known example of a variable radio source. Movements in the high solar atmosphere associated with active regions on the Sun produce highly variable non-thermal emissions which can reach flux densities as high as 10^{-18} W m^{-2} Hz^{-1}, or 10^8 Jansky.

An interesting class of variable radio source is the pulsating radio source, or pulsar, discovered in 1967. Pulsars are thought to be rapidly rotating extremely dense stars, neutron stars, from each of which a narrow beam of radio waves is emitted and received at the Earth as a regular series of pulses. Radio sources associated with the nuclear regions of certain galaxies and quasars are also known to be variable, usually on a timescale of months or years.

1.3 Why large telescopes are built

Increasing the diameter of a telescope aperture has two main effects on its performance. One is to increase the energy-collecting area (*effective area*) and hence the power that is received from any particular distant source towards which the telescope is directed. The other is to improve the angular discrimination, i.e. the *resolving power* of the telescope.

The radio power delivered to the receiver is directly proportional to the antenna effective area and so, with the same receiver, a large telescope gives a better sensitivity since it can detect weaker (lower flux density) radio sources. However, the sensitivity of a radiotelescope depends on many other factors such as the level of unwanted radio signals in the system, the time of observation (the integration time), and the receiver frequency bandwidth. Unwanted signals enter the system from the outside (radiation from other celestial sources and from the ground, man-made interference) but are also generated within the antenna–receiver system itself. If these disturbing signals are of the random fluctuation 'thermal noise' type, then the sensitivity can be improved by increasing the time of observation and/or the bandwidth of the receiver (not possible for spectral-line observations), and by using a receiver with as little internal noise as possible. Receivers built in recent years have achieved very low internal noise levels and this development has had a major effect on the sensitivity of modern radiotelescopes. The sensitivity of a telescope will be discussed in Chapter 8.

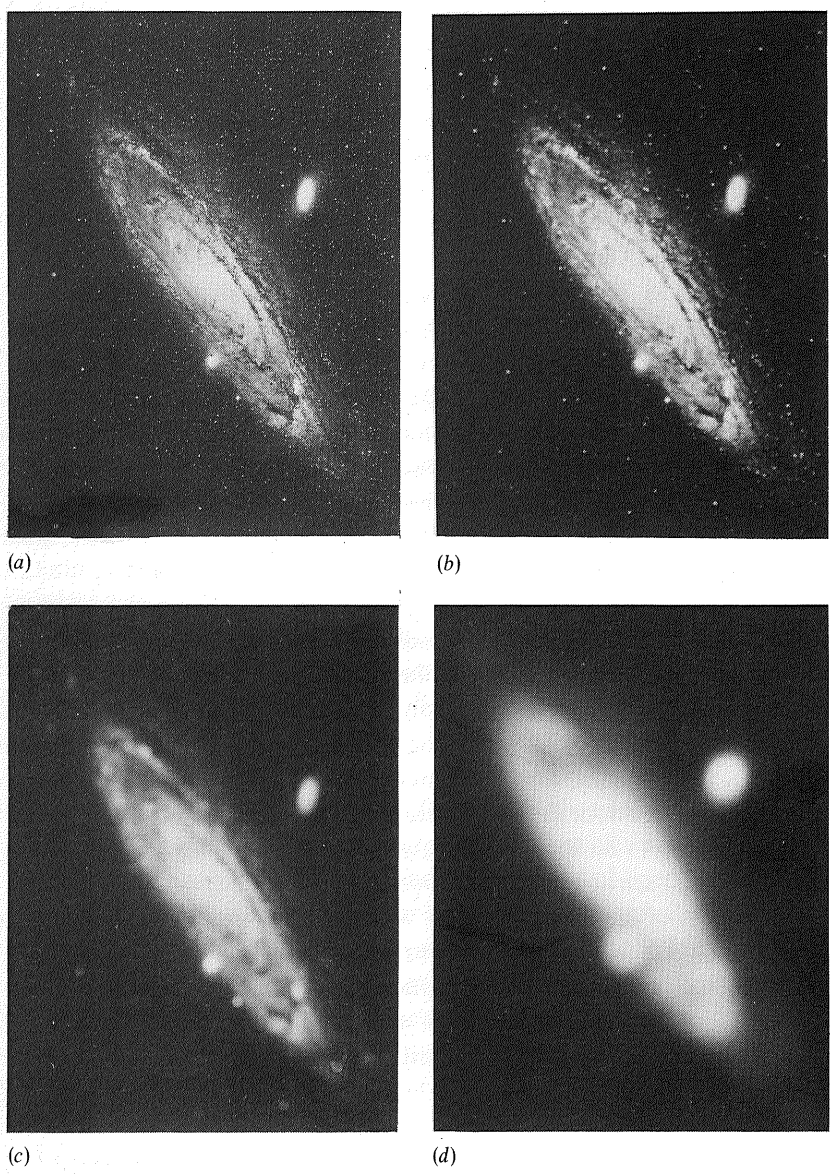
Very important in the case of radio observations is that a larger aperture increases the amount of detail that can be measured in the sky: it gives the instrument a better resolving power. It is well known from optics that a 'point' source of light observed with an ideal telescope gives an image in the focal plane which will not itself be a point but a *diffraction pattern* of finite size (the Airy disc) surrounded by faint rings. This is a consequence of the wave nature of light, and the diameter of the disc is inversely proportional to the telescope aperture expressed in wavelengths. If two point sources in the sky have such a small angular separation that their Airy discs overlap in the focal plane, then they cannot be resolved into two separate sources by the telescope. The so-called Rayleigh criterion for the resolution of 'point' sources is that their angular separation should be greater than the corresponding angular distance between the maximum and the first zero of the Airy disc. This convention makes the resolving power (measured in radians) equal to 1.22 times the inverse of the diameter of the telescope aperture expressed in wavelengths.

