Our knowledge of the universe has been gained by measuring electromagnetic radiation falling on the earth. To the light from the stars for the astronomer's telescopes there has been added radio waves for his receivers. Thus another probe into space is available for examining bodies which are capable of emitting, reflecting, or absorbing radio waves.

by Martin Ryle

Western half of interference aerial system at Cavendish for locating galactic sources. Photo at the left is the Dark "S" nebula. Mt. Wilson Observatory photo courtesy of Hayden Planetarium.

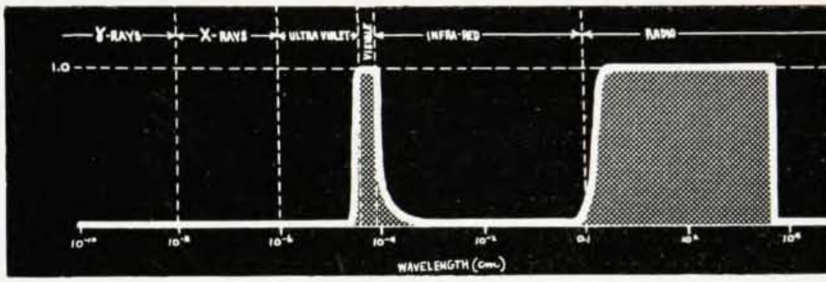
RADIO ASTRONOMY

Until recently astronomy was restricted to the visual band of the electromagnetic spectrum, and to wavelengths near to the visual band. Our immense store of astronomical knowledge has been obtained from observations made in a band of about four octaves of the spectrum, although measuring techniques are available for about forty octaves.

The extension of astronomical observations to a greater range of wavelengths should release new stores of knowledge, but unfortunately we are restricted in our choice of wavelength by the absorption of the earth's atmosphere for we find that over most of the electromagnetic spectrum the atmosphere is almost completely opaque. The development of high altitude rockets suggests the possibility of eventually being able to carry measuring apparatus right through the earth's atmosphere, and existing rockets have already enabled an extension of the ultraviolet spectrum of the sun to be made by carrying recording apparatus through a large part of the atmosphere; it seems unlikely, however, that we will in the near future be able to obtain a significant contribution to observational astronomy by such brief and expensive experiments.

For observations at ground level we must therefore restrict ourselves to those wavelengths which are not appreciably affected by the atmosphere, and we find that there are only two important bands over which the absorption is sufficiently small. One of these bands covers the visual and near visual wavelengths from about 3×10^{-5} cm to about 10^{-3} cm; the other extends from about 1 cm to about 20 metres, and is restricted by molecular absorption bands on the shortwave side, and by the ionosphere on the other (radiation of longer wavelength being reflected back from the upper surface of the ionosphere). Within recent years astronomical observations have been extended to the second, and relatively wider, band of radio wavelengths.

The importance of radio astronomy lies in the possibility of observing regions which cannot be explored using visual wavelengths. An ionized gas of low density does not emit, reflect, or absorb light waves appreciably, yet it may be capable of doing so for the much longer radio waves. The use of wavelengths between 1 cm and 20 metres should therefore make it possible to observe regions where the density is too low for detection at visual wavelengths even with the largest of telescopes. The possibility of using radio waves to make direct observations of the atmospheres of the sun and stars is of particular interest.



Electromagnetic spectrum showing approximate transmission coefficient of the earth's atmosphere

On the other hand, the use of the very much

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longer wavelengths makes it difficult to obtain a resolving power—or ability to distinguish two sources in nearly the same direction—which is comparable with even a small telescope. For this reason one of the major problems in radio astronomy lies in the identification of a source amongst a number of nearby sources, or even of detecting an individual source against the general background of the Milky Way.

First Observations

In 1932 K. G. Jansky noticed a background "noise" radiation on a radio transmission of 16 metres wavelength, which varied with the time of day. He at first put it down to diurnal changes in the ionosphere, but after several months it was apparent that the variations occurred at the same *sidereal* time; the radiation could not therefore be due to the ionosphere or the sun, but must have originated in the galaxy. Later experiments showed that the maximum intensity did in fact occur when his aerials were directed at the Milky Way. In spite of this result Jansky was unable to detect any similar radiation from the sun; it is now known that over most of the radio band, the "starlight" is normally far more intense than the "sunlight."

