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THE GALAXY EXPLORED BY RADIO WAVES

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Mr. Vice-Chancellor, Ladies and Gentlemen:

Science is discovery. We go to the limits of present understanding and then try to reach beyond. This characteristic holds for all intellectual endeavours, in the arts and the sciences. Very literally it holds for astronomy. The dome of the heavens with the twinkling stars as tiny dots on it has made place for a wide universe. Human view has extended far beyond its natural limits out into the depths of space and out into the realm of invisible radiation.

This extension of the natural view in astronomy is marked at an early stage by the invention of the telescope. It has continued with the introduction of photography, with spectrographs detecting infrared and ultraviolet radiation, and with counters registering cosmic rays. The most recent extension is radio astronomy, the reception of radio waves from celestial objects.

This lecture does not deal with all radio astronomy, not even with all radio-astronomical researches on the galaxy. I have selected a restricted problem, an episode in the long chain of discoveries that is science. But this episode is an extremely exciting one and holds out the prospect of splendid advances.

Radio Astronomy

Some fundamental remarks on radio astronomy must be made, though many readers will be quite familiar with these matters.

Our subject is radio and not radar. Radio astronomers, in the sense to which we shall restrict this word here, are content with the radiation the objects happen to send to them. They do not point a searchlight on the Moon in order to observe the reflected radiation (the radar principle). In this respect they are like the ordinary astronomers, only working in a different range of the spectrum.

We do not listen to the stars, as the newspapers say. Evidently man has no sense organ for radio waves. The waves have to be made accessible to our senses by special instruments. By means of suitable detectors we might hear, or see, or even smell them. If we make them audible, as is sometimes done, the result is a weak noise. If we make them visible, as is more often done, the result is an ink line on the paper of a recording meter. For fast recording a cathode-ray tube is sometimes used. But no music is heard, no television programmes seen.

Modern papers on radio techniques often explain the instruments by means of a so-called block diagram, in which each box represents a section of the receiver that has a special function; amplifier, mixer, etc. Since a block diagram is simplified anyhow, we shall simplify it even further and represent it in Fig. 1 by an instrument of two units, *d* and *c*. Here *d* is the dish, a paraboloidal telescope mirror for focusing the radiation from a certain area of the sky on the dipole at the focus. And *c* is the cabin in which the power received by this dipole is amplified in a narrow frequency band, detected and registered.

At first sight the results of radio astronomical observations may seem altogether different from those of ordinary (optical) astronomy. Yet we observe the same Sun, the same galaxy. Radio astronomy does not have a private universe; it is just a new avenue to the astronomical universe and its greatest charm lies in the recognition of common results gained along different lines of approach. Quite the same remarks hold for any new field of astronomical research, in particular for cosmic ray studies.

The only difference between radio waves and light waves is the wave length; radio astronomy now covers the range from about 8 mm to 18 meter wave length, i.e. from 10^4 to 10^7 times the visible waves. Some implications of this difference will now be put forward and may help us to realize the peculiar advantages and disadvantages of radio astronony over ordinary astronomy.

A radio telescope cannot be focused sharply on a particular region of the sky. The mirror at Kootwijk in Holland, where the 21-cm observations of the galaxy are made, has a diameter of 7·5 metres, i.e. bigger than the Hale telescope. Yet its beam width (or diffusion disk) is 3° on the sky. The sharpness of ordinary eyesight could be equalled only by an instrument more than a mile in diameter. For well-defined sources like the radiostars there are ways around this problem by means of interferometers; these investigations will not be described here.

A radio telescope has to be sensitive to very low energies. Visual rays from the Sun and stars form a large fraction of their total energy output. By measuring them we have access to an important item of the star's energy budget and can begin to form an opinion of the physical state resulting from gains and losses. Radio emission from the Sun and the interstellar gas is an altogether negligible part of the energy budget. It is a mere leakage of energy that may be interpreted as an indicator of the physical state but not as a determining factor. Unfortunately, this is also true for a car or a motorcycle. The radiowaves emitted are an altogether negligible part of the energy: they are unimportant for the fuel bill but may be extremely annoying for radio astronomical investigations in the neighbourhood!

