Radio telescopes

Science content

Electromagnetic waves, reflection, converging mirror, wavelength, beamwidth, star, galaxy.

Science curriculum links
AT15 Using light and e/m radiation
AT16 The Earth in space

Syllabus links
- GCSE Science, Physics

Lesson time
1–1½ hours

Links with other SATIS materials
1208 Are you made of Stardust?

NERIS
Search on
RADIOTELESCOPES or
TELESCOPES

SUMMARY

The unit uses radio waves to exemplify some of the properties of electromagnetic radiation. It considers the design of radio telescopes and the problems of obtaining good resolution, defining the 'beamwidth' of a radio telescope. Comparisons are made with other radio communication devices such as TV satellite dishes, microwave links etc.

STUDENT ACTIVITIES

- ☐ Interpreting photographs taken with optical and radio telescopes;
- ☐ Drawing a cross-section of a paraboloid, showing rays reflected by it;
- ☐ Calculating the beamwidth for a range of communication devices.

AIMS

- ☐ To link with work on electromagnetic radiation and astronomy
- ☐ To show some of the scientific principles involved in the design of radio telescopes

USING AND ADAPTING THE UNIT

- ☐ The unit in its entirety is suitable for more able students from the fourth to lower sixth forms. (Q7 requires an understanding of trigonometry.)
- ☐ Q1 and the 'Discussion activity' may be used with a wider range of students.

Author **Sir Francis Graham-Smith FRS**

First published 1991

Teaching notes

The resolving power of a telescope, its ability to distinguish between two objects close together, depends on the wavelength divided by the diameter of the aperture. To get the same resolution as an optical telescope, a radio telescope working at 1 metre wavelength would need to be a million times larger.

Beamwidth ($60\lambda/D$), the term used in the unit to describe the accuracy with which a radio telescope can be directed, is proportional to its *resolving power* (measured in degrees it is approximately $70\lambda/D$).

To make 'larger' radio telescopes, astronomers now use an array of radio telescopes and combine the data by interferometry.

Discussion activity

Good dictionaries and encyclopaedias may prove helpful, although students may compile their glossaries using the unit alone.

More detailed answers are provided here than would be expected from students themselves.

Radio waves Electromagnetic waves ranging in wavelength from millimetres to a few kilometres (frequencies of 10^{12} to 10^4 hertz).

Radio telescope A special aerial/antenna for receiving radio waves from space.

Galaxy A system of stars.

Optical telescope Receives and focuses light.

Paraboloid A geometric surface with the shape of a parabola: $y^2 = 4ax$.

Focal length The distance from the base of the reflector to the focus.

Beamwidth A measure of the antenna's directivity; the angle between the two directions in the main beam at which the power response has fallen to half its maximum value.

Array of radio telescopes Several radio telescopes, pointing towards a single object and connected to a single receiver.

Acknowledgements
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Figures 5, 6, 7, 8 and 9 supplied by F. Graham-Smith.

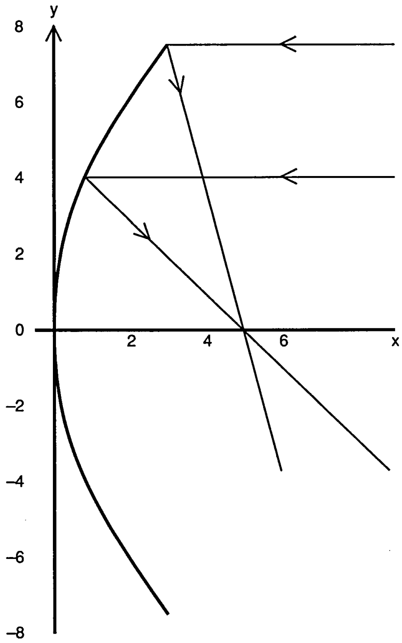
Answers to the questions

Q1 *Radio emission comes from outside the visible galaxy. (It is emitted by hot gas ejected from the central region in two oppositely directed jets.)*

Q2 *(a)* $y^2 = 20x$

(b) 0, (1.41) 2.00, 3.16, 4.47, 6.32, 7.74

(c) and (d) See diagram.



Q3 *(a) 0.27 cm (2.7 mm),*

(b) 0.1 mm.

