A SYMPOSIUM ON RADIO-ASTRONOMY AT JODRELL BANK

By R. Hanbury Brown

A variety of current problems in radio-astronomy was discussed at a Symposium held at the Jodrell Bank Experimental Station of the University of Manchester on July 13th, 14th and 15th, 1953. The Symposium was opened by *Professor A. C. B. Lovell* who extended a welcome to those attending the meetings and in particular to the considerable number of astronomers who had come from abroad.

The discussions were divided into four subjects:—

July 13th. The Solar Corona.
July 14th. The Radio Stars.
Techniques in Radio Astronomy.
July 15th. Galactic Structure.

Each of these subjects was introduced by a speaker and then a number of short papers were presented and were followed by discussion.

July 13th. *The Solar Corona.*

The chairman of this session was *Professor A. C. B. Lovell* and the subject was introduced by *Dr. H. C. van de Hulst.*

In his introductory talk *Dr. van de Hulst* reviewed our present knowledge derived from visual data of the density and temperature in the solar corona. He drew attention to certain discrepancies in the temperature given by different methods, for example, that given by considerations of ionization equilibrium ($\sim$ 800,000°K) is considerably lower than that given by the width of the emission lines of ionized iron ($\sim 2 \times 10^6$°K). He then turned to the radio data and pointed out that a few years ago there was little difficulty in explaining theoretically the integrated radiation from the Sun at metre wavelengths. However, more recent measurements of the distribution of radio-frequency intensity across the Sun's disk show a considerable discrepancy with the previous theory. In particular it has been found that the radiation from the outer regions of the disk is greater than that predicted. He outlined the difficulties in adjusting the temperature and density of the corona to fit the observations.

Mr. O'Brien described some measurements made at the Cavendish Laboratory, Cambridge, to determine the distribution of intensity across the Sun's disk at wavelengths of 0·60, 1·4, 3·7, and 7·9 m. by means of interferometers. The measurements at 1·4 m. (which are the most complete) show that the distribution of intensity across the Sun's disk is not radially symmetrical. The disk appears to be roughly elliptical in shape with a ratio of approximately 1·25 to 1·0 between the major and minor axes: the major axis lies along the equator. It has been found that the apparent diameter of the Sun varies with time and he showed that there was good correlation between the apparent diameter of the Sun at 1·4 m. and the intensity of the green coronal line (λ 5303 A).

Dr. J. F. Denisse presented some measurements of the intensity distribution across the Sun's disk at 3·2 cms. made by Mr. Steinberg with an interferometer. The distribution shows considerable limb brightening.

Dr. Hewish discussed a theoretical investigation of the radiation from the Sun's corona carried out by Mr. Bell. He showed that if the electron density given by Allen is used, then the theoretical model does not fit the observed distributions. The greatest discrepancy occurs at large radii where the observed radiation is greater than the theoretical value. He found that the best fit to the observations was given by:—

$$N = 5 \times 10^8 \rho^{-4}, \quad T = 1{\cdot}8 \times 10^6 \rho^{-3}$$

where N is the electron density, T is the temperature, and ρ represents the height in the corona. Assuming these values, which give a higher density in the outer regions than normally assumed, he showed that the theoretical model fits the observations reasonably well in the outer corona but there are discrepancies at smaller radii. He suggested that these discrepancies might be removed by introducing the effects of scattering into the theory. *Dr. Hewish* then gave an account of some observations of the occultation of the radio source in Taurus by the Sun's corona. Observations had been made at Cambridge of the intensity from this radio-source as it passed within 4·6 $R_\odot$ of the Sun's disk, using interferometers of aperture 157 λ and 105 λ at 3·7 m. and 49 λ and 8 λ at 7·9 m. The intensity of the source at various distances from the Sun's disk was calculated using the distribution of electron density given by Allen. The theory predicts that the intensity of the source at 7·9 m. should remain approximately constant until it reaches 5 $R_\odot$ from the Sun when it should decrease to zero abruptly. Measurements on 3·7 m. and 7·9 m. show that the intensity decreases steadily from about 20 $R_\odot$ and shows no abrupt decrease. *Dr. Hewish* showed that the experimental results could be explained entirely by scattering in the corona. A preliminary analysis suggested that the scattering might occur in irregularities of about 100 electrons/c.c. in regions of about 0·1 kms. size. If the irregularities were larger a greater electron density would be required to produce the same degree of scattering. *Professor Biermann* pointed out that the discrepancy between the temperature of the corona deduced from ionization equilibrium and from the width of the emission lines of ionized iron might possibly be due to the effects of energy transport in the corona. He discussed the evidence for the density in the corona at large radii and pointed out that the polarization of the zodiacal light, the acceleration of the matter in cometary tails, geomagnetic phenomena, radio observations of occultations by the corona and the radio brightness of the corona all require a fairly high density of matter at large distances from the Sun. He suggested that the required values could be explained in terms of the emission of particles from the Sun.

Mr. Fokker discussed the relation between "bursts" of radiation from the Sun and the "enhanced radiation". He analyzed observations made at 200 Mc/s and derived the statistical properties of the "bursts" and the associated "enhanced" radiation. He showed that the observed results are consistent with the theory that the "enhanced" radiation is composed of large numbers of small "bursts".

Mr. O'Brien presented an analysis of the emission polar diagram of sunspots based on the work of Dr. Machin. Observations of sunspot radiation at 81·5, 175 and 500 Mc/s had been analyzed by an auto-correlation technique to give the emission polar diagram of a sunspot; the total widths, to half intensity, were 15°, 20° and 36° at these frequencies. He showed that at 175 Mc/s the radiation often persisted for two solar rotations, while at 81·5 Mc/s it seldom persisted for even one rotation, *Mr. O'Brien* then described some measurements of the angular movement of sunspot sources at 81·5 and 210 Mc/s. He showed that there was considerable scatter in the heights of the source of the radiation in the corona derived in this way, and it seems probable that the measurements are affected by lateral gradients of the electron density above the sunspot. The position of the spot sources had also been observed to vary rapidly by an amount usually considerably less than 1′, while the observed angular diameter of the sources may be about 5′. He suggested that these results might be explained by scattering due to irregularities in the corona.

