Twenty-five years of radio astronomy at TIFR

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STARTING from the serendipitous discovery by Karl Jansky in 1930 that our galaxy, the Milky Way, is an intense source of radio waves, the science of radio astronomy has continued to make spectacular advances, unravelling a chain of extraordinary phenomena that have provided new insights into the nature of our Universe. In fact there is almost no branch of astronomy today that has not benefitted from observations made through the 'radio window'. Much of this success can be attributed to the continued development of a variety of radio telescopes, instrumentation and techniques leading to a million-fold improvement in the sensitivity and angular resolution of radio observations since the early pioneering work by Karl Jansky and Grote Reber.

The Radio Astronomy Group of TIFR, established in 1963, has taken an active part in the growth and development of this exciting field. In the next section we briefly describe the antennas and instrumentation built by the group to carry out radio astronomical research. Subsequent sections present some highlights of the group's work, which spans a considerable variety of topics in both galactic and extragalactic radio astronomy.

Telescopes and instrumentation

A grating interferometer

As a first step, a grating-type radio interferometer was set up in 1965 at Kalyan near Bombay for observing the Sun at a frequency of 610 MHz. The interferometer[1] consisted of 32 parabolic dishes of 1.8 m diameter each; 24 of them were placed along a 630-m east–west baseline and eight along a 256-m north–south baseline, giving an angular resolution of 2.3×5.2 arcmin^2. The telescope was used for studying the quiet and active regions of the Sun during 1965–68. It was found[2] that the quiet Sun shows considerable limb-brightening at 610 MHz and that the solar corona has a temperature of $\sim 10^6$ K.

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The Ooty Radio Telescope

The next major development was the construction of the Ooty Radio Telescope[3] (ORT), which was commissioned in 1970. In the early sixties the debate between supporters of the big-bang and steady-state models of the Universe was at its peak. Martin Ryle and his colleagues at Cambridge supported the big-bang model because the counts of radio sources in the Cambridge surveys were inconsistent with the steady-state model. As the fainter sources were required in this interpretation to be farther away, they were also predicted to have smaller angular sizes than the brighter ones; but suitable data for this simple test were not available. It had also been realized (Hoyle[4]) that the dependence of the observed angular size of a standard radio source on redshift could provide an independent test of cosmological world models. One of the principal objectives of the telescope, proposed by G. Swarup in 1963, was to determine the structures and sizes of hundreds of weak radio sources with high angular resolution in order to carry out such cosmological studies. It was to be specially designed to take full advantage of India's proximity to the geographical equator and to exploit the technique of lunar occultation, which had then recently been shown to yield high angular resolution (Hazard[5]).

The ORT consists of a parabolic cylinder, 530 m long × 30 m wide (Figure 1). The reflecting surface is made of 1100 stainless steel wires, each 530 m long and 0.38 mm in diameter. This surface is supported by 24 parabolic frames (Figure 2) placed 23 m apart. The unique feature of the telescope is that its long axis is aligned in the north–south direction along a hill with a natural slope of about 11°, which is equal to the latitude of the observatory. This enables ORT to track a celestial object for about 9.5 h every day by rotation of the telescope mechanically in the east–west direction about its long axis. The pointing in the north–south direction is achieved by electronic phasing of the 1056 dipoles placed along the 530-m-long focal line of the parabolic reflector. A useful declination range of ±40° can thus be covered.

The telescope operates in a band centred on 326.5 MHz ($\lambda = 92$ cm). The signals picked up by the dipoles are combined with suitable phase shifts to form 12 independent beams. Each beam has a half-power width of 2 degrees in the east–west direction and

Figure 1. The Ooty Radio Telescope

Figure 2. A close-up view of one of the 24 parabolic frames of the Ooty Radio Telescope

5.6 arcmin in the north–south direction, the north–south separation between adjacent beams being ∼3 arcmin. In the correlation mode, the beams produced by the north and south halves of the telescope are multiplied to produce a system that is less susceptible to receiver drifts or interference. ORT has an effective collecting area of about 8000 m^2, which is equivalent to a 138-m parabolic dish with an aperture efficiency of 60%. The system temperature is about 300 K. It is among the largest steerable telescopes in the world and was designed and fabricated fully indigenously. In recent years, the sensitivity of the dipole array has got degraded by a factor of more than two owing to corrosion problems. A new feed system, with a Gas-Fet RF amplifier behind every dipole, followed by a 4-bit PIN-diode phase-shifter, is to be installed by 1992 to restore the original aperture efficiency but with a much reduced system temperature (∼150 K).

Over the 20 years of its operation, many interesting and significant results have been obtained using ORT. Besides establishing the evolution with cosmic epoch in the properties of radio galaxies and quasars, the large collecting area of ORT has been exploited for studying a variety of other types of radio sources and phenomena such as pulsars, supernova remnants, interplanetary and interstellar scintillations; for search for protogalaxies, protoclusters and interstellar deuterium line, as well as for Very-Long-Baseline Interferometry (VLBI).

The Ooty Synthesis Radio Telescope

In order to routinely make two-dimensional images of radio sources an aperture synthesis telescope was built at Ooty in the early eighties using ORT as one of the main elements[6,7]. A synthesis telescope consists of a number of antennas; its angular resolution is given by $\sim\lambda/D$, where λ is the wavelength of observation and D is the separation between the farthest pair of antennas. The projected separation between any two antennas, as seen by the source, changes continuously as the Earth rotates. Tracking of a radio source thus amounts to 'filling in' the aperture and enables one to make reliable images of celestial objects with good sensitivity and resolution. Several powerful synthesis arrays have been built in the UK, the Netherlands, the USA, and recently in Australia. The Very Large Array (VLA) in the USA, consisting of 27 dishes of 25-m diameter placed at baselines of up to 35 km length, is among the most powerful instruments of this kind and has provided a wealth of astronomical data over the last decade.

At Ooty, the synthesis radio telescope was built by installing seven small and inexpensive parabolic cylinders of size 22 m × 9 m at distances of up to 4 km from the ORT. The pointing of these cylinders in both east–west and north–south directions was controlled from the central observatory by means of radio-telemetry. In order to achieve a wide field of view of 2° by 40′ arc, ORT was itself divided into five sections and the signals received from the 12 antennas were mutually combined to form a total of 66 interferometer pairs. The resulting image had a resolution of about 1 arcmin at 327 MHz. The array, known as the Ooty Synthesis Radio Telescope (OSRT), was used for studying many galactic and extragalactic radio sources. Its operation has been discontinued recently so that the group may concentrate on the much more challenging Giant Metrewave Radio Telescope (GMRT) now under construction near Pune. GMRT will be the world's largest radio telescope operating at metre wavelengths (see page 95, this issue).

Image processing

An important reason for the spectacular success of aperture-synthesis interferometry in the last two decades has been the development of sophisticated image-processing techniques (Perley *et al.*[8]; also ref. 9 for an earlier review) that have made it possible to make quality images of radio sources with high dynamic range in spite of the unavoidable presence of instrumental errors and wave-front distortions introduced by irregularities in the Earth's atmosphere. With the aim of making a variety of sophisticated astronomical software developed at leading observatories available to many users in the country, an Image Processing Centre has been set up at Ooty[10] as a national facility under the aegis of the Department of Science and Technology, Government of India.

Extragalactic radio sources

Radio galaxies and quasars are among the most energetic discrete objects known in the Universe. Most of the optical and UV radiation emitted by ordinary galaxies arises from the hot surfaces of the billions of stars that constitute a typical galaxy. Stars, however, make a negligible contribution to the radio radiation emitted by galaxies, most of which arises in the vast tenuous medium between the stars or in gigantic twin lobes of relativistic plasma and magnetic fields emitting nonthermal synchrotron radiation on either side of a galaxy (Figure 3). Some elliptical galaxies emit radio waves with a million times more intensity than typical spiral galaxies like our own Milky Way. Such powerful radio emitters (referred to by astronomers as 'radio galaxies' in contrast to the less powerful 'normal galaxies') can have a power output exceeding 10^{45} erg sec^{-1}, comparable to or even exceeding the total light output. Astronomers generally agree that this prodigious amount of energy is derived from the gravitational binding energy of a supermassive black hole (10^8 or 10^9 $M_\odot$) in the nucleus of the galaxy and is channelled into the twin radio lobes through narrow beams or jets. Such jets have actually been seen in many radio galaxies and quasars. Quasars (or, quasistellar radio sources) are often even more spectacular in their radio and optical radiation. Unlike radio galaxies, the optical appearance of quasars is usually compact and starlike, which of course is the reason they were so named. They are now known to be the bright compact nuclei of otherwise normal galaxies.