Q4 *Beamwidth of the JCMT = 60 × 1/ (1000 × 15) = 0.004° = 14.4 seconds.*

Astra satellite dish = 60 × 2.7/60 = 2.7°

Lovell telescope = 60 × 0.21/(76.2 × 100) = 0.16°

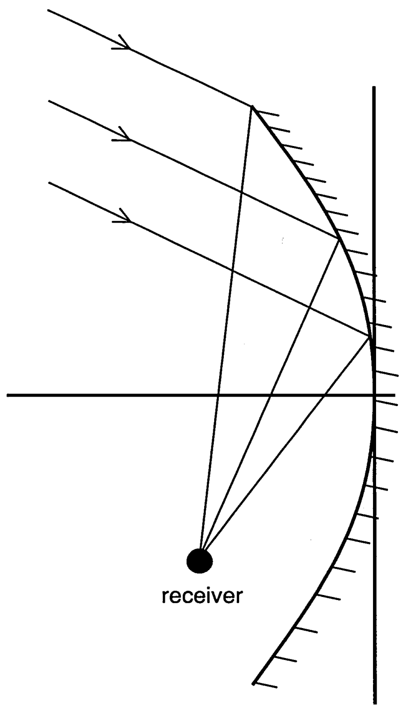
Microwave link = 60 × 3/ 200 = 0.9°

Airport radar = 60 × 10/(100 × 2) = 3° vertical,

60 × 10/ (100 × 5) = 1.2° horizontal.

Q5 *There is 4° between satellites. The beamwidth of a 40 cm dish = 4°. There will be no interference from Copernicus only if the dish is correctly aligned.*

Q6 *(a)*



(b) The dish may be mounted nearly vertically.

Q7 *Assuming a beamwidth of MERLIN of 0.1 second as given in the text (in practice considerably less), students will need to use* $s = r \sin \theta$ *or* $s = r\theta$, *(if* θ *is small and measured in rads) where s is the distance across beam, r is the distance from the radio telescope*

(a) s = 5000 km × sin (0.1/3600)°
= 0.00242 km = 2.42 m

(b) s = 400 000 × sin (0.1/3600)°
= 0.194 km ≈ 200 m

(c) s = 1 000 000 × sin (0.1/3600)°
= 0.485 light years ≈ 0.5 light years

Radio telescopes

Reading, discussion, questions and calculations. A4 graph paper is needed for Q2.

Radio telescopes are really no different from the satellite dishes people use to watch TV programmes. This unit explains how they work.

Radio waves from space were discovered by an American, Karl Jansky, who published his discovery in 1932. However, **radio telescopes**, which are aerials (antennas) specially designed for studying radio waves from space, were not built until after the Second World War.

Discoveries made with radio telescopes have helped to revolutionise our understanding of the universe. Astronomers found **galaxies** so far away that they could not be seen with ordinary **optical telescopes**. Radio waves from these giant systems of stars take billions of years to reach the Earth. They give information about what the universe was like a very long time ago. Such infomation has led astronomers to believe that the universe began with a 'big bang'.

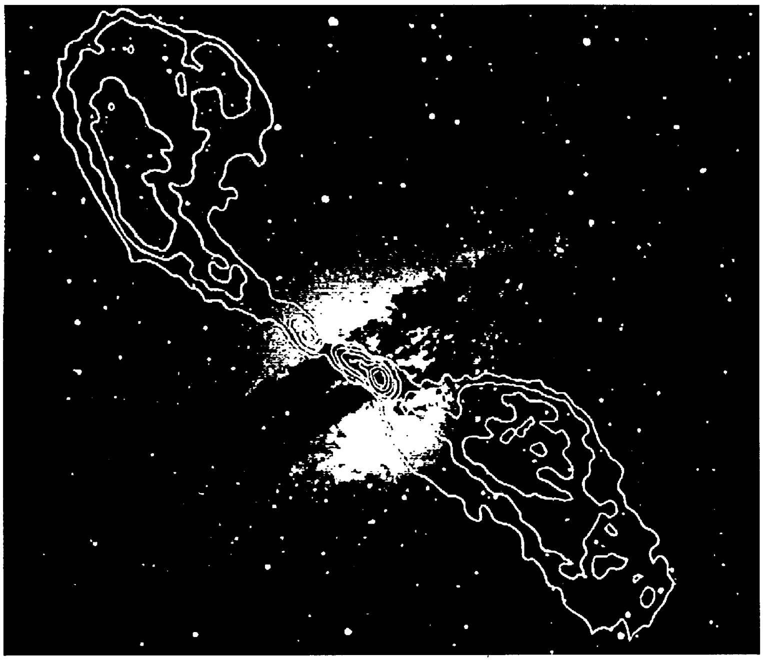


Figure 1 A galaxy, seen with an optical telescope and with a radio telescope. The contour lines show the strength of the radio emission

> ***Q1*** *Describe the differences you see between the shape of the galaxy seen by an optical telescope and a radio telescope in figure 1.*

An investigation with radio waves

- Try using a portable radio inside a cardboard box.
- Then cover the box with cooking (aluminium) foil.
- Try this with the radio tuned to long, medium, and short (VHF) wavelengths.