The afternoon was devoted to a short session in which participants were invited to give a short description of their plans for research in radio-astronomy. This session was followed by a tour of the Jodrell Bank Experimental Station.

July 14th. *The Radio Stars.*

The Chairman of this session was *Mr. Hanbury Brown* and the subject was introduced by *Mr. Martin Ryle.*

Mr. Ryle reviewed the history of the work on radio stars from the first observations to the present day. Some of the weaker sources observed have been identified with extra-galactic nebulae and the intensity of these sources is just of the order of magnitude which one would expect if our own Galaxy were placed in the appropriate position. While this result has demonstrated that whatever is responsible for the radio emission in our own Galaxy also occurs in our near neighbours, it does not explain the origin of the radiation, nor does it explain the majority of the radio stars. It seems clear that we must be dealing with some new type of celestial object. *Mr. Ryle* reviewed the experimental difficulties in observing the radio stars and drew attention to the difficulty of identifying the radio sources with visual objects when the accuracy of the coordinates was only about ± ½°. He discussed the various sources of error in the determination of the position of a radio star and in particular the effects of the ionosphere. The scintillation of the radio stars arises in irregularities in the ionosphere. The source of these irregularities is at present unknown and their occurrence does not appear to be related to any other geophysical phenomena. In the last few years accurate determinations of the position of the intense radio source in Cygnus have been made in Cambridge and in Australia, and the source in Cassiopeia has been measured accurately at Cambridge. These results have led to the visual identifications made by Dr. Baade and Dr. Minkowski. More recently the angular diameter of these sources has been measured at Cambridge, Jodrell Bank and in Australia. As a result of all this recent work we now know more about the type of object which emits radio waves but we do not understand how the waves are emitted.

It appears that we have both galactic and extra-galactic sources and the question arises as to whether the galactic sources can account for the radiation observed from the Galaxy, since it appears impossible to explain it in terms of the interstellar medium. Recent observations by Mills, and by Hanbury Brown and Hazard, have shown a significant concentration of the bright radio stars towards the galactic plane and this indicates that we can detect galactic objects at a great distance. However the number of radio stars available for analysis at present is small and it is important that future observations should produce a large number, both for analysis of their distribution, and in order to facilitate more identifications. In this way we may be able to find how many sources are members of the Galaxy and how many are extra-galactic.

Dr. Minkowski said that four different types of object had been identified as radio sources. The first type is represented by the Crab Nebula, which is the remnant of a supernova. Three supernovae are known to have occurred in the Galaxy in the years 1054 (Crab), 1572 (Tycho Brahe) and 1604 (Kepler). There is a radio source in the position of the Crab, and Hanbury Brown and Hazard have reported a source in the position of the supernova of 1572. The supernova of 1604 is quite close to the galactic centre and it is not surprising that a radio source has not been found in its position so far. The second type of object is represented by the source in Cassiopeia. An exposure with the 200-inch telescope shows a remarkable nebulosity in the position of this radio source. The nebulosity is of about 6 minutes of arc in diameter and consists of a number of filaments of a type which has definitely not been observed previously. The position of the radio source agrees quite accurately with the centre of the circle enclosing these filaments but does not coincide with the visually brightest area, which suggests that the optical and radio emission do not correlate directly. The spectrum of the filaments is found to be unique. One filament shows a velocity spread of at least 3300 kms/sec. The relative intensity of the oxygen and hydrogen lines in this spectrum suggests that the excitation of the filament is by collision and not by radiation. Two other filaments show spectra which are not quite as abnormal in composition and velocity, but the velocity spread in all the three filaments is very high. Measurements of the velocity difference between a filament near the edge and in the centre show that the rate of expansion is not high and the object is therefore definitely not the shell of a supernova. Neither is it permissible to assume that it represents a supernova shell stopped by interstellar gas since considerations of the mass require that the object must be inside one of the densest interstellar clouds, which is obviously not the case. One more object of this type has been found in Puppis. It shows similar filaments spread over an area of about $\frac{1}{2} \times \frac{3}{4}$ degree and agrees satisfactorily in position and diameter with a radio source. There may be another source of this type corresponding to the extended source in Cygnus found by Piddington and Minnett and confirmed by Hanbury Brown and Hazard. This region contains filaments of similar appearance to those found in Cassiopeia and Puppis, but so far no spectra of the filaments have been obtained. The third type of object is represented by the intense source in Cygnus. In the position of this source there is an unusual extra-galactic object and the picture may be interpreted as two nebulae in collision broadside on and viewed at an angle of about 45° to the line of sight. If this is really a collision one would expect the gas in the two systems to be highly excited and, in fact, the spectrum shows this to be the case. The red-shift indicates a velocity of about 17,000 kms/sec. which on the old distance scale represents a distance of about 34 megaparsecs. There appear to be two other possible examples of colliding galaxies. The source found by Hanbury Brown and Hazard in the Perseus cluster may correspond with the peculiar object NGC 1275—which appears to be two spirals in collision and which has a spectrum similar to that of the Cyngus source. The next example is the radio source corresponding with NGC 5128, an object which is now regarded as extra-galactic. It has a dark absorption band with spiral structure extending across the image at 90° to the main extension of the nebula. This suggests the interpretation that it is actually two nebulae superimposed, and possibly in interaction, and it is to be noted that the shape of the radio source determined by Mills fits well with the position of the absorbing band. There is another example of a peculiar extra-galactic object represented by NGC 4486 in Virgo. This object is a spheroidal nebula and has the peculiarity that out of the nucleus there is a "jet". This "jet" contains condensations which exhibit a continuous blue spectrum with no emission lines. The nucleus shows an emission line of (II O λ 3727) which is shifted relative to the nuclear spectrum by 300 km/sec. This suggests that matter is being ejected from the nucleus. The associated radio source has been studied by Mills who gives a diameter and position which correspond more with the whole nebula rather than the "jet". This would suggest that the radiation is associated with the whole nebula and the presence of the "jet" is an indication that something abnormal is occurring. The fourth type of object which has been identified as a radio source consists of normal extra-galactic spirals and more would be said about them by other speakers.

