40. RADIO ASTRONOMY (RADIO ASTRONOMIE)

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A. INTRODUCTION

Radio astronomy continues to develop at explosive pace. In addition to containing many notable pieces of observational work carried out with improved sensitivity, angular resolution and spectral detail – and aided by data-handling techniques of increasing sophistication – the last three years have seen a flow of new and sometimes startling results. These are exemplified by the discovery of organic matter in the galaxy, and by the first observations pertaining to what are almost certainly neutron stars. The latter, of course, came with the dramatic discovery of pulsars, which are the subject of an Invited Discourse at this General Assembly.

Following the custom of this Commission, I have asked different members to review the work done in each of the main fields. On this occasion a special section has been added on pulsars; since the announcement of their discovery in February 1968, the rate of publication within so narrow a field could scarcely have been equalled in the history of science. As in the past, radio studies of the planets are incorporated in the Report to Commission 16.

Over recent years this Commission has evolved a format for its Draft Report which is highly concentrated in information content. Few words have been wasted. Regrettably the advantages of this policy have proved illusory: for now that it has been necessary to reduce the size of the Reports, the reduction ratio has been applied on the basis of the size of the 1967 Reports (whether succinct or verbose) rather than on the magnitude of the work covered by each Commission. Each of the contributors to this report has nevertheless preferred to retain, within their limitation of space, the general spirit of previous Reports. Their task has been made more difficult by their having to decide what work to omit (much of it of considerable significance). I thank them sincerely for their efforts and co-operation.

J. P. WILD
President of the Commission

B. SOLAR RADIO EMISSION
(prepared by S. F. Smerd)

1. *Introduction*

The literature for the period late 1966 to late 1969 has been very extensive. Since space does not permit a complete bibliography, some contributions cannot be referred to at all, while some others are referred to by general reference to the proceedings of meetings (**1, 2**) in which they, or their abstracts (**3, 4**) have been published; in these cases only will authors be named to identify the paper. Though it has not been possible to list the many instrumental developments, particular mention may be made of the Culgoora 80 MHz radioheliograph (**5**) which came into operation in September 1967.

An international co-operative study culminated in the publication of the Proton Flare Project (the July 1966 Event) (**6**).

High-resolution observations have revealed multiple-source structure from cm (**7**) to m-wavelengths (Clavelier **1**; **8, 9**), polarization structure (**7, 10**) and, at times, unsuspected source complexity (**11**). Interaction between widely separated centres on the Sun has been recognized (**12**) in the form of

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separated burst sources which appear (i) simultaneously, (ii) ~ 10s apart, and (iii) several minutes apart; the implications on magnetic structure are new and important.

The suppression, by the ambient medium, of low-frequency synchrotron radiation has been discovered in type-IV spectra (Boischot and Clavelier **1**). The theory of the medium effect and its application to solar bursts have been extended to lower electron energies (**13**) and to emission at the first few harmonics (**14**).

In two theories of the band-splitting in type-II bursts (**15**, McLean **2**) the emissions are not generated at the same point; published (**11**) and unpublished observations support the theory of separate sources.

Observations of solar emissions at 9·6 and 21 cm showed marked effects (**16**) due to the passage near the Sun of the comet Ikeya-Seki. A strong association has been reported (**17, 18**) between microwave bursts and interplanetary electrons of high (MeV) and moderate (> 40 keV) energies; the latter also show strong correlation with type-III bursts (**18**).

2. *Reviews*

An introductory book on solar radio emission has been published (**19**). Reviews that have appeared include the theory of solar bursts (**20**), and emission mechanisms (**21**), radio evidence of coronal instabilities (**22**), connected activity (**12**), a summary of the Proton Flare Project (**1**), solar radar (**23**), occultation and scintillation studies (**24**) and, in part, radio investigations of the corona (**25**).

3. *The quiet Sun*

Brightness distributions have been derived from eclipse observations, e.g. on 1963 July 20 at 4·6 cm (Higgs and Broten (see **26**)), on 1966 May 20 at 1·2 mm (**27**) showing limb-brightening and on 1966 November 12 at 7 GHz (**28**) showing opposite polarizations from the two hemispheres.

Limb brightening was also detected at 1·2 mm (**29**), at 3·3 mm (Shimabukuro **3**), at 8·6 mm (**30**), asymmetrically at 9·1 cm (**31**) and at 49 cm (**32**), but not at 4·6 cm (see above), nor at 74 cm (Little **2**).

The spectrum has been studied at mm (**33**) and also cm-wavelengths (**26**); cyclic changes have been reported at 169 MHz (**34**).

Theoretical work includes interpretations (**26, 35**) of a possible minimum at 6 mm, and a determination of a corona temperature of 10^6 K from dm and m-wavelengths observations (Sinha and Swarup **2**).

4. *Active centres and the slowly-varying component*

Numerous eclipse observations include 1963 July 20 (**36**) in the range 1 to 33 cm, 1966 May 20 in the range 3·2 cm to 2·7 m (**37**, where several other observations are quoted) and 1966 November 12 (**38**) with polarization structure at 4·28 cm.

Studies of the slowly-varying component include those at 3·4 mm (Mayfield *et al.* **3**), at 8 mm (Efanov *et al.* **1**), at 2 cm (Nagnibeda **1**), in the range 3·2 to 10 cm (**39, 40**), at 9·1 cm (**41**), at 1424, 696 and 408 MHz (Cole *et al.* **2**), at 408 MHz (Little **2**) and at 160 MHz (**42**). A statistical study has been made (Kleczek *et al.* **1**) and spectra have been derived from cooperative observations (**43**).

Several theoretical models have been discussed (e.g. **44, 45**).