What do your observations tell you about the properties of radio waves compared with light waves?

Discussion activity

What do the following terms mean? Find where they are used in the unit. Work with a partner and decide on the best definitions you can. Then write them down.

radio waves
radio telescope
galaxy
optical telescope
paraboloid
focal length
beamwidth
array of radio telescopes

Telescopes – what do they do?

Optical telescopes collect light from distant objects and focus it, either within the eye or on to some recording instrument such as a camera.

Some stars, including our own Sun, emit radio waves as well as light. These radio waves can be collected by a radio telescope, which focuses them on to a radio receiver. Astronomers can then measure their strength and other characteristics.

Light and radio are both electromagnetic waves, but with different wavelengths.

Light

red	700 nanometres
yellow	600 nanometres
blue	400 nanometres

Radio

VHF	3 metres
TV	½ metre
microwaves	30 cm to 3 cm

(1 nanometre = 0.000 000 001 metre = 10^{-9} metre)

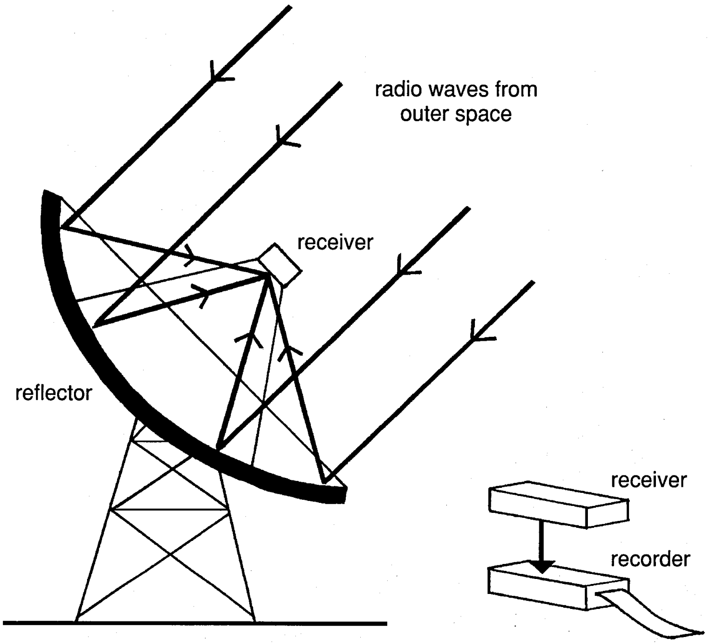


Figure 2 How a radio telescope works

How does a radio telescope work?

A radio telescope is a huge aerial for collecting weak radio signals from outer space. Radio telescopes and TV satellite dishes both use a large metal dish to reflect the radio waves onto the receiver. These dishes are made in the shape of **paraboloids**. The radio receiver is positioned at the **focus** of the paraboloid.

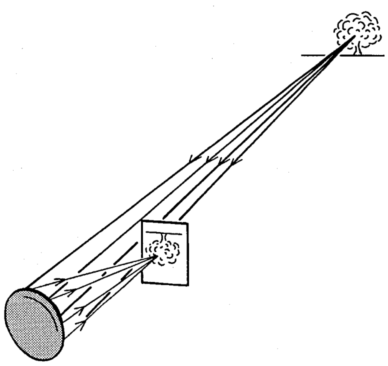


Figure 3 Projecting an image on a screen with a converging mirror

Have you tried using a converging (concave) mirror to focus an image from a distant point of light on a screen?

Reflector radio telescopes work in much the same way except the receiver replaces the screen.

The screen must be at the focus of the mirror to get a sharp image. The distance from the mirror to the screen is the focal length of the mirror.

The shape of the mirrors you use in school laboratories is part of the surface of a sphere. (They are known as spherical mirrors.) You can get a sharper image with a mirror curved in the shape of a paraboloid (a parabolic mirror). This is the shape used in reflector telescopes.

The **focal length** of the paraboloid is the distance from the base of the reflector to the **focus.** If this distance is written as ***a*** the shape of the paraboloid is described by the coordinates ***x*** and ***y***, which are related by:

$$y^2 = 4ax$$

Q2 A paraboloid radio telescope has a focal length of 5 m.

(a) What is the equation for this telescope?

x (m)	0	0.1	0.2	0.5	1.0	2.0	3.0
± y (m)		1.41					

(b) Copy the table and write in it the values of y.

(c) Draw a cross section of the paraboloid reflector with aperture 15 m (and focal length 5 m) using a scale of 1/100.