In the course of the subsequent discussion *Dr. Minkowski* said that there is no evidence of obscuration of the Cassiopeia object and that its distance is unlikely to exceed 500 parsecs. It must therefore be in the Galaxy. The total radio emission per unit mass from the object appeared to be somewhat similar to that found for sunspots.

Dr. Minkowski then discussed the Crab Nebula. He showed that the determination of the electron temperature in the nebula from the optical data is uncertain but that an upper limit could be assigned to it from considerations of the total mass of the nebula. The emission from the nebula in the photographic range is about $3{\cdot}4 \times 10^{21}$ ergs sec^{-1}, while in the radio spectrum it is about $2{\cdot}8 \times 10^{24}$ ergs sec^{-1}. Allowing for a variation of the Gaunt factor of about 10, this shows that the radio emission from the nebula is about 90 times too strong to be explained as a simple continuation of the optical spectrum. The radio spectrum of the Crab Nebula shows that the intensity decreases more slowly with increasing frequency than in other sources. In collaboration with Dr. Greenstein he had computed several theoretical spectra assuming that the radiation arose by some unknown mechanism in the nebula with a spectrum similar to that found for the other radio sources. The resulting spectrum would be modified by absorption in the ionized gas of the nebula and would depend on the position of the emitting source within the nebula. *Dr. Minkowski* showed that it is possible to explain the shape of the observed spectrum in this way, and he suggested that this hypothesis might be checked by detailed measurements of the apparent size of the emitting region in the Crab Nebula.

Professor Lovell enquired if it was possible to explain the total radiation from the Galaxy in terms of any of the objects which had been identified, *Dr. Minkowski* said that the total radiation could not arise from objects similar to the Crab since they would be too rare. It also seemed unlikely that objects similar to the Cassiopeia source could account for the radiation since one would expect to see several such objects and they had not in fact been observed. He also thought that such objects would probably be associated with Population I, while the bulk of the radio radiation appeared to be associated with Population II. He expressed the view that it was more likely that the bulk of the radiation is associated with stellar objects. *Professor Oort* pointed out that the radiation from NGC 4486 presented a difficult problem in interpretation since the radio measurements indicated that the radiation was associated with the nebula rather than with the "jet". It was difficult to see how the whole of the spheroidal galaxy could be stimulated into excessive emission. In answer to a suggestion by *Professor Biermann* he thought it was unlikely that the radio radiation could be associated with flare stars, since one would expect that the radio stars would then be variable and the evidence showed that they are, in fact, constant in intensity.

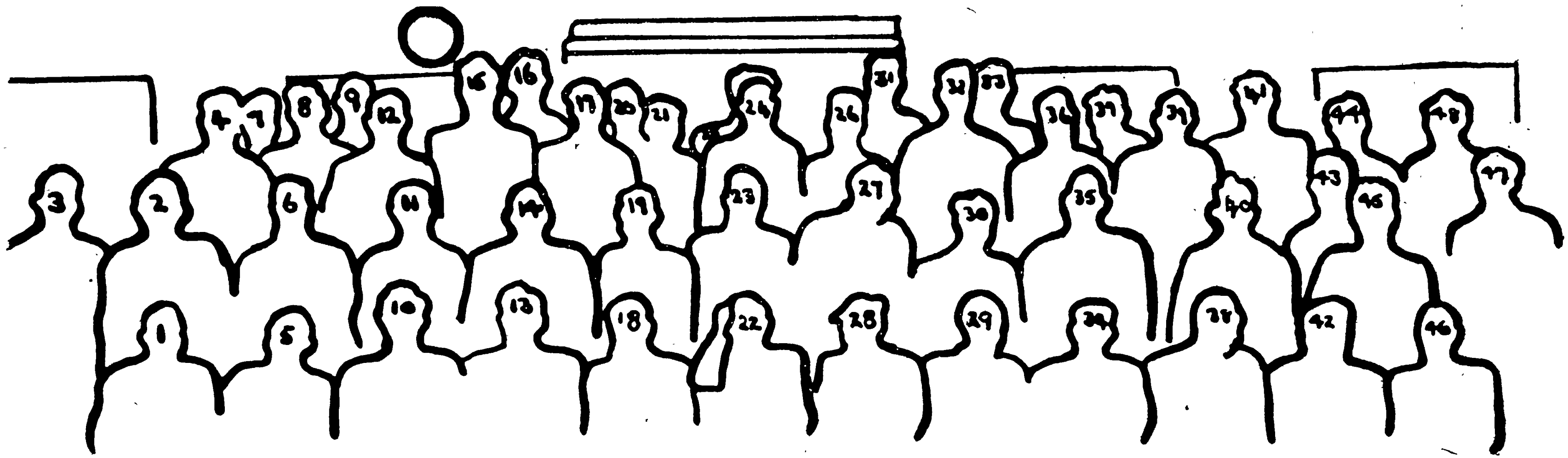
Mr. Baldwin described some measurements of the intensity distribution across the Crab Nebula made with an interferometer at Cambridge on a wavelength of 1·4 m. He showed that there was no evidence of a source reported by Stanley and Slee about 2 degrees away from the Crab. The distribution across the Crab was not simple and the measurements could be interpreted in at least two ways. The first interpretation showed a symmetrical distribution with a central peak of about 5′ angular diameter and two minor peaks spaced at about 10′ from the centre. The second interpretation was asymmetrical and showed a large peak of width 5′ with a minor peak spaced 10′ away. The intensity of the minor peak was 25 per cent of the large peak. He suggested that the distribution observed across the Crab might therefore be due to the presence of a strong source and a weaker nearby source.