A radio telescope can observe through clouds. The galactic observations at Kootwijk have continued irrespective of day or night, rain or sunshine. This property is quite welcome to astronomers used to the European climate. Far more important to astronomers all over the world is the penetration of radio waves through the cosmic clouds in our galaxy.

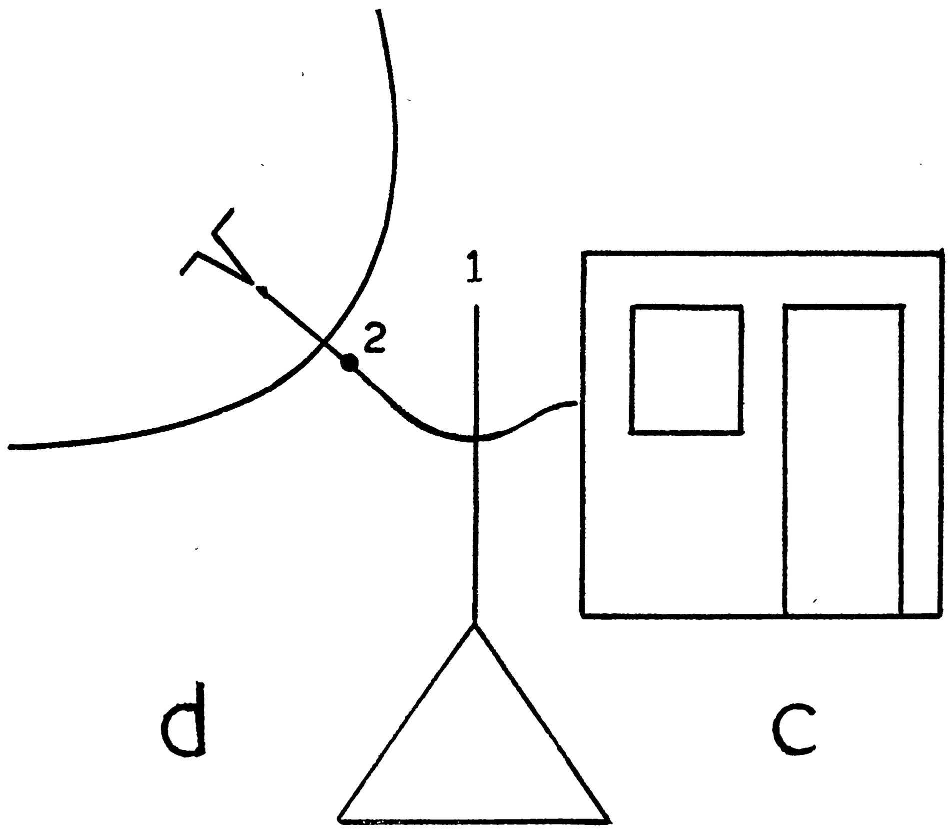


FIG. 1. A schematic diagram of the radiotelescope: *d* is the dish selecting the proper regions of the sky and *c* is the cabin containing the amplifiers that select the desired frequency. Everything rotates about axis 1, the dish also about axis 2.

Galactic research since the beginning of this century has shown more and more clearly that a thick layer of clouds limits our view in all directions in and near the galactic plane. The particles responsible for the strong scattering of light are probably ice crystals or ice needles with diameters of the order of the wave length of light. In this fog we can see through a circle of roughly 2000 parsecs radius. Many stars at that distance are obscured by 4 magnitudes, so that only a few per cent of the radiation penetrates through the fog; others are not visible at all. The nucleus of our galaxy is at roughly four times this distance and cannot be seen at all by ordinary astronomical means.

Optical astronomy has found two good ways of coping with this problem. The first one is to glance obliquely over the densest layers of clouds and stars. It is then possible to recognize not the nucleus itself but the haze of globular clusters and RR Lyrae stars above it. The other method is based on careful studies of the stellar motions in our immediate neighbourhood. Such motions reveal the rotation of our galaxy (see below) and place the centre of rotation in virtually the same direction in Sagittarius.