(d) Draw rays parallel to the axis and reflected at the surface. (All rays are reflected according to the simple law: angle of incidence equals angle of reflection.) All rays should then reach the focus.

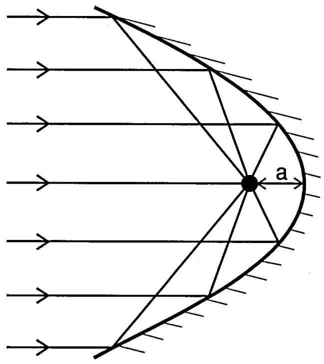


Figure 4 The shape of a paraboloid

The surface of a practical radio telescope must follow this shape with an accuracy depending on the radio wavelength being received. An accuracy of about *one tenth of the wavelength* is usually sufficient. The Lovell Telescope at Jodrell Bank in Cheshire works well at a 21 centimetre wavelength. Some radio telescopes can be used at wavelengths of less than one millimetre. These must have very accurate surfaces, and so they are comparatively small.

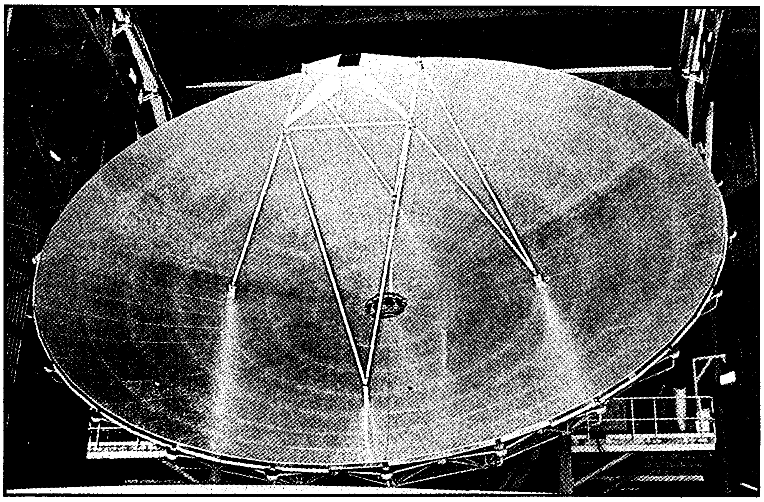


Figure 5 The 15 metre diameter James Clerk Maxwell Telescope on Mauna Kea, Hawaii completed in 1987. It is used to receive radio waves of millimetre wavelength. These waves are absorbed by water vapour, so the telescope is sited on a high mountain, above the lower atmosphere

Table 1 Diameters of some radio wave receiving dishes and typical wavelengths at which they work

Receiver	**Typical wavelength** λ	**Diameter** D
Astra TV satellite dish	2.7 cm	60 cm
Microwave link (Post Office Tower)	3 cm	2 m
Airport radar	10 cm	5 m × 2 m*
James Clerk Maxwell telescope in Hawaii	1 mm	15 m
Lovell telescope at Jodrell Bank	21cm	76 m

* Note that airport radar uses an elliptical reflector. The smaller vertical width gives a broader beam in this direction.

> ***Q3*** *Look at table 1. How accurate must the surface of each of the following reflectors be? (The surface of a radio telescope reflector must be accurate to one tenth of a wavelength.)*
> *(a) An Astra TV satellite dish.*
> *(b) The James Clerk Maxwell telescope in Hawaii.*

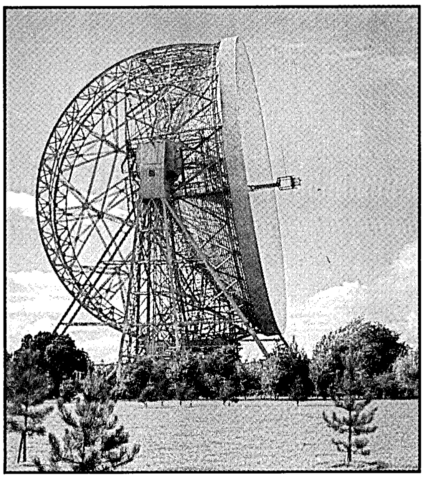


Figure 6 The Lovell radio telescope at Jodrell Bank, Cheshire

What is beamwidth?

A radio telescope is most efficient when it is pointing exactly in the direction of the source of the radio waves. This might be a star or a space probe. A small error in direction does not matter as long as it is within an angle called the **beamwidth**.

The beamwidth depends on the diameter (***D***) of the telescope and the wavelength (λ) of the radio waves.

This formula gives an estimate of the beamwidth

$$\text{beamwidth (degrees)} = \frac{60\,\lambda}{D}$$

(λ and D in the same units)

The bigger the radio telescope the smaller the beamwidth and the better it can separate radio sources that are close together in the sky.