Mr. Jennison described some measurements, made in collaboration with M. K. Das Gupta, of the apparent diameter of the intense sources in Cygnus and Cassiopeia, using a new type of interferometer at Jodrell Bank. The observations had shown that the source in Cassiopeia was roughly circular with a diameter of about 5′, while the Cygnus source appeared to be elliptical in outline. Detailed observations had been made along the major axis of the Cygnus source with baselines of 900, 1450, 1550, 1650 and 2100 wavelengths. The results showed that the Fourier transform of the distribution of intensity across the source fell to zero at about 1250λ and that there was a secondary peak in the curve of about 54 per cent of the value with a baseline of zero length. The observations made by Mills in Australia with very long baselines, and by Smith in Cambridge with short baselines, could be fitted to this curve with reasonable agreement after a small correction had been made for the different angles at which the observations had been made. The distribution of intensity across the Cygnus source could not be interpreted as a uniform distribution and the simplest model which would fit the observations consisted of two equal rectangular areas of constant intensity and of size $43'' \times 30''$ with a separation between their centres of 1′ 22″. In this model there is a central area $39'' \times 30''$ of zero intensity and *Mr. Jennison* suggested that the visual object observed by Dr. Minkowski lies in this central region with the two emitting patches arranged symmetrically on either side. A possible explanation of this model might be that the two nebulae had been distorted by gravitational forces during their approach and the interaction of the central regions had taken place before the interaction of their outer regions. The present source represented the interaction of the outer regions of these two nebulae. The angular dimensions of the source suggested an object of about 18000 parsecs size at the distance given by the red shift of the nebulae.

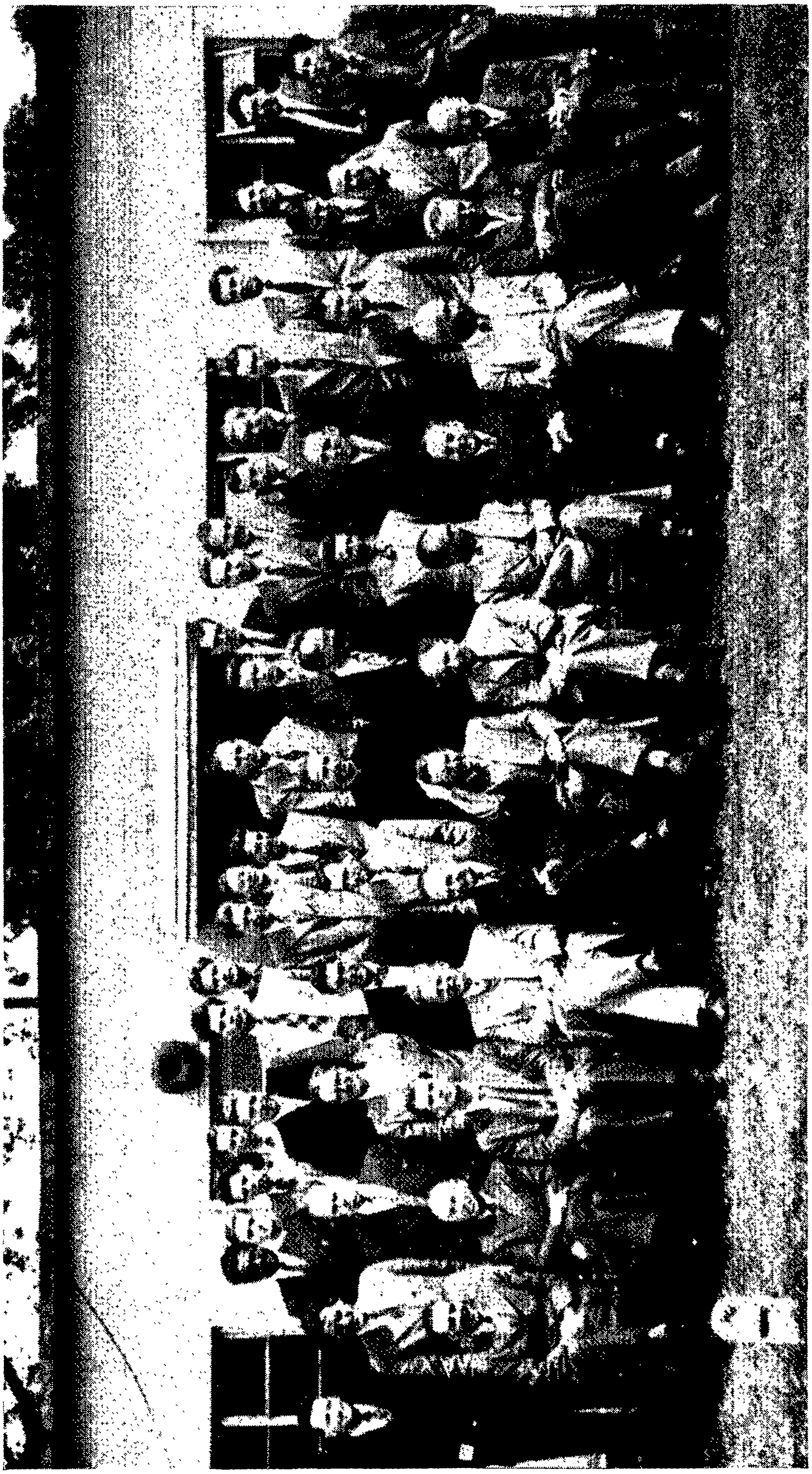
In the subsequent discussion it was remarked that the new distance scale increases the size of this object to 36000 parsecs, which is rather large for a source associated with the collision of two nebulae.