A far more direct observation is made possible by radio astronomy. Any survey of the intensity distribution on the sky in wave lengths from one to many meters shows two striking features: (1) a concentration of radiation towards the entire galactic circle and (2) an uneven distribution along this circle culminating in a very intense peak near galactic longitude 327°. We shall assume that this is the correct longitude of the galactic centre. Five or six of these surveys have now been made; they show that this radiation has a continuous spectrum. The isophotes of Bolton and Westfold's survey at $\lambda = 3$ metres are presented as an example in Fig. 2. The interpretation is not entirely clear. A small part of it is due to free-free emission of the ionized regions of the interstellar gas; this part is concentrated in a narrow strip along the galactic equator as shown most convincingly by Scheuer and Ryle's interferometer observations. The major part is probably due to separate sources (stars ?) distributed in a similar manner to the most common stars. In addition an even background is observed; this may perhaps be interpreted as the integrated effect of all extragalactic nebulae. I regret that time does not permit a further discussion of the fascinating problems suggested in the preceding sentences.

The 21-cm line

One advantage of the radio technique has not yet been mentioned. It is quite easy to select a particular frequency and to calibrate this frequency against absolute laboratory standards. Thus spectroscopy in the radio region is a method far less hampered by systematic errors and empirical corrections than spectroscopy in the photographic domain. Unfortunately, the continuous spectra in most fields of radio astronomy make it impossible to use this property to advantage. For this reason Oort insisted almost ten years ago that it would be extremely important to have at least one well-defined spectral line (in absorption or emission) in galactic radio astronomy. For a good deal of research on the structure of the galaxy in optical astronomy was based on stellar motions derived from radial velocities. This method, for which the measurement of Doppler shifts of spectral lines are essential, works excellently but was for optical work confined to our immediate neighbourhood. On the other hand, radio astronomical research went into the distant parts of the galaxy, as already suggested in the first observations of Reber, but was unable to reveal any radial velocities. A spectral line in the radio domain would combine both advantages and make a more complete investigation of galactic rotation and galactic structure possible.

Fortunately such a line presented itself and fortunately it is near the short wave-length end of the radio spectrum so that a fair angular resolution may be obtained with economically possible instruments. The line has a frequency of 1420·4056 Mc/sec, i.e. a wavelength of 21·1049 cm. It corresponds to the energy difference between the two levels in which the ground state of the hydrogen atom is split because of hyperfinestructure. This technical jargon may need some explanation. The hydrogen atom, the simplest and also the most abundant atom in the cosmos, consists of a proton as the nucleus and an electron whirling around it. Both particles carry an electric charge and both spin around their axes so that both of them act as small magnets. If the magnetic field of the nucleus