> ***Q4*** *Calculate the beamwidth of*
> *(a) the James Clerk Maxwell telescope,*
> *(b) one other receiver from table 1.*
>
> ***Q5*** *Two TV satellites, Astra and Copernicus are at 19° east and 23° east respectively. Could viewers receive Astra programmes on a 40 cm dish without interference from programmes broadcast by Copernicus?*

Steering a radio telescope

An astronomer may need to study a series of objects in different parts of the sky and the telescope must move to point in any direction. Most are mounted on a circular track, for azimuth motion, while the reflector can move to any elevation.

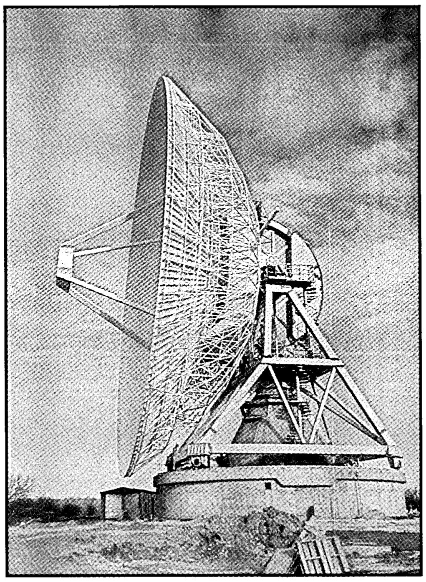


Figure 7 A 32 metre radio telescope at Cambridge. Electric motors drive the azimuth motion (round the azimuth track) and the elevation (through the vertical wheel)

Tracking a star

The Sun and the stars move across the sky as the Earth rotates. A radio telescope has to follow this movement. The pointing direction of the telescope is measured continuously. A computer checks the direction is the required one. Differences between measured and required directions are used to control the steering motors.

The bigger the better but . . . .

Radio waves are very much longer than light waves. Radio telescopes need to be much larger than optical telescopes to tell individual sources apart. The largest steerable radio telescope is in Germany and is 100 m across. A much bigger radio telescope would be impossible to steer. However, radio astronomers have devised some ingenious solutions to the problem!

The dish of the world's largest reflector telescope cannot be moved. It is built in a bowl-shaped valley at Arecibo, in Puerto Rico. Its reflector surface is part of a sphere rather than a paraboloid and points directly upwards. The telescope beam is directed over a range of angles by moving the receiver sideways, while the reflector stays still.

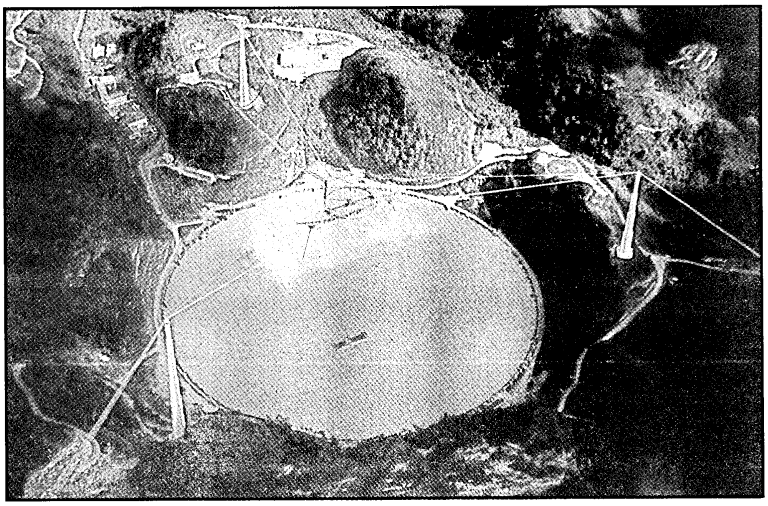
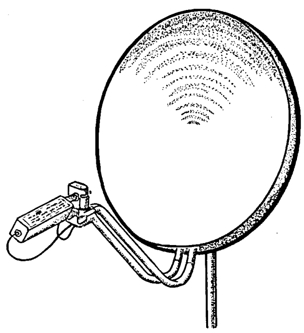


Figure 8 The Arecibo radio telescope

Q6 *You may have seen TV satellite dishes with offset receivers.*



(a) Draw a diagram to show how the radio waves reach the receiver.

(b) Suggest an advantage of this arrangement for mounting the dish on a wall.

Radio waves can be collected over a larger area with an array of antennas connected to a single radio receiver.

Another way of collecting radio waves falling on a large area is to use an **array of radio telescopes**. That means several radio telescopes, all pointing towards a single object, connected to a single receiver through microwave communication links. The beamwidth depends on the maximum spacing between the telescopes.