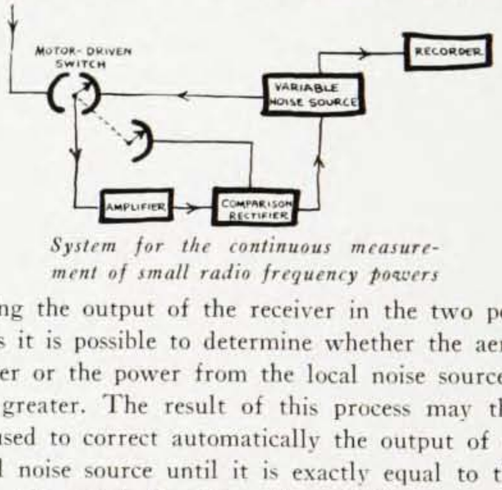
More recently, Southworth, using an aerial of large resolving power, succeeded in observing the sun on wavelengths of about 3 cm, whilst Appleton and Hey, using a wavelength of 4 metres, detected solar radiation whose intensity, during the presence of a large sunspot, was greater than that from the galaxy. Southworth's observation showed that the sun emits 3 cm radiation as if it had a temperature not greatly in excess of that deduced from visual observations (6000°); Appleton and Hey, however, concluded that at times of sunspot activity the intensity at a wavelength of 4 metres corresponded to a temperature about one hundred thousand times this value.

"Telescopes" for Radio Astronomy

After the first surprising observations of the sun and galaxy in the longwave radio band of wavelengths, it was natural that attempts should be made to design apparatus having sufficient sensitivity and resolving power to enable the sun to be observed continuously, and not merely at times of great sunspot activity. The development of better instruments has not only achieved this result, but has, in turn, led to the discovery of individual intense "point" sources of radiation in the galaxy.

The first requirement of a radio telescope is a very sensitive radio receiver, for it may be necessary to detect a signal from the aerial whose power is only one percent of the random "noise" signals occurring in the input circuit of the receiver. In order to detect the small additional power from the aerial (which is also random in character), it is necessary to take, effectively, the average of a large number of readings of the output of the receiver with and without the aerial connected. The result of such a process, however, can only be used to determine the contribution of the aerial if the amplification and the "noise" of the receiver remain constant to a high degree of accuracy; the maintenance of such stability over a long period is a matter of great practical difficulty.

An alternative system, which is shown diagrammatically in the figure, has therefore been developed at the Cavendish Laboratory, in which the input of the receiver is switched alternately between the aerial and a local source of random noise. By com-



System for the continuous measurement of small radio frequency powers

paring the output of the receiver in the two positions it is possible to determine whether the aerial power or the power from the local noise source is the greater. The result of this process may then be used to correct automatically the output of the local noise source until it is exactly equal to that from the aerial. By this null method the receiver is used only as an indicator of balance, and variations of its gain or internal noise do not affect the final adjustment. A recording milliammetre connected to the local noise source then gives a continuous record of the aerial power.

The next difficulty is to distinguish between the radiation falling on the aerial system from the sun or a "point" source in the galaxy, from that due to the general background of the galaxy.

The use of a large aerial system (by decreasing the solid angle over which the aerial was sensitive) would improve the ratio of the power from the required small source, relative to that from the general background, and thus make it easier to determine the contribution from the small source. Apart from the practical difficulties of constructing a very large aerial, this method has two serious disadvantages: the time for which a source may be observed is very limited unless provision is made for rotating the large aerial structure throughout the day; secondly, the total solid angle covered in each revolution of the earth is small, and even with a movable aerial a long time would be required to search the whole sky.

An alternative system has therefore been developed which makes use of the interference pattern produced by two spaced aerials. If such a system is mounted on an east-west line, the radiation pattern (shown on the cover) is swept across the sky by the earth's rotation. Any source whose angular diameter is small compared with the separation of the minima will therefore produce a power into the receiver which varies periodically from zero to twice the value due to a single aerial; the power produced by the general background, on the other hand, will remain steady, except for the slow variations caused by the movement of the envelope of the radiation pattern.

The radiation from a small source will therefore appear on the record as a periodically varying signal superimposed on a relatively steady component due to the galactic background.

It is possible in this way to detect sources which produce a power in the aerial which is only a few percent of that due to the galactic background. For recording the intensity of solar radiation it is therefore possible to use aerials of relatively small directivity, and thus maintain observations over a large part of the day without the need for rotatable aerial structures.

If the spacing between the two aerials is increased until the angular separation of the maxima decreases to a value which is comparable with the diameter of the source, the observed intensity will no longer fall to zero at the minima of the radiation pattern; by observing the ratio of maximum to minimum intensity obtained with different spacings, it is possible to deduce the angular diameter of the source. This method is analogous to the method used by Michelson to measure stellar diameters, the observed maximum to minimum ratio corresponding to the "visibility" of the fringes in the optical case.