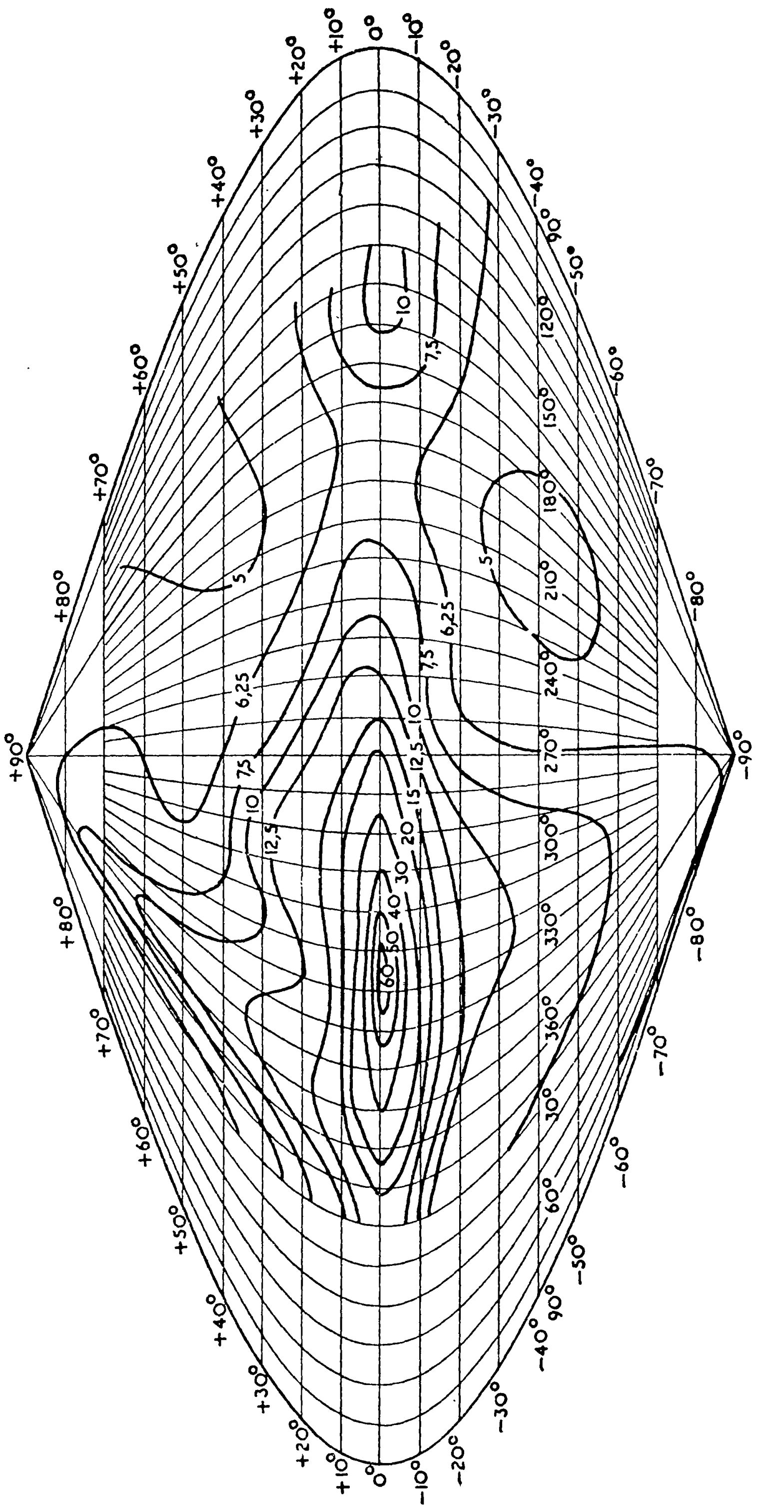


Fig. 2. Isophotes of the continuous radio emission from the galaxy according to the measurements by Bolton and Westfold at wave length 3 metres.