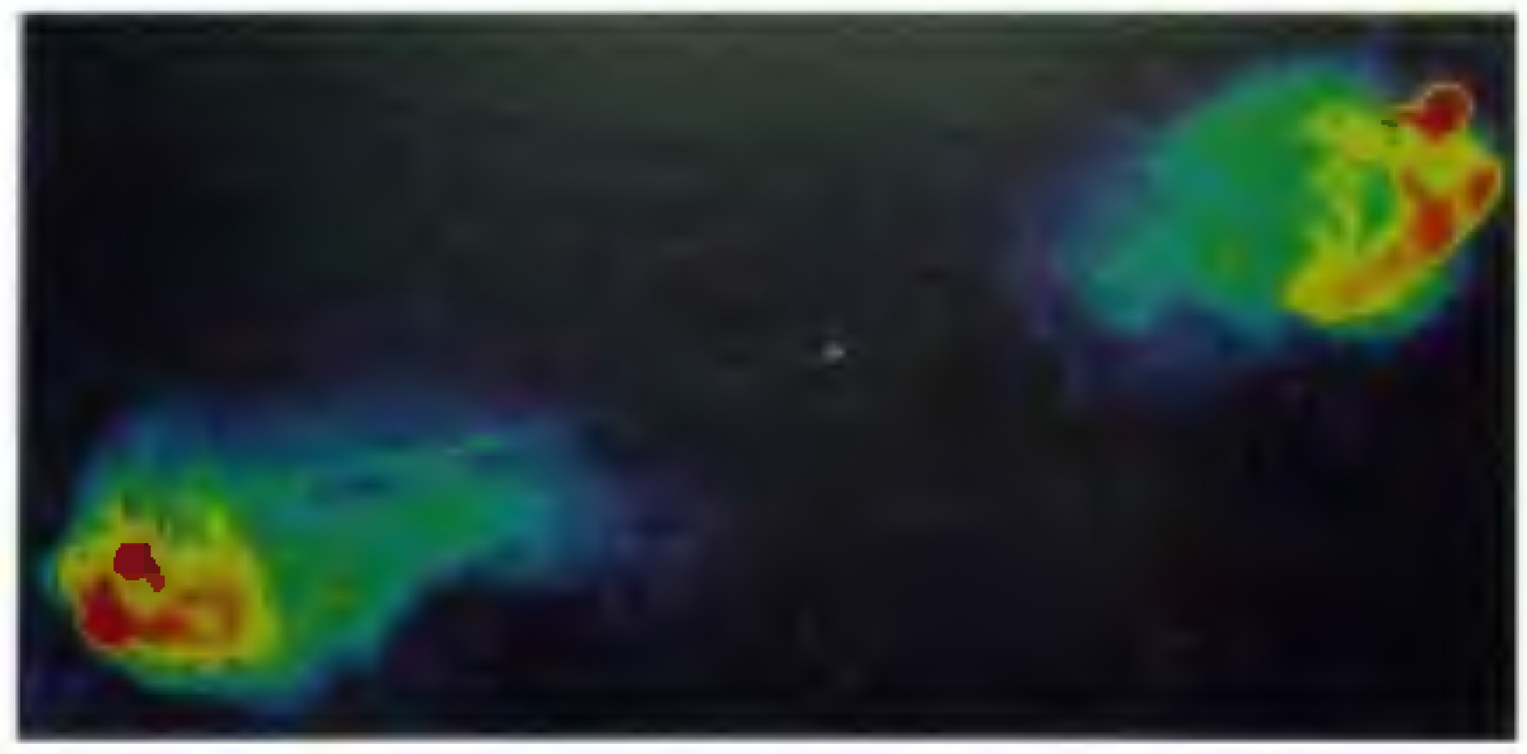

Figure 3. Radio image of well-known radio galaxy Cyg-A from VLA observations at 20-cm wavelength. [Courtesy: NRAO/AUI. Observers: P. Scheuer, R. Laing and R. Perley]

The most distant known radio galaxies and quasars have redshifts approaching 4 or 5, implying that the radiation being received from them now actually orginated a long time ago in the past when the Universe was only about 10% of its present estimated age of 15–20 billion years and had expanded to only a fraction of its present size. Because of these enormous look-back times, radio galaxies and quasars play a very important role in probing the overall structure and evolution of the Universe. We highlight below some salient contributions of TIFR's Radio Astronomy Group towards understanding the structure and evolution of radio sources, and in the field of observational cosmology.

Lunar occultations and brightness distributions

One of the first observational programmes undertaken with ORT was a survey of the Moon's path in the sky using the method of lunar occultation[11,12]. The survey was highly successful, yielding accurate positions and brightness profiles for about a thousand weak radio sources (ref. 13 and other references therein) with resolutions of about 1 to 10 arcsec at 92 cm. Such high resolutions had not previously been attained for any large sample of weak sources. The positional accuracy was sufficient to make reliable optical identifications on the Palomar Sky Survey prints, which is essential for estimating the distances of the radio sources. Besides enabling investigations of the physics of radio sources, this unique database was used to establish, for the first time, a correlation between their angular sizes and flux densities[14] which led to the important inference of evolution in physical sizes with cosmic epoch[15] (see section on observational cosmology).

While the occultation survey mostly included previously uncatalogued radio sources, predicted occultations of several well-known strong radio sources were used to compare the obtained brightness distributions at 92-cm wavelength with those available from aperture-synthesis maps at much shorter wavelengths (Figure 4). These were among the first detailed comparisons of radio structures over a large (>10:1) baseline in wavelength[16,17] and furnished the earliest examples of large double radio sources in which the diffuse features, believed to be filled with energy-depleted electrons, did not show the anticipated brightening towards metre wavelengths.

Fine structure of radio sources

Another major programme started soon after the completion of ORT was to observe interplanetary scintillations fluctuations (IPS) in the intensity of distant radio sources caused by electron-density irregularities in the interplanetary medium (solar wind). Such observations made at different solar elongations provide valuable information both on the properties of the medium and on fine structure (< 0.5 arcsec) in radio sources[18]. Scintillation observations of 3C33, a large double radio galaxy, when combined with occultation observations, provided unambiguous evidence[19] for very compact (< 1 kpc) 'hot spots' at the extremities of the twin lobes, highlighting the need for extremely tight collimation of the energy supply from the nucleus. Scintillation studies of hundreds of sources[20,21] were used to conclude that a large fraction of all powerful radio sources had a significant fraction of their flux density arising in such compact (< 0.5 arcsec) features. Statistically, the 'scintillation visibility' appeared to increase with decreasing source flux density as well as overall angular size of the source[22], which could be interpreted in terms of greater distance of the weaker sources. This also led to doubts about the validity of the conclusion from some earlier work at Cambridge, using IPS observations at 81 MHz, that hot spots at large redshifts rarely had a size smaller than about 0.3 arcsec. The Ooty work showed that Cambridge estimates of the sizes of scintillating components were likely to be affected by blending of different physical features in the radio lobes with increasing redshift[22].