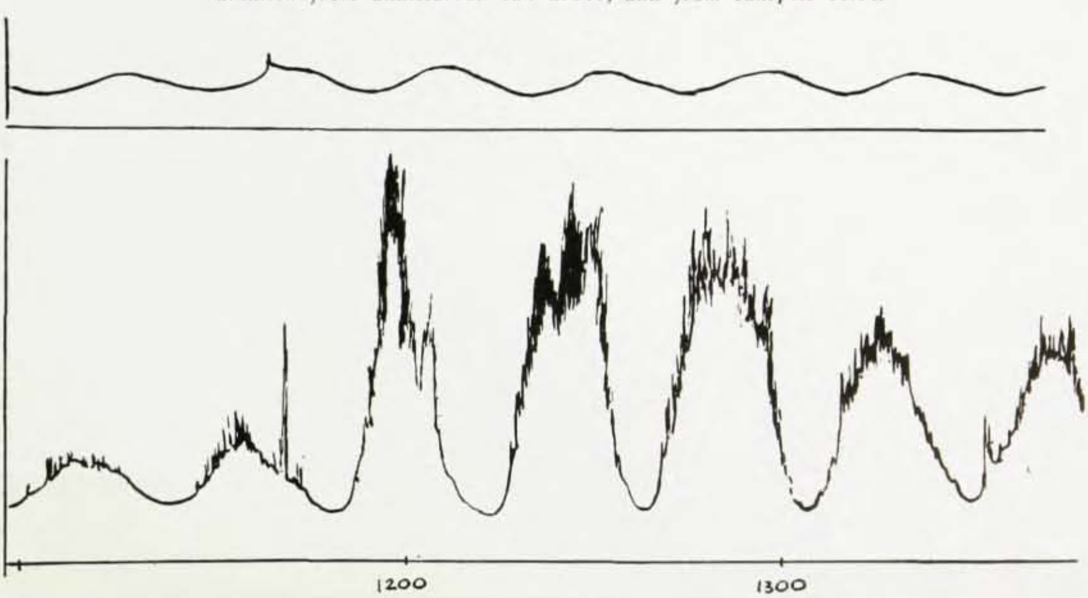
By observing the precise time of the central maximum of such an interference pattern, it is possible to obtain a very accurate determination of the direction of the source. This method has been used at the Cavendish Laboratory for locating active sunspots on the sun's disc, and for determining the positions of discrete galactic sources.

A rather similar system for the determination of the angular diameter and position of small sources has been used by the Australian workers, McCready, Pawsey, and Payne-Scott. This system, which is analogous to a "Lloyd's mirror" interferometer, makes use of the interference pattern produced by an aerial mounted on a high cliff by reflection at the surface of the sea.

Results of Solar Observation

Typical records obtained at the Cavendish Laboratory using the spaced aerial system described above

Records obtained with spaced-aerial system on 1.7 metres showing radiation from undisturbed sun above, and from sunspots below



are shown in the accompanying figure. The first record shows the radiation from the undisturbed sun on a wavelength of 1.7 metres; the second shows a similar record obtained when there was a large sunspot near the centre of the sun's disc. The rapid fluctuations of the intensity are typical of the metre wave radiation from sunspots. Regular observations of solar radiation are now made at the Cavendish Laboratory on four different wavelengths, from 50 cm to 7 metres, and observations on wavelengths of 1.7 metres and 3.7 metres have been maintained since December 1946. The results have shown that in the absence of sunspots the intensity of the radiation corresponds to the emission from a "perfect" or black-body radiator having the same diameter as the sun, and at a temperature of about a million degrees. At times of sunspot activity, the intensity at the longer wavelengths may be increased by a factor of more than a thousand.

It is clearly of importance to determine whether the increased radiation is actually emitted by regions near the sunspot, or is merely related to some more general disturbance which also gives rise to the sunspot. Measurements made in Australia and Cambridge using the high resolving power systems described earlier have shown that not only is the radiation emitted by the area near a sunspot, but that the diameter of the source does not greatly exceed that of the visible sunspot. Since the greatly enhanced radiation is emitted by a source whose area is considerably less than that of the sun, it has been deduced that regions of the solar atmosphere near sunspots are capable of emitting as if they were at a temperature of at least 10^{10} degrees K.

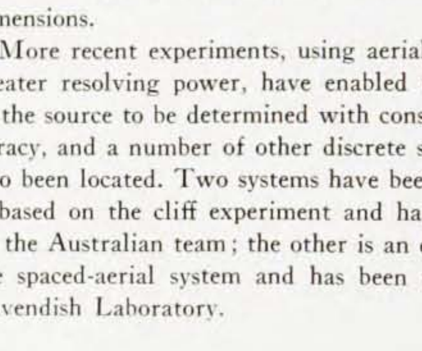
In addition to measurements of the intensity of solar radiation, regular observations of the polarization have been made; it has been found that the intense radiation from sunspots is nearly always circularly polarized, but that the radiation from the undisturbed sun appears to be randomly polarized.