5. *Microwave bursts*

Bursts have been observed at wavelengths down to 1·2 mm (**46**). Multi-source and polarization structure has been detected at 3·75 and 9·4 GHz (**7**). Among statistical results are spectra (**47, 48**, Castelli and Aarons **3**), source heights (**49**), and associations with Hα-features (Koeckelenbergh **1**).

Interpretations of microwave bursts have been given in terms of radiation from strong shock waves (**50**), coherent plasma radiation from very strong-field regions (**51**), coherent gyroradiation (Yip **14**) and synchrotron radiation (**13, 52**). The last two references arrive at different conclusions regarding the possible common source of microwave and X-ray bursts. Contracting and expanding source models have been investigated (Gopasyuk *et al.* **1**, Barney **3**); in another model (Kai **2**) upward movement in the sources of microwave type-IV bursts has been adduced.

6. *Storms and type I bursts*

New fine-structure features ('split pairs' and others) have been discovered (**53**) in the range 25–100 MHz. Linear polarization has been detected (**54**) at 74 MHz in type-I and stationary type-IV bursts. Multiple-source structure of storms has been reported at 408 and 169 MHz (**8**) and 80 MHz (**9**). Two apparently correlated storm sources, one compact, the other spread, have been observed (**55**).

Theories of type-I radiation include a 'Laser' theory (**56**) and amplified low-harmonic gyro-radiation (Fung and Yip **14**). The latter theory has also been applied to split pairs (**57**).

7. *Type-II bursts*

The position, large size and fluctuating brightness structure of type-II sources at 80 MHz has been explored (**58**, **12**) by radioheliograph; apparent outward movement has been observed at 80 MHz (**58**) and $\lesssim$ 40 MHz (Warwick **3**, **59**). In some connected activity the interaction between distant centres occurs at type-II source speeds (**22**).

The enhanced density in a type-II source, assumed to be a shock wave, has been invoked (**60**) to explain the different polarizations of types-II and III bursts and to account for II-derived densities to be twice those of the Newkirk model (Meyer **4**). As noted in Section 1, two band-splitting theories predict separate sources: one (**15**) invokes a Doppler shift between emissions from front and back of the shock wave, the other (McLean **2**) leads to bright emission from much more widely separated regions of greatest contiguity between shock front and plasma level; well separated sources have been observed (**11**).

Coronal magnetic fields have been derived from type-II observations (Meyer **4**, **61**). Homologous type-II bursts have been found (**62**) up to 2 days apart.

8. *Type-III and type-V bursts*

A theory of type-III bursts in terms of fundamental dipole and harmonic quadrupole radiation has been tested (Krämer **4**). Fine-structure spectra have shown some association between type-III bursts and the new split-pair chains (**53**). Combined satellite and ground-based observations (**63**, **64**, Haddock and Graedel **3**, Stone *et al.* **1**, Malitson *et al.* **3**) have yielded spectra of type-III bursts from 0·7 to 600 MHz; the lowest observing frequency was 0·3 MHz. Densities and temperatures of the outer corona have been estimated from these observations; earlier conclusions that the type-III sources show deceleration at great heights have now been questioned. The average starting frequencies of type-III bursts reached a minimum near the minimum of the solar cycle (**65**). Radioheliograph observations have shown (**9**) a marked displacement between the positions of type-III and type-V sources, and the occurrence of correlated bursts some 10s and $\sim 1\ R_0$ apart (Kai (see **12**)).

Various type-III theories have been reviewed (**66**) and the non-linear treatment of stream stabilization (**67**) developed further. In one interpretation (**68**) type-V bursts have been interpreted as type-III bursts from superheated source regions, in another (**69**) as second-harmonic radiation. The degree, longitude dependence, and linear content of type-III polarization have been investigated (**70**).

9. *Type-IV bursts*

The sources of stationary type-IV bursts have frequently shown double structure at 169 and 408 MHz (**8**). Large-scale motion, first outward and with a later return, has been reported (**59**) in the range 10–40 MHz. Radioheliograph observations have shown (**71**, **12**) moving type-IV bursts associated with triggered prominence eruptions and one such source near the top of an expanding magnetic arch (**10**); strong circular polarization in a moving type-IV burst was of opposite polarity to that of the concurrent, more intense stationary type-IV (**72**). The low-frequency cut-off in the spectrum of a moving type-IV burst has been attributed to the Razin effect (Boischot and Clavelier **1**). A model for the source of this burst has been developed (**73, 74**) in which electrons are accelerated to 'synchrotron' energies inside an advancing shock front. In another interpretation (**75**) the hot electrons are injected into the shock front and the Razin effect becomes effective only at much lower frequencies.

Other theoretical discussions of type-IV bursts refer to the ejection of a magnetic cloud (**76**), the conditions under which an ejected plasma cloud emits type-II and type-IV bursts (**77**), interpretations in terms of amplified cyclotron radiation at the long wavelengths (Fung **14**) and at the micro-wavelengths (Yip **14**) and the use of anisotropic pitch-angle distributions to explain a high-frequency cut-off (**78**).

It has been suggested that the overall radio spectrum of proton flares is U-shaped with a minimum at the dm-wavelengths (Castelli and Aarons **3**, Howard **3**, Urbarz **4**); such events have been found (**79**) to occur non-randomly in solar longitude. Different phases of m and Dkm type-IV bursts have been related to different stages of spot-field development (Böhme **1**).

10. *Radar observations*

The 1959 Stanford observations and those taken at 38·25 MHz at El Campo since 1961 have been reviewed (**23**) and interpreted in terms of backscattering from magneto-acoustic waves (**80**).

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C. CONTINUUM RADIATION FROM THE GALAXY

(prepared by G. Westerhout)

Several hundred papers in this area have been published since the last reporting period. We can only quote here typical papers and papers of particular importance.

