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A. INTRODUCTION

Radio observations are now relevant in so many branches of astronomy that I have followed the example of Dr J. F. Denisse and asked certain members of the Commission to prepare reviews covering each of the main fields. J. P. Wild has written on solar radio astronomy and the interplanetary medium, J. E. Baldwin and F. J. Kerr on the galactic continuum and spectral line radiation respectively, J. R. Shakeshaft on extragalactic radio observations and cosmology, and C. A. Muller on instrumentation.

Radio studies of the planets are included in the report to Commission 16, and those of the Moon in the report to Commission 17. By agreement with Dr R. L. Minkowski, his report to Commission 28 covers *optical* work on extragalactic radio sources and also, as an exception, both optical and radio studies of the Magellanic Clouds.

Such is the rate of growth of the subjects covered by our Commission, that there is not space enough for a critical survey of the field. In the following sections, therefore, we have tried to draw attention to all the relevant literature even though this has meant only a very brief discussion of the results achieved. It would be helpful if the Commission were to consider, during the General Assembly, the form which the Report might most usefully take in the future.

The striking progress during the past three years has been possible because of the existence of clear frequency bands; a number of recent events have emphasized the fact that our work will only continue if we are able to maintain effective protection against interfering transmissions and other disturbing influences. The organization set up to allocate frequencies for radio astronomy and for the registration of frequencies in use by astronomers has been described by Smith-Rose (1964) and Smith and Smith-Rose (1966), but its success depends on the active participation of individual astronomers, both through their national authorities and internationally.

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Attention must also be paid to other forms of activity which may give rise to man-made radiation capable of masking the natural radio signals. The radiation caused by high energy electrons released above the atmosphere by a high-altitude nuclear explosion has already caused concern.

The continuing expansion of radio astronomy is also demonstrated by a number of reports discussing future national and international programmes (e.g. Gold and Messel, 1964; Whitford *et al.* 1964; Report of Fleck Committee, 1965).

I should like to draw attention to the obituary (Lovell, 1964) of Joe Pawsey—President of Commission 40 for the 1955 and 1958 General Assemblies, who was not only a great pioneer in our subject but a great leader of men.

Finally I must express my sincere appreciation to the contributors to this report, and especially to J. R. Shakeshaft who has done much of the editorial work.

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B. SOLAR RADIO EMISSION

(prepared by J. P. Wild)

1. *Introduction*

This report covers papers published during the three years between late 1963 and late 1966, a period of low solar activity.

The period has been one of intensive studies of the interplanetary medium by satellite techniques, which are themselves outside the field of this report. But three new techniques of radio astronomy are now being developed to extend these studies closer to the Sun and to the region in which the corona proper merges with the interplanetary medium where the solar wind blows, *viz.*: the use of scintillations of radio sources of small angular diameter to study the irregularities and hence, with the aid of plausible assumptions, the electron density itself (**1**); the extension of spectrographic observations of type III solar bursts to frequencies below 1 MHz by means of satellite-borne equipment (**2, 3**); and the use of solar radar to detect the solar wind (**4**) and study irregularities (**5, 6, 7**).

Special mention may also be made of the emergence of a profound dilemma regarding radio observations and the coronal magnetic field. One finds results obtained by different methods leading to grossly differing values, which roughly sort themselves into two groups with values (at heights of half to one solar radius) of (*a*) $\lesssim$ 1 gauss, (*b*) $\gtrsim$ 10 gauss. Group (*a*) is supported by the interpretation of type II bursts as disturbances of high enough magnetic Mach number to maintain themselves as shock waves (**8, 9, 10**), by the supposition that the newly discussed 'chains' of type I bursts correspond to movements at the Alfvén velocity (**11**), and by simple *a priori* arguments on the likely coronal effects of sunspot fields. Group (*b*) is supported by gyro-synchrotron theories of type IV and other bursts, by Takakura's theory of type I bursts (**12**), and by the Sturrock-Tidman formula for band-splitting in type II bursts (**13**). The resolution of this question is vital to both coronal studies and the understanding of the physical processes of bursts.

2. *Reviews*

Comprehensive text-books have been published on solar radio emission by Zhelezniakov (**14**) and Kundu (**15**), the former dealing equally with observational and theoretical aspects, the latter with greater emphasis on the observed phenomena which are described in great detail. Review papers have appeared on solar radio astronomy in general (**16, 17**), on the quiet Sun (**18**), on radio investigations of the outer corona and interplanetary medium (**19**), on the slowly-varying component (**18, 20, 21, 22**), on the burst component (**23, 24, 25, 26, 27**) and its generation (**28, 29, 30**), on the study of the corona from burst observations (**31**), on the solar flare phenomenon at radio frequencies (**32**), on narrow-band spectral studies of bursts (**33, 34**), on noise storms (**35**) and type IV bursts (**36**), on microwave bursts (**37**), on the relation of bursts with X-rays (**38, 39, 40**), on eclipse observations (**41**) and on solar radar (**42**).

3. *The Quiet Sun*

Determinations of the Sun's brightness temperature have been made at wavelengths of 1·3 mm (**43**), 1·8 mm (**44**), 3·2 mm (**45**), 4 mm (**46**), 1·2 cm (**47, 48**), 1·8 cm (**49**), 2 cm (**48**). The basic thermal component has been investigated at centimetre and decimetre wavelengths (**50, 51**) and the coronal component calculated at 9 cm (**52**). The ellipticity of the Sun has been investigated at 3·2 cm (**53**) and the two-dimensional brightness distribution at various wavelengths (see *Slowly-varying component*). A polarization technique has been used to estimate the Sun's general magnetic field (**54**).

Quiet-sun theory has been developed and applied to make further evaluations of the coronal temperature, yielding the markedly different values of 2×10^6 °K (**55**) and $6{\cdot}4 \times 10^5$ °K (**56**). A temperature model of the lower chromosphere has been derived from observations at millimetre wavelengths (**57**).

Numerous results were published relating to the study of the chromosphere and corona (including plage regions) by eclipse observations: 1954 June 30 (**58**); 1961 February 15 (**59**); 1962, July 31 (annular eclipse) (**60, 61**); 1962 February 5 (**62**); 1963 July 20 (**63, 64, 65, 66, 67** and **68**); 1965 May 30 (**69**); and conclusions based on more than one eclipse (**70, 71**).

Further investigations have been made of the outer corona (interplanetary medium or 'super corona') based on observations of its occultation of the Crab Nebula (**72, 73, 74, 75, 76, 77, 78, 79, 80, 81, 82, 83, 84, 85**) and other sources out to 80 solar radii (**86**). A new method has been developed for studying the interplanetary medium by the observation of radio sources of very small angular size (**1**).

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

A detailed theory of the origins of the slowly-varying component in terms of the bremsstrahlung and synchroton radiating mechanisms has been given (**87**).

High resolution maps have been published and discussed at wavelengths of 3 mm (**45**) and 8 mm (**88, 89**), and other observations of active regions at 8 cm (**90**), 32 cm (**91**), 1·3 m (**92**) and 1·5 m (**93**). Spectra of individual centres have been obtained from observations of seven wavelengths between 2 and 21 cm (**94**).

Active centres responsible for radio emission at 3 cm wavelength have been found to possess distinctive optical properties—bipolar spots with penumbra large compared with their separation (**95**).

A bipolar structure has been found in certain polarized active centres at 3 cm (**96**). Further papers have been published on the general characteristics and interpretation of the active regions (**97, 98**); on the statistical variation of the slowly-varying component with sunspot number (**99, 100**); on an apparent east-west symmetry in the emissions (**101, 102**); and on the application of ray-tracing to investigate the effects of coronal scattering (**103**).

Statistical analyses have been made of the variation of the Sun's microwave radiation with the 11-year solar cycle (**104, 105, 106, 107, 108, 109**), the 27-day period of rotation (**110, 111, 112**) and other periodicities (**113, 114**). The intensity (**115, 116**), spectral slope (**117**) and position shifts (**118**) of the slowly-varying component have been found to be criteria for the occurrence of proton and type IV events; also the intensity for the occurrence of SID's (**119**). The inexactness of the correlation between the intensity and the Sun's total radiation in the extreme ultra-violet has been explored (**120**).

5. *Microwave bursts*

Extensive data on microwave bursts obtained at the Heinrich Hertz Institute have been published (**121**), and an investigation carried out of the microwave spectrum (**122**). Investigations have been made into the relation of microwave bursts with X-rays (**123, 124**) and its interpretation (**125, 126, 127, 128**), and various aspects of flares (**129, 130, 131, 132**), including type II and type IV bursts and SWF's (**131, 132**).

The wave-interaction theory for interpreting the polarization of microwave bursts has been re-examined (**133**). A theory has been given by which filaments of flares might give rise to accelerated particles and radio emission at multiples of the gyro frequency (**134**).

6. *Noise storms and type I bursts*

The elusive origin of type I bursts has been discussed in terms of a theory involving plasma radiation from electrons accelerated by two Alfvén wave packets (**12**), of the relative roles of incoherent synchrotron radiation and plasma radiation (**135**), and of instabilities arising in the interaction between coronal electron streamers and MHD shock waves (**136**). A new line of evidence on the origin of the bursts, relating to the tendency of the bursts to appear in long 'chains' with slow frequency drift, has been explored (**11, 137**). Some general conclusions drawn from 169 MHz observations with the Nançay interferometer (**138**) include the result that the majority of storms are initiated by flares. Observations have been reported on the polarization (**139, 140**), and narrow-band spectrum (**34, 141**) of the bursts, on their directivity (**142**) (which is found to be broader than that of the background continuum), on their relation with active regions responsible for proton flares (**143**), and on weak bursts with the aid of special equipment (**34, 144**). A single-frequency classification of storms has been given (**145, 146**).

7. *Type II bursts*

Theories have been given to interpret some of the main characteristics of type II bursts: the nature of the causal shock wave (**9, 13, 135, 147**), the intensities of fundamental and harmonic and the phenomenon of band-splitting (**9, 13, 135**), and inferences on the coronal magnetic field (**8, 13, 148**).

Other theoretical work, relevant to the same topic but not specifically related to type II bursts, has been published on the emissivity of a plasma at fundamental and harmonic frequencies (**149**), on the interaction of plasma and electromagnetic waves (**150, 151**), and on the growth and ultimate limitation of unstable electron plasma oscillations (**152**).

Comprehensive observations on the nature and velocity of the type II sources have been reported (**8**), and it has been shown that certain features (in particular 'herring-bone' structure) is sometimes highly polarized (**153**). Conclusions have been drawn on the dimensions of the exciting agency (**154**) and inferences made on harmonic structure and band-splitting from observations at a low (29 MHz) single frequency (**155**). The association between flares and type II bursts has been investigated and found to increase at the minimum of the solar cycle (**156**).

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8. *Type III and type V bursts*

Spectral observations have been used to investigate the speed and acceleration of the sources of type III and type V bursts (**157**) and the general characteristics and interpretation of type V bursts (**158**).