Mr. Hanbury Brown discussed a theoretical model of the radiation from the Galaxy derived in collaboration with Dr. Hazard. Inspection of the isophotes of radio-frequency radiation observed over the sky indicated that there was a strong concentration of the source of radiation towards the galactic centre even at very high frequencies. It therefore appeared highly unlikely that the major source of radiation lay in the ionized interstellar gas. The model assumed that the interstellar gas had the properties derived from visual observations. A detailed description of this model of the gas would be given in the session on galactic structure. The radiation from the gas had been calculated theoretically and had been subtracted from the observations made by Reber at 480 Mc/s with a $4\frac{1}{2}°$ beam. The process of subtraction took into account the effects of the beam width of Reber's aerial.

The radiation remaining after subtraction of the component due to the gas was assumed to arise in sources. The true distribution of this radiation had been found by correcting for the effects of Reber's beam and had been checked by calculating the results to be expected at other frequencies with different beam widths. These calculated results had been compared with the observations and it would be shown in the next session that good agreement had been obtained at all the frequencies investigated. The "true" distribution of the intensity from the sources had been used to derive a model of the space distribution of the sources on the assumption that they are distributed with radial symmetry about the galactic centre. This derived space distribution shows that the majority of the sources are contained in an ellipsoid of revolution about the galactic centre whose major axis is about 6 kiloparsecs and whose minor axis is about 800 parsecs. The distribution of the sources resembles that of planetary nebulae which suggests that the radio sources are members of Population II. The radiation from the sources per unit volume near the Sun required by the model is 10^8 watts/steradian/c.p.s./cubic parsec. at 100 Mc/s. Analysis of a survey made with the 220 ft. paraboloid at Jodrell Bank has shown that there is a class of intense sources concentrated into the galactic plane. This result had also been obtained by Mills for a larger section of the galactic plane. If it is assumed that these intense sources are at about 1000 parsecs distance then their intensity is $1{\cdot}6 \times 10^{15}$ watts/steradian/c.p.s. at 100 Mc/s and their density about 5×10^{-8} sources/cu. parsec. These values show that the radiation from these sources is about 8×10^7 watts/steradian/c.p.s./cubic parsec near the Sun. Comparison of the value required by the model and that deduced from the bright sources suggests that the aggregate radiation from the Galaxy might be due to a



1 Smith
2 Hanbury Brown
3 Bullough
4 Das Gupta
5 Becker
6 Neubauer
7 Gill
8 Kaiser
9 Hargreaves
10 Ryle
11 Huxley
12 Baldwin
13 van de Hulst
14 Savedoff
15 Scheuer
16 O'Brien
17 Adgie
18 Kourganoff
19 Denisse
20 Williams
21 Shakeshaft
22 Biermann
23 Koster
24 Schrader
25 Davies (occulted)
26 Fokker
27 Seeger
28 Lovell
29 Tuominen
30 Hey
31 Schmidt
32 Little
33 Hill
34 Laffineur
35 Stumpers
36 Hazard
37 Jennison
38 Minkowski
39 Thompson
40 Westerhout
41 Maxwell
42 Bok
43 Palmer
44 Dagg
45 Kahn
46 Oort
47 Storey
48 Browne



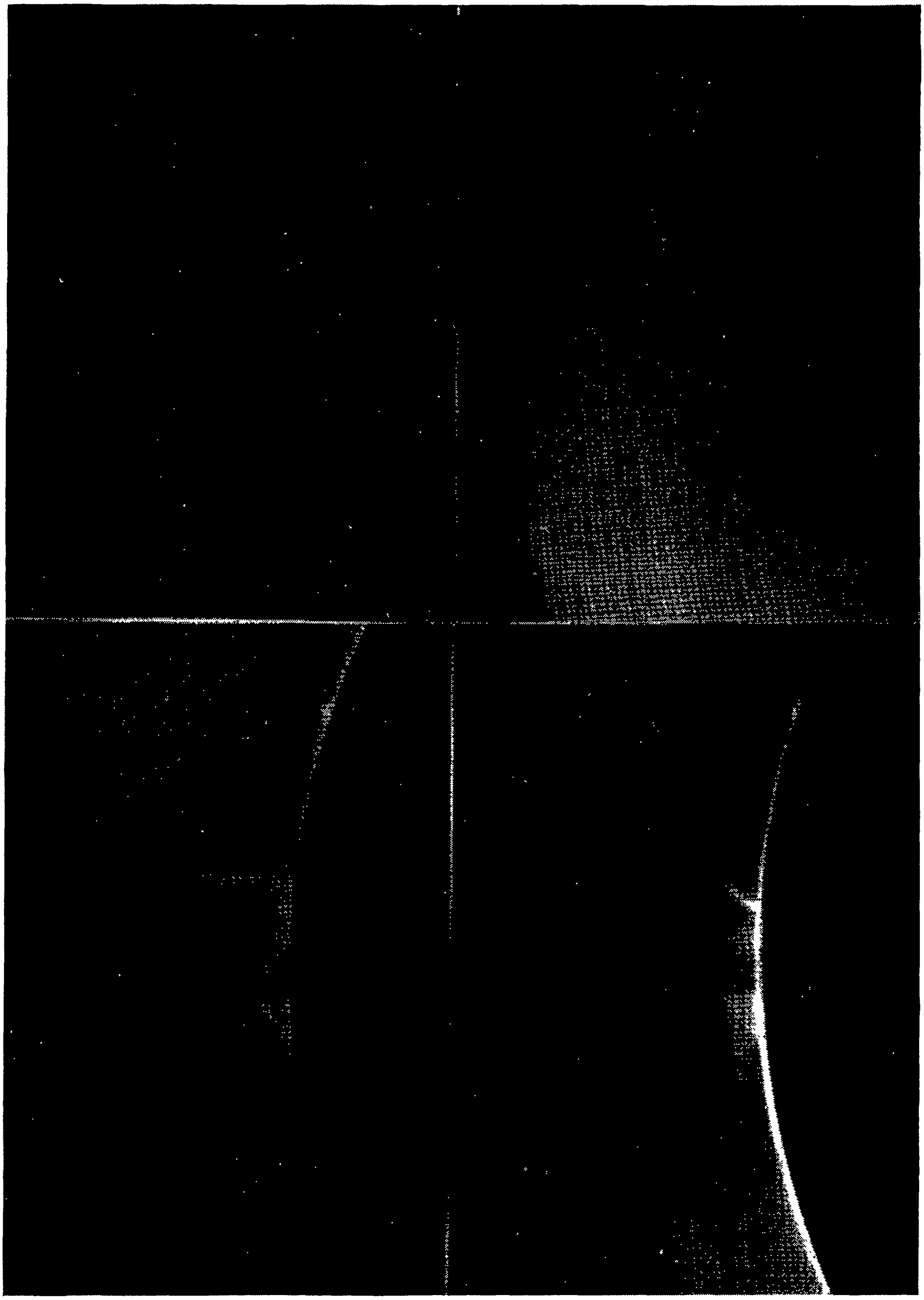
Symposium on Radio-astronomy at Jodrell Bank system of rare sources which are members of Population II and which have a density about one million times less than that of the common stars.