All detail in the sky measured with a telescope, even under perfect conditions such as in space, must be blurred by the Airy disc diffraction pattern (Fig. 1.2). This is seldom a major problem in ground-based optical astronomy since the observations are blurred more by the irregularities in the atmosphere (scintillation) than by diffraction effects. The atmospheric irregularities limit the resolving power to about 0.5 seconds of arc (0.5 arc sec) in good atmospheric conditions. The diffraction effects will be larger than this only when the telescope aperture is smaller than about 20 cm. With radiotelescopes, because of the enormous differences in wavelength, the situation is entirely different. Early radiotelescopes had an aperture of only some 50 wavelengths which gives a diffraction limited resolving power of about 1°. This is not even sufficient to see any detail on the Sun. The struggle to achieve a resolution as good as or better than that of optical telescopes has engaged the labours of radio astronomers for several decades. The problem is simply that of constructing huge apertures with sufficient accuracy. A resolution of 0.5 arc sec at the shortest useful wavelength, a few mm, would require an aperture approximately 1 km in diameter. Observations are needed also at much longer wavelengths, where telescopes have to be correspondingly larger. At a wavelength of 1 m, for example, a 400-km aperture would be needed. A telescope must be built to an accuracy of better than ±0.1 wavelengths, which imposes great constructional difficulties. Attempts to achieve a high angular resolution by a simple scaling up in size of optical-type telescopes will clearly be unrealistic and radically new types of telescope have been devised. We shall here review briefly some of the main designs used for modern radiotelescopes.

1.4 Filled-aperture radiotelescopes

A plane wave that falls on a telescope aperture is brought by reflection or by other means to an output port ('focus') in such a way that

Fig. 1.2. This figure illustrates the loss of information when observations are made with insufficient angular resolution. The galaxy M31 as it would appear with an angular resolution of (*a*) a large optical telescope, (*b*) 1 minute of arc, (*c*) 3 minutes of arc, (*d*) 12 minutes of arc. (Photographs courtesy of Sterrewacht Leiden)



the time taken to travel from each point on the incident wavefront to the output port is the same. The most commonly used reflecting surface is the *paraboloid of revolution* or 'parabolic dish'. A plane wave, arriving from the direction of the axis of an optical reflecting telescope, is brought to a focus at which the energy flux becomes concentrated to a diffraction pattern (Airy disc) centred on the axis of the paraboloid. Plane waves arriving from other directions close to that of the axis are focused to diffraction discs centred at other points in the focal plane. A photographic plate placed in the focal plane can record simultaneously and separately the signals from a large range of angles and so produce an image of a particular region of the sky.

