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NUFFIELD RADIO ASTRONOMY LABORATORIES JODRELL BANK

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(Report for the year ending 1970 August 31)

I. THE GALAXY

The structure of the Galaxy can be studied by the following techniques: (i) measurements of the continuum emission, both on the large scale and from discrete objects such as supernova remnants; (ii) measurements of line radiation, again both from large and small scale features; and (iii) measurements of the transmission properties of the interstellar medium. All these techniques have been pursued in recent work at Jodrell Bank. This section describes work in the categories (i) and (iii); work under (ii) is described in Sections 6 and 7.

The background survey at 70-cm wavelength is now published (**1**), and copies of the survey maps have been made available for detailed studies of spectral index. Some discrete sources, mainly supernova remnants and H II regions, have been studied in this way (**2**). Comparison of the continuum and hydrogen line emission maps has led to the discovery that the Galactic spurs contain both synchrotron and neutral hydrogen sources of radiation (**3**).

The polarization survey at 70-cm wavelength was presented at the IAU General Assembly, and it will shortly be published. The polarization survey at 50-cm wavelength is now being analysed, so that interstellar Faraday rotation and depolarization studies will be available in 1971.

The transmission properties of the interstellar medium have been studied through the hydrogen line absorption of continuum radiation from Cas A (**4**). The digital spectrometer gave a large improvement on previous measurements, and for the first time the absorption in the inter-arm hydrogen could be detected.

Radio waves from pulsars are diffracted by irregularities in the ionized interstellar gas, and show a major scintillation. A comprehensive study of this scintillation (5) shows that a characteristic size and density can be assigned to the irregularities. It should be possible to study the velocity of the irregularities by measuring differences in times of scintillation fades at widely-separated observatories. A first attempt between Jodrell Bank and Arecibo (6) was successful, giving a velocity of the order of 50 km s^{-1}. Further experiments are now in progress using a longer baseline, between Penticton and Jodrell Bank, including a range of position angles which will give a full measurement of the velocity vector.

Further measurements of Faraday rotation of pulsar radiation have also been made, confirming the previous result that the general magnetic field of the Galaxy is of the order of 3 microgauss. These results will be published in 1971.

2. SOURCE SURVEY AT λ 11 CM

The analysis of the source survey covering rather less than 1000 square degrees reported last year has been completed. Those sources in this region that lie more than 15° from the galactic plane have been measured with the Malvern interferometer. This instrument has enabled the positions of the 74 sources in this category to be measured with an accuracy of ± 4 seconds of arc. A programme using these positions together with the Sky Atlas prints has enabled 62 of the sources to be identified with optical objects.

A further survey covering nearly a third of the whole sky at low sensitivity has been completed. This survey is complete to a flux level of about 2 flux units. The detailed analysis of these results is still in progress, and is expected to be completed shortly. There are about 360 sources in this survey.

A deeper survey with a completeness level of 0·5 flux units or better is planned, and should start at the end of the current year. In order to improve the sensitivity of the system, many changes are being made in the equipment. I.F. amplifiers with a bandwidth double that used previously, and of accurately known phase characteristics, have been developed, and these will be used in a correlation receiver. The presence of an Argus 400 computer in the Mk II control room means that more efficient data handling can be employed. As a result of these improvements, it should be possible to survey a strip of sky about 35 degrees broad in declination to the required flux limit in four to six weeks.

3. MEASUREMENTS OF THE ANGULAR SIZES AND STRUCTURES OF RADIO SOURCES

(a) *Interferometric observations between the Mark I and Mark III telescopes*

A complete group of sources having declinations and galactic latitudes $\geq +20°$ was selected at 1420 MHz. Observations at 408 and 1420 MHz commenced during the summer of 1969, and were completed by the end of February 1970. Most of these sources gave detectable correlation at both frequencies, but this varied with hour angle in almost all cases, showing that these sources have significant structure in the range 0·5–5·0 sec. arc. The analysis is now almost complete.