A detailed investigation of the properties of type III and V bursts and their relation with microwave bursts has been made using single-frequency data in the metre and decametre range extending over a five-year period (**159, 160**). Low-frequency observations have been described in the 20–30 MHz range (**161**), at a fixed frequency of 26 MHz (**162**), at five fixed frequencies between 6 and 35 MHz (**163**), and at frequencies between 0·6 and 10 MHz obtained with the Alouette satellites (**2, 3**). The occurrence of type III bursts has been found to be associated with filaments (**164**) and to be correlated with the width of the Hα line of the flare (**163**). Further derivations from type III observations have been made on the height and scatter of the burst sources (**165**), other properties including the electron temperature of the corona (**166**), and the variation of electron density above a coronal streamer (**167**).

The majority of type III bursts at 74 and 200 MHz have been found to be partially elliptically polarized, and estimates of the coronal magnetic field have been deduced by comparing the Faraday rotation at the two frequencies (**168**). The bursts have been found to be more strongly polarized in their sharp short-lived features than in their diffuse background features, suggesting a two-component structure (**169**). A study of polarization with respect to the position of sources on the disk has suggested an origin in the differential absorption of two wave modes at the harmonics of the gyro frequency (**170**). Polarization data at low frequencies (23·5 and 39·6 MHz) have been tabulated and discussed (**171**).

Further contributions have been made to the theory of type III bursts in terms of electron streams (**172, 173**), and the escape of an initially isotropic burst of electrons in the vicinity of magnetically neutral planes has been shown to give rise to an outward-travelling pulse of electrons consistent with that required to explain a type III burst (**174**).

The origin of reverse-drift pairs connected with type III bursts has been discussed (**135**). A new type of burst consisting of two closely-spaced narrow-band components (distinct from drifting pairs) has been reported (**175**).

A well-documented case (**176**) was reported of 18 MHz type III bursts being observed at night-time. They were observed during daylight hours at Boulder and Hawaii, at 7 a.m. at Manila and midnight at Rome. The result was published in 1966, on April 1.

9. *Type IV bursts*

Two detailed observational studies of type IV bursts have been described: one gives data on the position, movement, angular size and polarization of 24 type IV sources at metre wavelengths (15–210 MHz) and establishes a clear distinction between 'stationary' and 'moving' phenomena (**177**); the other gives details of the complex polarization behaviour of 18 events (**178**) and discusses their origin in terms of alternative theories of gyro and plasma radiation (**179**). Two further examples of the comparatively rare 'moving' type IV bursts have been described (**180, 162**). An unusual form of fine-structure in type IV bursts has been noted; it consists of 'spikes' (superimposed on the continuum) which are preceded by a 'dip', interpreted as an absorption effect (**181**).

A model of a type IV burst has been proposed (**182**) to account for an E–W asymmetry in time of onset (**188**). The synchrotron theory of type IV bursts has been discussed and the distinction between decimetre-wave and metre-wave ('storm continuum') components emphasized (**183**). The influence of the medium on synchrotron radiation from relativistic electrons has been examined (**184**).

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A careful investigation has been made of the optical characteristics of active centres and flares that produce type IV bursts: specific types of configuration have been found to be most likely to produce the bursts (**186, 187**). A study of type IV-associated flares has been made with data covering the last 11-year cycle (**185**). Further optical relationships have been deduced from onset times of the different burst components (**188, 189**); the relation of the bursts with the 'flare nimbus' phenomenon has been discussed (**190**) The detailed relationships have been explored of type IV bursts with geomagnetic storms (**191, 192**) and with PCA events (**191**), and of type IV-producing active centres with recurrent geomagnetic-storm centres (**193**). Further lists of type IV events have been compiled (**194, 195, 196**).

The dynamic spectrum of several large outbursts (not only of type IV) have been described in detail: 12 events in the 2–3 metre band and their connection with flares, recorded in Crimea (**197**); one event in the metre-decimetre range, and its connection with X-rays and protons, recorded at Fort Davis (**198**); and two events in the range 5–2000 MHz recorded at Dapto (**199**). The tendency for outstanding solar events, including 200 MHz outbursts, to avoid the peak of the solar cycle has been noted (**200**).

10. *Radar Observations*

The 38·26 MHz radar observations at El Campo taken between 1961 and 1964 have been reported in detail (**4, 5, 201**). They indicate systematic outward motions, consistent with solar wind theory, of 16 km s^{-1} in the corona at a calculated height of 0·5 $R_\odot$ above the photosphere, and random mass motions of about 40 km s^{-1} at quiet times, increasing by a factor of 2 to 3 at other times. A coronal model can be found that gives consistency between the radar measurements and probe measurements of the solar wind by Mariner II (**6**). Allowance for the effects of scattering at coronal irregularities has been considered theoretically (**7**).

11. *Instrumental developments*

Descriptions have been given of radiometers operating at wavelengths of 8 mm (**202**) and 3 cm (**203, 204**); spectrographs operating in the frequency range 200–2000 MHz (parametric up-converter) (**199, 205**), 160–320 MHz (60-channel) (**206**), 35–250 MHz (simultaneous sweep over 5 bands), 7·6–41 MHz (interferometric) (**207**), and 200 kHz–6 MHz (satellite-borne) (**208**); interferometers at 225 MHz (**209**) and 136 MHz (**210**); high-resolution multi-element instruments at frequencies of 9·4 GHz (**211**), 5 GHz (**212**), 2·7 GHz (**213, 214**), 408 MHz (**215**) and 240 MHz (**216**); a radioheliograph giving high-resolution 80 MHz pictures at intervals of 1 second (**217**); and a fast narrow-band polarimeter at 74 MHz (**218**). Systems using conical scanning have been described for locating microwave centres in the Sun and measuring polarization (**219, 220, 221, 222**). The design of radiometers for precise measurements of the solar radio flux has been discussed (**223**).

The long series of Canadian observations of 10 cm solar flux has now been extended to three Canadian observatories to extend the hours of operation (**214**). The east-west aperture of the El Campo solar radar antenna has been doubled (**224**).

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C. CONTINUUM RADIATION FROM THE GALAXY

(prepared by J. E. Baldwin)

1. *Introduction*

Since 1963 the main lines of development in studies of the continuum radiation from the alaxy have been the extension of surveys to both lower and higher frequencies than previously nployed, accurate measurements of the galactic radio spectrum including the measurements

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at low frequencies from artificial satellites, attempts to relate this spectrum to observations of the flux of cosmic ray electrons at the Earth, observations of the polarization of the galactic continuum, attempts to determine the strength and form of the galactic magnetic field from polarization studies and other evidence, investigations of the nature of the North Galactic Spur, studies of H II regions, planetary nebulae, supernova remnants and the radio source near the galactic nucleus.

Many topics of current interest were discussed in the Symposium on Radio and Optical Studies of the Galaxy (Mt Stromlo Observatory 1966) and at the IAU Symposium No. 31 on Radio Astronomy and the Galactic System at Noordwijk in August 1966 (to be published). A number of papers relevant to cosmic ray electrons in the Galaxy were presented at the Ninth International Conference on Cosmic Rays, London 1965.

2. *Background Surveys*

The state of knowledge at the beginning of this period has been summarized by Mills (1964) and Pawsey (1965) and a compilation of the earlier surveys was made by Altenhoff *et al.* (1963). Continuum surveys covering large areas of sky have been completed in the southern hemisphere at 4·7 MHz by Ellis *et al.* (1963) and Ellis and Hamilton (1966*a*), at 30 MHz by Mathewson *et al.* (1965), at 144 MHz by Mackrell (1963), at 408 MHz by Komesaroff (1966) and at 960 MHz by Nicolson (1965). In the northern hemisphere similar extensive surveys have been made at 38 MHz by Kenderdine (1963*a*) and Williams *et al.* (1966), at 327 MHz by Braccesi and Vespignani (1964), at 400 MHz by Seeger *et al.* (1965) and at 610 MHz by Moran (1965). Smaller regions of the northern sky have been surveyed with somewhat higher resolution at 178 MHz by Crowther and Clarke (1966), at 610 MHz by MacLeod *et al.* (1965), at 600 and 1415 MHz by Dixon *et al.* (1965) and Scheer and Kraus (1966) and at 3200 MHz by Raghava Rao *et al.* (1965). In the southern sky Beard (1966*b*) made observations at 2650 MHz whilst more restricted observations were made by Klemperer and Ochs (1965) at 50 MHz and by Malumian (1963) at 960 MHz.

Further analysis of the thermal component of the radiation at low galactic latitudes has been discussed by Braude and Vaisberg (1964*a*), Ellis and Hamilton (1964) and (1966*b*), Razin and Khizhnyakov (1965) and Ariskin (1965). The broad features of the distribution of ionized hydrogen throughout the galactic disk seem now to be well established. By contrast, the distribution of non-thermal radiation in the galactic halo is not at all well established (Large 1966, Turner and Burke 1965) but observational discrepancies may soon be resolved. Observations of nearby spiral galaxies (Mills and Glanfield 1965) have been invoked to support the view that the Galaxy may have a radio halo.

3. *Spectrum of the Continuum radiation*

Considerable efforts have been made since 1963 to determine the galactic radio spectrum with some accuracy and, for observations with fairly low resolving powers, brightness temperatures accurate to better than 5% have now been determined at several frequencies. For observations with high resolving power it is doubtful whether accuracies of brightness temperatures of 10% have yet been realized at any frequency.

At the lowest frequencies, below about 10 MHz, much use has been made of observations with single dipoles mounted on artificial satellites. Observations have been reported in the frequency range 0·2–10 MHz by Hartz (1964), Harvey (1965), Hugill and Smith (1965), Huguenin *et al.* (1964), Huguenin and Papagiannis (1965), Lund (1965), Slysh (1965), Alexander and Stone (1965), Benediktov *et al.* (1965) and a discussion given of the results expected for various models of the Galaxy by Smith (1965). Lenchek (1964) discusses the effects of the solar H II region on the low frequency spectrum. These observations, and also

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ground based observations at low frequencies (Ellis, G. R. A 1964, 1965, Parthasarathy and Lerfald 1965) show a considerable scatter and the details of the low frequency spectrum have still to be established. Dipole observations at higher frequencies (10–100 MHz) now yield satisfactory agreement between those in the northern hemisphere (Andrew 1966) and those in the southern hemisphere (Wielebinski and Yates 1965, Yates and Wielebinski 1965, 1966). Measurements with scaled antennas of higher gain have been made over the frequency range 13–404 MHz by Turtle *et al.* (1962), Purton (1966) and Bridle (1967) and with comparable resolving power by Braude and Vaisberg (1964*b*). Recent observations by Penzias and Wilson (1966) at 4080 MHz offer the prospect of extending the galactic spectrum to much higher frequencies. The preliminary values suggest that the spectral variation of brightness temperature $T \propto \nu^{-2.4}$ at frequencies below 100 MHz steepens to a variation of perhaps $\nu^{-2.9}$ at the highest frequencies. An interpretation of the spectrum in relation to the galactic magnetic field has been given by Turtle (1963).