The aperture of a parabolic reflector radiotelescope will be much smaller expressed in terms of the wavelength, and the diffraction disc becomes quite large. It has a diameter of about one wavelength for a short-focus paraboloid and it is impossible to register an extended image of a piece of sky as is done in optical astronomy.

Parabolic dishes are usually equipped with a single pick-up point placed at the focus of the paraboloid. The power available at this pick-up point is that contributed by all diffraction discs that overlap at this point. Hence, the telescope will measure the flux density from a certain region of the sky centred at the direction towards which the telescope is pointed. In radio terminology this is the region occupied by the *power pattern* or '*beam*' of the telescope. We see that this is simply a reflection of the shape of the diffraction pattern in the focal plane.

The pick-up arrangements at the focus will not in fact be that simple. The shape of the power pattern differs somewhat from that of the Airy disc and will depend upon the exact focal arrangements. The Rayleigh convention for expressing the resolving power is not suitable because the angular distance to the first zero in the power pattern can be quite unrelated to the width of the main beam. The resolving power of a radiotelescope is usually equated to the *half-power beamwidth*. Fig. 1.3 shows the (normalized) power available from the antenna as a function of the angle by which the antenna has been steered away from the exact direction of a point source of emission. This function is the antenna power pattern. The half-power beamwidth is defined as the angular separation of the two points on this curve at which the received power has fallen to one half of its maximum value.

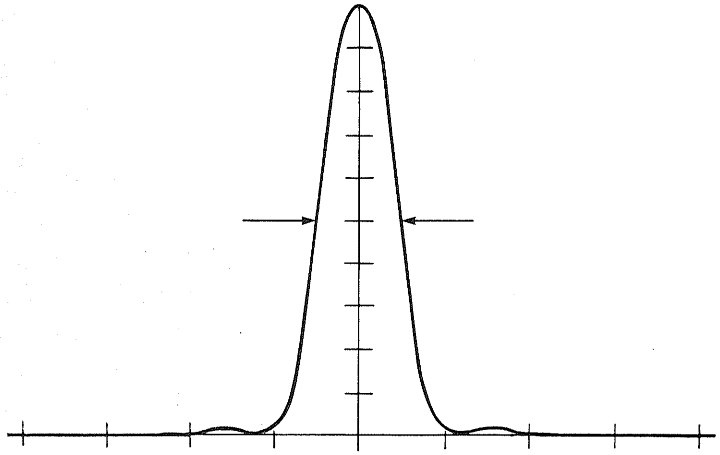
A parabolic reflector telescope is usually mounted in such a way that it can be steered mechanically to different directions. A map or image of the sky brightness distribution can then be produced by measuring sequentially the flux from a series of directions over the region in question. This is an extremely time-consuming procedure and a great practical disadvantage compared with the image-forming optical telescopes.

The largest parabolic dish in use at the time of writing (see Fig. 3.13) has a diameter of 100 m and it seems unlikely that steerable dishes very much larger than this will ever be operated from the ground. At its shortest usable wavelength this telescope has a resolving power of a little more than 0.5 arc min and this must be close to the best that can be achieved with ground-based telescopes of this type.

A fixed-position *spherical reflecting surface* (Figs 1.4 and 4.17) can be used provided that special means are employed to correct for the focusing error of the spherical reflector (aberration). The beam can be steered by moving the pick-up point over a spherical focal surface concentric with the reflector. Since the reflector need not be moved, it can be built much larger than other types of reflector.

Many special types of reflecting telescope have been used for radio astronomical observations. One is the analogue of the optical coelostat, a flat plate reflector which can be rotated around a horizontal axis to reflect waves from sources in the meridian plane into a fixed parabolic reflector which in turn brings the plane waves to a focus (Figs1.5*a* and 4.11). In another design, a strip section of a paraboloid is formed by means of a large number of individually movable small plates. The strip can be reformed continuously to form sections of paraboloids with different axial directions,

Fig. 1.3. The power available at the antenna output as a function of the direction of an observed point source. This function, normalized to unity in the maximum direction, is the antenna power pattern, the radio equivalent of the Airy disc in optics. The arrows mark the half-power beamwidth.



