make errors of judgment about fruitful directions for scientific effort, so also any individual administrator or committee which is charged with deciding on financial support for research proposals may also make an error of judgment. This possibility is minimized by the existence of parallel channels, for consideration by more than one group, of proposals for research projects. In the period since 1945, the federal government has evolved flexible and effective machinery for giving careful consideration to proposals from properly qualified scientists. What to some may seem like duplicated machinery actually acts as a safeguard against errors being made by some single official body. Even so, some errors could be made but the hazard is reduced nearly to zero.

Therefore we think that all of the agencies of the federal government, and the private foundations as well, ought to be willing to consider UFO research proposals along with the others submitted to them on an open-minded, unprejudiced basis. While we do not think at present that anything worthwhile is likely to come of such research each individual case ought to be carefully considered on its own merits.

This formulation carries with it the corollary that we do not think that at this time the federal government ought to set up a major new agency, as some have suggested, for the scientific study of UFOs. This conclusion may not be true for all time. If, by the progress of research based on new ideas in this field, it then appears worthwhile to create such an agency, the decision to do so may be taken at that time.

We find that there are important areas of atmospheric optics, including radio wave propagation, and of atmospheric electricity in which present knowledge is quite incomplete. These topics came to our attention in connection with the interpretation of some UFO reports, but they are also of fundamental scientific interest, and they are relevant to practical problems related to the improvement of safety of military and civilian flying.

Research efforts are being carried out in these areas by the Department of Defense, the Environmental Science Services Administration, the National Aeronautics and Space Administration, and by universities and nonprofit research organizations such as the National Center for Atmospheric Research, whose work is sponsored by the National Science Foundation. We commend these efforts. By no means should our lack of enthusiasm for study of UFO reports as such be misconstrued as a recommendation that these important related fields of scientific work not be adequately supported in the future. In an era of major development of air travel, of space exploration, and of military aerospace activities, everything possible should be done to improve our basic understanding of all atmospheric phenomena, and to improve the training of astronauts and aircraft pilots in the recognition and understanding of such phenomena.

As the reader of this report will readily judge, we have focussed attention almost entirely on the physical sciences. This was in part a matter of determining priorities and in part because we found rather less than some persons may have expected in the way of psychiatric problems related to belief in the reality of UFOs as craft from remote galactic or intergalactic civilizations. We believe that the rigorous study of the beliefs—unsupported by valid evidence—held by individuals and even by some groups might prove of scientific value to the social and behavioral sciences. There is no implication here that individual or group psychopathology is a principal area of study. Reports of UFOs offer interesting challenges to the student of cognitive processes as they are affected by individual and social variables. By this connection, we conclude that a content-analysis of press and television coverage of UFO reports might yield data of value both to the social scientist and the communications specialist. The lack of such a study in the present report is due to a judgment on our part that other areas of investigation were of much higher priority. We do not suggest, however, that the UFO phenomenon is, by its nature, more amenable to study in these disciplines than in the physical sciences. On the contrary, we conclude that the same specificity in proposed research in these areas is as desirable as it is in the physical sciences.

The question remains as to what, if anything, the federal government should do about the UFO reports it receives from the general public. We are inclined to think that nothing should be done with them in the expectation that they are going to contribute to the advance of science.

This question is inseparable from the question of the national defense interest of these reports. The history of the past 21 years has repeatedly led Air Force officers to the conclusion that none of the things seen, or thought to have been seen, which pass by the name of UFO reports, constituted any hazard or threat to national security.

We felt that it was out of our province to attempt an independent evaluation of this conclusion. We adopted the attitude that, without attempting to assume the defense responsibility which is that of the Air Force, if we came across any evidence whatever that seemed to us to indicate a defense hazard we would call it to the attention of the Air Force at once. We did not find any such evidence. We know of no reason to question the finding of the Air Force that the whole class of UFO reports so far considered does not pose a defense problem.

At the same time, however, the basis for reaching an opinion of this kind is that such reports have been given attention, one by one, as they are received. Had no attention whatever been given to any of them, we would not be in a position to feel confident of this conclusion. Therefore it seems that only so much attention to the subject should be given as the Department of Defense deems to be necessary strictly from a defense point of view. The level of effort should not be raised because of arguments that the subject has scientific importance, so far as present indications go.

It is our impression that the defense function could be performed within the framework established for intelligence and surveillance operations without the continuance of a special unit such as Project Blue Book, but this is a question for defense specialists rather than research scientists.

It has been contended that the subject has been shrouded in official secrecy. We conclude otherwise. We have no evidence of secrecy concerning UFO reports. What has been miscalled secrecy has been no more than an intelligent policy of delay in releasing data so that the public does not become confused by premature publication of incomplete studies of reports.

The subject of UFOs has been widely misrepresented to the public by a small number of individuals who have given sensationalized presentations in writings and public lectures. So far as we can judge, not many people have been misled by such irresponsible behavior, but whatever effect there has been has been bad.

A related problem to which we wish to direct public attention is the miseducation in our schools which arises from the fact that many children are being allowed, if not actively encouraged, to devote their science study time to the reading of UFO books and magazine articles of the type referred to in the preceding paragraph. We feel that children are educationally harmed by absorbing unsound and erroneous material as if it were scientifically well founded. Such study is harmful not merely because of the erroneous nature of the material itself, but also because such study retards the development of a critical faculty with regard to scientific evidence, which to some degree ought to be part of the education of every American.

Therefore we strongly recommend that teachers refrain from giving students credit for school work based on their reading of the presently available UFO books and magazine articles. Teachers who find their students strongly motivated in this direction should attempt to channel their interests in the direction of serious study of astronomy and meteorology, and in the direction of critical analysis of arguments for fantastic propositions that are being supported by appeals to fallacious reasoning or false data.

We hope that the results of our study will prove useful to scientists and those responsible for the formation of public policy generally in dealing with this problem which has now been with us for 21 years.

A noted woman astronomer discusses current knowledge, and lack of knowledge, concerning the evolution of galaxies. Dr. Burbidge concludes "It is difficult to understand in detail how one sort of galaxy can evolve into another, yet in a general way we know that it must happen."

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The Life-Story of a Galaxy

Margaret Burbidge

An excerpt from *Stars and Galaxies: Birth, Aging and Death in the Universe*, 1962.

A fairly coherent picture has been built up of the evolution and life-history of single stars; can we make such a coherent picture of the evolution or life-history of a galaxy? At the moment our success is not as clear-cut as in the case of the life-history of a star. For example, you have seen in Chapter VI that there can be opposite points of view about the radio stars; in one interpretation two galaxies are colliding; in the other, a single galaxy is splitting into two parts. At the moment, we have no physical theory or explanation which could fit this second suggestion. In fact, the whole problem of the probable course of evolution of a galaxy is more difficult and complex than for a star. This is not to say that we shall not solve it in the comparatively near future; after all, the evolution of stars was only poorly understood ten years ago. Since then most of the story (Chapters III and IV) has been put together, and who knows what the next ten years will bring to our understanding of the evolution of galaxies.

Chapter V describes the different kinds of galaxies that we see in the sky: spiral galaxies, irregular galaxies without much structure to them, and the smooth ones that we call elliptical galaxies. All these different kinds of galaxies are made up of three components—gas, dust, and stars. There is more gas and dust in irregulars and spirals than in the ellipticals, which have almost none. In trying to trace out the life-history of a galaxy, one way to begin is to look for a time sequence between these different kinds of galaxies. Might one kind of galaxy change into another? If so, which are younger? Which are older?

From Gas to Galaxy

In Chapter V two alternative cosmological theories were described. According to the "Big-Bang" Theory the universe was created at some definite time in the past; matter was then very much closer together in space. Somewhat later all the galaxies might have been formed at one time. By contrast, according to the "Steady-State" Theory, the universe has been about the same all along, and galaxies must be forming now. In either case it is likely that the material out of which the galaxies formed was originally all gas, containing no stars or dust, and spread more or less uniformly throughout space. If a gas is uniformly spread through space, it tends to "clot." If any little fluctuation takes place, one region by chance becoming a bit more dense than another, then the denser region tends to grow, attracting to itself more material by gravitational force. The clots would grow and might easily turn into galaxies.

On this basis, we shall sketch in quite general fashion what might be the life-history of a galaxy—not what can be proved, but what would be reasonable. Starting, then, with a gas spread uniformly throughout all space, fluctuations begin to form what we will call "proto-galaxies." At some stage there will be smaller fluctuations inside a proto-galaxy, and out of these smaller fluctuations stars could form. We will call these "first-generation stars"—the first stars to form in a galaxy—and the gas they formed from might have been pure hydrogen, according to the view that the chemical elements have been built up in the stars, as discussed in Chapter IV. The "Steady-State" Theory, of course, suggests that the gas was not *pure* hydrogen but had a slight mixture of heavier elements ejected from earlier generations of stars and galaxies that had always been around in space.

In either case, the gas that formed the first generation of stars in a new galaxy would have very little of the heavier elements.

It would be mostly hydrogen. From the early stages of a star's life discussed in Chapter IV, we know that the more massive a blob of matter that starts condensing, the faster it will contract under its own gravitation to form a star. During contraction, the gas becomes quite hot because of the release of gravitational energy as the gas falls in toward the center. Just as gravitational energy is released in the condensation of a star, so gravitational energy will be released in the formation of a galaxy; therefore the gas at an early stage in the proto-galaxy might be quite hot.

The Youth of a Galaxy

Because the large, hot, blue stars form rapidly, they will generally be imbedded in thinner gas that has not yet condensed into stars. The radiation from these hot stars would cause the gas they are imbedded in to shine quite brightly. Patches of glowing gas like this will show up very well in a galaxy and are seen in many irregular and spiral galaxies. This is the sort of situation we would expect in a young galaxy, and one that we see in the irregular galaxies shown in *Figures V-2* and *VII-1*. There is no pattern; an irregular galaxy is just an unorganized collection of blobs of hot gas shining because they are lit up by massive blue stars imbedded in them. So we might think that an irregular galaxy would be quite young, though there are possible pitfalls in this suggestion, as noted later on.

What would happen next in a young galaxy after the first generation of large, hot stars has formed? These first, massive stars will go through their life-histories fairly quickly, in the manner described in Chapter III, using up all their nuclear fuel. Ten or twenty million years later, at the end of their lives, they should turn into white dwarfs, but they are each so massive that the whole star cannot shrink to a white dwarf without losing a large part of its mass. So these first-generation stars

Figure VII-1. An irregular galaxy, NGC 4449. Such an unorganized collection of blue giant stars and blobs of glowing gas is generally considered young in age, since the blue giant stars are expected to be short lived. *Mount Wilson and Palomar Observatories*

Figure V-2. The Large Magellanic Cloud, an irregular galaxy. This is one of two such clouds easily visible in the southern hemisphere, but never above the horizon for us in the United States. These two clouds of Magellan are the nearest known galaxies outside our own.
Mount Wilson and Palomar Observatories

would have to put back into the interstellar material of the galaxy a good deal of the material of which they were made. And this material will have become enriched in the chemical elements "cooked up" in the interiors of the stars: elements such as helium, carbon, nitrogen, and iron.

Some of these heavier elements, once they get out into the space between the stars, can stick together and form dust grains, which pure hydrogen cannot do. (Two hydrogen atoms can stick together in a hydrogen molecule, but these molecules will not form solid dust particles.) And, once the oxygen, carbon, nitrogen, and so on, make dust grains, the gas, now with a mixture of dust in it, can cool. We saw that, in the early history of a galaxy, the gas would be hot; once some dust has formed, the gas can cool because the dust helps the gas to radiate away its heat energy. As the gas in a galaxy becomes cool, the pressure drops and it can fall together—condense under its own gravitational attraction—much more easily and rapidly. Thus it is much easier to form the second and later generations of stars from small density fluctuations.