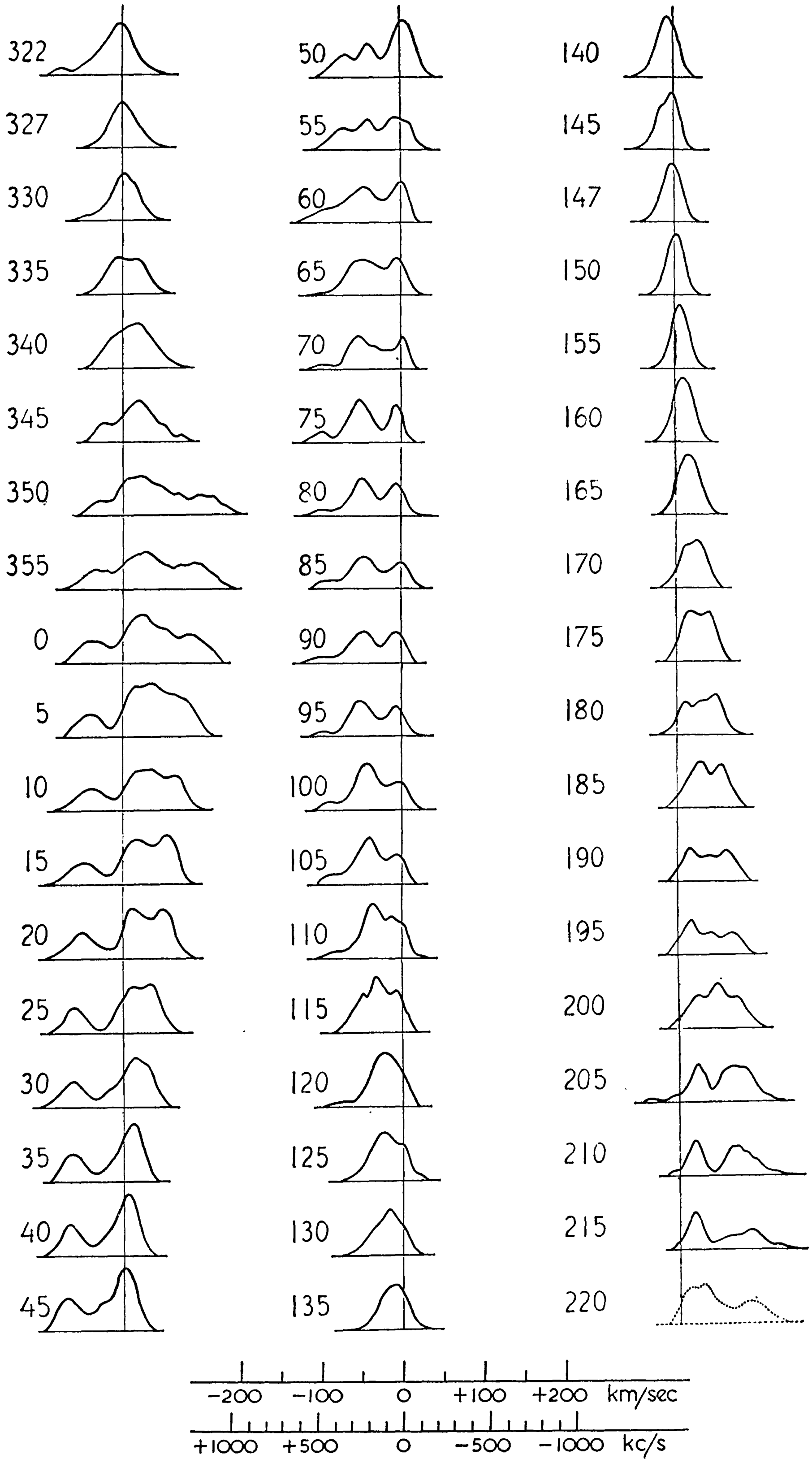
is disregarded, as is usually done in atomic physics, the hydrogen atom has one definite ground state, the state of lowest energy in which the electron is (on the average) closest to the proton. But the magnetic field implies a very small energy difference according as the two magnets have the same direction or opposite direction. The state of parallel directions may change spontaneously into the state of opposite directions with the emission of the very small amount of excess energy. In such a process a quantum of radiation with the wave length of 21 cm is emitted. The "lifetime", i.e. the average time before the transition occurs, is 11 million years. We—astronomers and amateurs alike—need some effort to take such numbers seriously that deviate so enormously from the numbers in ordinary quantum physics. The long lifetime and the very low density of the interstellar gas (a few atoms per cm^3) both tend to diminish the chance of ever measuring this emission in observable strength. But the galaxy is huge and the estimates made in 1944 indicated that looking for this line was worth while.

A number of radio-astronomy groups started out on this programme in the post-war years. In the meantime the accurate frequency had been measured in the laboratory by resonance experiments. These efforts resulted in the spring of 1951 in a spectacular three-fold discovery. Ewen at Harvard University, U.S.A., was first in March, Muller at Kootwijk, Holland, was second in May and Christiansen and Hindman at Sydney, Australia, followed again a few months later. At that time the line was well visible but the measurements were poor. The following years have been devoted to making many improvements in the instruments, alternating with observational tests or longer periods of astronomical measurements. In this work the Dutch group, sponsored by the "Netherlands Organization for Pure Research" has obtained the most precise and most extensive data so far. It is a great pleasure to me to present some of the first results here.