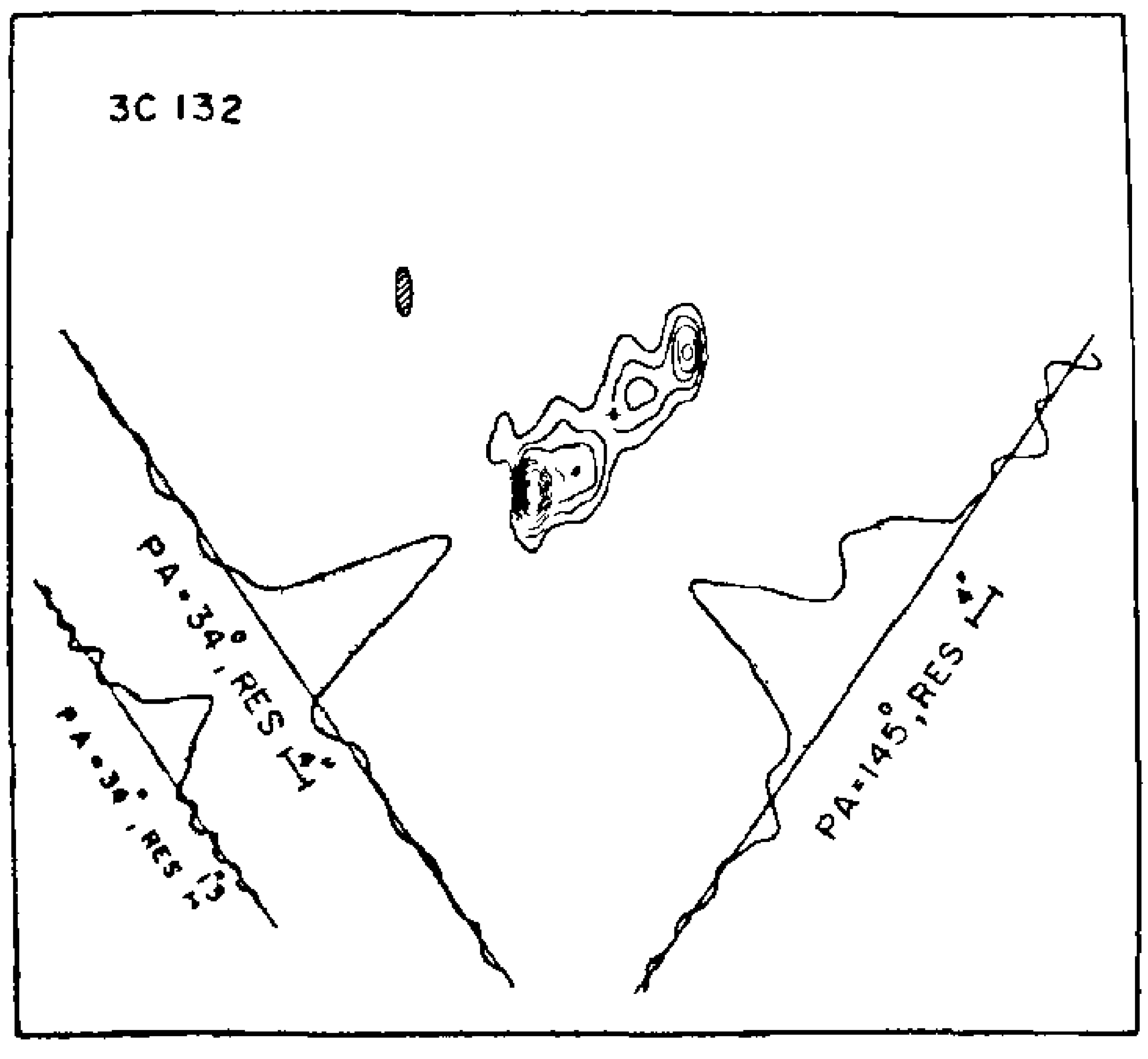

Figure 4. Brightness profiles of 3C132 along two position angles, obtained from lunar occultations at 327 MHz at Ooty, compared with those (dotted lines) derived from an aperture-synthesis map (shown as contours) at 5 GHz from Cambridge. Taken from ref. 17.

More direct estimates of the angular sizes of hot spots in a sample of 3CR radio sources at large redshifts were subsequently obtained in an important VLBI experiment[23] (using the Effelsberg 100-m dish in Germany and the 12 dishes of the Westerbork Synthesis Array in Holland) which showed that compact hot spots (sizes ≤ 0.15 arcsec) were fairly common in distant radio galaxies and quasars.

Detailed radio images of a large number of quasars, made with the VLA of the National Radio Astronomy Observatory* in the USA, were also used to infer many of their physical parameters and to show[24] that there was no significant dependence of hot spot sizes on either redshift or radio luminosity but the relative strength of the hot spot appeared to increase with radio luminosity. On the theoretical side, a physical explanation within the framework of the beam model was proposed[25] for this luminosity dependence.

While occultation and scintillation observations at Ooty provided valuable structural information, it was important to augment these studies by employing other instruments and techniques covering different parts of the spectrum. Several theoretical, observational and interpretational studies were undertaken to examine key questions concerning radio sources. Some of these are highlighted below.

Compact steep-spectrum sources

Till the late seventies it was generally believed that steep-spectrum radio sources—the kind found in low-frequency radio surveys—had an extended double structure while flat-spectrum sources (found in large numbers in high-frequency surveys) were compact (< 1 arcsec). Attention to a significant class of compact but steep-spectrum sources was first drawn[26] when high-resolution observations with the Westerbork Array of a complete sample from a 5-GHz survey showed that nearly 30% of the steep-spectrum population had a compact structure. The much lower incidence of such sources in low-frequency surveys was attributed to a

*The National Radio Astronomy Observatory and VLA are operated by Associated Universities Inc. (AUI) uner contract with the US National Science Foundation.

turnover in their spectrum at a few hundred MHz. This class of sources[27] is currently being actively studied at many leading observatories, including by the TIFR group, which has compiled and is studying a large number of the related and important class of 'gigahertz-peaked-spectrum' sources[28,29].

Comparison of carefully selected samples has recently shown[30] that the incidence of compact steep-spectrum sources increases rapidly with redshift and does not have a strong dependence on radio luminosity. Theoretical studies indicate[31] that this could be related to an enhancement in the beam efficiency and to a stronger confinement in a denser interstellar medium resulting from galaxy interactions and mergers which are likely to have been much more common at earlier epochs.

Relativistic motions in active galaxies and quasars

Among the outstanding developments in extragalactic astronomy in the seventies and eighties have been the discovery of radio jets on scales of parsecs to hundreds of kiloparsecs in many radio galaxies and quasars[32], and the recognition of the importance of relativistic beaming in these jets[33,34]. If the radio jet is aligned close to an observer's line of sight, its flux density gets Doppler-boosted by a factor of $\sim\gamma^3$ for the case of a relativistic plasma cloud moving with a bulk Lorentz factor γ. Many of the properties of core-dominated flat-spectrum quasars, such as the apparent 'faster-than-light' or superluminal motion, rapid flux variability, weak X-ray emission and misalignment of the VLBI and large-scale structure, can be understood if their nuclear radio jets moving with relativistic speeds are inclined at small angles to the line of sight. This also raised the possibility that core-dominated (flat-spectrum) as well as lobe-dominated (steep-spectrum) quasars could be intrinsically similar, differing in their apparent properties mainly on account of the different orientations of their jet axes with respect to the observer.

Some of the earliest tests to verify the possibility of such a 'unification' of different types of quasars and radio galaxies were carried out by the TIFR group using large samples of radio sources[35–38]. It was found that core-dominated quasars had smaller projected linear sizes and more misaligned radio structure[38,39], consistent with the predictions of the relativistic beaming model and the 'unified scheme' as developed independently by Orr and Browne[40] based on the observed fractions of flat-spectrum quasars in surveys at different frequencies and flux levels. The redshift distributions of nearly complete samples of flat- and steep-spectrum radio sources were also found to be consistent[41] with the 'unified scheme'. The lack of preferred orientation of the radio polarization vectors found for the core-dominated sources is also consistent with small inclination of their jets to the line of sight[42,43]. Further evidence comes from the recently observed anti-correlation of both optical and X-ray equivalent width of the (O III) emission line in quasars with the degree of dominance of the radio core[44]. Relativistic motion is also suggested[45] by the recent finding that the spectral turnover occurs at ~1 cm for the cores of extended quasars but only at ~1.5 mm for blazars in which the jets are likely to be strongly beamed towards us. Evidence has also been presented[46,47] for an aspect dependence of the optical/UV continuum emission of quasars, which implies that nearly all available optical magnitude-limited samples of radio quasars are likely to be biased with regard to the orientation of their jet axes.

As inferred from many statistical tests[30,40,41,48], the unified scheme for radio quasars requires the bulk Lorentz factor γ of the jet material to be ~5. It has been suggested recently[49] that both radio galaxies and quasars should be included in an enlarged unified scheme in which they are all intrinsically similar, objects with small viewing angles (<45°) being seen as quasars and those with larger viewing angles as radio galaxies. The compact nonthermal activity and the broad line clouds are hidden from our view in the case of radio galaxies by an obscuring torus in a plane perpendicular to the direction of the twin jets. There are many arguments in favour of such a scheme, including the much weaker radio cores in radio galaxies compared to quasars[50] and the larger lobe misalignments in quasars[51], although some problems related to the redshift and size distributions of quasars and radio galaxies remain unexplained[51]. Because of the much smaller ratios of core to extended emission observed in galaxies compared to quasars, unification of the two requires the typical values of γ to be a factor of 2.5 times larger[50] than inferred from earlier tests. Typical observed values of the apparent superluminal speeds in core-dominated quasars then support a value of the Hubble constant that is closer to 50 than to 100 km sec^{-1} Mpc^{-1}.

Asymmetries in double radio sources

Although radio lobes in nearly all quasars and radio galaxies are seen on both sides of the nucleus, the lobe intensities and the separations of their hot spots from the nucleus often show a certain amount of asymmetry. In spite of intrinsic symmetry, the hot-spot separations can appear unequal if the two hot spots are being viewed at different ages owing to the different light travel times to the two sides. The effect becomes increasingly important for large advance speeds of the hot spots and small orientation angles to the line of sight. This model was first employed to derive analytically the distribution of hot-spot velocities[52,53] which are about 0.25 c, as well as to make a statistical estimate of the orientation of the radio axis in space, needed for testing the beaming model[54,38,55]. It has been argued, however, that other effects, such as a difference in the density of the medium on the two sides[53] or a jet ejection mechanism that flip-flops alternately on the two sides[56], may in fact be responsible for the asymmetry. The recent finding[57] that, in nearly all radio galaxies for which data are available, the closer of the two hot spots lies on the same side of the nucleus in which the extended optical line emission has a higher surface brightness, appears to provide the first direct evidence that lobe distance asymmetries are intrinsic in nature, being caused most probably by density inhomogeneities of gas on the two sides of the nucleus[53].

An extreme form of asymmetry is exemplified by the well-known quasar 3C273 in which even the supposedly isotropic lobe emission is seen only on one side of the nucleus. One possibility is that the source is so young and expanding so fast nearly along the line of sight that its receding jet may not yet have formed the lobe until the time of its being viewed currently[58]. As expected such sources are rather rare and are usually accompanied by prominent radio cores, underscoring the importance of relativistic effects in them[36,59]. Nonetheless, a few one-sided sources have indeed been found[60] with surprisingly faint core emission, and are hard to understand in the beaming models.