During the reporting period, tremendous progress was made with the study of H II regions. The most recent overall review, discussing many of the points mentioned below, appeared in *Interstellar Ionized Hydrogen* (**2**); the long-awaited volume on *Nebulae and Interstellar Matter* (**4**) finally appeared. Other reviews dealing with H II regions are given in (**6**), (**8**) and (**9**). Electron temperatures appear to vary widely; values range from 3400 K to 14000 K for different objects (**32, 36, 40, 66, 67, 79, 82, 94**). Many compact H II regions or parts of H II regions have been discovered, with typical diameters of 0·1 to 0·5 pc, emission measures of 10^7 to 10^8 cm^{-6} pc, electron densities of 10^4 cm^{-3} and masses of 1 to 10 $M_\odot$ (**65, 66, 94**). Often these compact regions are closely associated with OH emission sources. A number of surveys concentrated on H II regions (**12, 30, 37, 50, 58, 74**); the Cygnus-X complex was studied in great detail (**34, 87, 90**), and attempts were made, still rather unsuccessfully, to find distance criteria (**45, 90**). Radio emission by planetary nebulae is extensively reported in (**5**). Many observations of the flux densities of individual nebulae have been reported in the last few years.

Several new catalogues of galactic sources have appeared, as well as a number of surveys of supernova remnants (**11, 48, 51, 69, 77**). A survey on the subject of supernovae was published in (**3**). A review of non-thermal source spectra appeared in (**7**). The occurrence of supernovae in the Galaxy is now generally believed to be approximately once every 50 yr (e.g. **52**). Important progress was made on the study of the intensity and the polarization distribution in several larger remnants. Two different types of magnetic field structure are present: either a radial field or a circular field in the shell (**24, 54, 55, 56, 64, 68, 91**). A correlation is suggested between the surface brightness and radius of supernova remnants, providing a distance criterion (**77**).

The Crab nebula has continued to be the most intensively studied source. Earlier measurements indicating a steep increase of the flux density with decreasing wavelength below 5 mm were confirmed (**19, 53**) although one group reports no effect of this kind (**73**). Accurate flux measurements in the visible and infrared, confirming a steeper decrease in flux with decreasing wavelength than in the radio region are reported in (**70**). Overall polarization measurements at cm-wavelengths have been reported by many authors. Only the detailed measurements of polarization distribution are reported here (**35, 64**). The small source reported at long wavelengths has been studied further (**20, 42, 62**) and is coincident with the central star and the Pulsar.

The most recent review of our knowledge about the galactic centre source is given by Lequeux (**59**). Since then, a number of occultations of the centre by the moon have been observed, showing the presence of a nonthermal source with dimensions of about 2×3 min of arc and a temperature spectral index of 2·25 (**63, 84**). This source coincides with the infrared source (**18**); the infrared point source has not (yet) been detected at radio frequencies.

The most recent review of galactic nonthermal emission is given by Baldwin in (**1**). Surveys of large portions of the sky were made at 4170 MHz (**47**), 3240 MHz (**49**), 2700 MHz (**14, 16, 17**), 1410 MHz (**16, 46**), 610 MHz (**88, 89**), 178 MHz (**29**), 150 MHz (**92**), 85 MHz (**92, 95, 97**), 13 MHz (**15**), and 10 MHz (**43**). High-resolution studies show that the ionized hydrogen is mainly concentrated in discrete sources (**14, 15**). It is not clear whether this is also the case with the nonthermal emission, but studies at higher galactic latitudes show that the non-thermal "halo" largely consists of local features or spurs; perhaps, a low-emissivity spherical halo could still exist (**28, 93, 97**).

Further study of the polarization of the background radiation and Faraday rotation in extragalactic sources is reported in numerous papers of which we can mention only a few (**22, 31, 33, 81**). A model emerges which describes the field as helical locally, possibly connected with Gould's belt, and more or less longitudinal further out, connected with the general disk. This model is based on an overall interpretation of interstellar optical polarization, radio background polarization and Faraday rotation (**60**, **61**). The North polar spur appears to be due to this general field and not a supernova remnant (**23**, **80**). Estimates of the field strength range from 3×10^{-6} G in between the spiral arms and in the halo to 5×10^{-5} G in dense clouds in the arms (**72**, Woltjer in **10**). Local nonthermal emissivity could be determined by observing the nonthermal emission between the observer and opaque H II regions at low frequencies (**26**, **79**). Background polarization and Faraday depolarization show the presence of irregularities with several scale sizes (100 pc, 10 pc, $<0{\cdot}5$ pc) (**33**).

The study of the nonthermal galactic spectrum has progressed considerably. The temperature spectral index between 4000 and 400 MHz is 2·9 (**76**), decreasing to 2·6 between 400 and 200 MHz (**57**, **96**) and about 2·4 between 400 and 10 MHz (**25**, **38**. **39**, **75**). Variations of the spectral index with direction are reported in (**25**, **57**, **85**). The spectrum is now extended by means of satellite observations down to 0·4 MHz with good agreement between observers and with ground-based higher-frequency data (**13**, **44**, **86**). All of these low-frequency observations clearly show the effect of absorption by galactic ionized hydrogen. Interpretation of these data, now in progress, promises new information on the density and temperature structure of the ionized hydrogen and the distribution of galactic cosmic ray electrons and magnetic fields, especially in the solar neighbourhood. "High" resolution low-frequency observations of parts of the sky are reported at 2·1 MHz (**78**), at 6 and 9 MHz (**21**), at 10 MHz (**43**) and at 13 MHz (**15**). Low-frequency observations, and the agreement of the radio spectrum with the energy spectrum of the primary cosmic-ray electrons indicate the possibility of ionization of part of the cold hydrogen gas by low-energy cosmic ray electrons (**27**, **41**, **71**, **83**).