Order Produced by Rotation

In Chapter V, it was shown that galaxies rotate about their axes. What would happen to an irregular galaxy if it rotates? Could it remain irregular? Star formation is going on, gas is contracting under its own gravitation, and the whole assemblage is rotating as well. We can expect a symmetrical and orderly structure to be produced from this formless mass of material just as a shapely vase can be made of formless clay. It is difficult to make a symmetrical object out of a lump of clay unless you have a potter's wheel to rotate the clay; then it is quite easy. So, we can understand how a galaxy could become more symmetrical-looking from its rotation. An irregular galaxy that started out with relatively few massive blue stars, and no pattern whatever in its structure, would gradually begin to take on a regular, symmetrical shape, with more of the mass collected at the center, and a generally circular outline. The cooling of the gas left over after the stars form would help this gas to contract toward the central or equatorial plane of the galaxy, and soon all of the gas and dust would lie in a thin layer or sheet in the central plane, as described in Chapter VI.

While this was happening—while the new galaxy was shrinking and speeding up its rotation, forming a more regular pattern—star formation would be going on continuously. As each generation of stars forms, the brightest members (which would be the most massive, high-temperature stars) will evolve and go through their lives most rapidly, come to the end stage, and return most of their substance to the space between the stars. But each generation will also contain some stars with a small mass. These small-mass stars, stars like our sun or smaller, with very long lifetimes, will not complete the full cycle that the hot bright stars go through—the cycle from dust to dust and gas to gas. Therefore, there should be a gradual using-up of the material of the galaxy; matter would gradually become locked up in low-mass stars whose lifetimes are so long that they take little part in the interchange between interstellar gas and stars.

Signs of a Galaxy's Age

There are also the stellar remains—skeletons, if you like—the white dwarfs left over after the massive stars have gone through their life cycle. An increasing fraction of the material of the galaxy will gradually get locked up in the form of white dwarfs; and that fraction can take no further part in the interchange between interstellar gas and stars. Thus, the gas in a galaxy will gradually get used up, until eventually there will be none left to form any new stars; in such an aged galaxy we expect only fairly cool stars of small mass, a few red giants into which such stars evolve, and some white dwarfs.

All this suggests that there are indicators of the evolutionary age of a galaxy—things which could be observed and measured from a large distance. We need features that can be measured from great distances if we are to get information about a large part of the universe, and about conditions billions of years ago—for we see the distant galaxies as they were then. We could measure, in the first place, the *color* of a galaxy. In Chapter II we saw how the colors of stars can be measured; the colors of galaxies, which are whole collections of stars, can be measured in the same way. If a galaxy has a red color it is likely to be made up mostly of old stars all of which have a reddish color—stars of a smaller mass than the sun and the red giant stars into which they would evolve. On the other hand, a young, irregular galaxy would have a bluer color because it is largely made up of hot, blue stars. Color thus would be an indicator of the evolutionary age of a galaxy.

We can also measure the *spectrum* of a galaxy, made up of the spectra of all the stars in it—an average or composite spectrum that might reveal the kinds of stars that make up a galaxy.

Another thing to measure is the *mass* of a galaxy, determined by studying how fast it is rotating (Chapter V). Having measured the mass of a galaxy, and the total light it puts out, we can determine the ratio: the mass divided by the luminosity. If we do this for a single star—the sun, for example—we get a certain value of tons mass per billion kilowatts of radiation. For a star cooler than the sun we find that the mass divided by the light is a larger number because of the way in which the luminosity depends so strongly on mass (Chapters III and IV). Stars of low mass put out relatively very little light, whereas stars of high mass are much more spendthrift of their energy. Hence the mass of a galaxy divided by its luminosity is a fairly good indication of the average kind of stars in that galaxy. Of course, it would be better if we could actually study the individual stars, but unfortunately galaxies are so far away that we can only study the brightest individual stars in a few of the nearest ones. What we need is a great deal of information about a very large number of galaxies.

A galaxy that we might think of as being at a somewhat later stage in its life history is shown in *Figure I-10*. This spiral galaxy still has many bright patches in it which we find to be patches of hot gas lit by bright stars. These are spread all through it, just as they are spread through an irregular galaxy. But this spiral has a clearly defined center, a fairly circular outline, and characteristic spiral arms. The color of a spiral like this is a little redder than an irregular galaxy, and from its composite spectrum it seems to have a higher proportion of yellow stars like the sun than does an irregular galaxy. All of this indicates that a loose spiral galaxy is at a later stage in its life-history than an irregular one. *Figure V-1* shows a tighter spiral galaxy (M31) where things have settled down and become still more orderly. M31 looks quite tidy; it has a nice bright little center, then a smooth region, and then the spiral arms neatly wound. Even in a galaxy like M31 there are many patches of gas not yet condensed into stars, which are lit up by nearby hot stars.

Factors that May Influence the Evolution of Galaxies

Finally, the elliptical galaxies in *Figure V-4* are quite smooth. They are much brighter in the center than in their outer parts but they have no bright patches of gas, and seem to be made up entirely of stars. All the gas has been used up. Elliptical galaxies have the reddest color of all, and their composite spectra show that their stars are, on the average, low-mass stars like the sun and the red giants into which such stars evolve.

What about the ratio of mass to luminosity? Unfortunately, we do not have much information yet on the masses of elliptical galaxies, but the average for a few shows that they have a much higher ratio of mass to luminosity than the spiral and irregular galaxies. This again suggests that they are at a later stage in their life-history.

Can we now say that an irregular galaxy will turn into a spiral galaxy and, when all the gas is used up, the spiral will turn into an elliptical galaxy? Can we say that we have an evolutionary sequence, irregular types evolving into spirals, and spirals evolving into ellipticals? Harlow Shapley, the famous Harvard astronomer, first suggested about a decade ago that this was happening. But we must keep in mind the warning example set by studies of the evolution of stars. We know that there are many different kinds of stars in the sky, but that we cannot put all these stars into one evolutionary sequence; we have seen in Chapter IV that the life-histories of stars of different masses are very different. In fact, if we want to make sense of the life-history of stars, we have to sort the stars first into groups with the same age but different masses. We cannot say that a high-temperature, massive star will evolve into a star like the sun. But in this first attempt at the life-history of a galaxy we are trying to arrange all the different kinds of galaxies in a single evolutionary sequence. Perhaps this is not right—perhaps the mass of a galaxy plays an important role in determining its life-history, just as the mass of a star is very important in its life-history.

Although we know the masses of only a few galaxies as yet, it does seem that irregular galaxies and spiral galaxies are, on the average, less massive than elliptical galaxies. How, then, could an irregular galaxy become a spiral galaxy and then an elliptical galaxy, with an *increase* in mass?

There is further evidence from the double galaxies—galaxy twins, so to speak. For instance, the irregular galaxy M82 lies

Figure V-1. The Andromeda Galaxy, Messier 31, a spiral galaxy. This largest and brightest of the nearby galaxies dwarfs its two companions, M32 on the left and NGC 205 on the right, in this photograph taken with the 48-inch Schmidt telescope. M31 is estimated to be over 2 million light-years from us. It is the nearest spiral galaxy, and can just be seen with the naked eye on a clear, dark night. *Mount Wilson and Palomar Observatories*

E0 NGC 3379

E2 NGC 221 (M32)

E5 NGC 4621 (M59)

E7 NGC 3115

NGC 3034 (M82)

NGC 4449

quite close in space to the large spiral galaxy, M81, and may have been formed out of the same general patch of material. It ought to have the same age, just as the stars in any one cluster are likely to have the same age. Is the irregular galaxy M82 the same age as the spiral galaxy M81 near it? M82 is probably a little less massive than the spiral galaxy M81, but it is rotating, and before very long it should surely settle down to a spiral structure. Why is M82 still an irregular galaxy? What stopped it from becoming a spiral galaxy like M81?

There must be other factors, then, that determine the way in which a galaxy evolves, beside the mass it had to start with. The *magnetic field* is a possible factor, since magnetic fields are needed (Chapter VI) to explain those galaxies that are radio sources, and it is quite likely that there are magnetic fields in all galaxies, including our own. These magnetic fields are quite small in comparison to the magnetic field on the surface of the earth that causes a compass needle to point north. The magnetic field in our galaxy is only a few hundred-thousandths of this. Nevertheless, a magnetic field of this strength spread out through a whole galaxy involves a great deal of energy.

If magnetic fields are stronger in some galaxies than in others, this might have an effect upon the speed at which interstellar gas could form into stars. A strong magnetic field could delay star formation because magnetic fields tend to "freeze" a conducting gas, making it behave more like a solid, and would tend to keep apart a blob of gas that was about to contract under its own gravitation into a star. In this way the magnetic fields in a galaxy may be important in determining its life-history.

Another factor that might be important is the original *density* of the gas that contracted to form a galaxy. Suppose gas is contracting, and that, before it has achieved high average density, some fluctuations initiate star formation. This might lead to a slower over-all rate of formation than if all the gas forming a galaxy collapsed at once, reaching high density throughout before the first generation of stars formed.

The Origin of S-Zero (So) Galaxies

Another objection to the idea that a spiral galaxy may turn into an elliptical one is connected with *rotation.* Looking at a spiral galaxy edge-on as in *Figure I-11,* we see how flat it is. Elliptical galaxies are never that flat. Once a galaxy has become extremely flat, it is difficult to see how it can round out again, as would be necessary if a spiral galaxy were to evolve into an elliptical galaxy. However, there is a kind of galaxy that has no spiral arms and yet is more flattened than the elliptical galaxies, and these are called So galaxies (see Chapter V). There are many galaxies of this sort in some of the giant clusters of galaxies, and it has been suggested that they were formed by chance collisions. In such a collision the stars of each galaxy just pass each other, simply because there is so much empty space between them. But the interstellar gas and dust clouds in the two galaxies *will* collide, and be separated from the stars. So collisions will sweep the gas out of spirals. S-zero galaxies, which are flat but have no interstellar clouds, might therefore be either the results of collisions between spiral galaxies, or simply aged spiral galaxies that have used up their gas and dust in forming stars.

Figure VII-2 shows an So galaxy in which a small amount of gas remains. You can see that there is a very thin line of dust through the center, the region where the spiral arms used to be. The gas that makes spiral arms is mostly gone, leaving just stars and the remnants of stars.

Winding Up of Spiral Arms

Let us now consider the spiral arms in galaxies. They are fairly symmetrical, and this has a bearing on how they might be "wound up." The central region of a galaxy rotates faster than

Figure I-11. Spiral galaxy in Coma Berenices, NGC 4565. This galaxy is seen in edge-on view by chance. Compare it with *Figure I-9* to see why the stars of the Milky Way are considered to form a similar object—a galaxy. *Mount Wilson and Palomar Observatories* the outer regions. An early idea about the formation of spiral arms, known as the "coffee-cup" theory, was based on the analogy of a cup of coffee stirred near the middle of the cup. The central part of the coffee goes around faster than the outer parts, and at the rim of the cup the coffee is not moving at all. A little thick cream poured in makes beautiful spiral arms, and it does not matter what shape the blobs of cream start with; the different speeds of rotation will spin them out into spiral shapes.