4. *Polarization of the continuum radiation and the galactic magnetic field*

Following the detection of polarization of the galactic background radiation, extensive surveys have been completed in both the northern and southern hemispheres. In the north surveys have been made at 408 MHz by Berkhuijsen and Brouw (1963), at 610 MHz by Berkhuijsen *et al.* (1964), at 408 MHz by Wielebinski and Shakeshaft (1964) and at 1407 MHz by Bingham (1966) and in the south at 408 MHz by Mathewson and Milne (1965) and at 408 and 620 MHz by Mathewson *et al.* (1966). The concentration on a great circle of areas of high polarization has been noted by Mathewson and Milne (1964). Faraday rotation in the interstellar medium leads to depolarization of the galactic continuum as discussed by Razin and Khroulyov (1965*a*, 1965*b*). Reviews of the present state of galactic polarization studies are given by Gardner (1966) and Gardner and Whiteoak (1966).

The detection of Zeeman splitting in absorption features in the 21 cm line of hydrogen was claimed by Davies *et al.* (1963*a*, 1963*b*, 1963*c*) but observations by Weinreb (1962) did not support this claim and Verschuur (Noordwijk Symposium) has now withdrawn the original results. Another attempt to measure the strength of the field by Faraday rotation in the 21 cm absorption spectrum of the Crab Nebula was unsuccessful (Morris *et al.* 1963). From the first studies of the rotation measures of extragalactic sources, Morris and Berge (1964) deduced the structure of the local magnetic field and this has been extended by Gardner and Davies (1966) and Whiteoak (1966) while Maltby (1965) has discussed the variation of source polarization with galactic latitude. The structure of the field in the local spiral arm has also been discussed by Mathewson (1966) and a detailed model of its form deduced from an analysis by Hornby (1966).

The strength of the magnetic field has again been the subject of speculation (Sironi 1965, Felten 1966). More general discussion of the physics of the magnetic field in the Galaxy have been given by Woltjer (1965*a*, 1965*b*).

5. *The galactic spurs*

Continuum surveys specifically aimed at elucidating the nature of the North Galactic Spur Haslam *et al.* 1964, Large *et al.* 1966, Quigley and Large 1966, Davies 1964) have lent support o the belief that this object may be a nearby supernova remnant. Attempts to observe optical mission lines from the region of the spur (Davies *et al.* 1963*d*, Lozinskaya and Shcheglov 965) were unsuccessful but there appears to be some correlation of the spur with neutral ydrogen (Lozinskaya 1964, Meaburn 1965*a*). Quigley and Haslam (1965) found that the purs could be represented by arcs of small circle on the sky. Meaburn (1965*b*) found evidence f optical emission lines close to the Cetus arc. Ellis, F. E. (1965) has made first epoch

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observations to detect proper motion of the spur. The possible association of the North Galactic Spur with the Sco X-ray source was discussed by Shklovsky (1964) and by Quigley and Haslam (1964). Quite different interpretations of the spurs as a feature of the local spiral arm (Rougoor 1966) or as the result of instabilities in the local magnetic field (Parker 1965) have been put forward and their true nature has not yet been determined with certainty.

6. *Galactic radio sources*

Work in this field has expanded very considerably covering H II regions, planetary nebulae, supernova remanants, the galactic nucleus and flare stars.

Catalogues of sources have been prepared from surveys (Wilson 1963, Bennett 1964) and observations of numbers of sources made over the wavelength range 0·8–21 cm (Barrett *et. al.* 1965, Golnev *et al.* 1965, Nguyen-Quang-Rieu 1963, Baars *et al.* 1965*a*, 1965*b*).

Observations of several H II regions are discussed by Menon (1964), Higgs and Thibodeau (1965), Terzian (1965), and Le Marne (1966*a*). Studies have also been made of individual objects—the Rosette nebula (Botinelli and Gouguenheim 1964), W49 (Akabane and Kerr 1965), NGC 3603 (Sher 1965), the Carina nebula (Beard 1966*a*), W51 and W43 (Bystrova *et al.* 1963*a*, 1963*b*), W3, W4 and W51 (Bourgois *et al.* 1965) and Orion and M17 (Kuzmin and Salomonovich 1963). Considerable attention has been paid to the Cygnus X region with studies by Pike and Drake (1964), Yang and West (1964), Higgs *et al.* (1964), Veron (1965), Higgs (1966), Dickel *et al.* (1966), Downes and Rinehart (1966) and Wendker (1966). Observations of the Cygnus Y region have been completed by Ko (1963) and Yang and Dickel (1965).

Detection of the thermal radiation from planetary nebulae has been described by Golnev and Parijsky (1964), Khromov (1964, 1965), Khromov *et al.* (1965), Menon and Terzian (1965), Davies *et al.* (1965), Ehman (1965), Kaftan-Kassim (1965, 1966), Osterbrock (1965), Slee and Orchiston (1965), Le Marne (1966*b*) and Terzian (1966).

Supernova remnants continue to play an important role observationally as objects of study and theoretically as sources of cosmic rays. Reviews of the subject include those by Minkowski (1964, 1965*a*), Hoyle (1965), Shklovsky (1966*a*) and Boischot and Lequeux (1964).

The Crab nebula is the most comprehensively observed remnant. Its known spectrum has now been extended to short centimetric and millimetric wavelengths (Lazarevskii *et al.* 1963, Troitsky *et al.* 1964, Staelin *et al.* 1964, Tolbert and Straiton 1965, Tolbert 1965) and has been discussed by Branson (1965) and Shklovsky (1966*b*). Gordon (1965, 1966) has discussed the expected secular variation of its flux density. Lunar occultations have frequently been employed to study its angular structure (Andrew *et al.* 1964, Matveenko *et al.* 1965, Matveenko and Khromov 1965, Matveenko 1966*a*, Matveenko and Artuh 1966, Lastochkin *et al.* 1965, Krishnan and Zisk 1966, Gotwols *et al.* 1966, Taylor 1966, Davies *et al.* 1966 and Artuh *et al.* 1966). Evidence from interferometric measures (Hewish and Okoye 1964) and from interplanetary scintillation (Hewish and Okoye 1965, Malitson *et al.* 1966) have revealed the existence at long wavelengths of a very small source of high brightness in the Crab nebula. Kronberg (1966) has described a possibly similar source at 1422 MHz. More details of the polarization of the Crab nebula have been obtained at centimetric wavelengths (Golnev *et al.* 1964, Gardner 1965, Matveenko 1966*b*). Further discussions of the nature of the Crab nebula have been presented by Johnson (1963), Gould (1965) and Shklovsky (1965).

Penzias and Wilson (1965) supply a 4080 MHz point on the spectrum of Cas A and a number of other measurements are included in papers on radio source spectra referred to in the report on extragalactic radio astronomy. Its spectrum is discussed by Malumian (1966), secular variations in its flux density by Lastochkin and Stankevich (1964), Sanamian and Aslanian (1965) and Sanamian (1966) and measurements of the distribution of brightness

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over it by Ryle *et al.* (1965) and Zisk (1966*a*, 1966*b*). A further suggestion concerning its history has been put forward by Minkowski (1966*a*). The distance of Tycho Brahe's supernova has been measured (Menon and Williams 1966) and subsequently modified (Menon, Noordwijk Symposium 1966) and an occultation of Kepler's supernova has been observed (Talen 1965).

Among the older supernova remnants which have received attention are the Cygnus Loop (Kenderdine 1963*b*, Poveda 1965, Ramana 1966), IC 443 (Howard and Dickel 1963, Hogg 1964, Higgs 1965), W44 (Scheuer 1963, Dagkesamansky and Korchak 1963, Bystrova *et al.* 1963*c*, 1965, Hollinger and Hobbs 1966, Bondar *et al.* 1965), HB21 (Crowther 1965), HB3 and HB9 (Bazelyan *et al.* 1966). In addition to studies of well known remnants, searches for previously unknown remnants have been vigorously pursued. Several have been suggested by Davies (1963) and Hogg (1966) and a number of individual identifications have been made—W22 (Heidmann and Heidmann 1964, Heidmann 1965), W28 (Courtès *et al.* 1964), a source in Auriga (Dickel *et al.* 1965), OA 184 (Dickel and Yang 1965), Vela X (Milne 1966) and the supernova of A.D. 1006 (Goldstein 1965, Goldstein and Yoke 1965, Gardner and Milne 1965, Minkowski 1965*b*, 1966*b*). Mathewson *et al.* (1963) have discussed a supernova remnant in the Large Magellanic Cloud. Ancient records of novae and supernovae have been reviewed by Xi Ze-Zong and Po Shu-jen (1966). A low upper limit has been set to the flux density of Nova Herculis by Haddock *et al.* (1963).

Work on the region of the nucleus of the Galaxy has been reviewed by Burke (1965). Recent observations of this region have been mainly at short wavelengths (Ryzhkov *et al.* 1964, Maxwell and Downes 1964, Downes *et al.* 1965, Hollinger 1965, Sinclair 1966, Kerr and Sinclair 1966) but some observations have also been made at longer wavelengths (Malumian 1965, Little 1966).

Studies of flare stars have now shown good correlation between the optical and radio events. (Lovell *et al.* 1963, Slee *et al.* 1963, Lovell and Chugainov 1964, Lovell *et al.* 1964, Lovell 1964, Migach 1965, Lovell and Solomon 1966). The nature of the radio emission from flare stars has been discussed by Slysh (1964).

A search for radio emission from the star α Orionis was unsuccessful (Kellerman and Pauliny-Toth 1966).

7. *Cosmic rays and the Galaxy*

The relation of the galactic radio emission to the cosmic rays and their origin remains one of the central problems of galactic research. Considerable progress has been made through the detection and measurement of cosmic ray electrons and positrons, by the spectral measurements discussed in section 3 and through theoretical analyses of the production and behaviour of cosmic ray electrons in the Galaxy.

Synchrotron radiation and the origin of cosmic rays have recently been reviewed by Ginzburg and Syrovatsky (1965*a*, 1965*b*) and Ginzburg (1965).

Measurements of the cosmic ray electron energy spectrum up to energies of 100 BeV have been achieved (Agrinier *et al.* 1965, Shong *et al.* 1964, L'Heureux and Meyer 1965, Daniel and Stephens 1965, Meyer 1965, Bland *et al.* 1966) giving reasonably good agreement with the observed radio spectrum for a magnetic field of about 10^{-5} gauss. Further evidence of the sidereal anisotropy of cosmic rays has been presented (Jacklyn 1966).

Several authors have analysed the generation of cosmic ray electrons (Lequeux 1963, Tsytovich 1963, 1964, Ginzburg and Syrovatsky 1964, Pollack and Fazio 1965, Abraham *et al.* 1966, Spergel and Scanlon 1966, Kurilchik 1966) particular attention being paid to their origin as secondaries, which is now shown to be unlikely. The physical processes acting on the electrons to modify their spectrum have also been discussed (Getmantsev and Tokarev 1964, Ohtrami and Kogure 1964, Souffrin and Chesnay 1965, Ramaty and Lingenfelter 1966*a*,

1966*b*, Daniel and Stephens 1966). The motion in the galactic magnetic field of the cosmic ray particles generated in supernovae may produce observational effects such as the galactic spurs (Oda and Hasegawa 1963). Another possibility is that the interaction of the cosmic ray particles with the field and the inter-stellar gas may produce spur shaped protuberances in the field (Parker 1965, 1966*a*, 1966*b*).