Radio-intensity variations in quasars

A 3-year flux monitoring programme at 327 MHz carried out at Ooty using OSRT has provided fresh support[61] for an 'extrinsic' origin (possibly due to refractive interstellar scintillations) of the metre-wavelength variability. A 'superluminal microlensing' model has recently been proposed[62] to explain the new finding of ultra-rapid variations (with day-like time-scales) at centimetre wavelengths[63]. The variations in this model arise as a result of the emission knots in a relativistic jet being observed to move superluminally across stars of an intervening galaxy and getting microlensed by them. The same basic model may also explain (see article by Gopal-Krishna, page **117**, this issue) metre-wavelength variability on time-scales of a few years in terms of refractive scintillations caused by irregularities in the intergalactic plasma, possibly associated with intervening cluster cooling flows.

Some interesting individual objects

Discoveries of particularly exciting phenomena in individual objects serve as a vital stimulant for the metabolism of any research team and some such cases are mentioned below.

The gravitational lens 1830–21. This uniquely bright pair of flat-spectrum radio knots separated by just 1 arcsecond was discovered serendipitously in the course of a Galactic plane survey[64], and can be best understood as the core of a distant radio source being lensed by an intervening galaxy[65] (Figure 5).

The giant radio galaxy 0503–28. This giant, with a size of 2.5 Mpc, is the largest known radio source in the

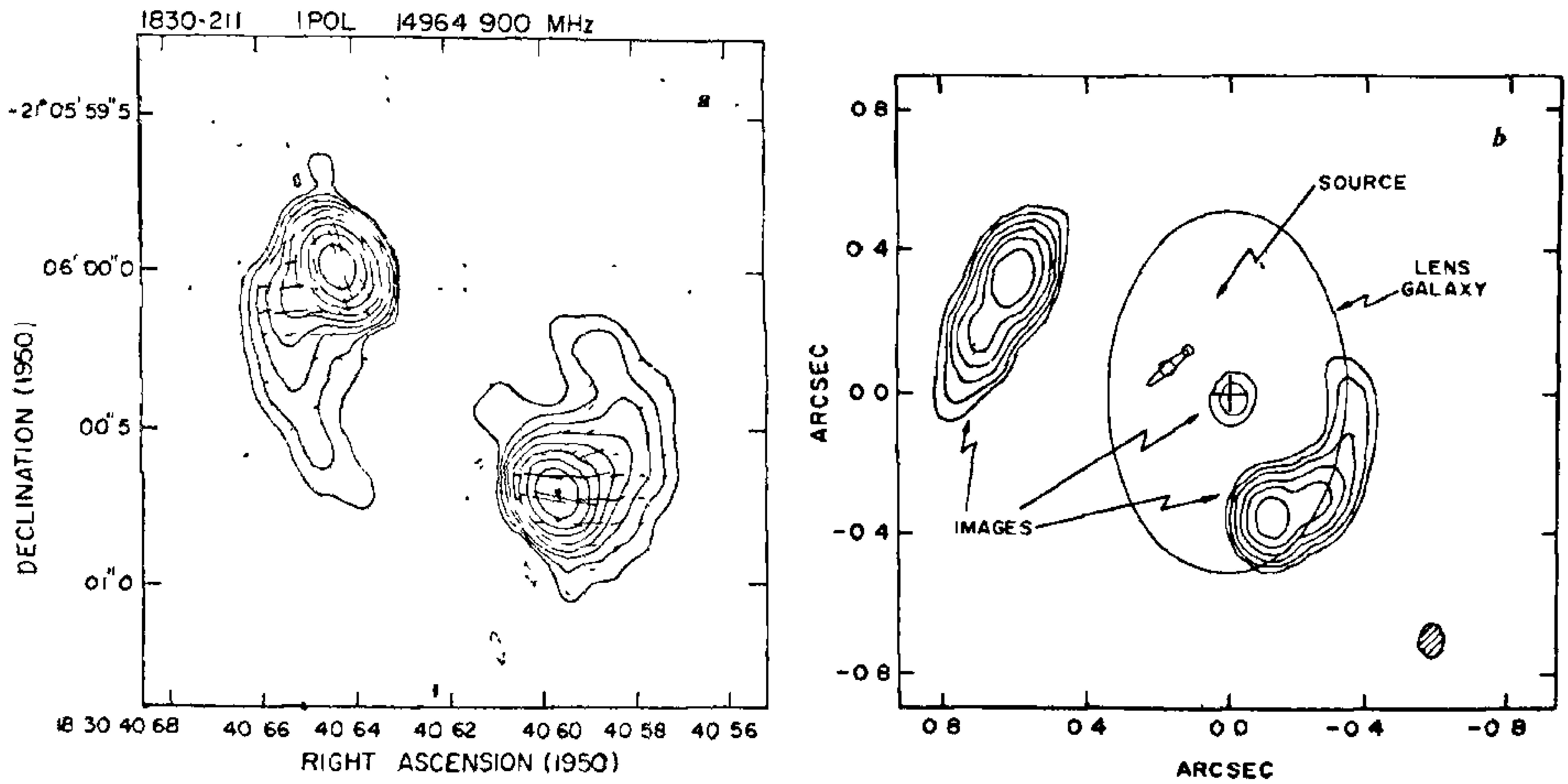

Figure 5. The gravitational lens 1830–211 (*a*) 15-GHz contour map obtained with VLA, and (*b*) the computed image of a core-jet source lensed by an intervening galaxy. Taken from ref. 65.

southern hemisphere, and was discovered independently by different members of the group working with OSRT[66] (Figure 6) and the Molonglo Synthesis Telescope[67] in Australia. A systematic study of giant radio galaxies has revealed some remarkable characteristics of this rare class of objects[66,68].

An ultra steep-spectrum source in Abell 85. As part of an extensive study of clusters of galaxies, an ultra-steep-spectrum radio source without any obvious optical counterpart was discovered in the cluster Abell 85 (Figure 7). The extremely steep radio spectrum of this object ($\alpha \sim -3$) probably reflects the prolonged confinement of the relativistic plasma by the hot X-ray-emitting intracluster medium[69].

Centaurus A. This well-known nearest radio galaxy appears to show direct evidence of a radio jet being deflected upon encountering a galaxy shell and forming a radio lobe[70].

The halo of the edge-on spiral NGC 4631. The variations of the high- and low-frequency radio spectra with increasing distance from the plane of this spiral galaxy were found to be distinctly dissimilar[71]. This has brought out the role of both diffusion and convection of electrons out of the plane of the galaxy[72]. A similar dynamic halo may exist also in the spiral galaxy NGC 4666 (ref. 73).

The Ooty VLBI programme at 327 MHz

An intercontinental network of antennas is necessary to achieve milliarcsecond resolution at metre wavelengths. A series of global VLBI observations including the ORT was initiated[74] in 1983. Apart from its large collecting area, ORT is geographically well situated for obtaining long north–south baselines, which cannot otherwise be attained by combining antennas in Europe and the USA. The other telescopes involved in the experiments are located in Germany, Holland, England, the Soviet Union and Poland (later joined by the Chinese). An atomic frequency standard together with a Mark-II recording system using commercial video tapes was used. The signals were intercorrelated at the Max-Planck-Institut für Radiostronomie in Bonn. A large number of flat-spectrum radio sources were observed[75] with baselines ranging between 0.2×10^6 and 7×10^6 wavelengths. Nearly all were found to be resolved at the longest baseline. The visibility coverage was just adequate to map two well-known sources, NGC 1275 and 3C237, though sizes of several other sources could be determined at 327 MHz, including 1148-00, which is found to be smaller than 12 milliarcsec.