It is easy, then, to understand how spiral arms are formed by the different rates of rotation in a galaxy; the difficulty is just the opposite: why don't all galaxies have much more extended spiral arms? If the galaxies are very old they must have rotated a great many times; an average galaxy will rotate, about halfway out from its center, once in perhaps a hundred million years, and will turn a large number of times in its full life (estimated to be ten billion years). We would expect to see spiral arms completely wound up in hundreds of turns, whereas the actual spiral galaxies (*Figures I-10, V-1, V-3*) usually have arms making just one or two turns. It seems that there must be some process that renews or preserves short spiral arms; otherwise the observed rotations of galaxies would wind them out of existence. Here again, it is tempting to assume that magnetic fields stiffen the material of a galaxy and prevent a spiral arm from winding up too far. They may also play some part in the formation or renewing of spiral arms.

In addition to the ordinary spiral galaxies, as noted in Chapter V, there is the class of "barred spirals"—galaxies that have a bar across the center and two spiral arms starting from the ends of the bar (*Figure V-3*). The bar in such a galaxy rotates more or less like a solid wheel, but just beyond the end of the bar the material rotates more slowly so that the arms get trailed out. Something must "freeze" the straight bar into a rigid form so that it does not wind up into spiral arms. But *Figure VII-3* shows a different sort of barred spiral. It has a bar and two

Figure VII-2. An So galaxy, NGC 5866. The S-zero (So) type of galaxy is flat like a spiral but shows no spiral arms and is often called a transition stage between spiral and elliptical types. This one has a thin line of dust in it, as a depleted spiral might.

Mount Wilson and Palomar Observatories large spiral arms, but in the very center there is another little spiral, which turns out to be rotating very fast. It is hard to see how the bar could last very long without getting wound up in the central spiral. There are several other barred spirals like this, and there is a great deal to be learned before we can hope to understand them.

Are Galaxies Forming Now?

Finally, do we see any galaxies that we think are really young—actually young in years? The "Steady-State" cosmological theory predicts that we should see some galaxies formed very recently; the "Big-Bang" Theory, although it does not say that there could be no young galaxies, must explain them in some special way. *Figure VII-4* shows one of the few galaxies we can claim are fairly young. It is a very odd thing—an ordinary elliptical galaxy accompanied by nearby patches of gas that must have bright, hot stars in them. A galaxy like this could not last very long in its present stage; perhaps this elliptical galaxy, moving through space, captured some left-over material—a blob of gas in which no stars had formed. As a result of the capture, this blob of gas could contract a little, until it was dense enough in some places for stars to form. That is, a young galaxy was formed in the presence of an old one.

Figure VII-5 shows two galaxies rather far away from us and located in one of the big clusters of galaxies, the Coma cluster. A long tail sticks out of the upper galaxy, and another tail from the lower one. You would think such tails must wind up; a tail cannot remain just sticking out into space from a galaxy if that galaxy is rotating at all. And these galaxies are rotating rapidly, as measured by Doppler shifts in their spectra (see Chapter II). That is, a straight, protruding tail makes it very likely that such a galaxy is very young.

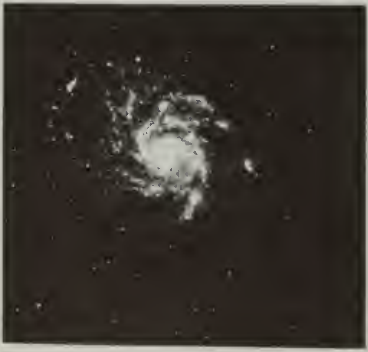
Figure I-10. An open spiral galaxy in Eridanus, NGC 1300. Its shape gives an impression of rotation, but since it takes hundreds of millions of years to turn once around, we cannot hope to detect changes in this view during one man's lifetime, or even during the whole history of astronomy. *Mount Wilson and Palomar Observatories*

Sa NGC 4594

SBa NGC 2859

Sb NGC 2841

SBb NGC 5850



NGC 5457(M 101)

SBc NGC 7479

Figure VII-3. A barred spiral galaxy with a spiral nucleus, NGC 1097. A normal barred spiral (SB) galaxy has a straight bar between two spiral arms (*Figure V-3*). The small spiral in the center of this one raises the question of how the bar can remain straight when a part of it is more rapidly rotating at the center.

McDonald Observatory

Another queer thing is shown in *Figure VII-6;* it looks unlike the galaxies we are used to and yet it certainly is a galaxy. It has two strings of material and a kind of loop. One would expect such an unstable structure soon to change; hence it is also likely to be young.

In summary, it is difficult to understand in detail how one sort of galaxy can evolve into another, yet in a general way we know that it must happen. We know that the stars in a galaxy are

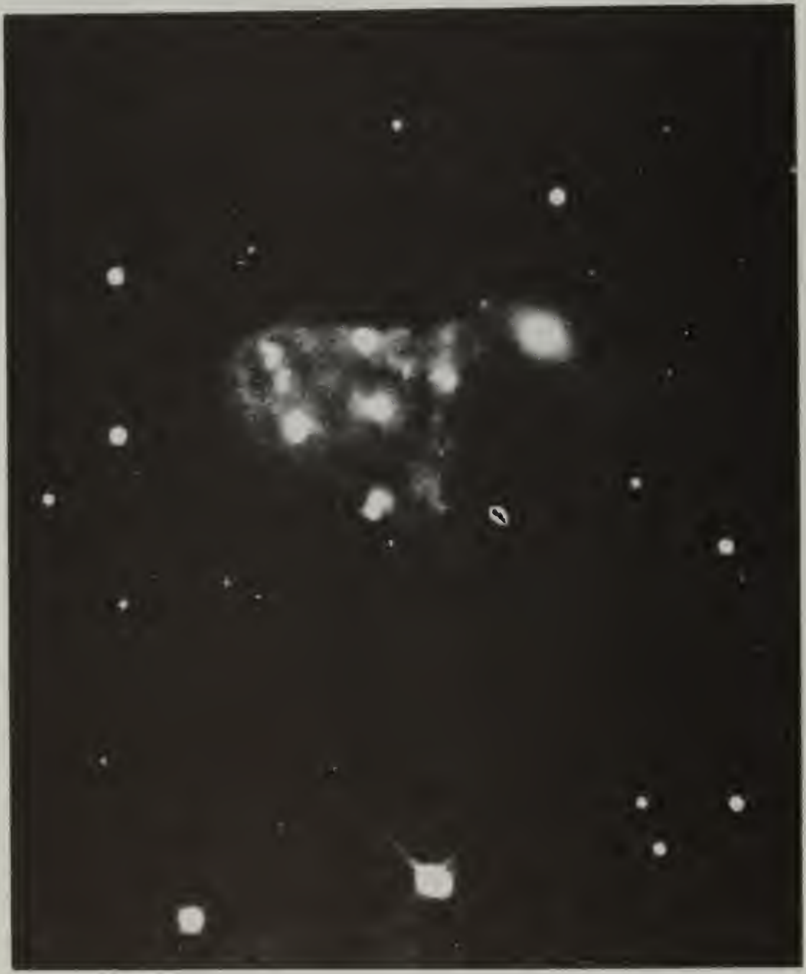


Figure VII-4. A new galaxy forming near an elliptical, NGC 2444, 2445. The bright patches to the left of the normal, presumably old, elliptical galaxy are glowing gas illuminated by young, blue giant stars. *McDonald Observatory*

Figure VII-5. A pair of galaxies with tails, NGC 4676. The question here is how the tails can remain sticking out without "winding up" into spiral arms. The spectra show that each galaxy in this pair is rotating rapidly. *McDonald Observatory*

Figure VII-6. A peculiar loop-galaxy, NGC 6621, 6622. Such a shape fits into no regular class of galaxies; it is a freak that appears to be unstable and therefore of short life in its present form.

McDonald Observatory

ageing (Chapters III and IV), and that the shapes of certain galaxies (*Figures VII-5* and *VII-6*) cannot last, as the motions in each galaxy go on—motions we have measured by Doppler shifts. This reasoning leads us to think that elliptical galaxies are older than spirals and irregular galaxies. But if we go on to say that all irregular galaxies turn into spirals after 100 million years, and that all spirals turn into ellipticals after a billion years, how can we explain mixed groups or close pairs of one spiral with one elliptical? How can elliptical galaxies be heavier than spirals? (Where did the added mass come from as a galaxy aged?)

One possible explanation is that ageing does not always proceed at the same rate. Perhaps in the "young" spirals we see among "old" ellipticals, something prevented for a long time the formation and ageing of stars. Perhaps the mass of a galaxy has an effect on how rapidly it ages, so that most of the heavy ones have already become "old" ellipticals. Irregular "young" galaxies seen close to "older" spirals or elliptical galaxies suggest that, whatever the cause, evolution goes on at *different rates* in different galaxies even when they are located close to each other in space. Two close galaxies in a double may be at widely different stages in their life-histories, even though they have the same age in years. In fact, there could well be many even younger galaxies that we cannot see—dark blobs of matter in which stars have not yet formed because of magnetic fields or low density or some other peculiar condition. These ideas of the evolution of galaxies can be fitted equally well into either the "Big-Bang" Theory or the "Steady-State" Theory.

From all this you can see that we do not have an adequate theory of how galaxies evolve. More observations and much more theoretical study is needed. The subject of evolution of galaxies is a field in which we can expect great changes in the next few years.

Bondi, a noted theoretical physicist and astronomer, presents the evidence for the over-all expansion of the universe, evidence which depends greatly on the observed red shift of light from distant galaxies. The number mentioned at the end of the paper, ten billion years, is sometimes picturesquely called the "age of the universe."

23

Expansion of the Universe

Hermann Bondi

An excerpt from his book *Relativity and Common Sense: A New Approach to Einstein*, 1962.

The most striking feature of the universe is probably its expansion. What exactly is the evidence for this and how strong is it? In Plate I we have a picture that displays some of the evidence in striking form. A series of pictures of galaxies is shown in the left-hand column. They are all taken with the same telescope, using the same magnification. On the right-hand side we see the spectra of these galaxies. Now, first, what is a spectrum? It is well known that white light is a combination of all the colors and that it can be broken up into these colors by suitable aids; a rainbow is a familiar instance. A handier means is the use of a prism of glass or other suitable material; with its aid the whole band of colors of sunlight is spread out. If one uses a prism that spreads out the sunlight very clearly, then one notices that the colors do not form a smooth band and that in numerous places dark lines run across the spectrum. The origin of these lines is rather complicated. In the main they are due to the light from the sun shining through cooler gases of the sun's atmosphere, and these gases happen to be opaque to very particular colors, to thin lines, and so leave a part of the spectrum dark. The astronomer can use spectroscopes of great power to analyze the light of individual stars and also of individual galaxies. Naturally, particularly for the very distant galaxies, rather little light is available, and because of that, and for more technical reasons, the spectrum of a galaxy will not be nearly as clear as, say, the spectrum of the sun. Nevertheless, a few of the very prominent dark lines do show up, even in the spectra of these distant galaxies. The remarkable phenomenon that was discovered nearly forty years ago is that these lines are not where they ought to be, not where they are in the case of the sun, say, but they are displaced; they are shifted. The shift is always toward the red and is indicated in the illustrations of the spectra in Plate I. You will notice that the fainter and smaller the galaxy looks, the greater the shift of the spectrum toward the red. This is a full description of the direct observational result. A red shift of the spectrum is observed and is correlated with the apparent brightness of the galaxy, so that the fainter the galaxy, the greater the red shift. From here on we start on a series of interpretations.