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D. LINE RADIATION IN THE GALAXY

(prepared by R. X. McGee)

The investigation of radio line radiation has reached the status of radio-astronomical spectroscopy in the period covered here – September 1966 to November 1969. The recent discovery of three molecular gases emitting or absorbing a number of lines each, the additional recombination lines of three elements and continuing discoveries in the hydroxyl gas spectrum have completely re-oriented the importance of the subject. With such rapid growth no suitable overall review has been made at this time. The search continues for such lines as those of sulphur hydride, carbon hydride, helium and molecular hydrogen.

1. *The new molecular lines of ammonia, water and formaldehyde*

Two lines corresponding to inversion transitions of rotational levels in the vibrational ground state of the NH_3 molecule ($\lambda \sim 1{\cdot}25$ cm) were detected in late 1968 (**1**) in the source Sagittarius A. Within two months the same authors (**2**) announced the observation of emission from the $6_{16} \rightarrow 5_{23}$ rotational transition of H_2O (λ 1·35 cm) in the directions of Sagittarius B2, the Orion Nebula and W49. In the following month interstellar formaldehyde (H_2CO) was detected in the directions of 15 radio sources (**3**). It was seen in absorption of the $1_{11} \rightarrow 1_{10}$ ground state rotational transition at λ 6·2 cm. So far the formaldehyde has been found in the same sources as the water and the hydroxyl molecules; ammonia and formaldehyde do not appear to occur in the same regions. The H_2CO is of great interest to biologists because it is known to be one of the by-products in the breakdown of amino acids. Again it supplies indirect evidence for the existence of methane, thought to be required in early forms of living matter.

The existence of these molecules is of extreme astrophysical importance, occurring as they do in the cool regions of gas and dust; their investigation must lead to a better understanding of star formation; the very presence of complex molecules indicates that the intensity of ultra-violet radiation is not as great as previously imagined.

Four inversion lines of NH_3 have been observed (**4**) since the early discoveries. The spectra, variability, size and polarization of the H_2O emission sources were reported (**5**). Formaldehyde absorption was noted in the directions of four dark nebulae (**6**) and examined in source W75 (**7**).

H_2CO was observed in the directions of 31 sources (**8**) in southern skies. A high abundance of the isotope ^{13}C near the galactic centre has been indicated from observations of $H_2\,^{13}CO$ (**9**).

2. *The hydroxyl lines*

Two quotations from a review article (**10**) in 1967 still seem to be most appropriate for the present state of the study of the hydroxyl gas. "Many observations have revealed totally unexpected anomalies in the radio-spectral properties of interstellar OH. As a result no reliable astrophysical information has been derived from the OH observations, but a large body of information is waiting to be unravelled." And "When OH emission was discovered it was given the Latin name 'mysterium'; a more appropriate name would be difficult to find". Other reviews (**11–16**) extend only to 1968.

a. *General OH source surveys*

Various aspects of absorption, emission, line widths, circular and linear polarization, satellite lines, association with dust and catalogues of OH sources appear in a number of surveys (**17–25**).

b. *Infrared stars and protostars – possible association with OH emission*

A relation between an OH source and an infrared object in the Orion Nebula has been suggested (**26**). Strong emission at the 1612 MHz line was discovered from the infrared star NML Cygni (**27**). The matter is further discussed in (**28**).

c. *Interferometry of OH sources* (**4**)

A review of very long baseline interferometry (v.l.b.i.) is given in (**13**). The use of v.l.b.i. has established that the sizes of many OH emission sources approach stellar dimensions. Intercontinental v.l.b.i. is discussed in (**29**).

d. *Occultations*

The lunar occultations of Sagittarius A and B2 were observed (**30, 31**). Interplanetary scintillations of the 1665 MHz emission from Sagittarius B2 are reported (**32**).

e. *Discussions of OH-line mechanisms*

Explanations of OH-line radiation have been offered in more than 20 papers. Recent treatments and references may be found in (**33**) and (**34**).

f. *Detection of other OH transitions*

The $^2\pi_{1/2}\ J=\frac{1}{2}$ transition at λ 6·3 cm (**35**), the $^2\pi_{3/2}\ J=\frac{5}{2}$ at λ 5 cm (**36**) and the $^2\pi_{1/2}\ J=\frac{5}{2}$ at λ 3·8 cm (**37**) have been detected.

g. ^{18}OH

The most recent published information is contained in (**38**) where ^{18}OH has been observed in both the 1637 and 1639 MHz absorption lines in Sgr B 2 as well as Sgr A. Abundance ratios ($^{18}OH/^{16}OH$) above and below the terrestrial value were found in separate regions.

3. *The recombination lines*

The investigation of recombination lines (from transitions between levels with large principal quantum numbers) expanded greatly up to 1968. Two important reviews of experimental (**39**) and theoretical (**40**) work are given in (**42**). The application of recombination-line radial velocities to galactic structure and kinematics is explained in (**41**).

a. *Hydrogen* α*-lines* $(n+1\rightarrow n)$

Hα lines have been reported over the range $n=253$ at 404 MHz (**43**) to $n=56$ at 36, 466 MHz (**44**).

The various observations have established that recombination lines are a property of H II regions and that they afford an excellent tool in the investigation of the physics of the nebulae. Close attention has been given to the calculation of electron temperatures, departures from local thermodynamic equilibrium, the population of atomic levels by dielectronic recombination and Stark broadening. However, as can be seen, for example, in the two reviews mentioned above much more caution is needed in the interpretation of results than has so far been shown.