Discrete Sources in the Galaxy

If the radiation from the Milky Way were due to the total emission from stars having characteristics similar to those of the sun, we should expect its intensity to bear the same relation to the intensity produced by the sun, as starlight bears to sunlight. Observations have shown that in fact the radiation from the Milky Way is usually far greater than that from the sun, and is about 10^8 times the value expected theoretically. We must therefore conclude either that the sun is not a typical star, or that there are a number of special stars whose radio emission is far greater than that of the sun, or that the radiation from the Milky Way is not due to stars, but to the interstellar gas.

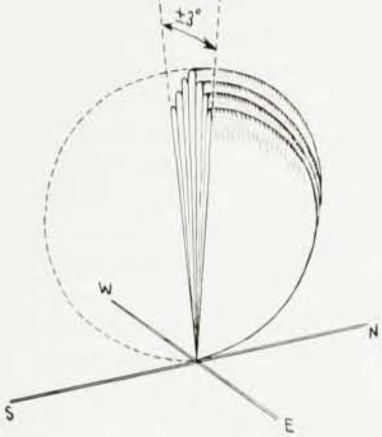
Observations in visual astronomy had suggested strongly that the sun was likely to be a typical star and earlier theories of the origin of the radiation from the Milky Way were therefore based on the emission from the interstellar gas; it was, however, necessary to postulate considerably higher random velocities for the interstellar particles than were suggested by visual observations. Recently, however, conclusive observations by Hey, Parsons, and Phillips have shown that at least part of the radiation from the Milky Way must be due to discrete sources. Hey observed that the radiation from the direction of the constellation of Cygnus showed rapid variations of intensity which could not be accounted for by refraction in the ionosphere; such fluctuations could not be explained on the basis of emission from an extended diffuse source, and suggested strongly that at least part of the radiation from this direction was due to a source of stellar dimensions.

More recent experiments, using aerial systems of greater resolving power, have enabled the position of the source to be determined with considerable accuracy, and a number of other discrete sources have also been located. Two systems have been used: one is based on the cliff experiment and has been used by the Australian team; the other is an extension of the spaced-aerial system and has been used at the Cavendish Laboratory.



Aerial system used for locating galactic sources

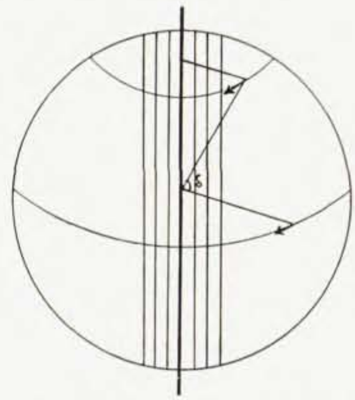
In the latter system two aerials are spaced 120 wavelengths apart on an east-west line, each aerial system having an aperture of 10 wavelengths in the east-west line, but considerably less in a north-south plane. The resulting polar diagram consists of a narrow "fan" beam, ± 3° wide in the east-west direction, but comparatively broad (± 40°) in the north-south plane. The interference between the two halves of the aerial system causes the fan to be



Radiation pattern of aerial system.

split up in the east-west plane into maxima and minima separated by about 30 minutes of arc. If this aerial system is mounted to radiate upwards at the latitude of Cambridge (52°), the fan will cover a narrow strip from the North Pole nearly to the equator. As the earth rotates this strip will therefore be swept across practically the whole of the Northern Hemisphere. As long as radiation is received only from the general background of the Milky Way, a slowly varying signal will be detected, but if the pattern crosses a discrete source of radiation, a periodic variation will appear on the record. By observing the time of the central maximum, it is then possible to determine the right ascension, or east-west coordinate of the position of the source.

The declination or north-south coordinate of the position may be determined from the observed period of the interference pattern; a source situated in the plane of the equator will produce a record whose period is equal to the time taken for the earth to rotate through the angle separating the interference maxima. A source situated near the North Pole will cross the interference pattern relatively more slowly, and therefore produce a trace on the record which has a correspondingly greater period.