(b) *Interferometric observations between Jodrell Bank and R.R.E. Malvern*

During April–June 1970 a new UHF and microwave link system between Defford and Jodrell Bank was commissioned. Repeater equipment was installed at hill-top sites at Clee Hill near Ludlow, and Camp Hill near Newcastle-under-Lyme (by permission of the Board of Trade, Civil Aviation Division). This link equipment uses entirely solid-state components, and maintains the closer frequency tolerances now required by the Ministry of Post and Telecommunications. The system has proved more reliable than the partly thermionic equipment used previously, though some difficulties are still encountered. The first observations were made in June and July 1970, when 10 radio galaxies and quasars were studied at 408 MHz. The 610 MHz system was also used simultaneously for some of these observations. The earlier measurements made over this baseline at wavelengths of 21, 11 and 6 cm are now being published. The first two papers (7) (8) describe the calibration and slightly resolved sources, and the detailed angular structure of 12 other sources respectively. A third paper (9) discusses the double structure observed at 21 and 11 cm of the quasar 3C 147.

(c) *An interferometer with independent local oscillators*

During November and December 1969 this instrument was tested between the Arecibo Observatory, Puerto Rico, and the Mark I telescope at Jodrell Bank. These measurements were made at a frequency of 610 MHz, which means that the physical baseline is 13 Mλ, giving a resolution of approximately 0·01 sec. arc. Correlation was observed on 11 sources. Further observations were made in April and May 1970. The sources chosen for study in this programme were selected from existing source catalogues on the basis of the usual indications of small angular diameter, e.g. peculiarities in the radio

spectrum, variability, or scintillation at long radio wavelengths. The 100 sources selected in this way constitute approximately 20 per cent of the sources in the catalogue in the declination range $-2°$ to $+38°$ with flux density in the vicinity of 610 MHz greater than 1·5 flux units. By August 1970 the recordings made on 40 of these sources had been analysed, and four further sources have been found which show measurable visibility. Technical difficulties which had held up the analysis of the remaining sources have recently been overcome, and it seems probable that several more sources will give detectable correlation.

Preliminary conclusions from these results suggest that amongst the weak radio sources the percentage with very small angular diameters is not very different from what might be expected from the results of measurements on rather stronger sources, for example, those in the 3C catalogue. The complete results of these measurements will be published later this year.

4. POLARIZATION OF RADIO SOURCES

(a) *Jupiter*

Measurements of the polarization of decimetre radiation (λ49 cm) were made in March–April 1970. The position angle of the linear polarization rocks to and fro as the planet rotates, providing values for the longitude and inclination of the magnetic axis. Comparison with earlier observations dating back to 1962 provides a revised value of the true System III rotation period. The radiation shows a small amount of circular polarization. Some doubt has been cast on the reality of earlier measurements, but our observations confirm the Australian work that the Jovian field is opposite in direction to that of the Earth, and between $\frac{1}{2}$ and 2 Gauss in the Jovian Van Allen belts. This work is in the course of publication (**10**).

(b) *Magnetic star*

Observations were made of the magnetic star α^2 CVn which has a period of magnetic reversal of five days. No signals other than those of the expected background were observed, setting an upper limit to the flux density from the star of 40×10^{-29}W m^{-2} Hz^{-1}. This means that the optical changes cannot be explained as synchrotron radiation, unless the synchrotron source becomes opaque in the radio domain (**11**).

(c) *Blue stellar objects*

Observations were made with the R.R.E interferometer to search for faint radio sources at the positions of some of the blue stellar

objects discussed by Braccesi *et al.* This instrument is very suitable for such a task, and limits of measurement of $\sim 9 \times 10^{-29} \mathrm{Wm}^{-2}\ \mathrm{Hz}^{-1}$ were achieved. Although in most cases no radio emission above this level was detected, in five cases faint signals, a few times noise, were detected (**12**).

(d) *Polarization of quasars*

Measurements of linear polarization of quasars have been made at $\lambda 49$ cm (**13**) and at $\lambda 73$ cm (**14**). Observations at such long wavelengths yield information primarily about the Faraday rotation occurring within and in front of the sources.