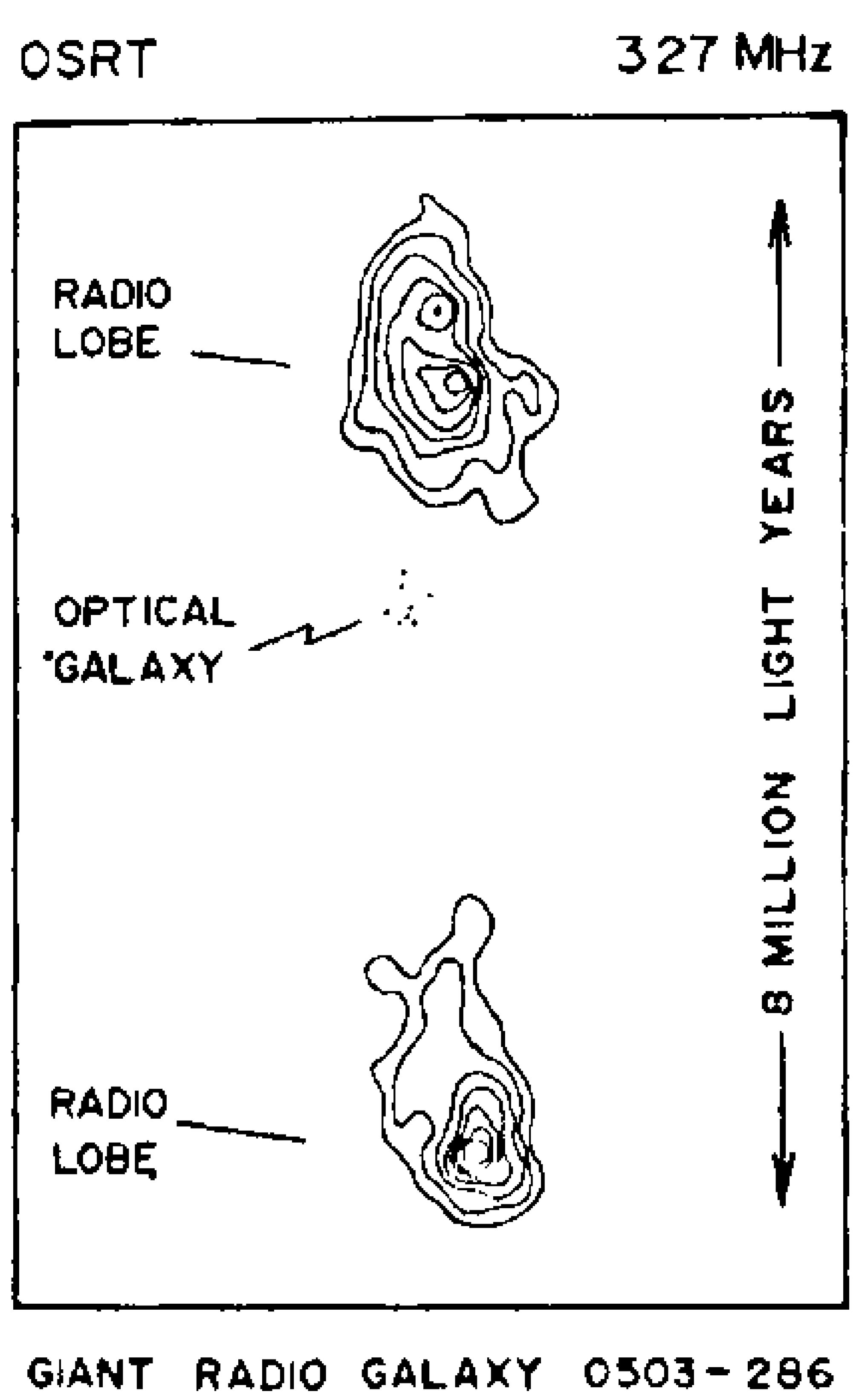

Figure 6. A 327-MHz map of the giant radio galaxy 0503–286 from Ooty Synthesis Radio Telescope. Adapted from ref. 66.

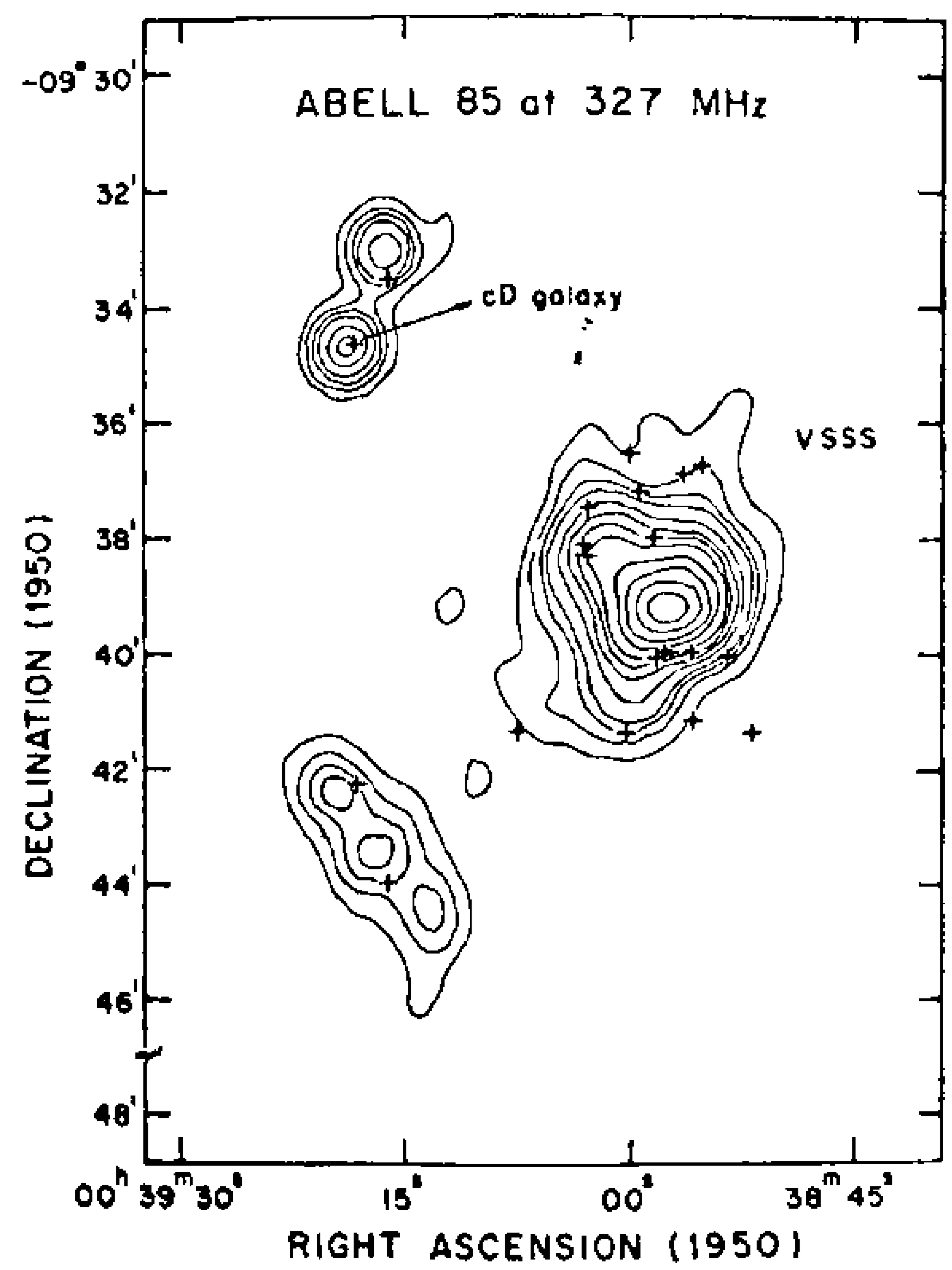

Figure 7. The very-steep-spectrum source in the rich galaxy cluster Abell 85 observed using OSRT at 327 MHz. Observers: J. Bagchi and M. N. Joshi.

Observational cosmology

Right from the early days of radio-source counts at Cambridge, radio astronomy has been a very important tool in observational cosmology. The discovery of microwave background radiation by Penzias and

Wilson in 1965 provided further key evidence in favour of the big-bang model for the origin of the Universe, which is also capable of accounting for the observed abundances of light elements in space. Recent advances in particle physics have provided new insights into the earliest phase of the Universe, which, according to the grand unified theories (GUTs), was marked by a unification of the electromagnetic, strong and weak nuclear forces.

Radio-source cosmology has been an active area of research in the Radio Astronomy Group of TIFR. Important contributions have been made in angular-size tests of cosmology in particular, and in modelling of the evolution of radio-source properties with cosmic epoch.

Cosmological evolution of source sizes

Although, even in the early seventies, fainter radio sources were suspected to be mostly located beyond $z>0.5$, rendering their angular sizes strongly dependent on the geometry of the Universe, the lack of CCD cameras precluded direct measurement of their redshifts. It was therefore decided to use the observed flux density as a statistical measure of distance to perform cosmological tests using angular sizes measured with the ORT from lunar occultations. This work led to the establishment of an angular size–flux density (θ–S) correlation which showed that the median angular size θ_m declines from $\sim 100''$ for strong radio sources to $\sim 10''$ for fainter ones[14]. Combining this result with the angular-size counts for stronger previously known sources, it was shown[15] that not only was the comoving number density of radio sources higher at earlier cosmic epochs but the linear sizes of the sources were also smaller. The results thus provided independent evidence against the steady-state theory of the Universe. Subsequent observations with synthesis arrays have confirmed and extended the relation and its interpretation[76]. Detailed modelling has also confirmed[77] (Figure 8) that the basic result concerning linear-size evolution is independent of the increasing contribution of compact steep-spectrum sources at higher redshifts or of any anti-correlation between linear size and radio luminosity, contrary to suggestions by some workers.

The availability of distance estimates for large samples of both bright and faint radio sources in recent years has made it possible to investigate the angular size–redshift relation directly[78] (Figure 9). Such studies have revealed a steep evolution of linear sizes l, $l \propto (1+z)^{-3}$ at least up to $z\sim 1$, as well as a mild direct dependence on radio luminosity, $l \propto P^{0.3}$ (refs. 79–83).