All our work has been devoted to radiation from the galaxy. (The Australians have very recently reported that they have observed the 21-cm line also from the Magellanic clouds.) The observations were made mostly by Muller, the reductions mostly by Oort and myself. The antenna is the 7·5 metre paraboloid with a 3° beam width that was described above; it is steerable, but not following automatically, in azimuth and altitude. Since the improved receiver was ready in July 1952 about 400 tracings have been obtained, each giving a double line profile* for a given point of the sky. Each tracing took two hours or more of observation and roughly twice that amount of reduction, many reductions being made necessary by the still provisional set-up. A full survey would require three-dimensional scanning, for the intensity is a function of l (galactic longitude) b (galactic latitude) and ν (frequency). In this first year we have stuck fairly well to the galactic plane, keeping $b = 0$ and scanning l and ν only. A point of the galactic circle was selected and followed by

* The differential technique used in these measurements essentially gives the line profile measured twice independently.

FIG. 3 Line profiles of the 21-cm line at 54 points of the galactic equator, indicated by their longitude l. In each figure the intensity is the vertical co-ordinate and the velocity is the horizontal co-ordinate, + meaning recession and − approach.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+1000 +500 0 −500 −1000 kc/s

manually adjusting the telescope at intervals of $2\frac{1}{2}$ minutes. In this way three or more double line profiles at many points of the galactic circle have been obtained. They have finally been averaged and brought to a common intensity and frequency scale and the results are represented together in Figure 3. The abscissa of each figure is the frequency or wavelength, long waves plotted to the right-side; the ordinate is the intensity. The vertical line was intended to denote the undisplaced line but corresponds actually to a small velocity of + 1 or 2 km/sec.

Galactic rotation and spiral arms

Omitting all details of measurement and reduction I wish to proceed at once with the interpretation of these line profiles. The fact that there is any r' diation at all outside the proper frequency of the line is certainly due to Doppler shifts arising from radial velocities. Other broadening effects are insignificant. The known velocities of the Earth in the solar system and of the Sun with respect to the surrounding stars have been eliminated. The velocities that are left are partly the thermal velocities of the atoms in a cloud; more important are the random velocities of the clouds with respect to each other, which tend to widen the line symmetrically. The most important effect, however, is the differential galactic rotation. This can be made clear by looking at the sign of the displacement. Emission left of the vertical line indicates approach, emission right of the vertical line recession. If we just assume that the angular velocity of rotation is larger for smaller distances from the galactic centre, it is clear that the locus of zero radial velocity consists of (1) the straight line SC (see Fig. 4), where C represents the galactic centre and S the neighbourhood of the Sun and (2) the circle with C as centre and going through S. These lines separate four areas two with positive and two with negative velocities, which for studies close to the Sun appear as four quadrants in a symmetrical arrangement. At $l = 327°$ and $147°$ the line is narrow and undisplaced. This is as predicted. From 220° to 147° the velocities are positive, from 147° to 60° they are negative; in the third quadrant from 55° to 327° both positive and negative velocities occur, all exactly as foreseen. It is most interesting that in the last quadrant negative velocities do occur; this clearly means that we observe parts of the galaxy farther from the centre of the galaxy than we are and at distances far above 10,000 parsecs.

The line of sight to points in the last-mentioned quadrant passes through regions of positive and negative velocity. The maximum velocity occurs at the point closest to C and near this point the velocity is nearly equal over a long path. This should result in a fairly intense radiation sharply dropping to zero at the plus side. Again the prediction is confirmed, as is illustrated very clearly by the profiles for longitudes 10° to 45°. It is possible to measure at what frequency this sharp drop occurs and thus to gain information on the rotational velocity of parts of the galaxy interior to the Sun. Let r be the distance from S and R the distance from C, let $\omega(R)$ be the angular velocity and $V(R)$ the linear velocity, related by $V(R) = R \times \omega(R)$ and let R_0, ω_0 and V_0 denote the corresponding values for S. Further let $l' = l + 33°$ be the galactic longitude measured from the centre direction.