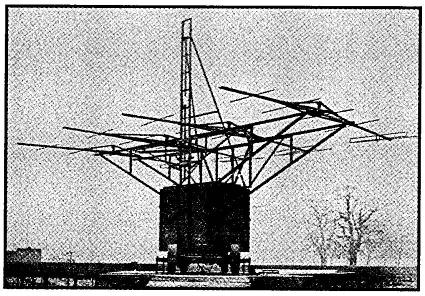


Figure 9 An array of antennas used in pioneering radio astronomical observations by J. S. Hey

A multiple telescope array called MERLIN extends from Jodrell Bank, near Manchester, to Cambridge, a distance of 220 kilometres. At a wavelength of 6 centimetres the beamwidth is less than 0.1 second. This array can be used to make maps of the radio emissions from galaxies and quasars with better detail than the largest optical telescopes.

Arrays of radio telescopes can be thousands of kilometres long. Each radio telescope records radio waves from the same object. These recordings are played into a single receiver.

Larger arrays of radio telescopes will have to extend into space. Astronomers would like to launch a series of radio telescopes into orbit around the Earth or even into orbit around the Sun. Such a telescope array would have a diameter of several hundred million kilometres across.

MERLIN stands for Multi-Element Radio-Linked Interferometer Network.

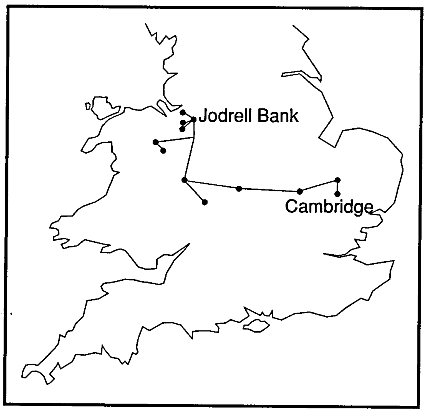
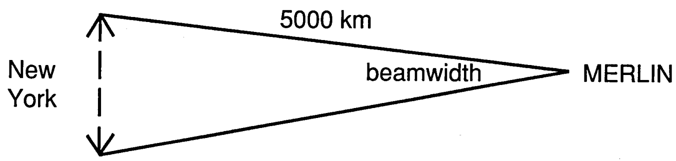


Figure 10 A map of MERLIN

A more challenging question

Q7 *How accurately would the beam of MERLIN (0.1 second) define the position of a radio emitter*
(a) over New York, 5000 km away,



(b) on the surface of the Moon, 400 000 km away,
(c) in a galaxy one million light years away?

Answers to the questions are given in the *Teachers' Notes*.

Are there fairies at the bottom of the garden?

Science content

Electrons, electric current, electrostatic phenomena, sensors, (neutrinos), nature of scientific evidence.

Science curriculum links

AT 1 Exploration of science
AT11 Electricity and magnetism
AT12 IT including microelectronics
AT17 The nature of science

Syllabus links

- GCSE Science, Physics
- Sixth-form General Studies

Lesson time

1 hour
(more for practical work)

Links with other SATIS materials

907 Your Stars – Revelation or Reassurance?

NERIS

Search on
ELECTRONS and UPPER SECONDARY
or on
ATOMIC STRUCTURE and UPPER SECONDARY

SUMMARY

What is the evidence for the existence of fairies, electrons and neutrinos?

STUDENT ACTIVITIES

- ☐ Information and questions considering the evidence and the tentative nature of proof: the fake Cottingley fairies.
- ☐ Information and questions on the properties and detection of electrons and neutrinos.
- ☐ Design, make and test a fairy detector (optional).

AIMS

- ☐ To provide opportunities to consider the nature of scientific evidence and belief
- ☐ To link with work on static electricity, electromagnetism and sensors in microelectronics
- ☐ To revise and deepen students' understanding of the properties of electrons and to link with new ideas on particle physics
- ☐ To consider evidence and spurious results
- ☐ To design, make and evaluate a piece of experimental apparatus

USING AND ADAPTING THE UNIT

- ☐ The questions may be answered by students working in small groups and reporting back to the class. Alternatively the unit may be done as a pencil-and-paper exercise.
- ☐ Students could prepare demonstrations of the experiments they describe in Q6 and show them to the class or to younger children.
- ☐ Build and test a fairy detector is an optional activity that may be linked to work with sensors.

Author **Anabel Curry**

First published 1991

Teaching notes

This unit may be used to draw together work on electricity, microelectronics, atomic theory and cosmology.