A new radio astronomical technique for the detection of extensive air showers has been developed (Smith *et al.* 1965, Jelley 1965). Radio pulses at a wavelength of 6·8 m have been observed coinciding with the arrival of showers of energy $10^{16} - 10^{17}$ eV.

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D. RADIO LINE EMISSION AND ABSORPTION IN THE GALAXY

(prepared by F. J. Kerr)

Several general reviews have appeared during the three-year period. The distribution of interstellar hydrogen in the Galaxy has been surveyed by Westerhout (1964) and Kerr and Westerhout (1965), and the structure and evolution of the Galaxy by Oort (1965) and Bok (1964). Radio line emission and absorption by the various constituents of the interstellar gas have been reviewed by Kerr (1966), and recent work on the interstellar medium in general by Dieter and Goss (1966). The whole subject was extensively discussed at IAU Symposium no. 31, held at Noordwijk, August–September 1966. The proceedings of this symposium will be published.

1. 21-*cm Hydrogen Line*

Hydrogen line studies are in the transition stage where a large amount of new observational data is now available from high-resolution surveys, but detailed study of the material has not yet proceeded very far. Much of the work published in this three-year period has been concerned with earlier low-resolution work.

The concluding papers describing the results of a low-resolution survey of the southern sky have been published by McGee *et al.* (1964, 1966). P. O. Lindblad (1966*a*) has presented the results of the 1953–55 Kootwijk survey in a new form, as isophote maps of optical depth in velocity-latitude planes. Makarova (1964) has measured profiles along the galactic equator at 10° intervals in longitude.

Two new high-resolution surveys have been carried out. The Maryland-Green Bank survey has been published in part (Westerhout 1966), covering 60% of the sky in the strip $l^{II} = 11°$ to 235°, $b^{II} = -1°$ to $+1°$, in the form of contour maps. The Parkes survey (Kerr 1966*b*) covers the longitude range 185°–63° over a varying range of latitude; these results will be published in 1967.

Several authors have discussed the problems of the large-scale distribution and motion of the hydrogen, but a new coherent picture of the whole system has not yet appeared. The most recent review of this part of the subject has been given by P. O. Lindblad (1966*b*). The variation of the rotation curve with galactocentric azimuth and the large-scale deviations from circular motion require the development of more complex models than have been used so far.

Shane and Bieger-Smith (1966) have made a new determination of the galactic rotation curve for northern longitudes. They discuss possible relationships between the irregularities in the curve and the spiral structure. The earlier 21-cm data on rotation have been reinterpreted by Agekyan *et al.* (1964) and Zhu Ci-Sheng (1964). Münch and Münch (1964) and Feast and Thackeray (1965) have compared rotation curves derived from optical and radio data. The latter obtained good agreement after applying statistical distance corrections to the stellar measurements. In a rediscussion of Muller and Westerhout's catalog, Pronik (1965) finds evidence for departures from circular motion in the outer spiral arms.

Comparisons have been made between the spiral structure patterns derived from optical and radio results by Becker (1964), Kostyakova (1965), and Behr (1965). The agreement is generally poor. Multi-arm models have been developed from earlier 21-cm observations by Kardashev *et al.* (1964), Pskovskii (1965), and Pavlovskaya and Sharov (1966). Mass models for the Galaxy have been derived by Schmidt (1965) and Innanen (1966), mainly on the basis of 21-cm data.

New observations on the shape of the outer part of the galactic hydrogen layer have been made by Lozinskaya and Kardashev (1964). The gravitational effect of the Megellanic Clouds has been considered by Avner (1964) and Elwert and Hablick (1965), who show that a systematic distortion of the observed order of magnitude could be produced in this way under certain conditions. Lynden-Bell (1965) has discussed another possibility, postulating a 1° deviation between the Galaxy's symmetry axis and that of its angular momentum. Zasov (1965) has searched the Palomar atlas for galaxies with distorted disks, and found that they are most frequently associated with close groups or small clusters.

Detailed studies of the galactic centre region have been described by Rougoor (1964) and Kerr (1966*a*), and structural models proposed. Kerr has suggested that the high-velocity hydrogen may be in a bar, coming out from the nuclear disk at an angle to the galactic plane. Shane has found material away from the plane at forbidden velocities, which suggests ejection of gas from the nucleus (Oort 1966*c*). Ariskin (1965) and Komesaroff (1966) have discussed possible relationships between the '3-kpc arm' of hydrogen and structural features found in the continuum.

Burton (1966) has made a detailed study of the longitude range 43°–56°, and has identified several structural features, including a stream of hydrogen apparently related to the Sagittarius arm which has a systematically higher velocity than the arm itself. Hill and Kerr (1964) have given additional evidence that a spiral arm is seen tangentially in the Norma region. Several studies of special regions have been reported, namely the anticentre (Locke, Galt and Costain 1964*a*), the continuum spur (Lozinskaya 1964), the Perseus region (Rickard 1965), and the region $l^{II} = 10°–40°$, Gosachinskii (1966). Dieter (1964, 1965) has made a detailed study of the north and south galactic polar caps. Muhleman and Walker (1964) have described a relationship between OB stars and neutral hydrogen in the Cygnus arm, while Balázs (1965) found a concentration of stars that coincides with two H I complexes found by Blaauw near h and χ Persei. McCarthy and Treanor (1965), on the other hand, found no stellar evidence for spiral structure related to Lindblad's narrow hydrogen arm out of the plane near the anticentre.

The Dutch group have made a detailed study of hydrogen clouds at high and moderate velocities at high latitudes. The observational results have been reviewed by Blaauw (1966), and the results are given in detail by Muller *et al.* (1966), Blaauw and Tolbert (1966), and Hulsbosch and Raimond (1966). The data for two individual clouds of particular interest are described by Smith (1963) and Prata (1964). Many of the clouds are found over a broad region centred at about $l^{II} = 120°$, $b^{II} = +40°$, and most move with negative radial velocities, but some clouds are found in other regions, and a few have positive velocities. Oort (1964, 1966*a*, 1966*b*, 1966*d*) has discussed a number of possible interpretations, and considers that

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the clouds are composed of gas falling in from outside the Galaxy, and decelerated by the galactic interstellar gas. Meaburn (1965) has looked for a relationship between the high-velocity clouds and several loops of continuum emission. Habing (1966) has studied a continuous feature of high-velocity gas at intermediate latitudes, which is probably in the outer part of the Galaxy.

Several studies have been made of the two associations in Monoceros, including the cluster NGC 2264 (Rohlfs 1963; Girnstein and Rohlfs 1964; Bystrova, Gosachinskii and Ryzhkov 1964; Viennot 1965; Raimond 1966*a*, *b*). The most detailed investigation was that of Raimond, who examined the interrelationships between H I, H II, stars and dust in the region. More general surveys of hydrogen in clusters have been carried out by Davies and Tovmassian (1963), Howard and Westerhout (1965), and Tovmassian (1966). Hydrogen was found in most of the clusters examined, including both young and old clusters. Riegel (1966) made 21-cm line observations of 27 small-diameter H II regions, and detected neutral hydrogen associated with four of them. Locke, Galt, and Costain (1964*b*) found an H I cloud in the direction of the nebulosity IC443, which may explain the apparent retardation of the expanding supernova shell. Neutral hydrogen has again been looked for in globular clusters without success. Goldstein (1964*a*) has set an upper limit of about 150 $M_\odot$ on the H I content of M13, and Robinson (1966) a limit of 50 $M_\odot$ for 47 Tuc and ω Cen.

Evidence on the small-scale cloud structure and local kinematical properties has recently been reviewed by van Woerden (1966). The results of a large survey at Dwingeloo, in which profiles were analyzed into Gaussian components, have been discussed by van Woerden (1963), Takakubo (1963*a*) and Terauti (1963). Cloud models were set up and tested against the observations with varying degrees of success. Another study of the density fluctuations has been discussed by Rohlfs (1964), Grahl (1965), and Rohlfs (1966). Heiles (1966) has surveyed a moderately large region to examine the cloud structure. He identified a number of individual clouds and 'cloudlets', but concluded that 90% of the hydrogen in his region was in a smooth distribution. A narrow emission line has been found which extends over a region of large angular size (Goldstein 1964*b*; Goldstein and Welch 1966). This may come from a discrete H I cloud with a small velocity dispersion.

The temperature of the hydrogen, and the possibility of temperature variations, have been discussed by Marx (1965), and the dispersion of cloud velocities by Wilhelmsson and Winnberg (1963) and Gershberg (1964). A cooling process for the gas involving spin-flip collisions between atomic hydrogen and positive ions of carbon and sulphur has been considered by Dalgarno and Rudge (1964).

Several comparisons have been made between gas and dust for small regions. Pronik (1963) reported a variation in the gas-to-dust ratio from 70 to 150 over the region of the Omega nebula, while Gosachinskii (1965) considered that the dust cloud obscuring much of the nebula is associated with a reduced H I density. Similar comparisons have been made for the direction of the Crab nebula by Brodskaya (1963) and for a region in Cassiopeia by Grigoreva (1964, 1965). In the latter case, dust and atomic hydrogen concentrations were found to coincide. On the other hand, Garzoli and Varsavsky (1966) reported an inverse correlation for a region in Taurus, from which they concluded that there is a significant abundance of molecular hydrogen in these dust clouds.

Howard, Wentzel and McGee (1963) compared the radial velocities of optical and radio interstellar lines, using the data available at that time, and found a fair correlation between the hydrogen and calcium velocities. The theoretical and observed ratios of neutral and ionized number densities were found to agree for sodium but not for calcium. Takakubo (1963*b*) compared a high-dispersion spectrum of the K line in ϵ Ori with a hydrogen profile, and obtained partial agreement. He was able to show from the line widths that the internal motions in the clouds must be mainly nonthermal.

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Many hydrogen absorption observations have been made during the survey period, but the results of recent work with large telescopes on a great range of sources have not yet been published. Clark (1965) has found absorption effects in 15 out of 21 sources. He developed a model in which the absorption was produced by a population of cool dense clouds ($T_s < 100$°K) immersed in a general medium at a high temperature ($T_s > 1000$°K). Shuter and Verschuur (1964) studied the three strongest sources with a high frequency resolution, and also found evidence for cool absorbing clouds.

Absorption studies have been made of a number of individual sources, mainly for distance determination. These are the Omega nebula (Bystrova *et al.* 1963*a*, 1964*a*), Tycho's supernova (Menon and Williams 1966), W49 (Akabane and Kerr 1965), several other Westerhout sources examined by Bystrova *et al.* (1963*b*, 1964*b*, 1965), and 3C 273 (Robinson *et al.* 1963; Williams 1965). Absorption in the galactic centre region has been studied by Egorova (1963, 1964), Ryzhkov *et al.* (1964), and Kerr (1966*a*). In this region there are several continuum components, and the absorption pattern is quite complicated. One theoretical study has been published (Smith 1964), on the absorption profiles to be expected for an expanding H I cloud.