An arbitrary point then has the radial velocity v with respect to S:

$$v = -\frac{dr}{dt} = R_0\{\omega(R) - \omega_0\} \sin l' \qquad (1)$$

For small r this reduces to the well-known relation

$$v = rA \sin 2l', \qquad (2)$$

where $A = -(R/2)(d\omega/dR)$ is Oort's constant. A somewhat more general approximation of (1) holds for small values of $R - R_0$ but arbitrary values of r. This relation reads

$$v = -2A(R - R_0) \sin l' \qquad (3)$$

Relation (3) has been applied to the points closest to the centre on the lines of sight in the range of longitudes $l = 15°$ to $l = 30°$. Here v is measured in the way described, A is known, l' is known and R is replaced by R_0 sin l'. In this way a direct determination of R_0 is made from galactic rotation effects. So far the estimates of R_0 and V_0 were quite uncertain and in poor agreement with the well-determined value of ω_0. The values that now seem most probable are: $\omega_0 = 26{\cdot}4$ km/sec.kps, $R_0 = 8{\cdot}2$ kps and $V_0 = 216$ km/sec. It is encouraging that a very recent estimate of R_0 by Baade from RR Lyrae variables found in the Sagittarius Cloud gives very nearly the same result.

The explanation given so far leaves out the most striking feature of the line profiles: their strong maxima and minima. They must indicate an irregular distribution of the densities or of the velocities of the interstellar gas. It seems most likely that most of the maxima and minima are due to a patchy density distribution, although it is already clear that some minor details cannot be explained in that manner. Granting the assumption of a completely regular rotation with a known function $\omega(R)$, the following elegant solution of the density distribution may be made. A certain velocity v observed in a certain direction corresponds by means of equation (1) to a certain value of R. This places the gases at one point (or two or zero) upon the line of sight. Its position in the galactic plane is thereby fixed and can be plotted in a polar diagram with S as the centre.

By means of this method we have obtained the diagram shown in Fig. 4. Each maximum of the line profiles was represented by a dot in the diagram and the dots connected by a cross-hatched band, the width of which corresponds approximately to the width of the maxima. These bands represent the regions in the galactic plane that have a high density of atomic hydrogen gas. These regions have the form of spiral arms and the direction of rotation is with the arms trailing. In viewing Fig. 4 it should be remembered that it is incomplete for three reasons: the sector that is invisible from Holland has been left out; narrow sectors near the centre and anticentre directions have been left open because the method used is not precise; and the entire portion closer to C than S has been left blank because the solution is ambiguous, one v and R corresponding to two values of r.

It is not necessary to emphasize the importance of these investigations: they stand out against the hopes and desires of several generations of astronomers. To observe the spiral arms in our own galaxy has been the distant aim of many researches. We may remind you that, in fact, it was not radio astronomy but ordinary astronomy which gave the first is not so great as it was, the development of the subject owes much to this body, since much of the recent work could not have been done without the help of the valuable records taken at Kew. *Dr. Deacon* mentioned that Prof. Ewing is from the University of Columbia, New York, and thanked him for the trouble he had taken to attend the discussion.

Professor M. Ewing said that the microseismic studies at Lamont were carried on by Dr. Donn, Dr. Press and himself. Observations of microseisms have been made at Palisades and two different types have been recognized.

The first type of microseism is associated with the passage of a cold front from North America out into the Atlantic Ocean and has a short period of 2 to 3 seconds. The second type is a longer period disturbance, whose period ranges from 4 to 8½ seconds, and is associated with deep depressions at sea. The greatest deficiency in the observational material is in the field of oceanic wave motions, which are not known in so much detail, nor over so wide an area, as is desirable. *Prof. Ewing* then showed slides of the meteorological conditions during the passage of a cold front over the coast line and of the associated microseismic activity. Analysis of the ground motion shows that these waves are Rayleigh waves travelling in a single direction past the station as long as the meteorological disturbance remains on the continental shelf. The ground motion associated with storms at sea beyond the continental margin is more complicated and cannot be accounted for by a single set of Rayleigh waves travelling in one direction—possibly refraction at the continental margins is responsible for the multiplicity of directions of approach.