The neutrino is introduced to indicate some of the imagination-stretching ideas used by physicists. Many physicists are working on experiments to detect and understand the origin of neutrinos produced in thermonuclear reactions such as occur deep inside the Sun.

Fairies appear in British folklore as fairies, elfs, pixies, leprechauns etc. Belief in the existence of 'fairy creatures' pervades many cultures from Eskimoes to Australian aborigines. A large encyclopaedia may provide a good starting-point for information on this subject.

It seems that the rigorous requirements of scientific evidence no longer enable people in Western cultures to sustain a belief in the existence of fairies.

Apparatus requirements

Fairy detectors: a wide range of solutions is possible for a pencil-and-paper activity – using light sensing circuits, pressure detectors, mechanical traps etc. If students are to undertake practical work it may be advisable to restrict them to using a range of equipment such as microelectronic kits or possibly electromagnetism kits.

Answers to the questions

Q1 *The quality of the photographs was not up to modern standards. They were examined to see if the fairies had been superimposed but the idea of strings was not taken seriously. People (including scientists) were predisposed to accept the evidence. A similar example of the gullibility of scientists is in Professor Blondlot's discovery of 'N-rays', which were eventually explained as due to streaking of the photographic plates by uneven development. A more recent example might be cold fusion.*

Q2 *It is hard to prove fairies do not exist. However, there is no scientific evidence that stands up to scrutiny to support their existence.*

Q3 *The existence of a Loch Ness monster may seem slightly more plausible: the Loch is deep and there have been recent discoveries elsewhere of animals believed to have been extinct. However, the lack of firm evidence seems to indicate that sightings, like those of fairies may be a result of wishful thinking. The tourist industry has a financial interest in perpetuating the monster myth.*

Q4 *Some captured specimens, photographs, video, triggering sensors such as IR, UV, magnetic, pressure etc.; less reliable evidence would be personal accounts of witnesses, drawings from many cultures.*

Q5 *Suggested answers:* ***1*** *C,* ***2*** *B,* ***3*** *A,* ***4*** *C,* ***5*** *A,* ***6*** *A/C?,* ***7*** *A/C?,* ***8*** *B,* ***9*** *A/C?,* ***10*** *A/C.*

Q6 *Effect of a current – heating, lighting, chemical (battery/electrolysis), magnetic (electromagnetism and electromagnetic induction); also electrostatic demonstrations, cathode rays (TV/oscilloscope), thermionic emission (Teltron tube), photoelectric emission (photocell), hydrogen line spectra, beta emission.*

Q7 *Spurious results. In a garden, sensors may be triggered by insects, leaves, pets etc.*

Acknowledgements

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Are there fairies at the bottom of the garden?

For generations people believed in fairies – small creatures with magical powers.

In Shakespeare's time, believing in fairies was common. Some of his plays had fairy characters like Titania and Ariel in the cast. There were numerous reports of sightings. However, fairies were only seen by people who were said to have 'second sight'.

A look at the problems of detecting fairies, electrons and neutrinos.

- Reading, questions for written answers or discussion
- Design a demonstration
- Design a fairy detector

The Cottingley fairies

By the twentieth century fairy folklore was declining – most fairies being relegated to children's story books and the top of the Christmas tree.

Then one day two young girls, Elsie Wright and Frances Griffiths, produced photographs. They had been playing in the garden.

Figure 1 The 'Cottingley fairies'. One of the photographs that fooled the world for 70 years

This was the proof believers had been waiting for. Girls so young and innocent could not have faked the photographs. The photographs were examined by experts. No evidence of forgery was found.

The girls held firmly to their story. There *were* fairies at the bottom of the garden!

Many believed them. After all, other people had seen fairies too. The reason nobody else had photographed fairies before was easy to explain – the girls had 'second sight', the ability to see fairies which were invisible to adults.

Men of learning were convinced too. Articles appeared in the press suggesting that fairies be studied seriously.

Time passed. Elsie and Frances grew up and grew old. But they always denied the fairy photographs were fakes. Public interest in fairies waned as no new evidence was found. The 'Cottingley fairies', named after the village where they were discovered, remained a baffling curiosity.

Figure 2 The 'Cottingley fairies'

A scientific explanation

Just over seventy years later in 1979, science solved the mystery of the Cottingley fairies. James Randi, a magician, suspected the photographs had been faked.

Randi examined the photographs using image enhancement. This is a computer process more often used to increase the clarity of pictures taken from satellites and spacecraft.

Randi found the 'fairies' were held up by black threads!

Two young girls had fooled the world for more than seventy years. In old age, they eventually confessed.