The Red Shift

First, what can be the explanation of such a red shift? In what other circumstances are red shifts observed? The answer is that, but for one rather insignificant cause, the red shift always indicates a velocity of recession. Unfamiliar as the phenomenon is in the case of light, it is commonly noticed in the case of sound. If a whistling railway train speeds past you, then you notice that, to your ears, the pitch of the whistle drops markedly as the train passes you. The reason for this is not difficult to understand. The whistle produces sound; sound is a vibration of the air in which pressure maxima and pressure minima succeed each other periodically; these travel toward your ears where they are turned into nerve impulses that enter your consciousness. While the train is approaching, each successive pressure maximum has a smaller distance to travel to reach you. Therefore, the time interval between the reception of the pressure maxima will be less than the time interval between their emission. We say that the pitch of the note is raised. Conversely, when the train is receding from you, each successive pressure maximum has farther to travel and, therefore, the pressure maxima will reach your ear at intervals of time greater than the intervals at which they were emitted. Accordingly, the pitch is lower. How great

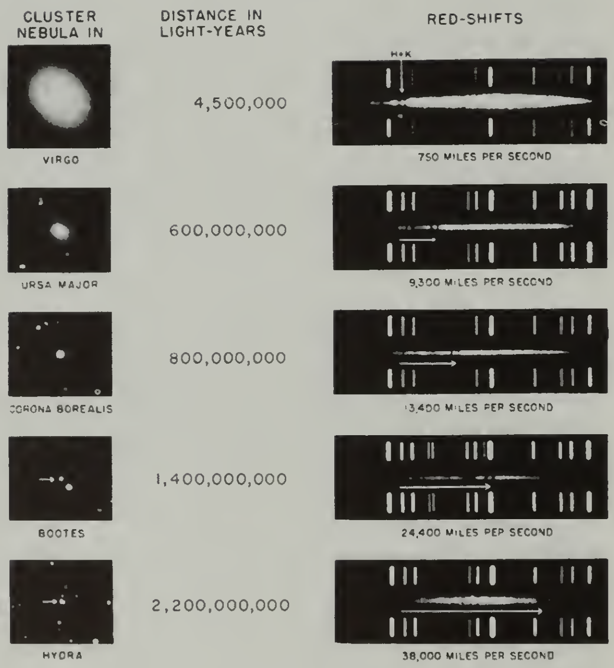


PLATE I. *The expansion of the universe is inferred from these and similar observations. The left-hand column shows galaxies at various distances photographed with the same magnification. In each photograph the galaxy appears as a diffuse object with its center in the middle of the picture, but the two most distant ones are marked by arrows for purposes of identification. The other diffuse objects in the photographs are other galaxies, the sharp ones being stars near to us. On the right are photographs of the diffuse-looking spectra of the galaxies stretching in each case from blue on the left to red on the right. The bright lines above and below each spectrum are produced in the laboratory and serve only as markers. The pair of dark lines in the spectrum of each galaxy above the tip of the arrow would be above the foot of the arrow if the source were at rest.*

the raising or the lowering of the pitch is, depends on the ratio of the velocity of the train to the velocity of sound, which is about 1100 ft. per second.

Very much the same thing happens with light, but here an increase in the pitch becomes noticed as a shift toward the violet; a decrease in the pitch becomes noticed as a shift toward the red. Also, the crucial velocity is now not that of sound, but the very much higher velocity of light at 186,000 miles per second. A red shift, therefore, indicates a velocity of recession of the source; a velocity standing to the velocity of light in the ratio given by the magnitude of the red shift—that is, by the change in wave length divided by the wave length. The velocities so derived from the observed red shifts are shown on the right-hand side of Plate I. Such a velocity of recession is, then, the only cause of the red shift that we can infer from our terrestrial knowledge of physics. What about the other characteristic of the picture, this time the characteristic of the photographs on the left, the increasing faintness and diminishing size? We all know that an object of a given brightness will look fainter the farther away it is. There is very little else in astronomy to guide us about the distances of these galaxies which we see so very far away. Accordingly, if we interpret the faintness of the galaxies as indicators of their distances, and the red shift of the spectra as velocities of recession, then we find that the velocity of recession is proportional to the distance of the object.

Velocity of Receding Stars

We have inferred a "velocity-distance law" from the red shift-brightness relation. For a long time physicists and astronomers felt rather uneasy about these enormous velocities of recession that seemed to follow from their observations. They argued that all our interpretation was based on our local knowledge of physics, and that unknown effects might well occur in the depth of the universe that somehow falsify the picture that we receive. Nowadays, we have little patience with this type of argument. For the expansion of the universe is not merely given by the observation of the spectrum. We have also noted the remarkable uniformity of the universe, how it looks the same in all directions around us if only we look sufficiently far. If, then, we suppose that the universe is, indeed, uniform on a very large scale, we can ask the mathematical question: How can it move and yet maintain its uniformity? The answer is that it can only move in such a way that the velocity of every object is in the line of sight and proportional to its distance. This is the only type of motion that will maintain uniformity. Therefore, we are again driven to the conclusion that an expansion with a velocity of recession proportional to distance is a natural consequence of the assumption of uniformity which is also based on observation. Furthermore, if we try to form a theory of the universe, whichever way we do it, we always come up with the answer that it is almost bound to be in motion, with objects showing velocities proportional to their distances.

I must again stress the uniformity of the system. We are not in a privileged position on the basis of these assumptions, but in a typical one. The universe would present the same appearance to observers on any other galaxy. They would see the same effects; the same red shift-brightness relation. Though no one can be certain of anything in this field, we do see that there are different lines of argument all converging to the conclusion that the red shifts should indeed be taken as indicating velocities of recession proportional to the distance of the objects. If we divide the distance of any galaxy by its velocity of recession, we get the same number whatever galaxy we choose. That follows from the proportionality of velocity and distance. This number is a time, a time that, according to the most recent work, is about 10,000 million years. In some way or other this is the characteristic time of the universe.

Does mass, like electric charge, exist in both positive and negative forms? If so, negative mass must have the most extraordinary properties--but they could explain the immense energies of the star-like objects known as quasars.

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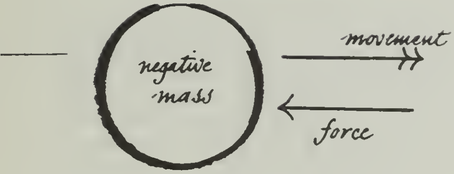
Negative Mass

Banesh Hoffmann

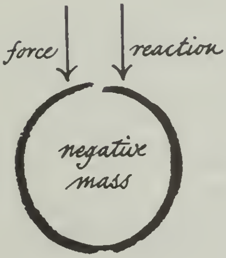
An article from *Science Journal*, 1965.



ONLY A RASH MAN would assert categorically that negative mass exists. Yet he would be almost as rash if, equally categorically, he said that it does not. True, if negative mass exists it must have extraordinarily perplexing properties. For example, if we pushed a piece of negative mass towards the left with our hand, it would move perversely towards the right; and, if that were not nonsense enough, as it moved towards the right we would not feel the negative mass resisting our thrust but actually aiding it.

If the behaviour of negative mass is so seemingly nonsensical, why should one even think about it further? It has never been observed. Surely anyone who said that negative mass does not exist would be far less rash than one who thought that it might.

So it would seem. Yet the history of science should give us pause. We have learned from bitter experience that what at first seems utter nonsense can prove to be excellent science. For instance, who would have believed, at one time, that no material object can possibly move faster than light? Or that an electron is, in a sense, both a particle and a wave? Or that when two people are in relative motion each finds that the other's clock runs slow compared with his own? Yet these, and many other such unlikely statements, are now part of the legitimate currency of science.



EVEN so, why should we seriously contemplate the idea of negative mass? The recently discovered quasi-stellar radio sources provide an answer. These objects, often referred to as quasars, pose a stark problem simply because they are, intrinsically, by far the brightest objects in the heavens. Not that they dazzle the eye. They are much too far away to do that, despite their brilliance. Indeed they are invisible to the naked eye. Though we owe their recognition in the first instance to the radio astronomers, it would be incorrect to say that the radio astronomers were the first to detect them. The quasars had often been photographed by the optical astronomers. But on the photographs they looked like faint stars of no particular interest; and with so many more glamorous celestial objects demanding their attention the optical astronomers had simply ignored them.

Whenever the radio astronomers detected a source of radio waves in the heavens they told their optical confrères who then directed their largest telescopes towards the region in question. For the most part all was neat and orderly: the optical astronomers found visible objects that were clearly the sources of the radio waves—usually galaxies of one sort or another. Sometimes they drew a blank. And just occasionally they could find nothing except a star-like object so faint that if it were indeed an ordinary star it could not have given rise to the relatively strong radio waves that had been observed.

Nevertheless, more precise radio bearings confirmed that these star-like objects were indeed the radio sources and from then on the puzzle grew until it reached massive proportions. In an expanding universe, the furthermost objects recede the fastest and this recession is evidenced by a shift of spectral lines towards the red. The quasars were found to have spectral red shifts corresponding to recession speeds as high as half the speed of light, implying that they were among the most distant known objects in the universe. This was incredible, if they were stars, since there are theoretical limits to the size and brightness of a star and no star could be bright enough to be observable at such distances. If the distances were correct, individual quasars must be emitting light at more than a million million times the rate of emission of the Sun and, indeed, something like a hundred times the rate of emission of a complete giant galaxy. Yet the quasars could not be anywhere near the size of an average galaxy which is tens of thousands of light years across: they would look larger if they were indeed that large. Another reason, less obvious, is that some of the quasars have rapid fluctuations in brightness, with periods measurable in years and even in weeks. Not only do galaxies maintain a steady brightness; there are also relativistic reasons for believing that an object whose brightness fluctuates with a period of a few years cannot be more than a few light years across.

Thus, the astronomers were faced with a major problem: how could they account for the prodigious rate at which quasars were radiating energy, and what was the source of this energy?

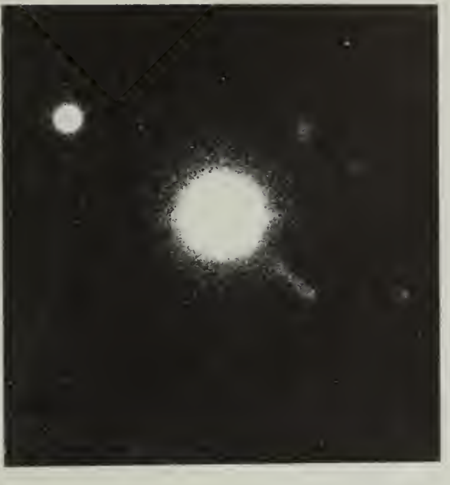
In FEBRUARY of this year, there were 45 known quasars. By now the number is likely to be significantly larger. Several theories have been proposed to explain the nature of quasars and the source of their energy. Indeed, it is only with the recent advent of new observational techniques that the rate of discovery of quasars has significantly outstripped the rate of production of theories to account for their properties. If one tries to account for their spectacular brightness by conventional astrophysical processes, in terms of Einstein's relationship of energy to mass and the speed of light ($E=mc^2$), one is almost driven to assume it is due to a prodigious rate of supernova explosions; even then one has to postulate enormous amounts of matter.

I. S. Shklovsky and G. R. Burbidge, among others, have suggested ways in which such explosions might occur frequently. Also, G. B. Field has proposed that a quasar is just an early stage in the evolution of a regular galaxy having relatively small rotational energy, the extraordinary brightness arising from the explosion of supernovae at the rate of about a hundred a year (the usual rate being one explosion every three or four hundred years in an average galaxy). Since the supernovae would explode at irregular intervals, this hypothesis could explain the fluctuating brightness but it would explain only the most rapid fluctuations and not one whose period was of the order of a decade.