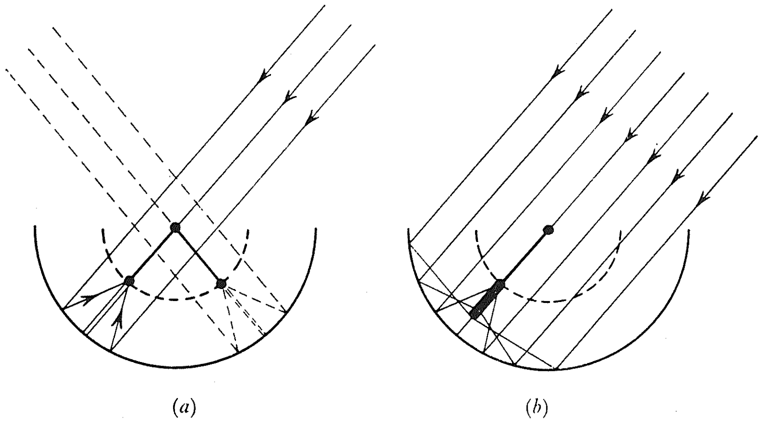
i.e. it can be 'steered'. The beam (power pattern) varies somewhat in shape as it is steered to different directions in the sky (Figs 1.5*b* and 4.12).

The designs described so far have the very convenient property that the incoming signals are brought to a focus by direct reflection by suitably shaped reflecting surfaces which are effective over a very wide range of frequencies. The single focus makes the telescope very flexible in that receivers for different frequencies and purposes are easily exchangeable. Most other types of telescope include frequency-specific transmission lines or other components that make such changes less convenient.

The *parabolic cylinder reflector* with a line focus (Figs 1.6 and 1.7) has been used quite extensively for observations at the longer wavelengths (40 cm and longer). The signals absorbed by the line focus are brought to an output port by transmission lines arranged in such a way that the electrical length from each point on the line focus to the output port is the same. The beam will then be pointed in a direction perpendicular to that of the line focus. The antenna can easily be extended in the direction of its axis. Telescopes of this type tend to have long thin apertures which give fan-shaped power patterns (beams). They are sometimes used as components of more complex telescope systems.

The beam of the parabolic cylinder reflector telescope can easily be steered mechanically in one dimension by rotating the reflector about its long axis. It may be steered electrically in the other dimension. *Electrical*

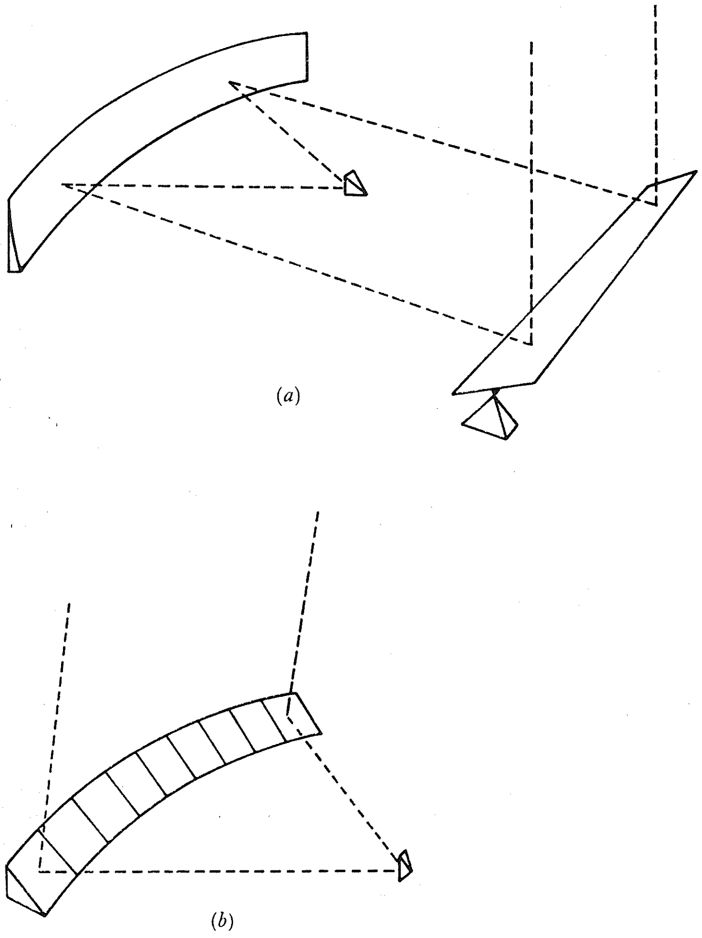
Fig. 1.4. A fixed hemispherical surface may be used for reception in different directions by changing the position of the 'feed' antenna. (*a*) A simple feed may be used if only a limited part of the spherical reflector is used. (*b*) A more complicated feed may be used to correct the aberrations produced by the spherical reflector.