Q1 *Why were people so easily fooled?*

Q2 *Does the fact that the Cottingley fairies were fakes prove that fairies don't exist?*

Q3 *People have reported sightings of a monster living in Loch Ness, Scotland. Scientists have investigated and no monster has been caught or photographed.*

Do you think that sightings of the Loch Ness monster are in any way different from sightings of fairies?

Q4 *What would you regard as proof that fairies exist?*

The physics of fairies?

You may not find a scientist who admits to believing in fairies. But physicists have discovered even stranger things.

At the time that interest in fairies was fading, physicists were finding particles whose properties were just as bizarre. In 1897 J. J. Thomson, experimenting with cathode rays, reported they were made of particles so small they seemed to have no size! Heinrich Hertz claimed that cathode rays were *waves* not particles. Eventually these particles with their strange properties were called **electrons**.

Electrons are so small, they are impossible to capture and look at. The best that scientists can do is look for evidence of their effects.

The discovery of electrons led to the technology of electronics. Television and computers are two examples.

Electrons

- have negative electric charge of 1.6×10^{-19} coulomb
- have a mass of 9×10^{-31} kilogram
- behave like particles or waves
- are acted on by magnetic and electric fields

Q5 *Are electrons like fairies? Decide which of the following statements describe:*

A **electrons,**
B **fairies,**
C **both electrons and fairies.**

1 They are invisible to the eye.
2 They have wings.
3 They move inside your calculator when you do sums.
4 They have almost no mass.
5 They make the picture light up on your TV screen.
6 They can get through solid metal.
7 They can travel nearly as fast as light itself.
8 They have magic powers.
9 They make magnetic fields when they move.
10 If you try to trap them they escape.

Q6 *Describe how would you demonstrate the effects of electrons to a friend or child.*

- *What experiments would you choose?*
- *How would you set them up?*
- *How would you make them interesting?*
- *How would you explain what is happening?*

The elusive neutrino

After the negatively charged electron was identified, a similar particle, the positron with a positive charge, was found. Another particle, but with no charge was suggested as long ago as 1931 and christened the neutrino. It remained undiscovered until 1956.

Physicists now know there are billions of neutrinos everywhere. They have no charge, little if any mass and are very difficult to detect. Neutrinos from the Sun usually pass right through the Earth as though it were not there.

Is believing in neutrinos like believing in fairies? Scientists have been able to detect the effects of neutrinos but no evidence for fairies has been found.

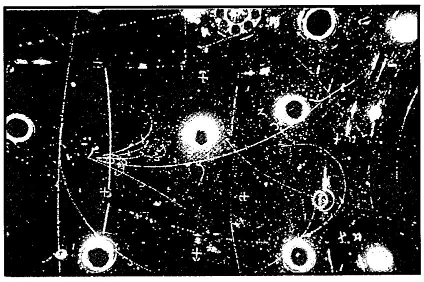

Figure 3 Photographic evidence of the effect of a neutrino. Neutrinos leave no track but they produce other particles which do leave a track. The photograph was taken in the Gargamelle heavy liquid bubble chamber at CERN

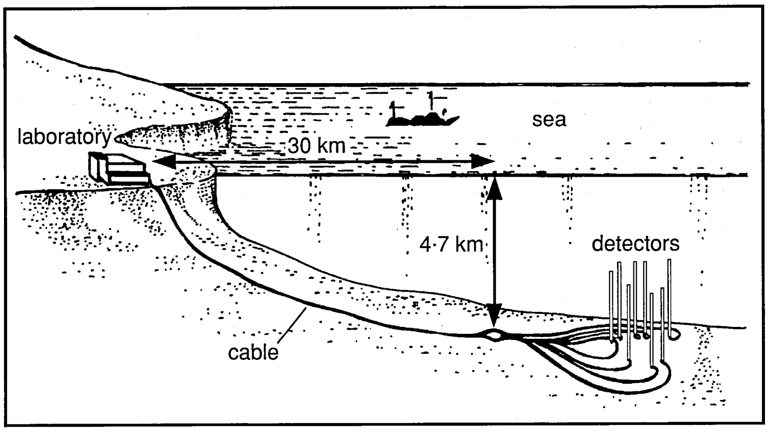

Figure 4 A neutrino detector which is being built more than 4 km under the ocean off the coast of Hawaii. It will detect neutrinos from outer space

Activity

You are asked to investigate a report of fairies in a garden. Design a fairy detector that you can make with science apparatus normally available to you.

- What effect or property of fairies would you try to detect?
- Make a list of the apparatus you would need.
- Draw a diagram of how you would put it together.
- Describe how it should work and what measurements you would take.
- If you have the opportunity, build and test it. Say what modifications you made to your original design.

Q7 If your detector 'works', what will you make of the result?

Answers to the questions are given in the *Teachers' Notes.*