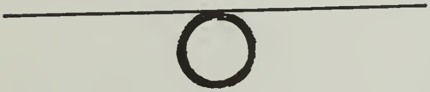
T. Gold has suggested that both the brightness and the fluctuations could come from frequent collisions of stars in a highly compact galaxy, the collisions tearing the stars open and exposing their glowing interiors.

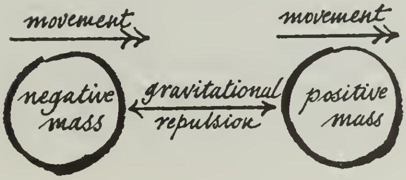
V. L. Ginzberg, among others, has looked to gravitation as a source of energy in the quasars. A tall building seems to be a placid unenergetic thing. But if its foundations crumble it falls to the ground with devastating effect. In its upright position it has stored gravitational energy—put there by the cranes that lifted the building blocks—and when it collapses this energy is released. We do not know how matter came into existence, but it is dispersed throughout the universe and, in its dispersed state, it has gravitational energy akin to that of the upright building. As portions of matter come together locally under the influence of their mutual gravitation they transform part of their gravitational energy into energy of

Quasi-stellar radio source 3C 147



Quasi-stellar radio source 3C 273





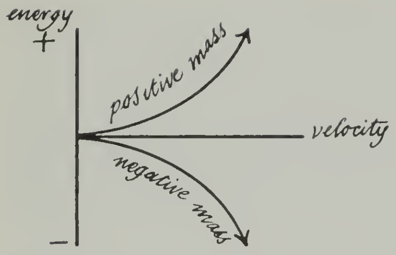
motion. Under normal conditions the celestial object built up in this way does not collapse. Its rotation tends to make it fly apart and thus counteracts the shrinking effect of gravitation. And if it does begin to collapse it usually tends to bounce back as the gravitational energy released is changed into motion. But F. Hoyle and W. A. Fowler, using the general theory of relativity, conceived of circumstances in which a gigantic 'star' might suffer a really radical gravitational collapse, becoming a relatively minuscule object of stupendous density. In the process it could give off light and radio energy at the observed quasar rate, but to do so the 'star' would have to contain an enormous amount of matter—a hundred million times that in the Sun.

Because the amounts of energy involved verge on the incredible, J. Terrell has suggested that the quasars are actually quite close, in astronomical terms, being fleeing fragments formed as a result of an explosion within our own galaxy. If so they would be much smaller and much less bright than had been supposed. But then one would have to ascribe the large red shifts of their spectral lines not to cosmological recession velocities, arising from the overall expansion of the universe, but to local recession velocities produced solely by the initial explosion. Although the amount of energy involved in this hypothesis is considerably less than that needed to account for quasars as very distant objects, it is nevertheless alarmingly large for a relatively local explosion, and to account for it Terrell feels a need to invoke a local gravitational collapse.

J. A. Wheeler has proposed yet another idea which he bases on the Einstein concept of curved space in a gravitational field. If only one could ignore rotation, a sufficiently large amount of matter would inevitably undergo radical gravitational collapse. As the matter fell together to a density of unheard of proportions, the curvature of space would increase locally until a sort of open pouch, or pocket, or blister was formed. The greater the amount of matter falling into it, the more rotund the blister would become and, as it grew more concentrated, its neck would become ever narrower. Eventually the neck would close and the blister would become a hidden cyst of space, with never an external pucker to reveal its presence. The matter that had fallen into it would be lost completely to the outside world. Not even its gravitational effect would survive. But in falling it could give up all its energy (mc^2) to the main part of the quasar, and this could be the fuel that kept the fire burning so brightly.

THERE IS YET ANOTHER possibility—if one can accept the idea of negative mass. For negative mass can act like a bank overdraft, allowing one to borrow energy for emergency purposes when high output is needed. And it has the considerable advantage over a bank overdraft that one can manage, in a sense, to avoid paying back what one has borrowed.

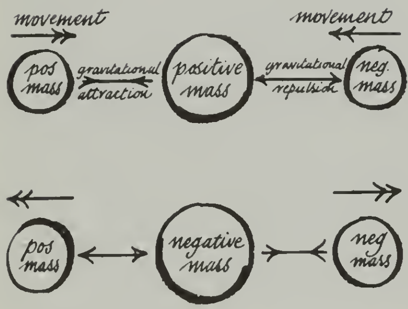
Let us, then, look more closely at the properties of negative mass, taking encouragement from the fact that neither the theory of relativity nor the quantum theory is a barrier to the existence of negative mass despite its awkward properties, and that negative mass can be excluded from those theories only by the arbitrary imposition of a ban from the outside. According to Newton, the gravitational attraction between two bodies is proportional to the product of their masses. If one of the masses is negative and the other positive, their product will be negative and therefore so, too, will the gravitational attraction between them. Since a negative attraction is a repulsion, we might expect the two masses to accelerate away from each other. But this is not the case. Negative mass does not do the expected thing. Imagine the two masses placed side by side, the positive mass to the right of the negative mass. Their mutual gravitational repulsion accelerates the positive mass towards the right, of course. But what of the repulsion that acts on the negative mass? Since it is directed towards the left, and since negative mass acts perversely, the repulsion will cause the negative mass to move towards the right, that is towards the positive mass. Thus both masses move towards the right, the negative mass chasing the positive. Enormous speeds could be built up in the course of such a chase; and it seems that we would be getting something for nothing—generating energy without doing work, and thus violating the law of conservation of energy. But in fact we would not. True, the faster the positive mass goes, the greater its energy. But the



same is not true of the negative mass. The faster it goes, the more deeply negative its energy becomes. So the negative mass can chase the positive mass and generate enormous speeds while the total amount of energy remains unchanged.

Once the perversity of negative mass is grasped, it is not difficult to see that positive mass causes both positive and negative mass to accelerate towards it gravitationally, but that negative mass gravitationally causes all mass, whether positive or negative, to accelerate away from it. Again, if two particles have electric charges that are either both positive or both negative, the particle of negative mass will still chase the particle of positive mass; but if the charges have opposite signs the particle of positive mass will do the chasing, provided that the electrical force is larger than the gravitational.

Thus, we begin to see that the idea of negative mass might help to explain the enormous brightness of the quasars. But it is not enough simply to postulate the existence of negative mass. We must be able to explain why it has not been observed and we must present a specific mechanism by which negative mass could indeed fuel the quasar furnaces.



If NEGATIVE MASS exists we would expect all particles of positive mass to decay spontaneously into particles of negative mass, emitting radiation in the process and causing the material universe to blow up. Though this appears to be a formidable obstacle, we would be faint hearted to let it deflect us from our purpose. Indeed one needs no great courage, for theoretical physics has often been—and still is—plagued by similar theoretical catastrophes.

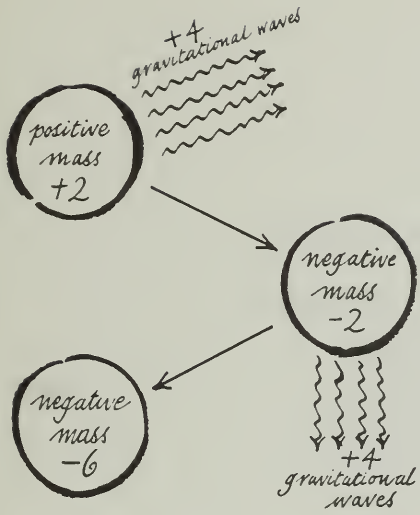
Many decay mechanisms that one could argue as conceivable seem not to occur in nature. To account for such absences, theoretical physicists impose on their theories special conservation rules which forbid decays that the theories would otherwise permit. We can introduce an analogous conservation rule that would prevent particles of positive mass from decaying into particles of negative mass.

But if we do, how are we ever going to generate particles of negative mass? Once again we take our cue from current atomic theory. Some of the conservation rules are not inviolate. We therefore make ours breakable too—but only under exceptional conditions.

Conservation rules are always related to symmetries and they are broken when the corresponding symmetries are marred. Since, according to Einstein, gravitation is a curvature of space-time, it could well warp symmetries. So we imagine that in the presence of an extremely strong gravitational field the conservation rule prohibiting the formation of negative mass can be broken; and we say that only under extreme conditions such as exist within a quasar is this likely to occur.

Next we recall that gravitation is different from all other forces, in that gravitational waves are generated by mass and themselves transport mass. (Electromagnetic waves, for example, are generated by electric charge but do not transport electric charge.) So we postulate that positive rest mass can decay into negative rest mass only if the energy is given off in the form of gravitational waves. This has two important consequences. First, gravitational waves are generated when a particle is accelerated by non-gravitational forces, and these will be particularly powerful in the hot, dense interior of a quasar. So much so that, with the requirement of an intense gravitational field, we can effectively confine the production of negative mass to such extreme circumstances as are likely to exist in the interiors of quasars.

The second consequence has to do with a curious asymmetry between positive and negative mass in Einstein's theory. Work by H. Bondi and others indicates that, irrespective of whether the matter producing the gravitational waves is positive or negative, the waves carry away only positive energy and thus only positive mass. So if a particle of, say, 6 units mass gave off gravitational waves whose energy had mass 4, it would end up with mass 2. But if a particle of mass 2 gave off gravitational waves of mass 4 it would be left with mass of -2, that is, a negative mass. It could not now give off gravitational waves of mass -4 and return to a



mass of +2. If it gave off further gravitational waves of mass 4 it would go to mass −6 and so on. The process would slow down, however, since the more deeply negative the mass became the less easily would the particle be accelerated.

The gravitational waves would be carrying energy to the more peripheral parts of the quasar while building up an energy deficit in the form of negative mass. Where, though, would the deficit be stored? We might imagine that since matter of negative mass has negative density it would be far more buoyant than matter of positive mass and density. But once again the perversity of negative mass betrays our expectations. A particle of positive mass in a quasar would be pulled gravitationally towards the centre but buoyed up by the impacts of other particles. A particle of negative mass would also be accelerated gravitationally towards the centre but it would react perversely to the same impacts. It would therefore plunge towards the centre, and there it would mix with positive mass to form a growing core whose average mass was zero. Here, then, at the centre of the quasar, the deficit would reside—and accumulate. If the above theory is at all close to actuality, it is no wonder that negative mass, if it exists, has not been observed.

But we are taking too easy a way out, a way reminiscent of the White Knight in "Through the Looking Glass" who

> "... was thinking of a plan
> To dye one's whiskers green,
> And always use so large a fan
> That they could not be seen."

The presence of a growing core of zero mass would increase the natural instability of a large celestial object. If an explosion occurred, negative mass could be ejected. What would happen to it? It could not form stars of negative mass. Why not? Because for negative mass gravitation is not a cohesive but a dispersive force. As a particle of negative mass travelled through space it would be attracted towards stars, and on falling into one would plunge to its centre.

In the course of its travels, when it encountered particles of positive mass, especially if the negative and the positive particles were charged, the particle of negative mass would generate high velocities by the chasing process; and if one of these fast moving particles of positive mass entered our atmosphere it could give rise to a shower of cosmic rays of very great energy. It is not completely impossible that cosmic ray showers of puzzlingly high energy that have been observed might be due to such a cause.

What if one of the particles of negative energy entered the detection apparatus of a cosmic ray experimenter? This would be a rare event, since at best neither particles of negative mass nor cosmic ray experimenters are abundant. But if a cosmic ray experimenter ever found evidence of a particle going in one direction but pushing in the opposite direction that would indeed be a decisive event for it would show that, despite the many theoretical problems to which it would give rise, negative mass does indeed exist.