steering of the beam to some particular direction in the sky is achieved by adjusting the lengths of the transmission lines in such a way that the time taken to travel from each point on the incident wavefront to the antenna output port is the same. Other means of steering are also available.

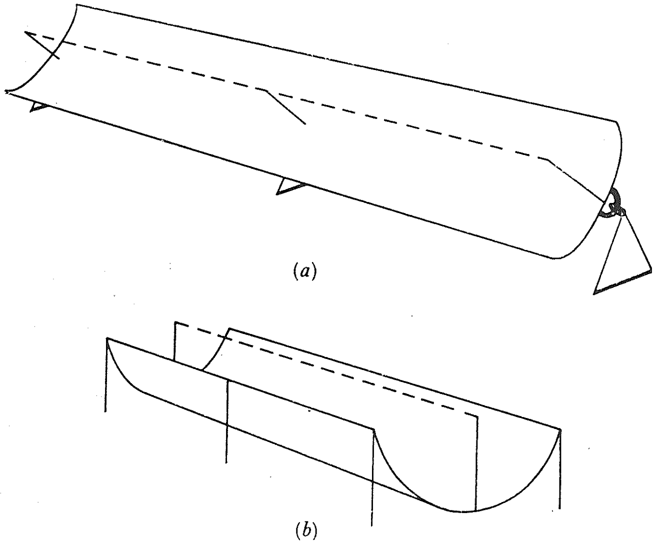
An electrically steerable antenna can be arranged for *multiple-beam operation.* The signals available at the antenna pick-up points, in the above case along the focal line, can be divided and fed into two or more different transmission line networks, each of which combines the signals for reception from a different direction in the sky. If necessary, the pick-up

Fig. 1.5. (*a*) A Kraus-type reflecting antenna with a fixed parabolic surface and a rotatable flat surface. (*b*) The Pulkovo reflector is made up of movable panels and can be reformed for different angles of elevation of the antenna beam.


(*a*)

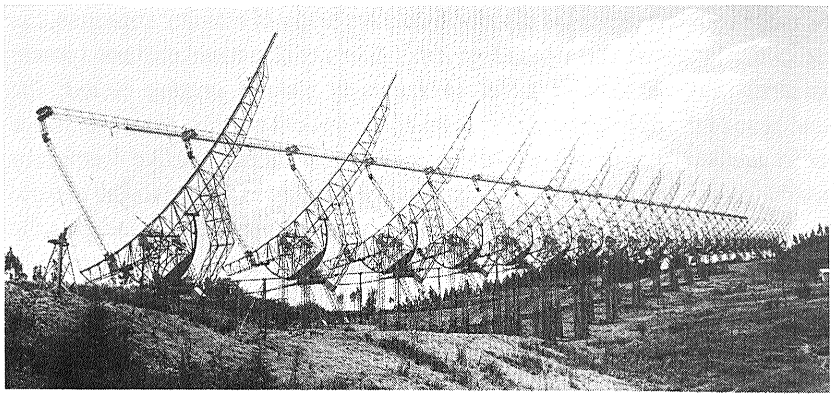
(*b*)

Fig. 1.6. Parabolic cylinder reflecting telescopes. (*a*) An east–west antenna steerable in elevation. (*b*) A fixed north–south antenna with electrical steering of the antenna response.