Dr. Hazard outlined some observations of extra-galactic nebulae made in collaboration with R. Hanbury Brown. Using the 220 ft. diameter paraboloid at Jodrell Bank, and working at a wavelength of 1·89 m. a radio source had been detected in the positions of NGC 224, NGC 3031, NGC 5457, NGC 5194, NGC 4258 and NGC 2841. The relation between the apparent photographic magnitude and the radio magnitude of these nebulae had been examined and the results indicated that for a normal late-type spiral the ratio of radio flux to light flux is a constant. Earlier work had suggested that this ratio increased for faint nebulae; however, this conclusion was probably vitiated by the failure to take into account the effects of orientation on the photographic magnitude of the nebulae observed. In the work at Jodrell Bank the radio magnitude of a source whose intensity is $5{\cdot}5 \times 10^{-26}$ watts/sq. m./ c.p.s. at 1·89 m. had been defined as 9·7. This definition was based on some observations of NGC 5194-5 and the definition was intended to make the radio magnitude at 1·89 m. and the photographic magnitude (Shapley-Ames) equal for this nebula. The resulting relation could be written:—

$$M_R = -53{\cdot}4 - 2{\cdot}5 \log I$$

where M_R is the radio magnitude and I is the radio intensity in watts/ sq.m./c.p.s. in both polarisations.

Observations had also been carried out on small irregularities in the radio isophotes of the sky and these had been correlated with irregularities in the distribution of extra-galactic nebulae. The radio isophotes show a strip of increased intensity between declinations $+40°$ and $+70°$ following approximately a line of constant right ascension (12 hours). This strip shows good correlation with a map of the distribution of nebulae in the region. The radio intensity had been compared with the integrated light from the nebulae, and after correction for the effects of red shift, orientation, nebulae below the limits of the plates and several other small corrections, it had been found that the radio intensity was greater than would be expected if all nebulae gave the same ratio of radio flux as that observed for normal late-type spirals. The discrepancy was uncertain but did not exceed 2 magnitudes. The same order of discrepancy had been found in observations of two clusters, and it was suggestive that the so-called "isotropic" component of the total radio radiation showed a similar discrepancy with the value calculated on the assumption that all nebulae radiate radio-frequency in the same proportion to their light as late-type spirals. *Dr. Hazard* suggested that the majority of the radio stars might be extra-galactic. The fainter radio stars, called Class II by Mills, appear to be distributed isotropically. Their distribution suggests that they are more frequently found in regions of the sky where there are concentrations of extra-galactic nebulae, for example the Ursa Major region. If a statistical analysis is made of their distribution in magnitude, and if it is assumed that they contribute a total radiation equal to that observed at the galactic pole, then their space-density and absolute intensity can be evaluated. The values deduced depend upon the dispersion assumed in their absolute magnitude. *Dr. Hazard* showed that, taking reasonable values for this dispersion, the space-density is of the same order as those



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of extra-galactic nebulae, while their mean absolute intensity corresponds with that found for normal late-type spirals. This analysis supports the suggestion that the so-called Class II sources are extra-galactic. *Professor Oort* remarked that the discrepancy found for the radiation from clusters was interesting and reminded him of the similar discrepancy found between the integrated light and the mass of clusters.

Mr. Shakeshaft gave a brief description of the new interferometer at Cambridge and exhibited a most striking record taken with the new instrument. The results of the work had not yet been fully analysed; however, he showed a map of the radio sources in a ten degree strip of sky at about declination + 30°. The most intense sources in the strip shown had an intensity of 3×10^{-24} watts/sq. m./c.p.s. and the faintest had an intensity of 4×10^{-26} watts/sq. m./c.p.s. He estimated that at least 500 radio sources would be observed with the new instrument.

Mr. Maxwell said that there were several people attending the symposium who were interested in the study of winds in the upper atmosphere by means of the scintillations of radio sources. He would therefore describe the technique used at Jodrell Bank together with some of the results obtained. The apparatus involved the use of three receivers spaced in a triangle. The scintillation of a radio source was recorded simultaneously from each receiver, and by observing the time delays between the same scintillation on each record it was possible to determine the direction and speed of motion of the irregularities in the ionosphere. The velocities recorded show that the F region irregularities have a steady translational movement which is usually maintained in a given direction for many hours. The favoured direction of the winds was towards the west during the first half of the night and towards the east in the latter half, with an average velocity of about 200 m/sec. Analysis of the records shows that there is a linear relation between the speed of the winds and the rate of fluctuation observed, which suggests that the size of irregularities in the F region remains constant. There is a remarkable correlation between F region velocities and the geomagnetic K index. He suggested that the irregularities themselves might be caused by turbulence in the F region and he showed that the value of the Reynolds number was consistent with such an explanation.