FURTHER READING

Quasi-stellar radio sources by J. L. Greenstein (in *Scientific American, 209, 54, December 1963*)

The international symposium on gravitational collapse (*University of Chicago Press, Chicago, 1965*)

Negative mass as a gravitational source of energy in the quasi-stellar radio sources by B. Hoffmann (essay obtainable from *Gravity Research Foundation, New Boston, 1964*)

ACKNOWLEDGEMENTS:

Mount Wilson and Palomar Observatories (page 75, bottom, and page 76, top)

25

Four Poetic Fragments About Astronomy

From Troilus and Cressida	William Shakespeare
From Hudibras	Samuel Butler
My Father's Watch	John Ciardi
Il Va Neiger . . .	Francis Jammes

from TROILUS AND CRESSIDA

The heavens themselves, the planets and this center,
Observe degree, priority and place,
Insisture, course, proportion, season, form,
Office and custom, in all line of order:
And therefore is the glorious planet Sol
In noble eminence enthroned and sphered
Amidst the other; whose medicinable eye
Corrects the ill aspects of planets evil,
And posts like the commandment of a king,
Sans check to good and bad: but when the planets
In evil mixture to disorder wander,
What plagues and what portents, what mutiny,
What raging of the sea, shaking of earth,
Commotion in the winds, frights, changes, horrors,
Divert and crack, rend and deracinate
The unity and married calm of states
Quite from their fixture! O, when degree is shaked,
Which is the ladder to all high designs,
The enterprise is sick!

William Shakespeare

from HUDIBRAS

Second Part, Canto III

The Egyptians say, The Sun has twice
Shifted his setting and his rise;
Twice has he risen in the West,
As many times set in the East;
But whether that be true, or no,
The Devil any of you know.
Some hold, the Heavens, like a Top,
Are kept by Circulation up;
And 'twere not for their wheeling round,
They'd instantly fall to the ground:
As sage Empedocles of old,
And from him Modern Authors hold.
Plato believ'd the Sun and Moon,
Below all other Planets run.
Some Mercury, some Venus seat
Above the Sun himself in height.
The learned Scaliger complain'd
'Gainst what Copernicus maintain'd,
That in Twelve hundred years, and odd,
The Sun had left his antient Road,
And nearer to the Earth, is come
'Bove Fifty thousand miles from home.

Samuel Butler

MY FATHER'S WATCH

One night I dreamed I was locked in my Father's watch
With Ptolemy and twenty-one ruby stars
Mounted on spheres and the Primum Mobile
Coiled and gleaming to the end of space
And the notched spheres eating each other's rinds
To the last tooth of time, and the case closed.

What dawns and sunsets clattered from the conveyer
Over my head and his while the ruby stars
Whirled rosettes about their golden poles.
"Man, what a show!" I cried. "Infinite order!"
Ptolemy sang. "The miracle of things
Wound endlessly to the first energy
From which all matter quickened and took place!"

"What makes it shine so bright?" I leaned across
Fast between two teeth and touched the mainspring.
At once all hell broke loose. Over our heads
Squadrons of band saws ripped at one another
And broken teeth spewed meteors of flak
From the red stars. You couldn't dream that din:
I broke and ran past something into somewhere
Beyond a glimpse of Ptolemy split open,
And woke on a numbered dial where two black swords
Spun under a crystal dome. There, looking up
In one flash as the two swords closed and came,
I saw my Father's face frown through the glass.

John Ciardi

from IL VA NEIGER . . .

On a baptisé les étoiles san penser
Qu'elles n'avaient pas besoin de nom, et les nombres
Qui prouvent que les belles comètes dans l'ombre
Passeront, ne les forceront pas à passer

Francis Jammes

The imagination of scientists often exceeds that of the science fiction writer. The question asked is how an advanced technological civilization could capture most of the sun's energy. (See note above title of article 19.)

26

The Dyson Sphere

I. S. Shklovskii and Carl Sagan

An excerpt from *Intelligent Life in the Universe*, 1966.

To discuss another possible modification of the cosmos by the activities of intelligent beings, consider the following question: Is it possible that in the future—perhaps the distant future—man could so change the solar system that his activities would be visible over interstellar distances? In Chapter 11, we discussed the difficulties in the detection of planets about even the nearest stars, with present techniques. But what of the future? Is it possible that someday we shall be able to conclude, from observed characteristics, that a star is accompanied by a planet populated by an advanced technical civilization? Let us consider some of the ideas of Constantin Edwardovich Tsiolkovskii, an illustrious Russian pioneer in problems of space exploration.

Three quarters of a century ago, this remarkable man suggested a plan for the rebuilding and reorganization of the solar system. In his book *Dreams of the Earth and Sky*, published in 1895, he pointed out that the Earth receives only 5×10^{-10} of the total flux of solar radiation. He speculated that eventually mankind would make use of all the heat and light of the Sun by colonizing the entire solar system. Tsiolkovskii suggested that first the asteroids be rebuilt. The intelligent beings of the future, he predicted, would control the motion of these small planets "in the same way that we drive horses." The energy necessary to maintain the inhabitants of the asteroids would come from "solar motors." Thus, we see that over 70 years ago, Tsiolkovskii predicted the invention of the solar battery, a device which is presently used to provide energy for space vehicles.

The transformed asteroids would form a chain of space cities. The construction materials would initially come from the asteroids themselves, "the mass of which would be dismantled in a day." ▽ Tsiolkovskii's ideas on the re-engineering and relocation of the asteroids have been echoed in recent years by the American engineer Dandridge Cole, of the General Electric Corporation. △ After the asteroidal material is exhausted, Tsiolkovskii envisions the rebuilding of the Moon. He allows several hundred years for this project. Then, the Earth and the larger planets would be reorganized. According to Tsiolkovskii, the entire transformation of the solar system would require hundreds of thousands—perhaps millions—of years. This plan would provide enough heat and light to support a population of 3×10^{23} manlike beings—approximately 10^{14} more people than presently inhabit the Earth.

Although to his contemporaries the daring ideas of Tsiolkovskii seemed to be merely the daydreams of a provincial school-teacher, his brilliant foresight is readily appreciated today. The eminent American theoretical physicist Freeman J. Dyson, of the Institute for Advanced Study, Princeton, basing his theories on the achievements of contemporary science, has recently independently repeated many of Tsiolkovskii's ideas, without knowing anything of the Russian's work.

Dyson, in a most interesting article published in 1960, attempted to perform a quantitative analysis of the problem of rebuilding the solar system. He first discussed the fact that scientific and technological development takes place very rapidly, after a society has entered its technological phase. The timescale of such development is insignificant, compared with astronomical and geological timescales. Dyson concluded that the one important factor which restricts the scientific and technical development of an intelligent society is the limited available supply of matter and energy resources. At present, the material resources which can be exploited by man are limited roughly to the biosphere of the Earth, which has a mass ▽ estimated variously between 5×10^{17} and 5×10^{19} gm △—that is, less than 10^{-8} the mass of the Earth. The energy required by contemporary mankind per year is approximately equal to that which is liberated in the combustion of 1 to 2 billion tons of hard anthracite coal per year. In terms of heat, we find that contemporary man is expending an average of 3×10^{19} erg $\sec^{-1}$. The Earth's resources of coal, oil, and other fossil fuels will be exhausted in a few centuries.

The question of our reserves of matter and energy becomes more acute when we consider the prospective long-term technological development of our society. Even if we assume that the average annual growth rate in production is only one-third of a percent (a very small figure, when compared to the annual growth rate ▽ of a few percent in modern industrial societies △), our productivity will double in about a century. In 1000 years, the rate of manufacture will increase by 20,000 times; and in 2500 years, by 10 billion times. This means that the energy requirements in 2500 years will be 3×10^{29} erg $\sec^{-1}$, or approximately 0.01 percent of the entire luminosity of the Sun. This figure is approaching cosmic proportions. Will all of our energy resources have been exhausted by the time we achieve this level of productivity?

To answer this question, let us now consider the material resources which are conceivably available to mankind in the future. We shall—perhaps optimistically—assume that we will be able to achieve controlled thermonuclear reactions. The total amount of hydrogen in the Earth's hydrosphere is approximately 3×10^{23} grams, while the amount of deuterium is approximately 5×10^{19} grams. Deuterium would be the basic fuel of a thermonuclear reactor. The amount of energy released by reaction of all the available deuterium would be about 5×10^{38} ergs. In 2500 years, this amount of energy—still assuming an increase in production of one-third of a percent per annum—would be sufficient for only a 50-year period. Even if we assume that controlled thermonuclear fusion can eventually be fueled by ordinary hydrogen, and that 10 percent of the world's oceans can be utilized as an energy source—to burn more would probably be inexpedient—in 2500 years we would be able to provide only enough energy for another few thousand years.

Another possible energy source would be the direct utilization of solar radiation. Each second, approximately 2×10^{24} ergs of solar radiation fall upon the surface of the Earth. This is almost 100,000 times more than the current production of all forms of energy. Yet it is 100,000 times less than the estimated energy requirements for the year 4500 A.D. Thus, direct solar radiation is inadequate to support a stable and sustained increase in production of only one-third of a percent per annum, over a long period of time. From this discussion, we can conclude that the energy resources of the Earth are insufficient to fulfil the long-term requirements of a developing technological society.

Before considering this question further, let us make a slight digression. A hypercritical reader may claim that the above calculations are similar to the discussions of the English clergyman Thomas Malthus. This is, however, not the case. Malthus predicted that world population growth would outstrip the development of productive forces, and that this would lead to a progressive deterioration of living conditions. His proposed solution was that the poorer classes—that is, the working classes—lower their birthrate. Malthus' views are invalid, because in an intelligent, organized society, the increase of productive forces always outstrips the increase in population. The population of a nation is related, sometimes in a complex way, to its productivity, and in fact is ultimately determined by it. Our discussion of future energy budgets bears no relation to the Malthusian doctrine. We have been discussing only the possibilities of the increase in the productive capacities of a society, which is naturally limited to the material and energy resources available.

▽ The exponential increase in the population of the Earth during historical times is indicated schematically in Fig. 34–1. The required future productive capacity of our society is dramatically illustrated—assuming no major population self-limitation occurs—by extrapolation of the curve to the future. △

Let us ask another question: Will there in fact *be* any appreciable increase in the future productive capability of our society? What is the basis for assuming that mankind's progress will be directly related to an increase in his productive capacity?

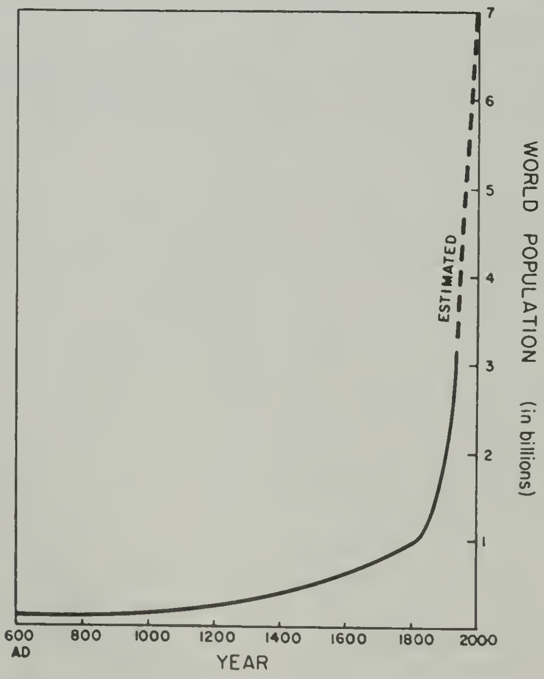


FIGURE 34–1. *Estimated past and extrapolated future rates of human population growth, planet Earth.*

Perhaps development will be in terms of qualitative, not quantitative, changes. These problems are philosophical in nature and cannot be discussed in detail here. However, I would like to state that I believe it to be impossible for a society to develop without a concurrent increase in production, both qualitatively and quantitatively. If an increase in productivity were eliminated, the society would eventually die. Note that if a society were to consciously interrupt its productive development, it would have to maintain a very precise level of production. Even the slightest progressive decrease would, after thousands of years reduce the technological potential to essentially nothing. Over these timescales, any civilization which consciously resolves to maintain a constant level of productivity would be balancing on a knife-edge.