(*a*)

(*b*)

Fig. 1.7. Stretched-wire parabolic frame reflector forming part of the Ootacamund synthesis telescope in India working at 326.5 MHz. The main parabolic cylinder reflector is 530 × 30 m and is lined up parallel to the Earth's axis along a slope in southern India. The antenna can then be steered in hour angle simply by rotation about its long axis while steering in declination is achieved electrically by phasing of the line feed. Blocking of the aperture by the feed is avoided with the off-axis paraboloid design (p. 93). The telescope has recently come into operation as a rotational synthesis instrument, using the large reflector in conjunction with several smaller reflectors. (Photograph courtesy of Tata Institute of Fundamental Research, Bombay)



signals can be amplified before entering the dividing networks in order to compensate for the division of power between the different networks. The antenna can in this way give several simultaneous outputs, each corresponding to a different direction of the electrically steered beam. The arrangement, in fact, gives the telescope a rudimentary image-forming capacity.

At the very long-wave end of the radio astronomical spectrum we find *plane arrays of dipoles* with a plane reflecting curtain behind them. Such antennas have been used for radio communication for more than half a century. Dipole arrays for radio astronomy are often built in a horizontal plane with the reflecting screen below the dipoles. The antenna response can be steered electrically and multiple-beam operation is possible. Arrays of 'fat' dipoles (Fig. 6.19) or of log-periodic elements can be used over a wide range of wavelengths. The well-known but narrow-band Yagi antenna has also been used in long-wave radio arrays (Fig. 7.9). In order to achieve even a moderate resolving power, these longer-wave telescopes must cover very large areas, measured in hectares rather than in square metres.

1.5 Unfilled-aperture radiotelescopes

The practical limit to the size of filled-aperture telescopes of the types just described is very much smaller than that necessary to approach the resolving power of even the smallest optical telescope. In addition, such telescopes measure the radio flux from only one direction at a time (with multiple-beam operation a very limited number of directions) so in this respect, also, they are very inferior to the image-forming optical telescopes. Radio astronomers were forced to develop new types of radiotelescope which could be made both larger and more efficient.

An important step towards modern high-resolution radiotelescopes was the realization that, in many cases, even *unfilled apertures* can be used to measure source brightness distributions. An array of smaller antennas, the radio analogue of the optical grating, has a diffraction pattern (power pattern) that consists of a set of regularly spaced *grating beams*, the analogue of the different order spectra of the optical grating. However, since radio measurements are normally made with small relative frequency bandwidths $\Delta\nu/\nu$, all grating beams will be similar in shape to the central beam (Fig. 1.8). Individual grating beams have the same shape and give the same angular resolution as the single beam of a filled antenna equal in length to the whole array. The array (see Fig. 6.2) responds to radiation from many different directions simultaneously, but this causes no confusion if the observed source is smaller in angular measure than the distance

between the different grating beams. As the Earth rotates, the source will pass through one beam after the other and the telescope records a set of separate scans through the source. Clearly, there must be no other sources of comparable intensity in the neighbourhood as this can lead to confusing overlapping records from the different beams. Arrays of small antennas are used extensively for studies of the radio emissions from the Sun and can easily be adapted for multiple-beam operation.

The array-type unfilled aperture is an example of how an incomplete antenna structure can give sufficient information *for the problem in question.* This is possible only because the measurements are, in fact, complemented by *a priori* knowledge about the observed piece of sky, in this case that the source (the Sun) is small in angular measure and that there are no confusing sources. If this were not true, then the records from the grating telescope would be more or less indecipherable, with several sources contributing to the receiver output at any one time. *A priori* knowledge has become a very important consideration in modern telescope design. It has made it possible to build radiotelescopes which consist of a limited number of relatively small antennas spread out over a vast area, but which can still deliver

Fig. 1.8. The power pattern of a regular array of parabolic reflectors consists of a regular set of grating beams. The envelope to the set of beams is determined by the power pattern of the individual parabolic reflectors. This particular pattern is that of a 32-element east–west array of parabolic reflectors (Fig. 6.2).