The list is most complete at $\lambda 49$ cm, where 126 sources have been measured. A few of these sources were measured earlier (**15**) and the agreement between the different sets of measurements is satisfactory. As reported earlier, a correlation was discovered between the degree of polarization at $\lambda 49$ cm and the spectral index (**16**). This correlation is confirmed in the most recent observations, and a further correlation is apparent, in the sense that quasars with high red shift show low polarization (**17**). The effect is most marked in those quasars which have absorption lines. It is not yet certain whether the phenomenon is indeed the result of the Faraday effect. This question requires the comparison of polarization measurements over as wide a range as possible (**18**).

Successful measurements were also obtained of the degree of circular polarization. Significant non-zero values were obtained for five (possibly six) out of the 21 sources studied. If the circular polarization is due to the synchrotron mechanism, the measurements provide a value of the magnetic field in each source, which in two cases is $\geq 10^{-3}$ Gauss. It is possible, however, that some other mechanism may be present. The observations should be repeated at different wavelengths in order to investigate this point (**19**).

5. THE PULSARS

The flow of new discoveries of pulsars reached a peak more than a year ago, and has notably declined since then. The whole sky has now been searched with a good sensitivity, and further discoveries must depend on improvement in techniques. Recent systematic and successful searches at Jodrell Bank have followed an intensive study of techniques using on-line computation. The computer has been programmed to recognize either a precisely periodic signal (**20**), or individual pulses which have suffered the characteristic dispersion in the interstellar medium (**21**). Altogether eight pulsars have been discovered in these ways: it is notable that this is the second largest

total from any observatory, even though all other discoveries have been made with telescopes of larger collecting area. The completion of these surveys has contributed to the establishment of the luminosity function of pulsars, described at the IAU Symposium No. 46 by Dr M.I.Large.

Further observations have been made of the polarization of individual pulses and of the integrated profiles. The first observations of the individual large pulses from the Crab Nebula pulsar showed large linear polarization (22). The integrated profiles from this pulsar can be compared with optical measurements. It is now found that both show a rapid rotation of plane of polarization. (Reported at IAU Symposium No. 46.)

The significance of the polarization measurements has been discussed, and it is now suggested that the pulses are formed by a relativistic beaming effect (23). This suggestion was presented as part of a general discussion concerning problems of the emission mechanism at a symposium in Rome (24) and at the IAU Symposium No. 46.

Accurate observations of pulse arrival times have continued for a series of pulsars. The rates of change of period were reported at the IAU General Assembly. The main characteristics of several of the pulsars discovered at Molonglo have been found, and the results made available to other observers.

6. NEUTRAL HYDROGEN EMISSION

(a) *Galactic emission*

Recent discussions of heating mechanisms of the interstellar medium prompted an investigation of the temperature of the inter-arm region of the Milky Way. The absorption spectrum of Cassiopeia A and the adjacent emission spectrum can be used to give one of the best estimates of inter-arm neutral hydrogen temperature. The Mark I telescope and the 256 channel autocorrelation spectrometer were used for this work, and gave an estimate of the spin temperature of 540 ± 230 K (4).

(b) *Extra-galactic neutral hydrogen studies*

The neutral hydrogen surveys of M31 and M33 with an 8·4 km s^{-1} and $14' \times 18'$ arc resolution have been reduced to contour maps at fixed velocities and spectra at a grid of points for each galaxy (25) (26) and (27).

The individual maps show interesting detail which can be compared with optical data and models of the velocity field and neutral hydrogen surface density distribution. The integrated neutral hydrogen map of M31 shows a neutral hydrogen distribution similar to the Milky Way

with a deficiency in the central regions and with elongated spiral features (**28**). An examination of the optical and neutral hydrogen data indicates that the rate of star formation is greatest in the areas of greatest hydrogen density. The agreement between the velocity of groups of H II regions and neutral hydrogen is close (**29**). A mass distribution derived from the rotation curve of M31 follows the blue luminosity distribution 20′ to 85′ arc from the centre with $M/L = 12 \pm 2$.