July 14th. *Techniques*

The chairman of this session was *Mr. Martin Ryle.*

Mr. Ryle introduced the subject by reviewing the various techniques used in the measurement of low values of noise power. He also described the techniques used in interferometers and gave a brief review of the "phase-switching" technique in which the connection between the two aerials of an interferometer are reversed periodically. *Mr. Hanbury Brown* discussed briefly the application of the "Ryle" type of receiver to the measurement of aerial temperatures below room temperature. He also gave a brief description of a new type of interferometer in which the polar diagram is rotated continuously in one direction. In this equipment the signals from the two aerials are heterodyned by two local oscillators which differ slightly in frequency. This causes the polar diagram to "revolve" at the difference frequency. The signals are detected in a phase-sensitive rectifier which is energized by a reference wave produced by the beat-frequency between the two local oscillators. *Mr. Laffineur* described a receiving equipment at 400 Mc/s which employs an electronic switching circuit for comparing the noise received with that from a standard source.

Mr. Adgie discussed the calibration of standards of noise power, with particular reference to noise diodes. *Dr. Seeger* described the construction of receiving equipment in Holland for work at 400 Mc/s. The receiver employed two cascade amplifiers before the mixer, and by means of a Phillips type EC 56 valve a noise factor of less than 2·0 had been achieved at 400 Mc/s. For the purpose of making accurate absolute measurements of the temperature of the sky it was proposed to use horn type antennae since the gain could be calculated accurately. He proposed to measure the aerial temperatures at high frequencies by comparison of the received power with a load at a low temperature, and he described the technique employed to produce suitable load resistances at very low temperatures.

Dr. Stumpers described the equipment used in Holland for observations of the 1420 Mc/s radiation from neutral hydrogen. *Dr. Little* described the system under development at Jodrell Bank for the same purpose. *Dr. Bok* described the equipment for observation of the hydrogen line under construction at Harvard for installation in the Agassiz observatory. *Dr. Storey* described the equipment under construction at T.R.E. (Malvern, England), for observation of the neutral hydrogen radiation from the Andromeda Nebula. The predicted width of the line is about 3 Mc/s and the actual temperature with the aerial proposed is only 1/20°K.

July 15th. *Galactic Structure*

The chairman of this session was *Mr. M. Laffineur* and the subject was introduced by *Professor J. H. Oort.*

Professor Oort outlined briefly the characteristics of the various populations of objects in the Galaxy. He also discussed the significance of these different populations in terms of the evolution of the Galaxy. Turning to the problem of the radio-frequency radiation from the Galaxy he discussed some of the attempts which had been made to account for this radiation in terms of the radio stars. In one analysis the majority of the radio stars had been assumed to be in the Galaxy; while in another the intense radio stars near the galactic plane were assumed to be galactic objects and those at high galactic latitudes had been treated as extragalactic. The two methods gave different values for the space-density of the radio stars and at present it was not possible to decide between them. *Professor Oort* then described the results of some recent work on the radiation from neutral hydrogen at 21 cms. The majority of the interstellar hydrogen in the Galaxy is neutral. The radio observations allow the apparent velocity of this gas to be determined relative to the observer by means of the Doppler shift. The spectrum of the radiation observed towards the galactic centre and the anti-centre is symmetrical about the theoretical frequency of the emission line and indicates that the motion of the gas is about the galactic centre and that it does not exhibit a radial component of velocity. The angular velocity of the gas about the galactic centre can be determined by means of observations of the Doppler shift at various galactic longitudes. By combining the radio observations with visual data on star motions it is possible to derive a value of 8·26 kps.

for the distance from the Sun to the galactic centre. This value agrees well with that deduced from RR Lyrae variables. The random velocities of the gas clouds can be obtained from the shape of the "tail" of the 21 cm. spectrum. It is necessary to correct the observed spectra for the broadening effect of these random motions. *Professor Oort* displayed a set of spectra measured in Holland of the 21 cms. radiation at various galactic longitudes and he showed how this data could be interpreted to give the details of the spiral arms in the Galaxy. He compared the spiral arms shown with those given by Morgan from observations of hydrogen emission. The majority of the observations made in Holland had been restricted to the galactic plane; however, they had made some observations of a dense cloud in the Taurus region, a few degrees from the plane, and it did not show 21 cm. radiation. This result suggested that the majority of the hydrogen in the cloud is molecular.

Mr. Hanbury Brown described a model of the Galaxy. As described in the session on Radio Stars he and Dr. Hazard had assumed in this model that the ionized interstellar gas followed the model used by Westerhout and Oort in their paper. This model assumed that the ionized gas is distributed in clouds of average diameter 10 parsecs with an optical depth of 0·021 at 100 Mc/s. and an electron temperature of 10,000°K. The clouds are contained in a disk of diameter 25 kps. with a thickness of 200 parsecs. On an average a line of sight in the galactic plane intersects 1 cloud per 2,000 parsecs. The radiation from this theoretical model of the gas had been calculated and subtracted from the observations of Reber at 480 Mc/s. to arrive at the "true" distribution of intensity from the radio source in the Galaxy. This "true" distribution of the radiation from the sources, together with that from the gas, could then be used to calculate the observed isophotes at any frequency. He showed a comparison between the calculated results at 100 Mc/s and the observations of Bolton and Westfold. For the purpose of this calculation he had assumed that in addition to the radiation from the Galaxy there was also an isotropic component of about 500°K. which was of extra-galactic origin. The calculations showed that most of the apparent change in shape of the isophotes at frequencies greater than 100 Mc/s was due to the effects of the various beam widths used in the surveys. The effects of the absorption of the radiation from the radio sources by the ionized gas had been calculated for a system of gas clouds and this absorption became important below 100 Mc/s. The isophotes of the radiation at 18·3 Mc/s had been calculated and showed a band of low intensity along the galactic plane corresponding to absorption in the gas. These theoretical isophotes were compared with the observations of Shain at 18·3 Mc/s. It had been found difficult to account for the observations at 18·3 Mc/s, and also to account for the observed change with frequency of the ratio of the temperature at the galactic centre to the anti-centre, without invoking the presence of the ionized gas. However the model dealt with these problems satisfactorily. The model was then compared with the results observed by Scheuer and Ryle which gave the intensity distribution across the galactic plane at 210 Mc/s. *Mr. Hanbury Brown* pointed out that the model explained the curious shape of these curves in terms of the very different longitude and latitude distributions of the radiation from the sources and from the ionized gas.