No further observations have been published of the Zeeman effect in interstellar hydrogen. The conclusion from work carried out so far is that the magnetic field inside absorbing hydrogen clouds is less than 5×10^{-6} gauss.

A number of precise measurements have been reported for the frequency of the hyperfine transition of ground-state atomic hydrogen. The most recent determinations are those by Beehler *et al.* (1966), Johnson and McGunigal (1966), Peters *et al.* (1965), and Ramsey (1965). A mean of their results gives a free-space value of:

$$1420\ 405\ 751{\cdot}786 \pm 0{\cdot}01 \text{ Hz},$$

corrected to zero magnetic field and zero absolute temperature.

2. *Hydroxyl Lines*

The outstanding development in radio line studies in the last three years has been the detection of the group of four Λ-doubling lines near 18 cm produced by interstellar OH radicals. A recent review has been given by Robinson (1966). The lines have been observed both in absorption and emission, and many unexpected results have been reported. The first discovery was made by Weinreb, Barrett, Meeks, and Henry (1963), who found the 1665 and 1667 MHz lines in absorption in the spectrum of Cassiopeia A. Other early absorption observations were made by Bolton *et al.* (1964*a*), Dieter and Ewen (1964), Weaver and Williams (1964), and Barrett, Meeks, and Weinreb (1964); the values reported for line strengths and shapes were approximately as expected.

Detailed studies of OH absorption effects in and around the direction of Sagittarius A revealed the existence of intense concentrations of OH in the galactic centre region, (Robinson *et al.* 1964; Goldstein *et al.* 1964; Bolton *et al.* 1964*b*; Bystrova *et al.* 1964). The strength of the absorption in this region led to the detection of the other two lines of the group at 1612 and 1720 MHz (Gardner *et al.* 1964). The intensity ratios between the four lines were found to be generally lower than expected theoretically, and to vary considerably from point to point over the region. The distribution of OH in the central region is quite different from that of the hydrogen. Some reasons for the observed systematic increase in the relative abundance of OH towards the galactic nucleus have been suggested by Carroll and Salpeter (1966).

OH emission was not at first detected, but in observations with a narrow-band receiver Weaver *et al.* (1965) discovered some very narrow emission lines in a number of sources Further observations by Weinreb *et al.* (1965), Zuckerman *et al.* (1965), McGee *et al.* (1965)

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and Weaver *et al.* (1966) showed the great complexity of the emission phenomena. Narrow lines are emitted in very localized portions of H II regions, often near their peripheries. The intensity ratios of the four lines of the group are highly variable from source to source, and even from one emission component to another in the same source, clearly indicating non-equilibrium populations.

Linear polarization of many of the emission components has been reported by Weinreb *et al.* (1965), Zuckerman *et al.* (1965), Davies *et al.* (1966), and Williams *et al.* (1966). Circular polarization has also been found in some sources by Davies *et al.* (1966), and Barrett and Rogers (1966*a*). The polarization is often very strong, with great differences in degree and direction for neighbouring emission components. A simple Zeeman interpretation is not able to account for the observed phenomena. Possible interpretations have been proposed by Meeks *et al.* (1966), Verschuur (1966) and Cook (1966*b*).

Interferometric studies by Rogers *et al.* (1966) and Cudaback *et al.* (1966) have shown that some OH emission features have an angular size well under one minute of arc; consequently their brightness temperatures must be very high. Dieter *et al.* (1966) have reported secular variations in individual emission components in two sources over a period of a few weeks. These results have not yet been confirmed by other workers.

The basic theory of OH absorption and the early observations was reviewed by Barrett (1964). Attempts have been made to explain the anomalous emission phenomena in terms of a maser action in which population inversion is produced by ultraviolet or infrared radiation (Cook 1966*a*; Shklovskii 1966; Perkins, Gold, and Salpeter 1966). Symonds (1965) discussed the anomalous intensities in terms of the abnormal formation of OH molecules through a process involving negative oxygen ions.

Precise laboratory frequency measurements have been reported for the four lines by Radford (1964), while Powell and Lide (1965) have made an improved measurement of the OH dipole moment. Goss and Weaver (1966) have calculated improved values for the Einstein A coefficients.

The possibility of detecting lines from other isotopic species of OH has been discussed by Barrett and Rogers (1964), and the radio detection of interstellar $O^{18}H^{1}$ has recently been announced (Barrett and Rogers 1966*b*).

3. *Hydrogen and Helium Recombination Lines*

Kardashev predicted in 1959 that high-excitation lines of hydrogen should be detectable in H II regions. The first observation of such a line was made by Dravskikh *et al.* (1964*a*, 1964*b*, 1965), who detected an emission line at 5763 MHz, corresponding to the transition $n = 105$ to $n = 104$, in the Omega nebula. On more recent usage, this is called the H 104 α line.

The most extensive work has been done on the H 109 α line at 5009 MHz, which has been detected in emission from sixteen sources, for which distances, Doppler widths and electron temperatures have been determined (Höglund and Mezger 1965*a*, *b*; Mezger 1966; Mezger and Höglund 1966). Other lines that have been reported are H 90 α (Sorochenko and Borodzich 1965), H 156 α and H 158 α (Lilley *et al.* 1966*a*), and H 166 α (Palmer and Zuckerman 1966). In addition, three lines from neutral helium, He 156 α, He 158α, and He 159 α, have been detected by Lilley *et al.* (1966*b*).

The derivation of electron temperatures and other parameters from observations of these lines has been discussed by Sorochenko (1965) and Goldberg (1966). A table of frequencies for the hydrogen series has been computed by Pulley and Shuter (1966).

The detection of the recombination lines has provided a new method for the study of ionized regions, and also a new approach to the large-scale kinematics of the Galaxy.

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4. *Other Lines*

Encouraged by the unexpected strength of the OH lines, several workers have attempted to detect the CH line near 10 cm wavelength, but no detailed accounts have yet been published. One major difficulty has been the uncertainty of the line frequency, for which new determinations have been given by Douglas and Elliott (1965) and Goss (1966). The electric dipole moment of the ground electronic state of CH has been measured by Phelps and Dalby (1966).

Malville (1964) has discussed the possibility of detecting two lines near 5 and 6 cm from metastable hydrogen molecules. General reviews of other line possibilities have been published by Robinson and McGee (1965) and Kerr (1966).

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21-cm Hydrogen Line

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E. EXTRAGALACTIC RADIO ASTRONOMY: COSMOLOGY

(Prepared by J. R. Shakeshaft)

1. *General Remarks*

The past three years have seen considerable progress in studies of extra-galactic radio sources, with the completion of large-scale surveys in both hemispheres, with improvements in positional accuracies and, consequently, the number of optical identifications, and with advances in knowledge of the spectra, brightness distributions and polarization of sources. Our understanding of these phenomena, however, remains rudimentary and it is not yet clear at the time of writing, for instance, what relationship, if any, exists between quasi-stellar sources (QSS) and radio galaxies, nor even whether the QSS are local objects or at cosmological distances.

The situation as of December 1963 is described at length in the proceedings of the first Texas Symposium (Robinson *et al.* 1965). Other reviews include those by Priester and Rosenberg (1964), Bolton (1965), Ryle (1966), Schmidt (1966), Smith, H. J. (1966), and Burbidge, E. M. (1967). The proceedings of the NASA Symposium held in New York in December 1962 have been edited by Maran and Cameron (1964).

2. *Surveys, accurate positions and identifications*

All the information available in May 1964 on 1292 discrete sources was collated by Howard and Maran (1965), but since then Pauliny-Toth, Wade and Heeschen (1966) have used the N.R.A.O. 92 m antenna to check the 3C survey, the 4C survey has been completed in two parts (Pilkington and Scott 1965, Gower *et al.* 1967) with a total of 4843 sources in the range $-05° < \delta < +80°$ and having flux densities $> 2 \times 10^{-26}$ w m^{-2} Hz^{-1} at 178 MHz, and the Parkes catalogue has been published in four parts (Bolton *et al.* 1964, Price and Milne 1965, Day *et al.* 1966, Shimmins *et al.* 1966*a*) with a total of 1673 sources in the range $-90° < \delta < +20°$.

Further surveys have been carried out by Heeschen and Wade (1964) to determine the radio emission from bright galaxies, by Braccesi *et al.* (1965) at 408 MHz for the range $-30° < \delta < -20°$, by Davis *et al.* (1965) at 400 MHz, by Kellermann and Read (1965) at 1421 MHz which is, so far, the highest frequency at which a substantial area of sky has been surveyed in detail, by MacLeod *et al.* (1965) at 610·5 MHz, by Dixon *et al.* (1965) and Nash (1965) at 600 and 1415 MHz, by Kraus *et al.* (1966) at 1415 MHz, by Williams, P. J. S., *et al.* (1966) of 1067 sources at 38 MHz and by Kenderdine *et al.* (1966) with the aperture synthesis telescope at Cambridge. The latter is the 5C·1 survey at 408 MHz which lists 106 sources in an area of about 12 square degrees, the weakest having flux densities $S \approx 25 \times 10^{-29}$ w m^{-2} Hz^{-1} and positional accuracies $\approx 5''$ arc.

In order to identify sources (Minkowski 1964) with galaxies fainter than 16^m–17^m better positional accuracies are required than are, in general, provided by the large-scale surveys. Special observations have therefore been made at the Owens Valley Radio Observatory (Fomalont *et al.* 1964, Wyndham and Read 1965), at Pulkovo (Bystrova *et al.* 1964, Gol'nev and Parijskij 1965, Gol'nev *et al.* 1965), at the Mullard Radio Astronomy Observatory (Clarke, M. E., 1964, Wills and Parker 1966) and at Parkes (Shimmins *et al.* 1966*b*). These have reduced the errors to values typically $10''$–$15''$. For smaller numbers of sources positions have been determined to within a few seconds of arc by the method of lunar occultation (references later) and by interferometric techniques such as those at the Royal Radar Establishment, Malvern (Adgie 1964, Adgie and Gent 1966), at the N.R.A.O., Green Bank (Wade *et al.* 1965, Clark, B. G. and Hogg 1966) and at Cambridge (Parker *et al.* 1966). These measurements rely upon calibration of the equipment by means of accurately determined optical positions of sources (e.g. Griffin 1963, Véron 1966*a*).

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Identification work following from these and other surveys has been described by Shobbrook (1963), Hazard *et al.* (1964) Ryle and Sandage (1964), de Vaucouleurs (1965), Longair (1965), Shakeshaft and Longair (1965), Shobbrook and Hunstead (1966) and Wyndham (1965, 1966); the latter paper gives finding-charts and descriptions of objects in the neighbourhood of most of the sources in the revised 3C survey. Many identifications have been suggested from study of the Parkes catalogues by Bolton *et al.* (1965*a*, 1965*b*), Ekers and Bolton (1965), Bolton and Ekers (1966*a*, 1966*b*, 1966*c*, 1966*d*), Bolton and Kinman (1966), Bolton *et al.* (1966), Clarke, M. E. *et al.* (1966), Westerlund and Smith (1966), both with galaxies and also blue stellar objects. Comparison of lists of such objects with the 4C catalogue has also revealed significant coincidences (Aizu 1966, Scheuer and Wills 1966, Wills 1966*a*, Caswell and Wills 1967), although for the great majority of them the radio emission is either extremely weak or undetectable (Dickel and McVittie 1965, Braccesi *et al.* 1966*a*, 1966*b*, Kellermann and Pauliny-Toth 1966*a*, Kinman 1966, Shapiro and Weinreb 1966).