A survey of nearby Sc and Irr I galaxies is continuing. Contour maps at fixed velocities and spectra on a grid across each galaxy have been derived for the Sc spirals NGC 5457 (M101), IC 342 and NGC 2403 and the irregular galaxies NGC 6822, IC 1613 and IC 10. For each of these the integrated neutral hydrogen density, the velocity field and total mass distribution is being computed. The neutral hydrogen distribution changes with morphological type from showing a central deficiency for Sb galaxies, and a smaller deficiency for Sc galaxies, to showing a central concentration in Irr galaxies (**30**). The H II regions in all these morphological types are found in the regions of highest neutral hydrogen density.

An investigation has also been made of larger redshift galaxies in the velocity range 1545 to 2620 km s^{-1} (**31**). Four (NGC 772, 2776, 4303 and 5668) produced signals strong enough to obtain an integrated spectrum from which the total neutral hydrogen content, the total mass and the systemic velocity could be derived.

7. OTHER SPECTRAL LINES

(a) 18-*cm observations of the OH radical*

A continuing programme to investigate the time variability of anomalous emission OH sources is providing data on possible intensity changes over a period of several months to a year. The same data can be compared with early published observations from other observatories to determine the variability over a period of about four years. A number of new variable components have been discovered. Most strong components however are constant and change at a rate less than a few per cent per year. The OH source associated with the VYCMa infra-red object appears to be the most highly variable OH source (**32**).

Interferometer observations of OH sources on the Jodrell Bank–Malvern baseline have provided relative positions of the more intense components to a precision of about 0·01 sec arc (**33**). These observations have now been extended with higher sensitivity and higher frequency resolution using the digital spectrometer in the cross-correlation mode over the Mk II–Mk III baseline. The observations were successful and they are now being analysed to derive the relative positions of many more components of anomalous emission OH sources.

(b) *Recombination lines*

The Mark I telescope has been used to study radio recombination lines at 1424 MHz (166α), 922 MHz (192α) and 613 MHz (220α). Lines have been detected from both low and high density H II regions. These data are being used to investigate Stark broadening effects in recombination lines. By comparison with observations at higher frequencies (**34**), the departure from local thermodynamic equilibrium can be determined (**35**). A feature of the radio recombination line observations is the existence of an anomalously strong line at a frequency close to that expected for the carbon atom. These lines have been detected in the observations for the 166α line (**36**).

8. LUNAR RADAR MAPPING BY APERTURE SYNTHESIS

The 162·4 MHz radar system was completed a year ago, and it was used to make aperture synthesis observations of the Moon on several consecutive days each month over the course of last winter. The receiver was sensitive to only one sense of circular polarization for any particular run, but whole days were devoted to runs on both the specular and non-specular sense of circular polarization of the return. The system is essentially a CW radar so that the only spatial discrimination achieved is that made available by the doppler spread of the return caused by the Moon's apparent rotation.

Owing to the change in the position angle of the Moon's apparent rotation axis relative to the surface features, it is possible to recover a two-dimensional picture of the radar brightness distribution of the lunar disk. Suitable observations can only be made on certain days when the Moon's apparent motion is favourable, and three or four such days occur in each lunation about the time when the Moon is at its maximum declination. The recovery process is akin to the aperture synthesis technique developed by the Cambridge school of radio astronomers.

Only a fraction of the data acquired has yet been analysed. A preliminary map, however, has been produced in the non-specular return, with an angular resolution of 2 minutes of arc. This map and a brief report on the work was presented at the meeting of the I.A.U. in Brighton. It is hoped to obtain a resolution of about 1 minute of arc using more of the data, but this has yet to be achieved owing to two systematic errors, one in the computation of the real-time ephemeris used, and the other by an ionospheric effect which was inadvertently overlooked. These errors can be allowed for in the analysis, but the necessary alterations to the computer programs have caused a delay in the production of the final maps. This analysis is being conducted on the University's ATLAS computer.

The apparatus constructed to do the computations required during the observations has had the necessary additions made to allow it to be used for the data analysis. A second and potentially more flexible approach to the analysis has been started using this equipment. This should allow the data acquired in the new 400 MHz observations to be analysed more quickly.