Let us now return to the subject of the material resources available to a developing society. After reaching a high state of technical development, it would seem very natural that a civilization would strive to make use of energy and materials external to the planet of origin, but within the limits of the local solar system. Our star radiates 4×10^{33} ergs of energy each second, and the masses of the Jovian planets constitute the major potential source of material. Jupiter alone has a mass of 2×10^{30} grams. It has been estimated that about 10^{41} ergs of energy would be required to completely vaporize Jupiter. This is roughly equal to the total radiation output of the Sun over a period of 800 years.

According to Dyson, the mass of Jupiter could be used to construct an immense shell which would surround the Sun, and have a radius of about 1 A.U. (150 million kilometers). ▽ How thick would the shell of a Dyson sphere be? The volume of such a sphere would be $4\pi r^2 S$, where r is the radius of the sphere, 1 A.U., and S is its thickness. The mass of the sphere is just the volume times its density, ρ, and the mass available is approximately the mass of Jupiter. Thus, $4\pi r^2 \rho S = 2 \times 10^{30}$ grams. Thus, we find that $\rho S \simeq 200$ gm cm^{-2} △ of surface area would be sufficient to make the inner shell habitable. We recall that the mass of the atmosphere above each square centimeter of the Earth's surface is close to 1000 gm. ▽ If the over-all density of the shell were 1 gm cm^{-3} or slightly less, the thickness of the shell, S, would be a few meters. △ Man today, for all practical purposes, is a two-dimensional being, since he utilizes only the surface of the Earth. It would be entirely possible for mankind in the future—say, in 2500 to 3000 years—to create an artificial biosphere on the inner surface of a Dyson sphere. After man has accomplished this magnificent achievement, he would be able to use the total energy output of the Sun. ▽ Every photon emitted by the Sun would be absorbed by the Dyson sphere, and could be utilized productively. △ The inside surface area of the Dyson sphere would be approximately 1 billion times greater than the surface area of the Earth. The sphere could sustain a population great enough to fulfil the predictions made by Tsiolkovskii three quarters of a century ago.

We shall not at this time enter into a discussion of how such a sphere would be constructed, how it would rotate, or how we would guarantee that the inhabitants would not fall into the Sun. The fact is that the sphere would have different gravitational characteristics from those of a solid body. These problems, although complex, are not the principal problems. Dyson himself gave special attention to one interesting circumstance: A number of completely independent parameters—the mass of Jupiter, the thickness of an artificial biosphere, the total energy of the solar radiation, and the period of technological development—all, in Dyson's words,

> have consistent orders of magnitude. . . . It seems, then, a reasonable expectation that barring accidents, Malthusian pressures will ultimately drive an intelligent species to adopt some such efficient exploitation of its available resources. One should expect that within a few thousand years of its entering the stage of industrial development, any intelligent species should be found occupying an artificial biosphere which completely surrounds its parent star.

Up to this point, Dyson's speculations have been essentially the same as those of Tsiolkovskii, but based upon more recent scientific knowledge. At this point, Dyson introduces an idea novel ▽ even to Tsiolkovskii △: How will a civilization living on the inner surface of a sphere surrounding its star appear from outside? Dyson says:

> If the foregoing argument is accepted, then the search for extraterrestrial intelligent beings should not be confined to the neighborhood of visible stars. The most likely habitat for such beings would be a dark object having a size comparable to the Earth's orbit, and a surface temperature of 200 to 300°K. Such a dark object would be radiating as copiously as the star which is hidden inside it, but the radiation would be in the far infrared, at about 10μ wavelength.

If this were not the case, then the radiation produced by the star inside the shell would accumulate, and produce catastrophically high temperatures.

Since an extraplanetary civilization surrounded by a Dyson sphere would be a very powerful source of infrared radiation, and since the atmosphere of the Earth is transparent to radiation between 8 and 13μ, it would be possible to search for such infrared stars with existing telescopes on the Earth's surface. ▽ The sensitivity of contemporary infrared detectors is such that with the use of large telescopes, Dyson spheres could be detected over distances of hundreds of light-years even today. However, there is not necessarily any way of distinguishing a Dyson sphere detected at 8–13μ from a natural object such as a protostar, contracting towards the main sequence, and emitting infrared radiation with the same intensity. If the sky were mapped in the infrared for possible Dyson spheres, each radiation source could then be investigated by other techniques for characteristic radiation of an intelligent species—for example, at the 21 cm radio frequency. △

It is also possible that Dyson civilizations might be detected by existing optical techniques.

> Such radiation might be seen in the neighborhood of a visible star, under either of two conditions: A race of intelligent beings might be unable to exploit fully the energy radiated by their star because of an insufficiency of accessible matter, or they might live in an artificial biosphere surrounding one star of a multiple system, in which one or more component stars are unsuitable for exploitation and would still be visible to us. It is impossible to guess the probability that either of these circumstances could arise for a particular race of extraterrestrial intelligent beings, but it is reasonable to begin the search for infrared radiation of artificial origin by looking in the direction of nearby visible stars, and especially in the direction of stars which are known to be binaries with invisible companions.

Dyson's idea is notable for the fact that it presents a specific example of how the activity of an intelligent society might change a planetary system to such an extent that the transformation would be detectable over interstellar distances. But a Dyson sphere is not the only way a civilization can utilize the available energy resources of its planetary system. There are other sources which may be even more effective than the complete utilization of local solar radiation.

First we shall consider using the mass of the large planets as a fuel for thermonuclear reactors. The Jovian planets consist primarily of hydrogen. The mass of Jupiter is 2×10^{30} gm, and the store of energy which would be released from the conversion of this quantity of hydrogen into helium would be approximately 10^{49} ergs, a vast amount of energy comparable to that released in a supernova explosion. If this energy were liberated gradually, over a long period of time—for example, at a rate of 4×10^{33} erg $\sec^{-1}$, comparable to the present solar luminosity—it would last for nearly 300 million years, a time span most likely greater than the life of the technical civilization itself.

Perhaps a highly developed civilization could also use a fraction of its own star as an energy source. For example, it might be possible to "borrow" a few percent of the solar mass without any significant decrease in luminosity. Certainly, we do not yet know the methods for arranging such a loan, but it would probably be accomplished gradually. The conversion of, say, 5×10^{31} gm of solar hydrogen —25 times more than the mass of Jupiter—would provide some 3×10^{50} ergs, an energy supply adequate to satisfy the requirements of a technical civilization for several billion years.

It is also conceivable, but much less likely, that such utilization of the mass of a star would occur at a more rapid pace, perhaps regulated so that the lifetime of the star would correspond to the lifetime of the civilization. The spectral characteristics of such a star would slowly vary. At the time that the star finally was turned off, the civilization would cease to exist. ▽ But while we can imagine such a cosmic Götterdämmerung, it is not likely to be staged often. △

If intelligent use is made of the enormous stores of energy available in the solar system, it would not be necessary to construct a Dyson sphere about the Sun. Assume, for example, that half the mass of the Jovian planets were used to construct artificial satellites, the "space cities" of Tsiolkovskii. These cities would be established in orbits close to the Sun. We may imagine thermonuclear reactors installed in these satellites and fueled by the remaining material in the Jovian planets. This picture preserves the essential direction of the development of a technical civilization envisioned in *Dreams of the Earth and Sky*, but it adds controlled thermonuclear reactions as an energy source.

Now, given these enormous controlled energy sources, civilizations could expand their activities on a much larger scale. We shall presently consider several additional ways in which a civilization might announce its presence over interstellar distances. These methods seem fantastic. We wish to emphasize that we are not saying that such methods are actually in existence; but the probability of their existence is not zero. ▽ And what we have encompassed as "fantastic" has declined progressively with the centuries. △ The fundamental point is that the possibilities open to advanced technical civilizations are almost unlimited.

ISAAC ASIMOV

Isaac Asimov, born in 1920 in Petrovichi, Russia, came to the United States at the age of three, He graduated from Columbia University in 1939, and received his Ph.D. there in 1948. Since 1949 he has been in the department of Biochemistry at Boston University. Pebble in the Sky, Asimov's first book, published in 1950, started him on a prolific career of writing for the layman. For his contribution in explaining science to the public he won the James T. Grady Award of the American Chemical Society in 1965. He is also well known as a writer of science fiction.

HERMANN BONDI

Hermann Bondi, Professor of Applied Mathematics at King's College, University of London, was born in Vienna in 1919, and received his education at Trinity College, Cambridge (B.A. 1940, M.A. 1944). He also taught and did research in the United States. Professor Bondi's interests are the composition of stars, cosmology, and geophysics.

MARGARET BURBIDGE

Margaret Burbidge often works with her husband, an astrophysicist, as a husband-and-wife team. The Burbidges met and married while she, an astronomer, was working at the University of London Observatory, and he, a physicist, was studying meson physics at the same university. They have held appointments successively at Mt. Wilson and Palomar Observatories and the University of Chicago's Yerkes Observatory at Williams Bay, Wisconsin. Currently they are in the physics department of the University of California at San Diego, and are frequent contributors to scientific journals.

SAMUEL BUTLER

Samuel Butler (1612–1680), the English satirist, was born at Strensham, Worcestershire. After the Restoration he became successively Secretary to Earl of Carbery, Steward of Ludlow Castle, and then a full-time writer. Between 1663 and 1678 he published the three parts of his most famous work, Hudibras. Just as Cervantes in his Don Quixote satirized the fanaticism of knight errantry, Butler in his Hudibras, a burlesque heroic poem, ridiculed the fanaticism, pretentiousness, pedontry, and hypocrisy of the Puritans of his time.

JOHN CIARDI

John Ciardi, a poet and an educator, was born in Boston in 1916. His bachelor's degree is from Tufts, and he has a master's degree from the University of Michigan. He has taught at Kansas City, Harvard, and Rutgers. He is the director of the Bread Loaf Writers Conference and the poetry editor of the Saturday Review. Recipient of many awards in poetry, including the Prix de Rome, his works include Homeward to America, Other Skies, Live Another Day, I Marry You.

ARTHUR C. CLARKE

Arthur C. Clarke, British scientist and writer, is a Fellow of the Royal Astronomical Society. During World War II he served as technical officer in charge of the first aircraft ground-controlled approach project. He has won the Kalinga Prize, given by UNESCO for the populorization of science. The feasibility of many of the current space developments was perceived and outlined by Clarke in the 1930's. His science fiction novels include Childhoods End and The City and the Stars.

I. BERNARD COHEN

I. Bernard Cohen was born in Far Rockaway, New York, in 1914. At Harvard he received a B.S. in 1937 and a Ph.D in history of science in 1947. Since then he has been on the Harvard faculty in the history of science. He has been editor of Isis, the journal of the History of Science Society, and has written many books and papers in his field, among them a number of studies of Newton's works.

EDWARD U. CONDON

Edward U. Condon was born in Alamogordo, New Mexico, in 1902 and obtained his degrees from the University of California. After teaching physics at Princeton, he became the director of the U.S. National Bureau of Standards for six years. Among his subsequent positions were a professorship of Physics at Washington University (St. Louis, Mo.) and one at the University of Colorado. In 1945–46 he was the science advisor to the Special Committee on atomic energy of the 79th Congress. His research interests include quantum mechanics, atomic and molecular spectra, nuclear physics, micro-wave radio, and solid state physics.