To understand the physical cause for the steep l–z dependence, an analytical model was developed[84,68], which invoked the propagation of jets through the hot gaseous halo of the parent galaxy and then through a

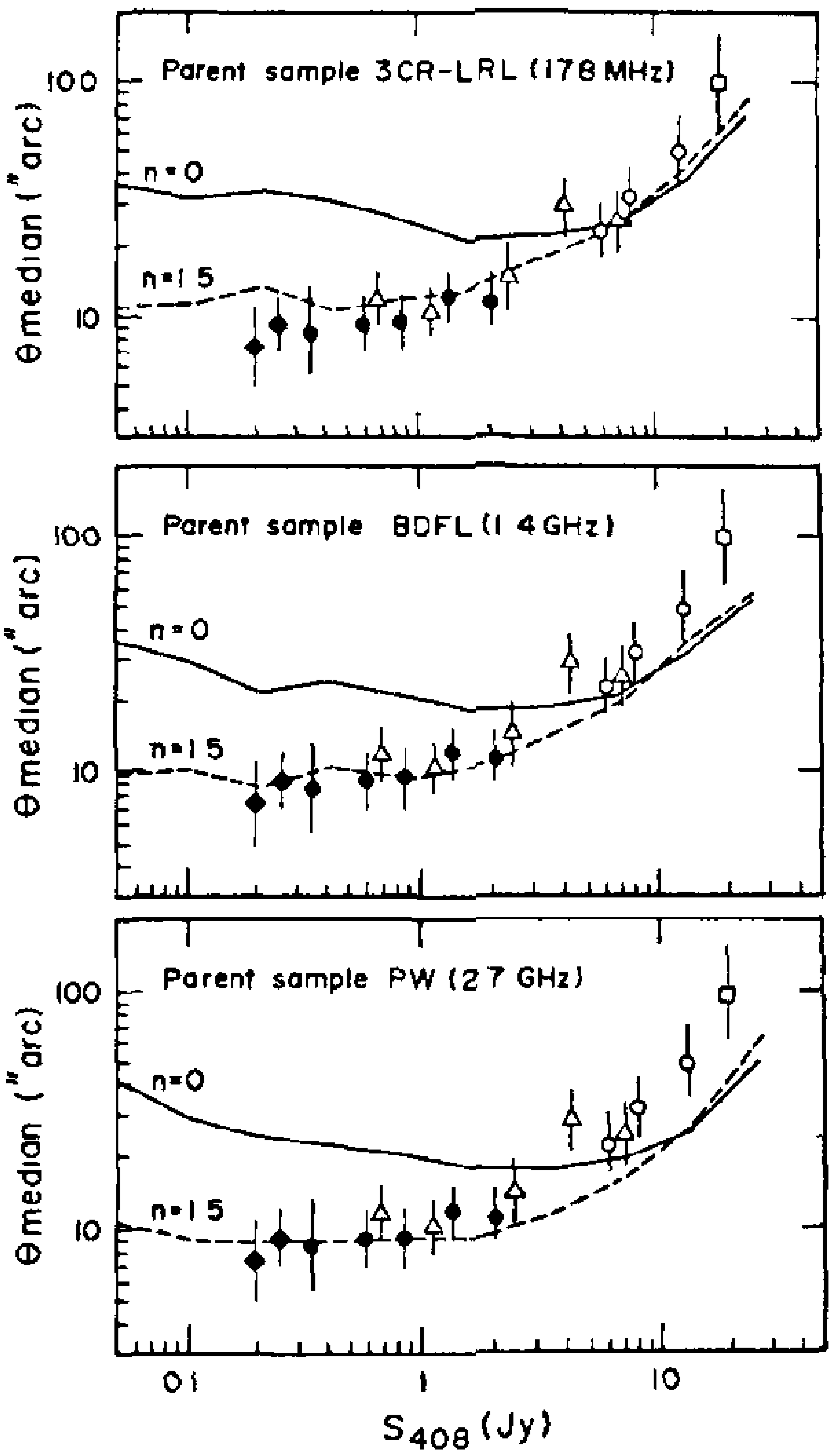

Figure 8. The observed angular size–flux density relation for extragalactic sources and predictions of an evolutionary model[93] of the radio luminosity function applied to the observed properties of strong-source samples in catalogues at three different radio frequencies. Curves marked $n=0$ correspond to the case of no evolution in physical sizes of radio sources with cosmic epoch. Taken from ref 77.

hotter, intergalactic medium (IGM). Although this model seems quite successful in reproducing the observed l–z and l–P dependences, it is now clear that the required IGM can only be intracluster gas (whose cosmic evolution is as yet poorly understood); an all-pervasive hot IGM postulated originally to explain the X-ray background appears to be ruled out by the recent COBE satellite measurements of the microwave background radiation. The X-ray background could instead arise owing to accretion of baryonic matter onto discrete potential wells on the scale of superclusters[85].

An alternative scenario is that the galaxy halos were at a higher pressure in the past, leading to smaller sources[86]. By theoretically tracing the development of the halos over the history of the Universe, it is inferred that an order-of-magnitude increase in the halo density between $z=0$ and $z=0.5$ would be needed to explain the l–z effect[87]. However, since a larger ambient density would also simultaneously boost the efficiency of

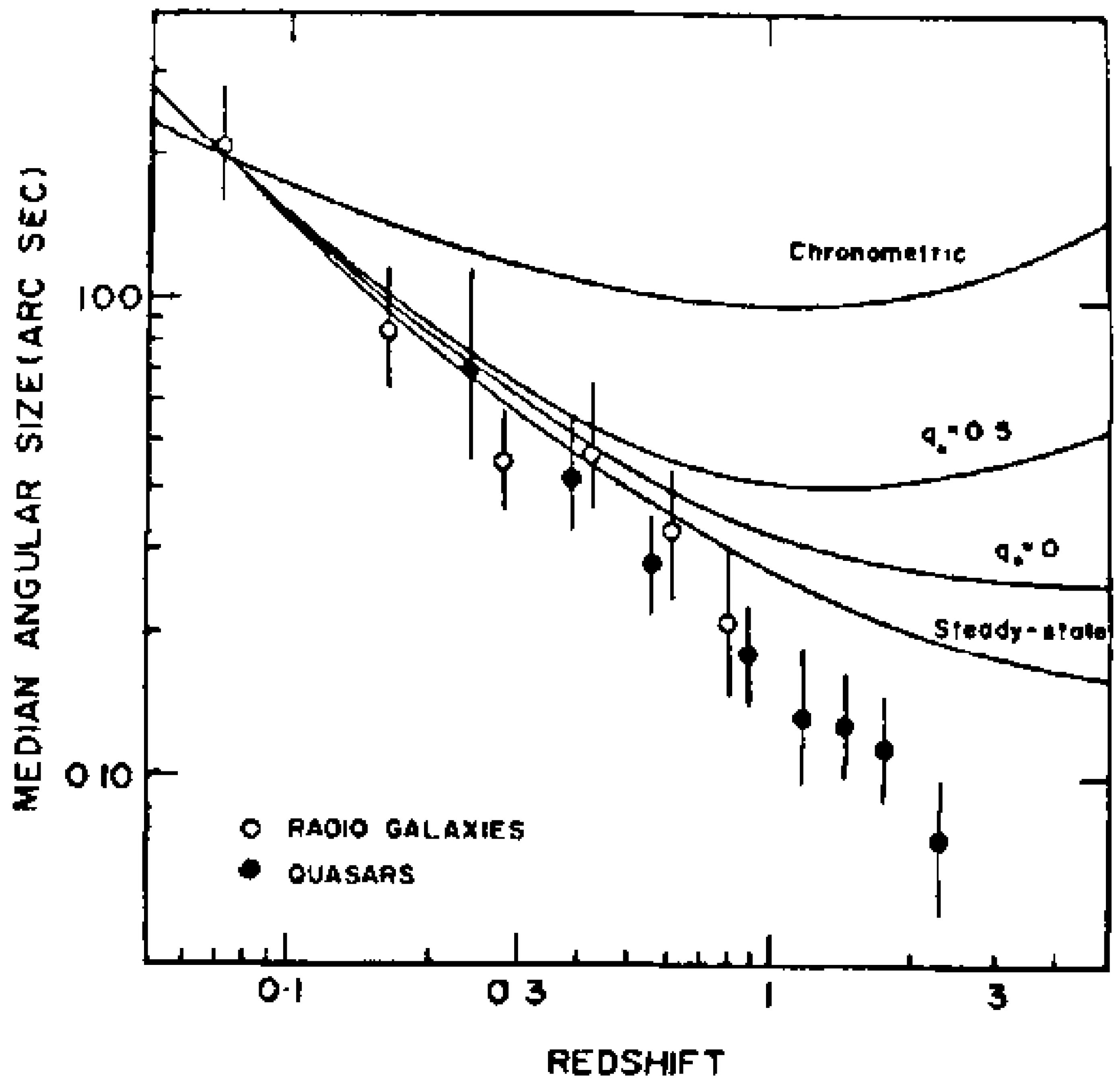

Figure 9. The observed angular size–redshift relation for radio galaxies and quasars compared with the predictions of several uniform cosmological world models. Adapted from ref. 78.

converting beam power into radio luminosity, it has been estimated[31] that only a modest scaling-up of the halo density ($\sim$3 times by $z=0.5$) would suffice to explain the observed l–z and l–P dependences.