Some other progress has been made towards modifying the system for operating on the new frequency. In particular the aerial feed and the polarization and T/R system hydrids have been designed. These should be capable of handling 1 kw of transmitter power. This will be provided by the penultimate driver stage of the 10 kw 410·25 MHz transmitter last used in 1964 for radar observation of Venus. This transmitter has been transferred from the tower of the Mk 1 radio telescope to the 50 ft polar axis telescope that will again be used for the lunar observations. The transmitter has been on indefinite loan from Space Technology Laboratories Inc. of the U.S.A. since 1961. As a result of being left unused for several years it appears to be in poor condition, and the task of restoring it to working order has not yet been started.

Some other modifications to the system have also been made towards converting it to the new frequency. The task is handicapped, however, by the fact that a precise frequency allocation has not yet been made. Nonetheless, it should be possible to make observations on the new frequency in the spring of 1971.

Owing to the death of the leader of the group in the summer of 1969, no progress has been made in the last year with the studies of a radar technique, akin to holography, which might make it possible to resolve the Moon unambiguously as a three-dimensional object. It is hoped to be able to continue this study, and to prepare it for publication in the coming year.

9. SATELLITES ARIEL 3 AND U.K.4

The radio noise measurements from satellite Ariel 3 have now been used to determine the impedance of the loop antenna under a wide range of ionospheric conditions. A new form of damping has been shown to exist (37). An error in the published theory of radiative transfer in a magneto-ionic medium has been pointed out (38). Preparations for the assembly, launch and operation of satellite U.K.4 are now well advanced. This experimental work is carried out in collaboration with the Radio and Space Research Station.

10. RADIO PULSES FROM COSMIC RAY SHOWERS

The Jodrell Bank work on the radio pulses emitted by cosmic ray showers is directed towards studies of the emission process through measurements of intensity and polarization over a range of radio

frequencies. New apparatus which has been developed is intended to extend this study by measuring differences in arrival time of the particles and the radio pulse.

Observations on a remote site in Wales, which were completed this year, provide extensive information on the background of radio pulses against which a shower detection radio experiment must operate. These results have been made available to the S.R.C. in connection with proposals for extending large-scale cosmic ray studies in this country.

Isolated pulses of radiation have been studied at Jodrell Bank in collaboration with several other radio observatories. The origin of these pulses is unknown; whether they are terrestrial or astronomical in origin, it seems important to continue this work. A preliminary account is in course of publication.

II. MISCELLANEOUS

For most of the period covered by this report the 250-ft Mk I radio telescope has been fully operational. The second phase of the changes to the Mk 1A, which were referred to in the previous report, involved the complete re-laying of the original double railway track. This was completed as scheduled, but the final phase 3 modifications involving the major steel work changes did not begin in the Spring of 1970, as expected, because of unfortunate delays at the contractors. In fact, the telescope continued in use until early August 1970, when the work commenced. It is hoped that the telescope will come into use again as the Mk 1A in the early Autumn of 1971.

Further investigations have been made of the surface accuracy of the Mk II telescope. The tests which were made by the introduction of strengthening ribs behind certain panels showed that the performance of the instrument could be still further improved in the centimetre waveband, and it is hoped to complete this work in the Spring of 1971, when it is anticipated that the telescope should retain its theoretical efficiency down to λ 5 cm.

The arrangements whereby two of the staff at the Royal Radar Establishment, Malvern, have been seconded to the University of Manchester have continued satisfactorily, and full use has been made of the two 85-ft radio telescopes situated at Defford belonging to the Royal Radar Establishment. The use of these telescopes has been important to a number of the researches referred to in this report. In some cases the two Defford telescopes have been used for S band interferometric measurements; otherwise one of these telescopes has been linked to one of the Jodrell Bank telescopes for the angular structure measurements. The arrangements for the continued availability of the Royal Radar Establishment telescopes in the immediate future will be

an important factor in the Jodrell Bank researches in view of the long period for which the Mk I telescope will be out of action.

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