Many of the identifications recently proposed remain to be confirmed, or otherwise, by improved radio positions and optical studies; this work is described in the report to Commission 28.

3. *Spectra*: *flux density variations*

Because of their uniformity the spectral results by Conway *et al.* (1963) (see also Long *et al.* 1963, Conway 1964*a*, Conway and Moran 1964) have been widely used, although further measurements (Long and Shuter 1963, Razin and Fedorov 1963, Kellermann 1964*a*, 1964*b*, Zaharov *et al.* 1964, Boischot *et al.* 1965, Clarke, M. E., 1965, Conway *et al.* 1965, Vetuhnovskaja and Kuz'min 1965, Artjuh *et al.* 1966) are now available. Kellermann (1964*c*) has reviewed some of these new data and their interpretation.

Howard *et al.* (1965) have also derived a uniform flux density system based on many earlier surveys but present studies (e.g. Long *et al.* 1966) make use of the more reliable surveys recently completed (see section (2)).

In virtually all of these papers, the flux densities quoted have been measured by comparison with those of intense sources. To calibrate them, absolute flux density measurements (Findlay 1966) are required. These are not easy and for low frequencies the errors are still 10–20%. At high frequencies, however, the use of horn antennas (Lastochkin *et al.* 1963*a*, 1963*b*, Findlay *et al.* 1965, Medd and Ramana 1965*a*, 1965*b*, Allen and Barrett 1966, Wilson and Penzias 1966) has enabled the errors to be reduced to a few percent only.

The range of frequencies over which flux densities have been measured has been extended; at low frequencies (< 38 MHz) by the group at Kharkov (Bazeljan *et al.* 1964, Bazeljan *et al.* 1965*a*, 1965*b*, Braude 1966*a*), by Erickson and Cronyn (1965) at 26 MHz, Andrew (1967) at 13·1 MHz and by Guidice (1966). At high frequencies (> 3 GHz) observations have been made by Broten *et al.* 1965, Dent and Haddock (1965*a*, 1966), Gol'nev and Parijskij (1965), Williams, D. R. W. *et al.* (1965), Kellermann (1966*a*), Kostenko and Matveenko (1966), Maxwell and Rinehart (1966) and Yokoi *et al.* (1966). From these and other measurements it has become clear (e.g. Howard *et al.* 1964) that the spectra of a number of sources cannot be represented by the usual power law. In the microwave range, for example, the fluxes of 3C 84 (NGC 1275) and 3C 279 increase with increasing frequency (Dent and Haddock, 1965*b*). This phenomenon is associated with time variations of flux (see later) and small angular size (Barber *et al.* 1966).

At low frequencies it is found that some sources exhibit a relative reduction of flux (Williams, P. J. S. 1963) which is correlated with high brightness temperatures. This result has been interpreted in terms of synchroton self-absorption (Slyš 1963) though there are other possibilities (Gajlitis and Cytovič 1963, Braude 1965*a*, Scheuer 1965*a*, Hornby and Williams 1966). In other cases there is a relative increase at low frequencies which can be attributed

to components in the source with different spectral indices. Two examples are 3C 273 (Bailey *et al.* 1964, Conway *et al.* 1964, Šolomickij *et al.* 1965*a*, Hazard *et al.* 1966*a*, von Hoerner 1966) and 3C 84 (Baars *et al.* 1965, Roger *et al.* 1965, Slepcova *et al.* 1965, Braude 1966*b*). Šolomickij *et al.* (1964*a*, 1964*b*, 1965*b*) have found some other sources with apparently peculiar spectra but confirmation of this work is required.

The spectra of some of the stronger sources have been studied in detail (Braude 1963, 1965*b*, Hrulev 1963, Baars *et al.* 1964, Lastočkin 1964, Slyš 1964, Stankevič 1964, Bazeljan *et al.* 1965*c*, 1966, Braude *et al.* 1966, Clark, T. A., 1966). A particularly interesting one is 1934–63, the radio spectrum of which is broadly peaked near 1400 MHz and falls off rapidly above and below this frequency (Bolton *et al.* 1963, Kellermann 1966*b*). Šklovskij (1965*a*, 1965*b*) points out that there may be a detectable secular variation of its spectrum. This has not yet been found but the reality of irregular flux variations in certain other sources is now well established (after searches by Mayer *et al.* 1965), following the work of Dent (1965) on the quasi-stellar objects 3C 273, 279 and 345. It appears (Maltby and Moffet 1965*a*, Bartlett 1966, Kellermann and Pauliny-Toth 1966*b*, Moffet 1966*a*, Pauliny-Toth and Kellermann 1966, Yang and Dickel 1966) that the magnitude of the variations in these sources tends to increase with frequency above about 1 GHz; at centimetric and millimetric wavelengths there can be very rapid changes (Epstein 1965*a*, 1965*b*, Low 1965, Epstein *et al.* 1966). Another variable source (Dent 1966) is 3C 84, particularly significant because of its association with the Seyfert galaxy NGC 1275 rather than a quasi-stellar object.

The first QSS reported as variable was CTA–102, (Šolomickij 1965*a*, 1965*b*) from observations at 920 MHz. His later results (1966*a*) indicate a very regular fluctuation of intensity of a circularly-polarized component with a period 102 days. No other observers (Boischot 1965, Caswell and Wills 1965, Maltby and Moffet 1965*b*, Bologna *et al.* 1966, Nicholson, G. D. 1966) have detected any variation, though none has used precisely the same frequency or polarization.

The evolutionary changes to be expected in source spectra are the subject of papers by Gajlitis and Cytovič 1964, Ohtani and Kogure (1964), Lequeux (1965), Souffrin and Chesnay (1965), de la Beaujardière (1966) and Kellermann (1966*c*, 1966*d*).

Studies of the radio spectra of 'normal' galaxies have been made by Hazard (1963), Kuril'čik (1964, 1965*a*, 1966*a*), Kenderdine and Baldwin (1965) and Kuril'čik and Sycko (1965).

4. *Brightness distribution*

Work on the structure of extragalactic sources has been reviewed by Moffet (1964*a*, 1966*b*), Hazard (1965) and Palmer (1965).

Information on the brightness distribution in relatively extended sources can be obtained directly by means of antennas with narrow beams (Boischot *et al.* 1963, Little, A. G. 1963, Balklav 1964, Ko 1964, Labrum *et al.* 1964, Little, A. G. *et al.* 1964, Milne and Scheuer 1964, Parijskij and Prozorov 1964, Parijskij and Timofeeva 1964, Boischot and Kazès 1965, Broten *et al.* 1965, Scheuer 1965*b*, Thompson and Krishnan 1965, Little, A. G. and Bracewell 1966), but for higher resolution it is necessary to employ interferometric techniques or the method of lunar occultation (for zodiacal sources, Nicholson, W. 1965). A discussion of errors in measuring diameters has been given by von Hoerner (1965). The principal developments in interferometry have been the use of extended base-lines (Adgie *et al.* 1965, Anderson *et al.* 1965, Barber *et al.* 1966, Palmer 1966), revealing that some sources, particularly QSS, have structure subtending 0″.1 arc or less; and the production of a pencil-beam as small as 23″ by means of 'aperture synthesis' (Ryle *et al.* 1965*a*, 1965*b*, Macdonald *et al.* 1966, Shakeshaft 1966), which has shown, *inter alia*, that the QSS 3C 47 has a double structure indistinguishable from that characteristic of most radio galaxies, and that some radio galaxies, e.g. 3C 465, have multiple components. Other interferometric work included that by Maltby

et al. (1963) who discuss 24 identified sources in detail, by Moffet (1964*b*, 1964*c*), Tanaka *et al.* (1965), Zisk (1965), Clark, B. G. and Hogg (1966), Hogg (1966) and Wade (1966) who has found fine structure in each of the two radio components of Cyg A.

The technique for analysing observations of a lunar occultation devised by Scheuer (1963) and developed by von Hoerner (1964*a*) has been applied to observations of 3C 273 by Bailey *et al.* (1964), Conway *et al.* (1964), Hughes (1965), Scheuer (1965*a*, 1965*c*), Hazard *et al.* (1966*b*) and von Hoerner (1966). Occultation observations of other sources include those of CTA 21 (Clarke, R. W. and Batchelor 1965, Taylor 1966), 3C 444 (de Jong 1966*a*, Taylor 1966), MSH 19–27 (Brown 1966*a*), MSH 21–23 (Brown 1966*b*), 0938 + 18 and 1101 + 11 (Cohen and Kundu 1966), NGC 6523 (Larionov and Šolomickij 1966, Šolomickij 1966*b*), 3C 17 and 3C 132 (Taylor 1966). The prediction of occultations of radio sources for 17 radio observatories has been continued by the Nautical Almanac Office of the Royal Greenwich Observatory; details are given in the Explanatory Supplement.

Information on small-scale structure (< 1″ arc) in sources can come from two other types of observation: (*a*) that of interplanetary scintillation due to the solar wind (Hewish *et al.* 1964, Cohen 1965, Hogg and Menon 1966, Sinigaglia 1966, Vitkevič *et al.* 1966). The manner in which scintillations vary with the angular distance between a source and the Sun is dependent upon the angular size and structure of the source (Cohen *et al.* 1966, Little, L. T. and Hewish 1966); (*b*) low-frequency spectral cut-offs. If it is assumed that such a cut-off is due to synchroton self-absorption then there is a relationship between the brightness temperature, red-shift, magnetic field and cut-off frequency for the source (e.g. Hornby and Williams 1966). Knowledge of angular sizes can then put upper limits on the field strengths in sources (Williams, P. J. S., 1966*a*) or, alternatively, assumptions about field strengths give upper limits to angular sizes. Williams, P. J. S. (1966*b*) has shown in this way that the ratio of separation to component sizes in the double source 3C 343/343·1 (previously studied by Moffet 1965) is at least 2000:1. Gardner and Bolton (1965) have described another widely-spaced double source MSH 13–33.

The dependence of source structure upon wavelength has been considered by Moffet and Palmer (1965) and by Jennison (1965).

5. *Polarization*

The whole subject of polarization, for the galactic continuum radiation as well as for sources, has been reviewed recently by Gardner and Whiteoak (1966).