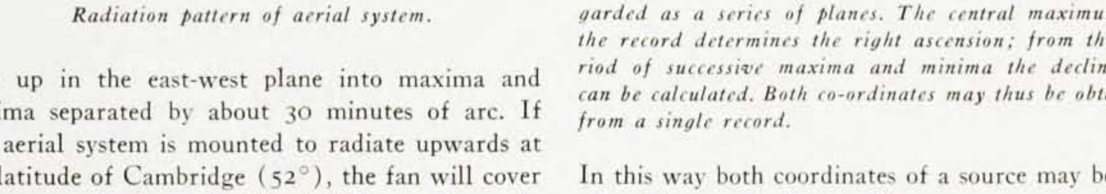


The intersection of successive maxima and minima of the interference pattern with the celestial sphere may be regarded as a series of planes. The central maximum on the record determines the right ascension; from the period of successive maxima and minima the declination can be calculated. Both co-ordinates may thus be obtained from a single record.

In this way both coordinates of a source may be obtained from a single record.

Observations made at Cambridge on a wavelength of 3.7 metres with this system have enabled twenty-five sources to be located in the Northern Hemisphere. A typical record showing the source in the constellation of Cygnus (first observed by Hey), and a second more intense source in the constellation of Cassiopeia is shown in the accompanying illustration. The latter more intense source does not normally exhibit any rapid fluctuations, and could not therefore be identified as a "point" source by the method used by Hey.

The accuracy with which the position of a source



Record showing sources in the constellations of Cygnus and Cassiopeia.

may be determined depends, of course, on the intensity of the radiation, but for the two most intense sources it is possible to obtain an accuracy of five to ten minutes of arc; this accuracy corresponds to a resolving power which is not much worse than that of the unaided human eye.

So far it has not been possible to identify any of the sources with outstanding visual stars; the two most intense sources, for which the best accuracy can be achieved, do not appear to be associated with any visual star of greater than 8th magnitude. The absence of correlation between intense radio sources and intense visual stars is not really surprising since in the one case the diffuse outer atmosphere is being observed, and in the other the relatively much more dense and cooler surface regions of visual emission. It is possible that certain stellar bodies may have extremely high temperature atmospheres whilst the visual temperature or opacity may be too low for appreciable emission of light radiation. Such a situation might arise if an electric field were maintained in the atmosphere of the star.

Nature of the Galactic Sources

In spite of the lack of association with visual stars, it is tempting to regard the galactic sources as stars having atmospheres of high temperature; at the same time the very great intensities which are observed at the earth from the two major sources (which are comparable with that produced by the undisturbed sun), suggest that if they are stars, they must be of very different character than the sun. We must therefore examine in more detail the experimental evidence for the stellar nature of the sources. Up till now we have given no evidence which might lead to a deduction of either the size or the distance of the sources; all we have concluded is that they subtend an angle at the earth which is smaller than the resolving power of the apparatus (about 5 minutes of arc).

Recently, however, careful measurements have been made at the Cavendish Laboratory, of the apparent position of the two intense sources at periods six months apart in order to try to detect any change in direction caused by the movement of the earth in its orbit. No change greater than the experimental accuracy could be detected, and it was therefore concluded that both of these sources are situated at distances greater than 2×10^{11} km.

Whilst this distance is relatively small in astronomy, the experiment was sufficient to show that the sources of radio waves are not relatively local bodies, such as clouds of ionized gas, situated within the solar system.

Other arguments, based on the duration of the rapid fluctuations of intensity which are occasionally observed from some of the sources, have suggested that the physical dimensions of the sources cannot greatly exceed those of a star.

If these deductions are correct the observed intensity of the radiation would correspond to the emission from a source at a temperature of at least 10^{14} degrees K. It is possible that intense radio waves could be emitted by the coherent oscillation of a large number of electrons of comparatively low energy, as in a radio transmitting aerial, and such oscillations have been observed in gas discharge tubes and in certain types of electron tube. Existing theories of such oscillations, however, are based on the interaction of coherent electron streams, the existence of which is extremely difficult to account for in the large scale conditions of a stellar atmosphere.

In the absence of other mechanisms it seems more probable that the intense radio waves are generated by the random motion of high energy electrons; the observed intensity would then require an electron temperature of 10^{14} degrees K, a value which corresponds to a mean electron energy of about 10^{10} electron volts.

Radio astronomy is still in its infancy; the observations which have been made so far are little more than an exploratory survey of this new branch of astronomy.

Already we have learned that unforeseen processes occur in the solar atmosphere, whilst observations of galactic sources suggest that still more energetic processes may exist in the atmospheres of certain stars; arguments based on the present incomplete experimental evidence even suggest that certain stellar bodies may not only emit intense radio waves, but may also be responsible for the origin of cosmic rays.

These and other possibilities can only be investigated by more refined observations, and we may hope that the development of new techniques may give us results not only of astronomical interest, but of fundamental physical importance.