Records taken by the Beach Erosion Board showed that, in many cases, there are no large waves at sea during microseismic activity associated with the passage of a cold front. Passage of each cold air mass at Palisades is shown by a striking increase in level of pressure fluctuations in the period range ½ sec. to 10 minutes, probably produced by turbulence or gustiness. Short period microseisms begin sharply when each cold air mass reaches ocean water (about 30 miles away).

There is a correlation between the period of microseisms produced by a storm at sea and the depth of water at the position of the storm. The meteorological conditions and microseismic activity connected with several storms were illustrated with slides and, in particular, one large burst of 8½ second period microseisms was correlated with a stationary storm over deep water. Microseismic observations have recently been started at Bermuda, where the neighbouring water is of greater depth, and it is found that the microseisms due to cold front passage are generally of longer period than at Palisades. No storms in the Gulf of Mexico have produced microseisms with periods longer than 3 seconds. Observations on 28 hurricanes and a much greater number of cyclones lead to the conclusion that the longer period disturbances are associated with storms over deeper water.

Dr. M. S. Longuet-Higgins began by discussing previous objections to the theory that microseisms are caused by waves at sea. The wavelength of a typical microseism is of the order of 15 kms whereas that for a sea wave is only about 60 metres. Thus any pressure fluctuations that may be produced by a sea wave tend to cancel out when averaged over a distance comparable with the wavelength of a microseism, unless there is a degree different from the plane of the middle arm. A discussion of the effects of optical depth in the hydrogen line, which has till now been made only incompletely, may reveal further puzzling features. I hope that these few remarks will serve to efface the initial impression that everything fits perfectly to our previous ideas and will indicate the prospect of further fascinating problems to come.

References

(1) Introduction to radio astronomy in general:
A. C. B. Lovell and J. A. Clegg, *Radio Astronomy*, London (Chapman and Hall), 1952.
H. C. van de Hulst, *A Course in Radio Astronomy*, mimeographed lecture notes, Leiden, 1951.

(2) Galactic structure: J. H. Oort, *Ap. J.*, **116**, 233, 1952.

(3) Continuous galactic radiation. Figure 2 is based on:
J. G. Bolton and K. C. Westfold, *Australian J. Sci. Res.*, A**3**, 19, 1950.

(4) The 21-cm line—prediction: *Ned. Tydschrift Natuurkunde*, **11**, 201, 1945.
—discovery: *Nature*, **168**, 356, 1951.
—full details of the measurements in Holland will be published in a forthcoming number of *B.A.N.*

GEOPHYSICAL DISCUSSION

A Geophysical Discussion was held in the rooms of the Royal Astronomical Society at $16^h\ 15^m$ on 1953 Feb. 27. Dr. G. E. R. Deacon was in the chair and the subject for discussion was "Ocean Swell and Microseisms".

Dr. Deacon recalled that this was not the first Geophysical Discussion to be held on the subject. Before the war, it had been agreed that microseisms are associated with deep depressions at sea and not particularly with waves breaking on the coast. It was, however, difficult to see how storms over deep water could transmit energy to the sea bed, for the wavelength of the seismic waves is much longer than that of the water waves and in a progressive wave the disturbance of the water decreases very rapidly with depth. Whipple* suggested, in 1934, that these difficulties arose because the actual conditions had been oversimplified in the mathematical treatment. Both Whipple and Lee (1934)† felt that, as the water waves progress and change their form, they might behave very differently from the infinite train of regular waves, which had been the basis of the theoretical arguments, and this idea has been developed since then. Although the interest of the Meteorological Office in microseisms

* Whipple, F. J. W., *U.G.G.I., Sec. Seis. Trav.*, **10**, 127, 1934.
† Lee, A. W., *Met. Office Geophys. Mem.*, **62**, 1934.