Further observations of the linearly polarized radiation from sources have been made by Seielstad and Wilson (1963), Seielstad *et al.* (1963), Conway (1964*b*), Haddock and Hobbs (1964), Hollinger *et al.* (1964), Mayer (1964), Mayer *et al.* (1964), Morris and Berge (1964), Morris *et al.* (1964*a*), Radhakrishnan (1964), Roberts (1964), Rose (1964), Bologna *et al.* (1965), Gol'nev and Soboleva (1965), Boland *et al.* (1966), Gardner and Davies (1966) and Maltby and Seielstad (1966). These are nearly all measurements at various centimetric wavelengths of the percentage polarization and position angle of the electric vector for the integrated radiation from sources. It will clearly be vital to a full understanding of sources to know the distribution of polarization across them as a function of wavelength (as already determined for Centaurus A by the group at Parkes, e.g. Cooper *et al.* 1965). Examples of such measurements are those for Cygnus A with the fan-beam of the Pulkovo antenna (Soboleva and Timofeeva 1963, Soboleva 1966) for Pictor A (Broten *et al.* 1965), for Fornax A (Gardner and Price 1967), and for the source MSH 13–33 (IC 4296) (Gardner and Davies 1964) in which the intrinsic position angle of the electric vector from each of the three widely separated components is closely parallel to the axis of the source. Interferometric studies are, however, necessary in most cases in order to obtain higher resolution. These have so far been carried

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out only at the Owens Valley Radio Observatory (Morris *et al.* 1964*b*, 1964*c*, Seielstad 1966) and at Parkes (referred to by Gardner and Whiteoak 1966).

It is now clear that nearly all of the Faraday rotation observed for sources occurs in the Galaxy and can give information on magnetic field structure therein (Ginzburg and Pisareva 1963; see Section (C) for other references), but the decrease of polarization with increasing wavelength must be largely due to Faraday rotation occurring within the source; this has been considered by Pacholczyk (1963), Burn and Sciama (1964), Morris *et al.* (1964*d*), Slyš (1965) and Burn (1966) among others. The relation between polarization and other source properties has been discussed by Bolton *et al.* (1964), Moffet (1964*b*), Morris and Berge (1964), Seielstad *et al.* (1964), Maltby (1966) and Davies (1966*a*). The most convincing correlation found is that between intrinsic position angle and that of the major axis of elongated sources. The orientation difference is related to the brightness temperature of the source.

Mayer *et al.* (1964) have put low upper limits on possible circularly polarized radiation from a number of sources at λ 3·15 cm.

6. *'Normal' galaxies*

It appears (e.g. Matthews *et al.* 1964, Longair and Scott 1965, Matthews 1965) that a more or less clear distinction may be drawn between the 'normal' galaxies which have been detected and 'radio galaxies', with enhanced emission. The former are spirals or irregulars and have radio luminosities less than $\approx 10^{23}$ w Hz^{-1} ster^{-1} at 178 MHz while the latter are nearly all D or E galaxies (though see Sandage 1966*a*) and have radio luminosities greater than this value. Possible intermediate cases have, however, been found by Tovmasjan (1966*a*, 1966*b*), and Heeschen and Wade (1964) believe that there is a smooth transition.

Heeschen and Wade (1964) have observed 515 galaxies in the Shapley-Ames catalogue north of $\delta = -19° 23'$ and found detectable continuum emission from many of the spirals. Observations have also been made by de Jong (1965, 1966*b*) and by Mills and Glanfield (1965). Individual 'normal' galaxies studied include

M 31 (NGC 224): Kraus (1963, 1964*a*, 1964*b*), Leibacher (1964), MacLeod (1964), Dickel *et al.* (1965), Kraus and Dixon (1965), Kraus *et al.* (1966), Makarenko (1966),
M 33 (NGC 598): Venugopal (1963),
M 83 (NGC 5236): Kuril'čik (1965*b*),

but the situation with regard to the presence or absence of radio 'haloes' in such objects remains controversial.

More detailed work on the distribution of neutral hydrogen in galaxies other than our own is now under way (Epstein 1964*a*, 1964*b*, Seielstad and Whiteoak 1965). The subject has been reviewed by Roberts (1966*a*, 1967). Apart from the Magellanic Clouds, reviewed in the report to Commission 28, M 31 is the object most studied (Argyle 1965, Brundage and Kraus 1966, Davies 1966*b*, Gottesman *et al.* 1966, Roberts 1966*b*) but NGC 55 (Seielstad and Whiteoak 1965, Robinson and van Damme 1966), NGC 925 (Hoglund and Roberts 1965), NGC 3109 (Seielstad and Whiteoak 1965, Botinelli *et al.* 1966, van Damme 1966), M 33 (Davies 1966*b*, Meng and Kraus 1966), NGC 5668 (Roberts 1965) and galaxies in the Virgo cluster (Robinson and Koehler 1965) have also been observed, among others (Davies *et al.* 1963).

It is often possible to derive a rotation curve for each galaxy (though see Elvius 1964) but it is found in addition that (*a*) the hydrogen usually extends well beyond the optically visible region, (*b*) in nine out of the ten objects studied with sufficient resolution the neutral hydrogen is concentrated to a ring of radius 5–10 kpc in the galactic disk. The relationship between the hydrogen and spiral arms as indicated by OB stars etc. is not yet clear.

Roberts (1966*c*) has been able to put upper limits of 10^{-3} atoms cm^{-3} on the neutral hydrogen density in the halo regions of NGC 4244 and NGC 7640.

7. *The nature of radio sources*

An understanding of the nature of radio sources requires the solution of two main problems, i.e. the origin of the very large energies involved, and the mode of evolution of the sources.

It is now widely accepted that 'violent events' of some kind (Burbidge, G. R. *et al.* 1963) must be responsible for the energy generation but, until the relationship between QSS and radio galaxies is clarified, we cannot be sure that the same type of event gives rise to each, though this is suggested by the fact that the energies are comparable. These violent events may give rise to cosmic rays (Aizu *et al.* 1965*a*, Burbidge, E. M. and Burbidge, G. R. 1965*a*).

Theories of the origin of radio sources have been reviewed by Burbidge, E. M. and Burbidge, G. R. (1964, 1965*b*), Burbidge, G. R. (1964) and Burbidge, G. R. and Burbidge, E. M. (1965). The following possibilities have been discussed: gravitational collapse, either of gas (Fowler 1964, 1965*a*, 1965*b*, Ginzburg 1964, 1965, Ginzburg and Ozernoy 1964, Miller and Parker 1964, Hoyle and Fowler 1965, Herzenstein and Aivazyan 1966, Wagoner 1966) or due to stellar collisions (Hoyle 1964, Ulam and Walden 1964, Woltjer 1964*a*, Gold, T., *et al.* 1965, van den Bergh 1965*a*); delayed expansion from a condensed state (Novikov 1964, Ne'eman 1965, Zel'dovič and Novikov 1966*a*, 1966*b*); collective star formation (Cameron 1964, 1965, Field 1964*a*, 1964*b*, Sugimoto 1965); magnetic field models (Kardašev 1964, Piddington 1964, 1966, Layzer 1965, Sturrock 1965, 1966); matter-antimatter annihilation (Gray and Browne 1965, Ekspong *et al.* 1966); sudden creation (Stothers 1965, 1966) and a model involving quarks (Blatt and Gutfreund 1966). None of them has gained any general acceptance.

The properties and nature of QSS have been reviewed by Schmidt (1964, 1966*a*) and by Burbidge, E. M. and Burbidge, G. R. (1966). A crucial issue is whether QSS are at the cosmological distances suggested by the large red-shifts found in many cases, or whether they could be comparatively local (within $\approx$ 10 Mpc). This question has been reviewed recently by Hoyle and Burbidge (1966*a*), by Schmidt (1966*a*) who favours the cosmological hypothesis and by Terrell (1966) who does not. Evidence and discussion on the matter includes that put forward by Robinson *et al.* (1963*a*), Terrell (1964), Dent (1965), Field (1965), Šklovskij (1965*c*, 1965*d*, 1966*a*), Williams, D. R. W. (1965), Barnothy, J. M. (1966*a*, 1966*b*, 1966*c*), Barnothy, M. F. and Barnothy, J. M. (1966), Faulkner *et al.* (1966), Hillier (1966), Hoyle and Burbidge (1966*b*, 1966*c*, 1966*d*), Hoyle *et al.* (1966), Hunter *et al.* (1966), Koehler and Robinson (1966), Lozinskaja (1966), Noerdlinger (1966), Odgers and Stewart (1966), Rees (1966), Rees and Sciama (1966*a*), Sandage and Miller (1966), Setti and Woltjer (1966), Strittmatter *et al.* (1966), Woltjer (1966) and Zapolsky (1966) in addition to that on flux variations etc. mentioned elsewhere.

Evidence not already cited which must be taken into account in considerations of the nature of extragalactic sources is that of their association with clusters of galaxies (Matthews *et al.* 1964, Pilkington 1964, Heidmann 1965, Ko 1965, Rogstad *et al.* 1965, Šolomickij and Kokin 1965, van den Bergh 1965*b*, Fomalont and Rogstad 1966, Wills 1966*b*), and with certain peculiar galaxies (Arp 1966, Holden 1966*a*, Lynden-Bell *et al.* 1966). An association is definitely established in the former case, and not so definitely in the latter, but in neither case is the significance entirely clear. A statistical investigation (Holden 1966*b*) of the 4C catalogue reveals no significant clustering on any scale from 0°.5 to 60°.

The luminosity distribution and luminosity function of sources have been discussed by Pskovskij (1964, 1965) Tovmasjan (1964), Longair and Scott (1965), Zasov and Ozernoy (1965) and Longair (1966*a*) and seem now to be fairly well established. They are closely

related to the lifetimes of sources (Schmidt 1966*b*). Other statistical correlations between the physical properties of sources have been reviewed by Lequeux (1966) and discussed by Aizu *et al.* (1964*a*, 1965*b*), Zasov (1964) and Heeschen (1966), but at present this approach seems less promising than studies of individual sources in as much detail as possible, e.g. those by Heidmann (1963*a*, 1963*b*), by Matthews and Sandage (1963) of 3C 48, 3C 196 and 3C 286; by Greenstein and Schmidt (1964) of 3C 48 and 3C 273; by Matthews (1964, 1966) and Matthews *et al.* (1964) of the characteristics of galaxies identified with sources; by van der Laan (1963*a*), and by Cooper *et al.* (1965) of Centaurus A.

Although the origin of the energy remains a mystery, it may be possible to devise models of sources which will account for their observed properties. For radio galaxies, such attempts have been made by Kardašev 1963, van der Laan (1963*b*, 1964, 1966*a*), Šolomickij (1964), Gold, T. (1965), Kogure (1965, 1966), Pacholczyk (1965) and Kuril'čik (1966*b*) (see also Šklovskij 1963, 1966*b*, Woltjer 1964*b*, Sato 1966, Syrovatskij 1966).

More authors have been brave (or rash) enough to voice opinions on the nature of QSS, including Aizu *et al.* (1964*b*), Anand (1964), Ginzburg *et al.* (1964, 1965), Hoffmann (1964, 1966), Šklovskij (1964*a*, 1964*b*, 1964*c*, 1966*c*), Ahmad (1965), Kalinkov and Sadowsky (1965), Menon (1965), Ozernoy (1965, 1966), Rees and Sciama (1965*a*, 1965*b*), Williams, I. P. (1965), Zel'dovič (1965), Zel'dovič and Novikov (1964), Boccaletti *et al.* (1966), Falla (1966), Gordon (1966), Heidmann (1966), Ozernoy and Čertoprud (1966), Pfleiderer and Grewing (1966) and van der Laan (1966*b*).