Earlier surveys of 16 nebulae in H109α (**45**), of 39 nebulae in H158α (**46**), and 34 sources in H126α and H127α (**47**) have given way to large surveys (**48, 49**) in which 75 and 131 sources respectively have been located in H109α.

Useful tables have been published recently which greatly aid the study of recombination lines: tables of oscillator strengths (**50, 51**) and tables of frequencies of the α, β, γ, δ and ε H lines and α and β He lines for quantum numbers $n = 40$ to $n = 889$ (**52**).

b. *Discoveries of other recombination lines*

The first two-level transition lines, H158β and H159β were reported early in 1967 (**53**). The H148δ line in Orion Nebula (**54**) and the H197β and H225γ lines in six intense H II regions (**55**) followed.

An unidentified line near He 109α was detected in NGC2024 and IC1793 (**56**). It has been suggested that the line is Carbon 109α (**57**).

c. *Helium abundance*

It was found that the mean abundance ratio of helium to hydrogen for 5 nebulae is $0{\cdot}084 \pm 0{\cdot}003$ (**58**). Other authors (**59**) find a ratio of 0·12 for 9 nebulae but with much poorer accuracy.

4. *Neutral hydrogen*

a. *The two components of interstellar HI*

The most important contribution was the firm establishment of a model of the two components of H I – dense cool absorbing clouds are immersed in a tenuous hot medium (**60–62**). It was found that the temperature of this medium in at least one direction was > 1000 K; in the cool clouds with an average density of 10 H atoms cm^{-3} the temperature is about 50 K. Supporting observations are reported (**63–65**). Using a model in which heating is effected by low-energy cosmic rays a similar conclusion is reached (**66**). Earlier work along these lines is reviewed in (**67**). Pulsar data have been applied to support the above temperature values (**68**). Finally, it has been pointed out that low spin temperatures in clouds may be the reason for the apparent discrepancies between the densities of H atoms observed at 21 cm and in Lα absorption experiments (**69, 70**).

b. *The Zeeman effect*

Considerable activity has again arisen in experiments of H I Zeeman effect. The recent achievements are reviewed and a value of 2 ± 1 μG placed on the mean interstellar field (**71**).

c. *HI surveys and galactic structure*

A succession of general H I surveys have continued to appear and are reviewed in (**72**). Further references and discussions may be found in the Proceedings of IAU Symposium no. 38. Of great interest was a presentation (**73**) of a recent derivation of H I spiral structure differing entirely from the traditional, albeit recently updated, Leiden-Sydney model.

d. *Miscellaneous*

A number of other H I topics have been discussed or reviewed. Included are hydrogen at intermediate latitudes (**74**), high-velocity clouds (**75, 76**), "intermediate cloudlets" (**77**), the lack of apparent association of H I gas and dust (**78**), the proposal that hydrogen becomes molecular in dust clouds (**79**), the use of H I observations in pulsar work (**80**), and determinations of the Astronomical Unit (**81, 82**).

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E. PULSARS

(prepared by S. P. Maran)

As of 1 Sept. 1969, about 330 papers on pulsars had appeared since their discovery (**1**). Only typical references can be listed here; a complete bibliography is available from the reporter. General reviews are given in (**2**) and (**3**); a review of theories also exists (**4**). Several pulsar conferences have been held; the proceedings of one are published as a tape recording (**5**). An anthology of early pulsar articles has appeared (**6**), as has a catalogue of the first 37 pulsars (**7**).

Except for highly variable sources or those with atypical spectra, it is likely that most of the pulsars that are detectable with present equipment have been found; the "dispersion remover" technique offers good prospects for future discoveries (**8**). Pulsar search techniques are reviewed in (**9**).

PSR 0833-45 is probably associated with the supernova remnant Vela X (**10**). NP 0532 (**11**) is associated with the Crab Nebula (**12**), is the source of optical (**13**) and X-ray (**14**) pulses, and is identified with the central star of the nebula (**15**). No other pulsars are associated with known supernova remnants and no pulsar except NP 0532 is optically identified (**16**). Deliberate searches of other supernova remnants by radio (**17**) and optical (**18**) methods failed to reveal pulsars.

Pulsar periods range from 0·033 to 3·7 s and are lengthening in all cases of observed secular trends (**19**), (**20**), (**21**). Pulse widths are typically 5% of pulse periods. Structure as fine as 100 μs has been found (**22**), (**23**) in pulses. The mean pulse profile, averaged over $\sim 10^3$ pulses, is a reproducible "signature" for each pulsar (**24**). At least 7 pulsars exhibit periodic modulation of pulse intensity at rates incommensurable with the pulse frequencies (**25**), (**26**), (**27**), (**28**). Wavelength-dependent intensity variations on time scales up to months in length have been reported (**1**), (**24**), (**29**), as has been time-variable spectral fine structure (**30**), (**31**), (**32**). Some variations may be intrinsic to the pulsars, but the scintillation data yield valuable models for the interstellar medium (**33**), (**34**), (**35**). A discontinuity was observed in the period and period slow-down rate of PSR 0833-45 (**36**), (**37**), as was a second time derivative for the period of NP 0532 (**38**).

Distances are available for the two pulsars associated with supernova remnants. Distance estimates based on galactic rotation models have been made for several sources in which 21-cm absorption is found (**39**), (**40**). Distances based on interpretations of dispersion measures, models for the interstellar medium, *etc.* have been widely discussed (**41**), (**42**), (**43**), (**44**).