A comparison between the observed temperature towards the galactic centre and that calculated from the model had been made over the frequency range 18·3 Mc/s to 3000 Mc/s. This comparison showed satisfactory agreement over the whole range if the spectrum of the sources was assumed to follow the law $T_S \propto \nu^{-2\cdot 8}$ and the extra-galactic component followed the law $T_{EG} \propto \nu^{-2\cdot 5}$. It was extremely important to allow for the effects of beam width carefully in making this comparison. In conclusion the model showed that the observed radio isophotes of the Galaxy could be accounted for in terms of three components; firstly, a population of sources showing a Population II-type distribution; secondly, a disk of ionized gas with the normally accepted properties; thirdly, an isotropic component probably of extra-galactic origin. *Mr. Ryle* said that he thought there would be difficulty in reproducing from the model the "skirts" of the distribution across the galactic plane at 81·5 Mc/s. observed by Mr. Scheuer and himself *Dr. Hazard* said that he thought a small adjustment to the density of the sources in the other ellipsoids of the model would probably meet this objection. *Mr. Scheuer* pointed out that this could not be done without a corresponding decrease of the intensity of the radiation in the galactic plane. *Mr. Hanbury Brown* said that the objection did not appear serious but that further calculations would be needed to check this point.

Mr. Scheuer presented the results of an investigation made at Cambridge in collaboration with Mr. Ryle. Theoretical estimates of the radio-frequency radiation from H II regions had been made by Westerhout and Oort who had shown that a temperature of about 2000 to 3000°K would be expected towards the galactic centre at 100 Mc/s. This radiation would be confined to a narrow strip in the galactic plane. Calculations showed that at frequencies greater than about 60 Mc/s the strip should appear as a "bright" band of emission while at frequencies less than 60 Mc/s the strip should appear as a "dark" strip of absorption. A variable spacing interferometer had been constructed at Cambridge to measure the distribution of intensity normal to the galactic plane at various galactic longitudes. Measurements had been made with this instrument at 81·5 and 210 Mc/s. The instrument gave the Fourier transforms of the intensity distribution across the galactic plane and they had been used to find the true distribution of intensity on the assumption that it is symmetrical about the galactic plane. The measurements show a narrow peak of intensity in the galactic plane superimposed on a broader distribution. *Mr. Scheuer* interpreted the narrow peak as due to the radiation from ionized interstellar hydrogen in the H II regions. The intensity of the peak due to the ionized gas alone was found by subtracting the general background radiation from the observed curves. A comparison of the intensity of the observed brightness temperature of the radiation due to the gas at the two frequencies was used to derive the electron temperature and density in the H II regions. The value obtained for the electron temperature was about 20,000°K. The observations also give a rough outline of the distribution of the radiation from the gas in galactic longitude. The observed distribution shows a pronounced concentration towards the galactic centre and suggests that there is little, if any, observable band towards the anti-centre. The results therefore suggest a marked concentration of the gas towards the centre of the Galaxy. Mills has recently reported a concentration of bright radio stars towards the galactic plane;

however, it does not appear that these stars can account for more than a few per cent of the radiation observed in the narrow band.

Mr. Baldwin reported an attempt made at Cambridge to detect the radio-frequency radiation from the Orion nebula. He reviewed the expected value of the optical depth at radio-frequencies and showed that if the angular diameter was assumed to be about $\frac{1}{2}°$, with an electron temperature of about 10^4°K, then the radiation at metre wavelengths would be about 1 per cent of the quiet Sun. Attempts to detect this radiation had been made using an interferometer at 210 Mc/s with a short baseline. The observations were limited by the presence of a radio star in Taurus at about the same right ascension which it was not possible to exclude completely. The measurements showed that the radiation from the Orion Nebula at 210 Mc/s does not exceed a value of 9×10^{-25} watts/sq.m/c.p.s. He showed how this limit could be used to evaluate certain parameters of the nebula.

Dr. Minkowski remarked that some calculations made by himself and Dr. Greenstein indicated that the intensity to be expected from the Orion Nebula is about $3{\cdot}5 \times 10^{-25}$ watts/sq. m/c.p.s.

Dr. Little reported some attempts to observe radiation from interstellar hydrogen atoms in the first excited state. The theoretical value of the frequency of this radiation is about 177·5 Mc/s. A radio spectrometer for this frequency had been constructed at Jodrell Bank. It employed an aerial of 30 ft. diameter with a beam width of 14°. The frequency range covered by the equipment was 177·37 to 177·89 Mc/s. No evidence of the radiation had been found and it was possible to put an upper limit to the effective temperature of the radiation (when observed with a 14° beam) of 1°K. The measurements had been made with the aerial beam directed towards the galactic plane in the Sagittarius region and in Cygnus. They had also been made with the beam directed towards the Orion nebula.

Dr. Westerhout reviewed the method by which the temperature of the interstellar ionized gas had been estimated and discussed the calculations of Spitzer, and also of Spitzer and Savedoff. He showed how the estimated temperature depends on the values assumed for the effective temperature of the illuminating radiation and for the absorption cross sections and ion abundances. He discussed the alterations in the assumed values of the constants necessary to give a temperature of 18,000°K as found in the experiments of Scheuer and Ryle.

A SIMPLE MODEL FOR EXPANDING PLANETARY NEBULAE AND ITS STATISTICAL CONSEQUENCES

By H. Zanstra

The fine work done by O. C. Wilson[1] on the expansion of planetary nebulae in various spectral lines raises the question whether a simple model for an expanding planetary nebula might be suggested as a starting point for a discussion. As he points out, the first observational work which was fundamental was done by Campbell and Moore[2], who found that in a number of cases the green nebulium lines, now interpreted as