Although there are strong reasons for believing that the synchroton mechanism is of prime importance in the radio radiation of QSS, other mechanisms may have a role (Gold, L. and Moffat 1964, Surdin 1965, Ginzburg and Ozernoy 1966*a*, 1966*b*, Gold, L. 1966, McCray 1966).

8. *Cosmology*

The implications of radio astronomical investigations in cosmology have been reviewed recently by Minkowski (1966) and in more detail by Davidson and Narlikar (1966) and Scheuer (1967). As Scheuer points out there are three distinct ways in which radio observations may be used to test cosmological models:

(*a*) *By determining limits for the mean density of the Universe.*

Attempts to detect emission or absorption by intergalactic neutral hydrogen have been made by Goldstein (1963), Davies and Jennison (1964) and Koehler and Robinson (1966) with no clearly positive results. The interpretation is discussed by Davies (1964) and Koehler (1966). Robinson *et al.* (1963*b*) and Koehler and Robinson (1966) have, however, found absorption due to hydrogen in the Virgo cluster of galaxies, although Goldstein (1966) could not detect this in emission, setting an upper limit of $5{\cdot}6 \times 10^{12}$ solar masses.

It may well be that the intergalactic medium is highly ionized (Ginzburg and Ozernoy 1965, Gunn and Peterson 1965, Scheuer 1965*d*, Gould and Ramsay 1966, Rees and Sciama 1966*b*). The free-free emission to be expected from it in this case has been considered by Field and Henry (1964), Kaufman (1965) and Weymann (1966) but has not been detected. Other possible effects are Thomson scattering (Kardašev and Šolomickij 1965), free-free absorption (Sciama 1964*a*) and dispersion (Haddock and Sciama 1965) in the intergalactic medium.

(*b*) *By measurement of residual radiation from the highly condensed stage of an evolving cosmology.*

An unexpected and comparatively intense microwave component has been found with a brightness temperature $\approx 3°$K and a spectrum close to that of a black-body (Penzias and Wilkinson 1965, Howell and Shakeshaft 1966, Roll and Wilkinson 1966). A further point on

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the spectrum may come from observations of interstellar CN at λ 2·6 mm (Field and Hitchcock 1966*a*, 1966*b*, Thaddeus and Clauser 1966). The most plausible explanation (Dicke *et al.* 1965) is that this is residual radiation from a primordial fireball. The significance is discussed by Felten (1965), Kaufman (1965), Peebles (1965, 1966*a*, 1966*b*), Layzer (1966), O'Connell (1966), Peebles and Dicke (1966), and Sciama (1966) among others. Weymann (1966) points out that the intergalactic medium may cause modifications to the black-body spectrum.

(*c*) *By studying the development of the radio source population.*

There seems now to be substantial agreement between independent observers about the log N–log S relationship for sources. The largest range of flux densities is covered by the Cambridge observations (Gower 1966) but the slope of approximately $-$ 1·8 for bright sources has also been found by Bolton *et al.* (1964) and Price and Milne (1965) in the Southern hemisphere. In addition Braccesi *et al.* (1966*c*) have presented some preliminary results. The interpretation of the number-counts has been discussed by Clarke, R. W. *et al.* (1963), Scott (1963), Davidson and Davies (1964*a*, 1964*b*), Scheuer and Shakeshaft (1964), Sciama (1964*b*, 1964*c*), Davidson (1966), McVittie and Schusterman (1966), Sciama and Saslaw (1966) and, in most detail, by Longair (1966*a*) who has used a digital computer to derive distributions of sources having luminosities and red-shifts chosen to reproduce the observed source counts, luminosity distribution and integrated sky brightness (see also Zasov 1966). It is clear that geometrical effects do not explain the number-counts, and source evolution is important, probably of the QSS (Bolton 1966, Longair 1966*a*, 1966*b*, Roeder and Mitchell 1966, Rowan-Robinson 1966, Sciama and Rees 1966, Véron 1966*b*, 1966*c*) which, together with the 3°K black-body radiation, is a powerful argument against the original form of the steady-state theory (Hoyle 1965, Sciama and Rees 1966) if the cosmological nature of QSS is confirmed.

Other evidence on cosmology from study of sources could come from variations of radio spectra (Ko 1966) or angular diameter (von Hoerner 1964*b*) at different flux levels, but the interpretation of such observations will be even more difficult (Scheuer 1967) than that of the number-counts. In addition Sandage (1964) is making use of identified radio galaxies to determine the m–z relationship.

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F. RADIOASTRONOMICAL INSTRUMENTS

(prepared by C. A. Muller)

In the last three years a number of new radiotelescopes have come into use. General trends in the design of new radiotelescopes and in receiver techniques are higher operating frequencies and the increased use of digital techniques, including the use of on-line computers for the control of telescopes, receivers and data processing equipment. In this report we will summarize the major developments in the fields of radiotelescopes and receivers.

1. *Filled-aperture telescopes*

Several new large reflector telescopes have come into use, whose design reflects the general tendency towards increased surface accuracies and higher operating frequencies. Recently completed instruments in the U.S.A. include a 43 metre reflector (**1**) (Greenbank), a 36 meter reflector (Haystack) (**2**) and a 25 meter telescope (N.R.L.) (**3**), all having good efficiencies at centimeter wavelengths. In Canada the 46 meter reflector (**4**) at Algonquin Park, also operating at cm wavelengths has been completed, while in the United Kingdom the new Jodrell Bank Mk II (**5**) telescope with an elliptically shaped reflector, 24 by 36 meter has come into regular use.* Millimeter wavelength instruments include two 5 meter reflectors (**6, 7**) used at 3 millimeters, and an 11 meter reflector (**8**) under construction, all in the U.S.A.

*See Addendum on page 908.

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The fixed-tiltable reflector telescopes of Ohio (**9**) and of Nançay (France) (**10**) are now completed, while the Pulkovo telescope in the U.S.S.R. has been reconstructed for use at centimeter wavelengths (**11**).

New plans include a 90 meter telescope in Western Germany (**12**).

2. *Unfilled-aperture telescopes*

The clear distinctions between the various types of unfilled-aperture telescopes gradually seem to vanish, as several new instruments can be used in different modes of operation, corresponding to previously separate instruments. Examples are the compound interferometers in Japan, which also can be used as crosses (see below), the 10 cm multielement interferometer under construction at Algonquin (**4**), and the proposed eight-element telescope for Owens Valley (U.S.A.) (**13**), that includes the possible use as a total power array, as a cross, as a compound interferometer and as an Earth rotation synthesis instrument. Earth rotation synthesis has been shown to be a powerful approach to pencil-beam unfilled-aperture telescopes and is incorporated now in several new designs.

The Cambridge (U.K.) One-Mile telescope (**14**) consisting of three 18 meter reflectors, is now in full operation on 408 and 1407 MHz with beamwidths of 80″ and 23″ respectively. A similar instrument using 12 telescopes 25 meters in diameter with the same beamwidth at 21 cm is under construction near Westerbork in the Netherlands. The original Christiansen grating cross is being converted into a pair of compound interferometers, which system will give a 40″ beam at 21 cm with the use of Earth rotation synthesis (**15**). A compound interferometer that should give a 4′ beam at 200 MHz is under construction near Peking (China) (**16**). At Greenbank a two-element interferometer, using 25 meter reflectors and operating at 10 cm (**17**), has been operated as a prototype study for a very large array telescope. This interferometer is now being extended to a three element system. At Owens Valley the reflectors of the two-element interferometer have been resurfaced for better efficiency at 10 cm (**18**). A 40 meter reflector is being added to the system.

The large cross telescopes near Kkarkov and Serpukhov (**19, 20**) in the U.S.S.R., near Medicina (Italy) (**21**) and near Canberra (Australia) (**22**) are now nearing completion and in partial operation. Low frequency cross arrays operating on 10 and 22 MHz have been built near Penticton (Canada) (**23**). A 500 meters long reflector similar to one arm of a cross is under construction in India, which instrument will be used primarily for lunar occultation studies, operating at 240 MHz. Descriptions have been published for the Clark Lake decametric array (**24**) and a radar astronomy array operating in the range 20–55 MHz (**25**), both in the U.S.A.

The solar ring telescope (**26**) near Culgoora (Australia), consisting of 96 reflectors 13 meters in diameter arranged in a ring 3 kilometers in diameter, is expected to be completed during 1967.

New telescopes for solar observations in Japan include the enlarged compound interferometer at Toyokawa (**27, 28**), which has a 21″ fan beam on 3 cm, but which also can be operated as a T-shaped interferometer with a 1·5′ pencil beam. A similar instrument is under construction for a wavelength of 8 centimeter, while at Mitaka an eight-reflector grating interferometer with a 4′ beam at 17 GHz is being built. Plans exist for a large grating interferometer at 160 MHz at Nobeyama with either a 1·5′ fanbeam or a 4′ by 10′ pencil beam (**29**).

A long-baseline interferometer has been operated in the United Kingdom between Jodrell Bank and Malvern at 21 and 11 cm wavelength with satisfactory phase stability (**30**). Very-long-baseline experiments will be undertaken in Canada and in the U.S.A., using completely separate receivers with atomic frequency standards as local oscillators and intermediate-frequency videotape-recording and correlation between the recorded signals with a large

computer. The Canadian project will use a 3000 kilometer baseline between Algonquin and Penticton and will operate at 448 MHz (**31**).

Equipment for absolute flux density measurements using standard horn antennas is in use at Greenbank (**32**), in Canada and in Japan, the latter being used for solar flux measurements at 1000, 2000 and 3750 MHz (**33**). A new method for gain calibrations of large reflectors (**34**) using an artificial satellite, has been used for calibration of a 20 meter reflector in Japan.

3. *Receivers*

The use of low-noise receivers with masers, parametric amplifiers and tunnel diode amplifiers has further increased. A survey of the use of these amplifiers has been made recently by Robinson (**35**). Descriptions of receivers using maser amplifiers (**36, 37, 38, 39, 40, 41**) or parametric amplifiers (**42, 43, 44**) have been given by several authors. In Australia a solar spectrograph using an up-converter (**45**) as a first stage is in regular use. A new multichannel high sensitivity spectrograph is under construction in the Netherlands (**46**).

Important advances have been made in the techniques for accurate antenna temperature measurements as has been shown by the recent observations of a weak isotropic component in the cosmic background radiation in the U.S.A. (**47, 48**) and the United Kingdom (**49**).

A number of multichannel receivers is in use for H- (**50**) and OH-line (**51**) observations. Some H-line receivers use autocorrelation techniques for determining the spectral distribution either in analog (**52**) or in digital form (**53**). A 20-channel receiver (**54**) for the Nançay telescope uses correlator channels.

In Italy several articles have been published on the design of the receiver system (**55, 56, 57, 58**) for the large Bologna cross. In Canada studies have been made on several types of phase comparator systems (**59**) for use in large arrays. In the U.S.A. a discussion of the problems of polarization distribution measurements (**60**) has been published.

A description has been given of the receiver system operating between 0·7 and 3·5 MHz (**61**), used in the satellite Ariel II.

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