Radio spectra of pulsars usually show high-frequency cut-offs (**45**); the emission implies very high brightness temperatures, $\sim 10^{21}$ K (**46**). Some low frequency cut-offs are also found (**47**). The infrared measurements of NP 0532 (**48**), combined with the optical (**49**), (**50**), (**51**) and X-ray (**52**), (**53**) fluxes, clearly delineate a spectral component that is distinct from the radio spectrum. However, the radio, optical and X-ray pulses occur simultaneously, to the limit of measuring accuracy (**54**), (**55**). There are important spectral differences between sub-pulses (**56**). The linear polarization of radio pulses (**57**) is accompanied by strong circular polarization in only one case (**58**). A smooth variation of position angle during the pulse occurs in the radio emission of PSR 0833-45 (**59**), (**60**) and the optical emission of NP 0532 (**61**), (**62**). The highly variable polarization of other pulsars shows complex but reproducible characteristics in the synchronously integrated parameters (**58**). Time-resolved image tube spectra of NP 0532 show no absorption or emission lines (**63**). Recent searches for Cerenkov radiation due to pulsar gamma rays are negative (**64**), (**65**) as are searches for nanosecond optical pulses from NP 0532 (**66**), (**67**). Measurements of interstellar Faraday rotation in pulsar radiation are combined with dispersion measures to evaluate the galactic magnetic field (**68**), (**69**). A review of the observations (**70**) emphasizes that pulsars are concentrated to the galactic disk (**71**).

The "old" idea of a rotating, highly magnetized neutron star as the present energy source of the Crab Nebula (**72**) provides a natural clock mechanism for pulsars (**73**). In fact, the observed slow-down of NP 0532 (**74**) corresponds to a loss of rotational energy sufficient to account for the nebular emission (**75**), (**76**). The pulsar emission may originate at distances from the star of order $r = c/\Omega$, where the radiating particles have been accelerated by magnetic dipole radiation (**77**), (**78**) or by electrodynamic processes in a magnetosphere (**79**). It is shown that these two phenomena are complementary, so that the total loss to the star is independent of the obliquity of the magnetic axis (**2**). Alternatively, the emission may arise on the stellar surface near the magnetic poles (**80**) or in plasma above but near the poles (**81**). Although all supernovae may generate cosmic rays, pulsars are cosmic ray producers (**82**), (**83**) with distances and ages (**84**), (**85**) appropriate to the sources of the galactic particles actually observed at the Earth today (**86**). Oscillations of neutron stars cannot account for the secondary modulation of pulsars (**87**), but structural effects might cause period changes like that found in PSR 0833-45 (**88**), (**89**), (**90**). A number of pulsar emission mechanisms have been discussed (**91**), (**92**), (**93**), (**94**). Nearly all theories require very high magnetic fields, which may be due to compression or Landau orbital ferromagnetism (**95**). The dragging of inertial frames (**95**) requires that careful attention be paid to general relativistic effects in rotating neutron stars (**97**), (**98**). Theoretical explanations for the paucity of long-period pulsars have been given (**99**), (**100**).

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F. EXTRAGALACTIC RADIO ASTRONOMY: COSMOLOGY

(prepared by J. Lequeux)

1. *General remarks*

At the time of writing, it seems that progress in extragalactic radio astronomy since the last IAU meeting has been less spectacular than in the preceding period, which will be remembered as the great era of quasars. The last three years have rather seen considerable improvements in the quality and accuracy of radio data (positions, diameters and structures, polarization, spectra and flux

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variations, etc.); advances in angular resolution are especially remarkable, thanks to the novel technique of interferometry with independent local oscillators.

Little decisive progress has been made in the theory of extragalactic radio sources. Even the problem of the nature of quasar red-shifts is still unsettled, and the fundamental mechanisms for energy production and particle acceleration are badly understood. However decisive advances exist in certain limited fields.

Given the small space available and the general trends of extragalactic radio astronomy during the last three years, emphasis will be put on observational work; no attempts are made to give an exhaustive bibliography, as it would have to include more than 600 references.

2. *Surveys, accurate positions, identifications*

The Parkes survey has been completed in the declination zone $+20+27°$ (**1**), and the rest of the survey is edited in a useful single volume (**2**). Other surveys at relatively low frequencies include Cambridge aperture-synthesis deep surveys (**3, 4, 5, 6**). Much work has been done and is in progress at shorter wavelengths: near 21 cm at NRAO (**7**) Dwingeloo (**8**), Penticton (**9**), Ohio (**10, 11, 12**), at 11 cm at Parkes and at 6 cm at NRAO (**13, 14**). These surveys contain many sources with flat or inverted spectra which seem to constitute a major fraction of the total at high frequencies. Current positional accuracies in the surveys are about 10″, but source positions have been measured with better accuracies, notably at Parkes, Cal Tech and Green Bank.

Many new identifications have been given, but a large fraction of the possible identifications proposed in the previous period have not been confirmed. As a result, the number of certain quasars in the 3C revised catalogue is still rather low, and a large percentage of sources in this catalogue do not correspond to any visible object.

3. *Spectra, flux density, variations*

Two review articles on this subject (**15, 16**) cover the literature until the end of 1967.

Considerable progress has been made in the accuracy and number of flux measurements, both at low and high frequencies. New absolute measurements have been made, mostly at decameter wavelengths. The flux-density scales are sometimes correct to better than $\pm 5\%$ at high frequencies, but systematic errors may still reach $\pm 10\%$ at 178 MHz, 15% at 38 MHz and more at lower frequencies (see a recent discussion in ref. **17**). Emphasis has been put on measurements on complete or nearly complete samples of radio sources (**17** to **21**). A number of source fluxes are available at frequencies as low as 10 MHz (**22**), and at millimeter wavelengths.

Although a large proportion of sources have curved spectra, 40% of the revised 3C sources have perfectly straight power-law spectra between 38 and 5000 MHz at least. Intrinsically stronger radio galaxies appear to have steeper spectra. Many spectra show a downward curvature at low frequencies, perhaps connected with synchrotron self-absorption; others have concave or complex spectra, and are often variable quasars or Seyfert galaxies (**23, 24, 25**).