HENRY S. F. COOPER, JR.

Henry S. F. Cooper, Jr., writer for the New Yorker since 1956, was educated at Phillips Academy, Andover, and at Yale University. At Yale he took a course in astronomy from Harlan Smith, and this led him to write an article about Professor Smith. This article, in part, started his writing career for the New Yorker.

COPERNICUS

See Unit 2 Text, Section 6.1

JEAN BAPTISTE CAMILLE COROT

Jean Baptiste Camille Corot (1796–1875), one of the greatest nineteenth-century landscape painters of France, was born in Paris and studied at the Lycee de Louen. Corot was one of the first to paint out-of-doors. He traveled extensively throughout the continent. Corot's works are admired for their idyllic romanticism injected into the paintings of mountains, cathedrals, and villages. His "Chartres Cathedral," "Chateau de Rosny," and "Belfry at Douai," all in the Louvre, exemplify his touch.

ROBERT H. DICKE

Robert H. Dicke, Professor of Physics at Princeton, was born in St. Louis, Missouri, in 1916, and he earned his Ph.D. at Rochester University in 1941. He was a staff member of the Radiation Laboratory at Massachusetts Institute of Technology during World War II. Dr. Dicke is widely known for his studies in gravitation, relativity, geophysics, and astrophysics.

STEPHEN H. DOLE

Stephen H. Dole is a researcher for the RAND Corporation. Born in West Orange, New Jersey in 1916, he attended Lafayette and the United States Naval Academy. Presently he is a member of the steering committee for the Group for Extraterrestrial Resources. His work has dealt with chemistry and space programs; he studies oxygen recovery, human ecology in space flight, properties of planets, and origin of planetary systems.

RICHARD PHILLIPS FEYNMAN

Richard Phillips Feynman was born in New York in 1918, and graduated from the Massachusetts Institute of Technology in 1939. He received his doctorate in theoretical physics from Princeton in 1942, and worked at Los Alamos during the Second World War. From 1945 to 1951 he taught at Cornell, and since 1951 has been Tolman Professor of Physics at the California Institute of Technology. Professor Feynman received the Albert Einstein Award in 1954, and in 1965 was named a Foreign Member of the Royal Society. In 1966 he was awarded the Nobel Prize in Physics, which he shared with Shinchero Tomonaga and Julian Schwinger, for work in quantum field theory.

ANATOLE FRANCE

Anatole France (1844–1924) was the nam de plume of Anatole Francois Thiboult. The son of a bookseller, he began his productive literary career as a publisher's reader, "blurb" writer, and critic. Under the patronage of Madame de Calillavet, he published numerous novels, such as Le Livre de Mon Ami. His early writings were graceful. Later they grew skeptical and solipsistic, as in Les Opinions de Jerome Cognard. In 1886 France was elected to the French Academy, and in 1921 he was awarded the Nobel Prize for Literature.

GALILEO GALILEI

See Unit 1, Section 2.2

CHARLES COULSTON GILLISPIE

Charles Coulston Gillispie, born in 1918 in Harrisburg, Pennsylvania, was educated at Wesleyan, Massachusetts Institute of Technology, and Harvard. After teaching at Harvard, he went to Princeton, where he is now Professor of History. He has been president of the History of Science Society, and a Fellow of the American Academy of Arts and Sciences, and member of the Academie Internationale d'Histoire Des Sciences. His books include Genesis and Geology, A Diderto Pictorial Encyclopedia, and The Edge of Objectivity.

OWEN JAY GINGERICH

Owen Jay Gingerich, born in Washington, Iowa, in 1930, is an astrophysicist and historian of astronomy at the Smithsonian Astrophysical Observatory in Cambridge, Massachusetts. Among his responsibilities has been the task of directing the Central Bureau for Astronomical Telegrams, the world clearing house for comets, sponsored by the International Astronomical Union. He is interested in applying computers to the history of astronomy, and his translation from Kepler's Astronomia Nova, published for the first time in this Reader, was aided by a Latin dictionary program on an I.B.M. 7094 computer.

BANESH HOFFMANN

Banesh Hoffmann, born in Richmond, England, in 1906, attended Oxford and Princeton. He has been a member of the Institute of Advanced Study, electrical engineer at the Federal Telephone and Radio Laboratories, researcher at King's College, London, and a consultant for Westinghouse Electric Corporation's science talent search tests. He has won the distinguished teacher award at Queen's College, where he is Professor of Mathematics. During the 1966–1967 year he was on the staff of Harvard Project Physics.

GERALD HOLTON

Gerald Holton received his early education in Vienna, at Oxford, and at Wesleyan University, Connecticut. He has been at Harvard University since receiving his Ph.D. degree in physics there in 1948; he is Professor of Physics, teaching courses in physics as well as in the history of science. He was the founding editor of the quarterly Daedalus. Professor Holton's experimental research is on the properties of matter under high pressure. He is a co-director of Harvard Project Physics.

FRED HOYLE

Fred Hoyle is an English theoretical astronomer, born in Yorkshire in 1915. Now Professor of Astronomy at Cambridge University, he is perhaps best known for one of the major theories on the structure of the universe, the steady state theory. Hoyle is well known for his scientific writing, and his success in elucidating recondite matters for the layman.

FRANCIS JAMMES

Francis Jammes was a French poet whose verses celebrate the pure and simple life. He was born on December 2, 1868 in Tournay. After his education in Bordeaux and Pau, he became a lawyer's clerk. He began writing at an early age and published his first work in 1898. He spent the latter part of his life in the city of Hasparren in the Basque country. He devised a compelling kind of free verse, using lines of varying lengths. Some of his favorite topics include the simple country folk of the Pyrenees, animals, young girls, as well as religious themes. He died in 1938.

JOHANNES KEPLER

See Unit 2 Text, Section 7.1.

PAUL KLEE

Paul Klee (1879–1940), one of the most imaginative painters of the twentieth century, was born near Berne, Switzerland. He taught at the Bauhaus, the influential German art and design school in Weimar. Klee's style is unbounded by tradition: his figures are visually unrealistic, his space and design seem incoherent, and his colors are symbolic and emotional rather than descriptive.

ROBERT B. LEIGHTON

Robert B. Leighton, born in Detroit, Michigan in 1919, was first a student and then a faculty member at California Institute of Technology. He is a member of the International Astronomical Union, the National Academy of Science and the American Physics Society. Professor Leighton's work deals with the theory of solids, cosmic rays, high energy physics, and solar physics.

RICHARD LIPPOLD

Richard Lippold, sculptor, was born in Milwaukee in 1915. He attended the University of Chicago and graduated from the Art Institute of Chicago with a B.F.A. degree in 1937. Since graduating he has taught at the Layton School of Art in Milwaukee, the University of Michigan, Goddard College, served as head of the art section of the Trenton Junior College from 1948–52, and since 1952 has been a professor at Hunter College in New York. His works have been exhibited internationally, and frequently in the Whitney Museum in New York City. He has had several one-man shows at the Willard Gallery. In 1953 he was awarded third prize in the International Sculpture Competition, Institute of Contemporary Arts, London, and in 1958 the Creative Arts award from Brandeis University. He is a member of the National Institute of Arts and Letters.

TERRY MORRIS

Terry Morris, a free-lance magazine writer since 1951, was born in New York City. After earning her B.A. and M.A. in English, she taught English for six years in New York high schools. During World War II, her husband in the service, she wrote her experiences as an army wife in her first article, "Armytown, U.S.A." in The New Republic, wnich was expanded into a novel No Hiding Place (1945) at publisher Alfred A. Knopf's suggestion. Her work has appeared in many American and foreign magazines, and she has also worked for newspapers, radio and television.

ISSAC NEWTON

See Unit 2 Text, Section 8.1.

PABLO RUIZ PICASSO

Pablo Ruiz Picasso, the initiator (with Georges Braque) of Cubism and probably the most seminal contributor in twentieth century art, was born at Malaga, Spain in 1881. After lessons in art from his father, an artist and professor at the Academy of the Arts in Barcelona, Picasso settled in Paris. His early paintings were somber pictures, many of the life of a circus or a big city. But after 1905 he evolved toward Cubism. Picasso moved away from three-dimensional perspective and created a surrealistic two-dimensional picture. Perhaps his most famous picture is "Guernica" (at the Museum of Modern Art in New York), his reaction to the bombing of civilians in the Spanish Civil War.

PETER GUY ROLL

Peter Guy Roll was born in Detroit, Michigan, in 1933. At Yale he received his B.S., M.S., and Ph.D. He worked as Junior Scientist on the design of a nuclear reactor for the Westinghouse Atomic Power Division. After teaching and research experience at Yale, Princeton, and the University of Michigan, he became Associate Professor of Physics at the University of Minnesota. He has also been a staff physicist for the Commission on College Physics.

CARL SAGAN

Carl Sagan, born in 1921, is Assistant Professor of Astronomy at Harvard University and a staff member of the Smithsonian Astrophysical Observatory. He has made significant contributions to studies of planets, of the origin of life, and of the possibilities of extraterrestrial life. An experimenter on the Mariner 2 Venus misson, he has served on advisory committees for the National Academy of Sciences and for the National Aeronautics and Space Administration.

MATTHEW SANDS

Matthew Sands was born in Oxford, Massachusetts, in 1919. He attended Clark College, Rice Institute, and Massachusetts Institute of Technology. During World War II he worked at the Los Alamos Scientific Laboratory. He was Professor of Physics at the California Institute of Technology before joining the linear accelerator group at Stanford University. Professor Sands specializes in electronic instrumentation for nuclear physics, cosmic rays, and high-energy physics. He served as chairman of the Commission on College Physics.

GEORGES SEURAT

Georges Seurat (1859–1891) was educated at Ecole des Beaux-Arts. His most famous painting, "Un Dimanche d'Eté à la Grande Jatte" (Chicago Art Institute) exemplified his characteristic technique of Pointillion painting with a very large number of small spots of strong primary colors mixed only with white. Seurat is considered to be a neo-impressionist owing to his use of orderly fundamental structures—a form antagonistic to the intuitive method of the Impressionists.

WILLIAM SHAKESPEARE (1564–1616) needs no introduction.

I. S. SHKLOVSKII

I. S. Shklovskii is a staff member of the Sternberg Astronomical Institute of the Soviet Academy of Sciences, Moscow. One of the world's leading astrophycists, he has played a major role in Soviet space achievements and in radio astronomy. His books include Physics of the Solar Corona, Cosmic Radio Waves, and Intelligent Life in the Universe. He is a Fellow of the Royal Astronautical Society of Great Britain, and a Corresponding Member of the Soviet Academy of Sciences.

WALTER S. SULLIVAN

Walter S. Sullivan was born in New York City in January of 1918. He received a BA from Yale in 1940 and joined the staff of the New York Times in the same year. He was first a foreign correspondent but then turned his interest to reporting science. He has been the Science Editor of the Times since 1964, and has also published several books. Mr. Sullivan has two daughters and a son, and currently lives in Riverside, Connecticut.

JOSEPH WEBER

Joseph Weber, now Professor of Physics at the University of Maryland, wos born in Paterson, New Jersey, in 1919. He received his B.S. at the United States Naval Academy, and his Ph.D. from the Catholic University of America. He has been a fellow at the Institute of Advanced Study, a Guggenheim Fellow, and a Fellow at the Lorenz Institute of Theoretical Physics at the University of Leyden, Holland.

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