Evolution of the radio luminosity function

The variation of the radio luminosity function (RLF, the space density of sources of different luminosities) with redshift is one of the foremost tracers of the cosmologically evolving physical conditions in the Universe. The first step in such an investigation involves the construction of a 'local' RLF which is directly measured for the nearby low-luminosity galaxies[88] but is hard to obtain for the most luminous radio galaxies; because of their low space density the latter are observed in significant numbers only at high redshifts. The variation of RLF with z is then constrained by the observed counts (Figure 10) of radio

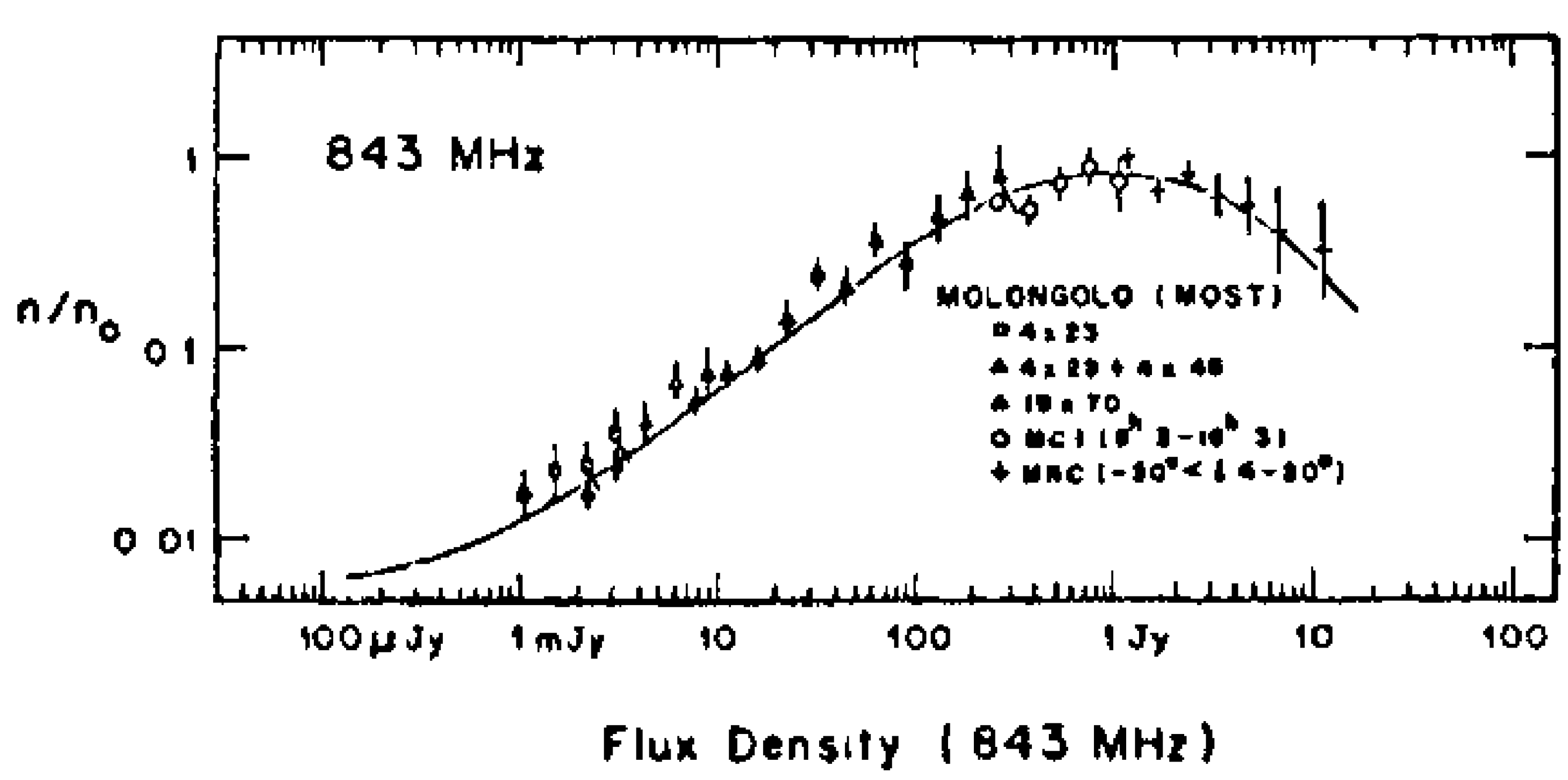

Figure 10. Normalized differential counts of radio sources obtained from source surveys at 843 MHz made with the Molonglo Synthesis Telescope[89].

sources (e.g. ref. 89) at different frequencies and flux levels as well as by the observed rates of optical identification and/or redshift distributions for different samples of radio sources[90–92]. The recent study by Dunlop and Peacock[93] has indicated that the increase in the comoving space density of luminous sources with increasing redshift tapers off, or perhaps even declines, above $z\sim2$. At least out to $z\sim1$ or 2, the inferred evolution of RLF can be described as 'pure luminosity evolution'. Such a behaviour can be quantitatively explained[94] if the gaseous halos detected around nearby elliptical galaxies from X-ray observations were denser at earlier cosmic epochs, leading to an increased 'radio efficiency'. The required order-of-magnitude density enhancement by $z=1$ is similar to that needed to explain[31] the observed decrease in linear sizes with redshifts. A common physical cause may therefore be responsible for the cosmic evolution of both the RLF and the linear sizes of radio sources[94].

A fundamental property of the local RLF is a flattening of its slope at luminosities below $P_0\sim10^{24}$ W Hz^{-1} at 1 GHz, which is also accompanied by a change in the radio morphology from being edge-brightened to being edge-darkened. Both these phenomena have been explained[94,95] by showing that the beams of sources with $P<P_0$ would get decelerated to the sound velocity of the ambient halo medium, well within the active lifetime of the central engine. The consequent decollimation would render them edge-darkened and radio-inefficient, thus flattening the RLF at $P<P_0$.

Spectral index–flux density (α–S) relation

The spectral measurements of the Ooty occultation sources, combined with several other data sets, were used to establish a statistical variation of radio spectral index with flux density for extragalactic sources found in metre-wavelength surveys[96–98]. This provides an additional constraint on the evolution of the RLF. With the availability of multifrequency flux densities and distance estimates for complete samples it also became possible to construct the α–S relation by obtaining the value of α for each source at a fixed emitted frequency in the rest frames of the sources[99,30]. Such relations have raised serious doubts about the long-held view by many that the average radio spectral index was steeper at earlier epochs.

Do the misalignments in radio quasars evolve?

Another important parameter of double radio sources that does not seem to vary with redshift[100] is the bending angle, which quantifies the deviation of the hot spots on the two sides from collinearity with the nucleus. The earlier claim that bending angle increases with redshift[101], providing evidence for a clumpier circumgalactic medium in the past, could be an artefact of inadequately matched observational parameters used for mapping low- and high-redshift quasars.

High-redshift radio galaxies

Until a few years ago, quasars were the only tool available for directly probing the Universe beyond $z>1.5$. But since the emission from their point-like cores swamps the underlying galaxy component, quasars are ill-suited for studying the cosmic evolution and kinematics of the associated stellar population. The situation underwent a major change in 1988 with the discovery of a radio galaxy at the very high redshift of 3.8 (ref. 102). Presently, over 20 galaxies have been reported at $z>2$ and roughly a quarter of them lie at $z>3$. Almost all these galaxies were originally detected as radio sources in metre-wavelength surveys; many have an unusually steep radio spectrum. Another intriguing aspect of distant galaxies is their elongated morphology at optical as well as near-infrared wavelengths, which is roughly aligned with the radio structure[103,104]. These dramatic findings have triggered intensive theoretical and observational activity in recent years as such studies are of crucial importance to understanding the era of galaxy formation.

The TIFR group has undertaken two major programmes to search for distant galaxies using samples of steep-spectrum radio sources. Together, these programmes account for roughly a third of all galaxies discovered beyond $z=2$. The first sample contains about 150 sources from a Molonglo survey of southern radio sources carried out by C. R. Subrahmanya during 1984–85. Apart from radio studies using the VLA, it is being followed up optically[105] by V. K. Kapahi and C. R. Subrahmanya with their US collaborators P. J. McCarthy and W. van Breugel, using the American telescopes at Cerro Tololo (Chile). The other sample, containing about 100 sources, is derived from a spectral survey of Ooty occultation sources carried out at Efflesberg by Gopal-Krishna and H. Steppe in 1979–80. This sample is being followed up by Gopal-Krishna and collaborators, using the ESO telescopes at La Silla (Chile) as well as the 3-metre Lick telescope. The results published so far include a galaxy found in the Molonglo sample with $z=3.13$, which is among the most distant galaxies known[105].