Flux variations of radio sources have been extensively studied and variations with time scales of weeks exist. A large number of cases can be explained by the well-known Kellermann-Van der Laan model of expanding optically thick clouds of relativistic electrons, but some require a different or less simplified model (**26**).

4. *Brightness distribution*

Major advances have been made in this field, especially towards very high resolution (see a review in ref. **27**). 2-antenna interferometry has been done for a large number of sources (**28, 29, 30**). There are similar observations without phase (**31**), some reaching resolutions of $0''.1 - 0''.2$ (**32**).

Aperture synthesis observations have been made at Cambridge on most of the revised 3C sources (**33**; in preparation), and more are in progress at the NRAO with resolving powers of a few arc seconds.

Lunar occultation observations have been pursued. A large number of scintillation observations have given information on structures in the range $0''.01 - 1''$ (see **27**), and more are being done at Cambridge.

Very long baseline observations have been organized by American and Canadian observers, using many radiotelescopes scattered around the Earth (see **27**). Nearly 100 sources have been observed, mostly QSS and Seyfert galaxies, with baselines as large as several 10^8 wavelengths, corresponding to resolving powers of the order of 10^{-3} arc second. A variety of information, including very accurate positions, are foreseen as by-products of these observations.

Our understanding of source structure is much better than 3 years ago. The classical double source structure is obviously an oversimplification in many cases; radio galaxies frequently contain small-size components, but quasars may not contain such components. Unidentified sources tend to have small diameters, but this gives no clue as to their nature. Very small diameter quasars or Seyfert galaxies may be interpreted without difficulty as compact synchrotron sources with magnetic fields of the order of 10^{-4} to 10^{-2} G. It seems that inverse Compton losses are smaller than synchrotron losses, and that expansion is not relativistic at least in the case of 3C 84 (**25, 34**).

5. *Polarization*

Linear polarization of many sources has been observed up to wavelengths as short as 1 cm (see e.g. **35**). Major progress has been achieved in our knowledge of the structure of the polarized flux of radio sources, which bears little or no resemblance to the distribution of total flux (**36**). Under these conditions it is no surprise that no clear relationship has been found between polarization and other parameters of radio sources, except that low-brightness sources are likely to be more polarized (**37**). Linear polarization has been found to vary with time at short wavelengths in several quasi-stellar sources (**38, 39**).

Several authors have attempted to detect circular polarization in extragalactic radio sources, which would indicate large magnetic fields (**40**). Most of these attempts have been unsuccessful (see e.g. **41**), but variable circular polarization may exist in several compact sources (**42**).

6. *Spiral and weak elliptical galaxies*

Extensive studies of the continuum emission of many spiral galaxies have been made in many observatories and more are in progress (**43** to **49**). These observations show that the dimensions of the radio source are equal to, or smaller than, those of the optical galaxy, and that the emission is distributed in a disk and in a nucleus with dimensions sometimes as small as 30 parsecs. No definite evidence for radio haloes has been found. The spectra of these objects are non-thermal and seem to show a flattening at low frequencies like the spectrum of our galaxy (**49**); the spectrum of the central nucleus is not known. No clearly established relationship exists between radio and optical properties of spiral galaxies. An advance in this field has been the production of detailed supersynthesis maps for M 31 (**50**) and NGC 4631 (**51**); the former shows a correlation between radio emission and the spiral arms, and the latter galaxy has definitely no radio halo.

A radio survey of nearby elliptical galaxies at 11 cm (**52**) and work in progress at Cal Tech and NRAO have shown that half of the detected nearby ellipticals are point sources with flat or even inverted spectra, like NGC 1052 and 4278 (**53, 54**).

Hydrogen-line work on spiral galaxies has been partly summarized in ref. **55**: the 21-cm line has been observed in more than 77 objects. This has confirmed with a larger sample the relations already known between galaxy type and the (hydrogen mass)/(optical luminosity) and (hydrogen mass)/(total mass) ratios. Much work has been done or is in progress on the neutral hydrogen structure of nearby galaxies (**56** to **62**). It seems that only Sb galaxies have the ring structure in neutral hydrogen discovered in M 31; Ir galaxies have a central condensation and Sc galaxies are of both types. Asymmetries in the velocity field or hydrogen distributions are fairly common, and a bridge of neutral hydrogen has been studied between two interacting galaxies (**63, 64**).

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7. *The nature of radio sources*

Although much effort has been devoted to theoretical studies of radio sources, the origin of the very large energies involved is still very uncertain and the evolution of sources is still poorly known. One has the general feeling that the physical processes taking place in quasars, radio galaxies and even the nuclei of spiral galaxies are basically the same (see e.g. **65**, **66**), and there may even be similarities between quasars and pulsars (**67**); ref. **68** and **69** are review papers on the problems of the nature of radio sources, mostly concerned with quasars.

A number of new models for the evolution of radio galaxies have been presented (see e.g; **70**, **71**, **72**); recent data on spectra of radio sources has put severe limits on their evolutional properties (**73**).

Much work has been done on physical mechanisms in compact radio sources (see e.g. **74**, **75**), including relativistic effects (**76**); as we have already said, their radio properties can often be accounted for by relatively simple models (**25**, **34**).

Not much new is known on the luminosity function of radio galaxies; for quasars, a luminosity function with time evolution has been presented (**77**).

8. *Cosmology*

No really decisive progress has been made during the 3 years by radio astronomers in the field of observational cosmology, except on the cosmic microwave background:

a. *Intergalactic matter* (see the review article ref. **78**).

More attempts have been made to detect intergalactic hydrogen, and only negative results have been obtained so far, even in the Virgo Cluster (**79**, **80**).

b. *Cosmic microwave radiation*

There are now ground-based observations of this radiation up to 3-mm wavelength (see e.g. **81**), and upper limits up to 0·36 mm are derived from observations of interstellar molecules (**82**). All agree on a blackbody radiation of about 2·7 K temperature. However, two direct rocket measurements around 1 mm give a much higher flux (**83**). The origin of the discrepancy is not clear. Careful measurements of the isotropy of this radiation have finally detected a slight anisotropy, which is interpreted as due to a relatively slow motion of the Galaxy with respect to the local Universe (**84**).

Several attempts have been made to explain the microwave background as due to unresolved discrete sources (**85**, **86**); however, there are difficulties in this interpretation (**87**).

c. *Radio-source counts*

The present status of radio-source counts at relatively low frequencies has been summarized in (**88**); the slope of the $\log N/\log S$ curve goes from about $-1{\cdot}85$ for bright sources to $-0{\cdot}8$ at the smallest observed flux densities (corresponding to 10^5 sources/steradian). At higher frequencies, there have been claims for a different $\log N/\log S$ curve (**89**); the discrepancy is discussed in (**90**).

A large number of papers have been published on the interpretation of source counts (see e.g. **91**). It seems that introduction of an evolution with cosmic time is necessary even in Lemaître-type cosmologies, but it is still extremely difficult to give more than qualitative statements because of the composite nature of the $\log N/\log S$ curve: radio galaxies, quasars and the many unidentified sources may behave differently (see e.g. the discussion in **92**), and other little-known types of sources may give an important contribution at certain frequencies and flux levels (weak radio elliptical galaxies at high frequencies, for example). There are however some hopes of using angular diameters, spectra or other parameters of radio sources to gain insight into their nature and of being able to derive separate $\log N/\log S$ relations for different groups of sources.

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G. INSTRUMENTS

(prepared by J. W. Findlay)

1. *Radio Telescopes*

a. *Filled aperture*

There have been relatively few new filled-aperture instruments to come into use during the last three years. The first new 130-ft telescope for the Owens Valley array has started observing (**1**); a new 22-m telescope good for mm waves has been built in the Crimea (**2, 3**); the 210-ft telescope at the Goldstone station of the Jet Propulsion Laboratory (**4**) has also been used for radio astronomy, and the 36-ft mm-wave telescope of the U.S. National Radio Astronomy Observatory is operating on Kitt Peak, Arizona (**5**). A 25-m dish has been completed at Chilbolton, England (**6**). The parabolic cylinder antenna in south-central India is nearing completion (**7, 8**), and the largest fully-steerable dish in the world, the 100-m Bonn telescope (**9**) should start observing by mid-1970. More information about existing large telescopes has been published (**10, 11, 12, 13, 14, 15, 16, 17**). New

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design ideas for minimizing the effects of structural deformations have been developed (**18, 19, 20**). There has been a growth of interest in developing means of feeding spherical reflectors (**21, 22, 23, 24, 25**) and improvements in aperture efficiency and antenna temperature have also been achieved for paraboloids (**25, 26, 27, 28**) and for the Nançay telescope (**29**).

b. *Unfilled apertures*

The variety of unfilled aperture telescopes continues to grow. For solar work, a notable event was the start of the Culgoora radioheliograph in 1967 (see reference **30** and successive papers). Other new solar instruments were built in India (**31**) and Canada (**32**). The solar array at Fleurs, near Sydney, has been converted to a synthetic array (**33**). The two-element interferometer in Haute-Provence has been described (**34**). Several groups of experimenters have used the techniques of very-long baseline interferometry first described in (**35**) and (**36**). A new synthetic antenna is almost ready to observe at Westerbork, in The Netherlands, and work has started on the Cambridge, England three-mile telescope (**37**). The one-mile Mills cross (**38**) has, among other observations, distignuished itself as a pulsar discoverer. A low-frequency array has been operating in Canada (**39**). Designs for very large arrays for the Owens Valley Observatory (**40**) and the National Radio Astronomy Observatory (**41**) are in an advanced stage.

2. *Radiometers*

There has been considerable progress in the development of low-noise stable radiometer systems. Two examples of low total system-noise may be quoted: the maser system on the Onsala, Sweden 84-ft telescope (**42**) and that used at the Jet Propulsion Laboratory (**27**). An experimental travelling-wave maser has been built at 36 GHz (**43**), and recombination line observations have been made using masers at this frequency in the U.S.S.R. Noise in travelling wave masers has been studied (**44**) and good phase stability achieved (**45**).

Many observatories now use parametric amplifiers either cooled or at room temperature. The development of closed-cycle helium cooling systems (**27**) has enabled continuous operation of masers and parametric amplifiers at temperatures down to that of liquid helium (**46**); many descriptions have been given of various types of parametric amplifiers with low noise and other desirable characteristics (**46, 47, 48, 49, 50**).

The use of low-noise transistor amplifiers has remained valuable at the lower frequencies (**51, 52, 53, 54**) as the noise characteristics of the transistor have been improved.

Methods of stabilizing radiometers have not changed very markedly. Special radiometers for interferometry (**55**), for extra stability (**56**) or using correlation (**57**) have been built.

Although considerable progress has been made in many observatories in data processing at the radiometer output, not very many details have been published. Spectral line receivers using filter techniques (**58**) and auto-correlation techniques (**59, 60**) are now widely used.

3. *Noise Sources*

The development of well-engineered sources of noise at microwave frequencies suitable for use as noise standards has proceeded in a very satisfactory way (**61, 62, 63, 64, 65**).

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