Although most searches for high-redshift galaxies to date have concentrated on radio sources with very steep spectral indices, the physical connection of distant galaxies with radio spectra is far from clear[30]. To probe this connection further, Kapahi and collaborators have recently taken up another Molonglo sample of about 120 sources, in which the radio spectra are not very steep, for detailed optical and radio investigation.

The deuterium abundance

As deuterium (D) is thought to have been produced in the first hundred seconds after the big-bang, a measurement of its abundance relative to hydrogen (H) is of considerable cosmological importance. Attempts were made using ORT to estimate the D/H ratio in the interstellar medium by looking for the deuterium absorption line at 327.4 MHz (due to the ground-state hyperfine transition of D) in the direction of the Galactic centre[106,107]. The observations by Anantharamaiah and Radhakrishnan[107] using ORT have led to an upper limit to D/H of 5.8×10^{-5}, only a factor of 3 higher than the optically derived ratio.

Search for primordial hydrogen

The detection of primordial HI clouds can be of vital importance to our understanding of the formation of galaxies and larger structures in the Universe. In principle it may be possible to detect HI before the epoch of galaxy formation at large redshifts ($z\gtrsim3$) by looking for the well-known line from HI at 1420 MHz which would be expected to be redshifted into metre wavelengths. The expected line strengths and width are quite uncertain and vary for different theoretical scenarios of galaxy formation[108,109]. It is therefore important to allow for a considerable variation in the parameter space while looking for the signal. Two complimentary searches for HI at $z=3.3$ (corresponding to the line being shifted to 327 MHz) have been made using ORT[110] and VLA[111]. These observations have allowed interesting upper limits to be placed on the HI mass of clusters and superclusters at $z=3.3$. If superclusters were indeed the first objects to condense out of the Hubble flow, such condensations must have taken place at $z>3.3$.

It would be possible to undertake much more sensitive searches for HI at even higher redshifts using the Giant Metre-wave Radio Telescope now under construction near Pune.

Galactic radio sources

Supernova remnants

When a massive star exhausts its nuclear fuel in about 10 million years, it explodes as a brilliant supernova. While the core of the star collapses under gravity to become an extremely dense neutron star or perhaps a black hole, the outer layers of the star are thrown out with enormous speeds reaching 10,000 km sec^{-1}, releasing up to 10^{50} erg of energy. The envelopes of supernovae continue to expand, interacting with the ambient interstellar material and dispersing heavy elements cooked in the interior of the progenitor star. New stars born out of this material are richer in heavy elements and this cycle of birth and death of stars thus influences both the physical and chemical evolution of the galaxy.

Supernova remnants (SNRs) emit a copious amount of radio radiation generated by the nonthermal synchrotron process. About 150 radio SNRs have been detected in our galaxy, whose ages range from about 300 to more than 50,000 years. Radio studies of the spectrum and polarization structure in several SNRs using different radio telescopes have provided a significant amount of information on the nature of their expanding shells (e.g. refs. 112, 113). The structures of Kepler's SNR and the Crab nebula were obtained[114] with high angular resolution from lunar occultations recorded with ORT at 327 MHz. Comparison with high-frequency data showed that, while the radio continuum spectrum close to the outer boundary of the Crab may be similar to that of other SNRs, the emission in the interior has a flatter spectrum owing to the continuous supply of energetic electrons from the pulsar at its centre. Observations of the Crab at 20 cm with VLA[115] and at 92 cm with OSRT (Figure 11; see article by T. Velusamy and Anish Roshi, page 120 this issue) have revealed a jet-like feature coincident with that found optically by van den Bergh. This jet is of great astrophysical interest as it is likely to have resulted from the high-velocity flow originating from the pulsar. Besides Crab, a number of other SNRs with peculiar morphologies have been investigated using OSRT and other radio telescopes. The OSRT map of SNR W28 (Figure 12) was used to study an encounter between its expanding shell and a dense interstellar molecular cloud along its eastern boundary[116]. Such encounters may induce star formation in the cloud. The nonthermal radio source G18.95–1.1 has been shown from OSRT observations[117] to be a normal shell-type SNR with a central source perhaps similar to the accreting binary SS433 in W50. Two other SNRs, W50 and CTB80, were observed with the NRAO 300-foot radio telescope[113]. The map of W50 showed not only a roughly spherical structure typical of SNRs, but also a lobe structure elongated in the east–west direction, which was later related to precessing jets from the accreting binary SS433 near the centre. The observations of CTB80 were the first to reveal its peculiar structure[118, 119]. With its small-diameter (1 arcmin) core, extended ridges (size ~1°), X-ray point source, and the recently discovered 39-msec pulsar, it is indeed a peculiar SNR with a unique morphology which may be understood in terms of the dynamical effects on the expanding envelope due to the surrounding interstellar medium and also due to the motion of the pulsar.

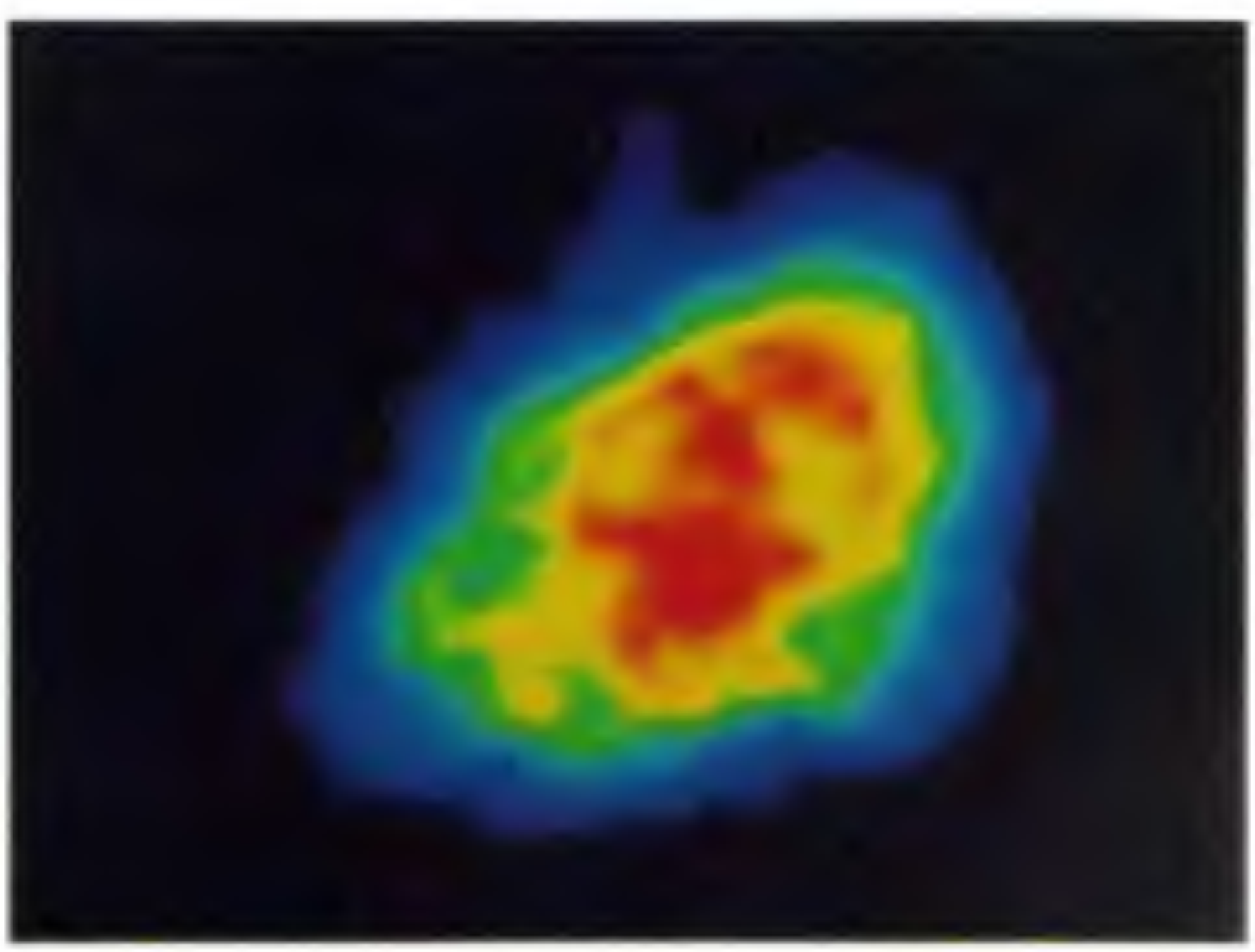

Figure 11. 327-MHz OSRT image of the Crab nebula, showing the radio jet-like feature to the north (top). [Observer: T. Velusamy]

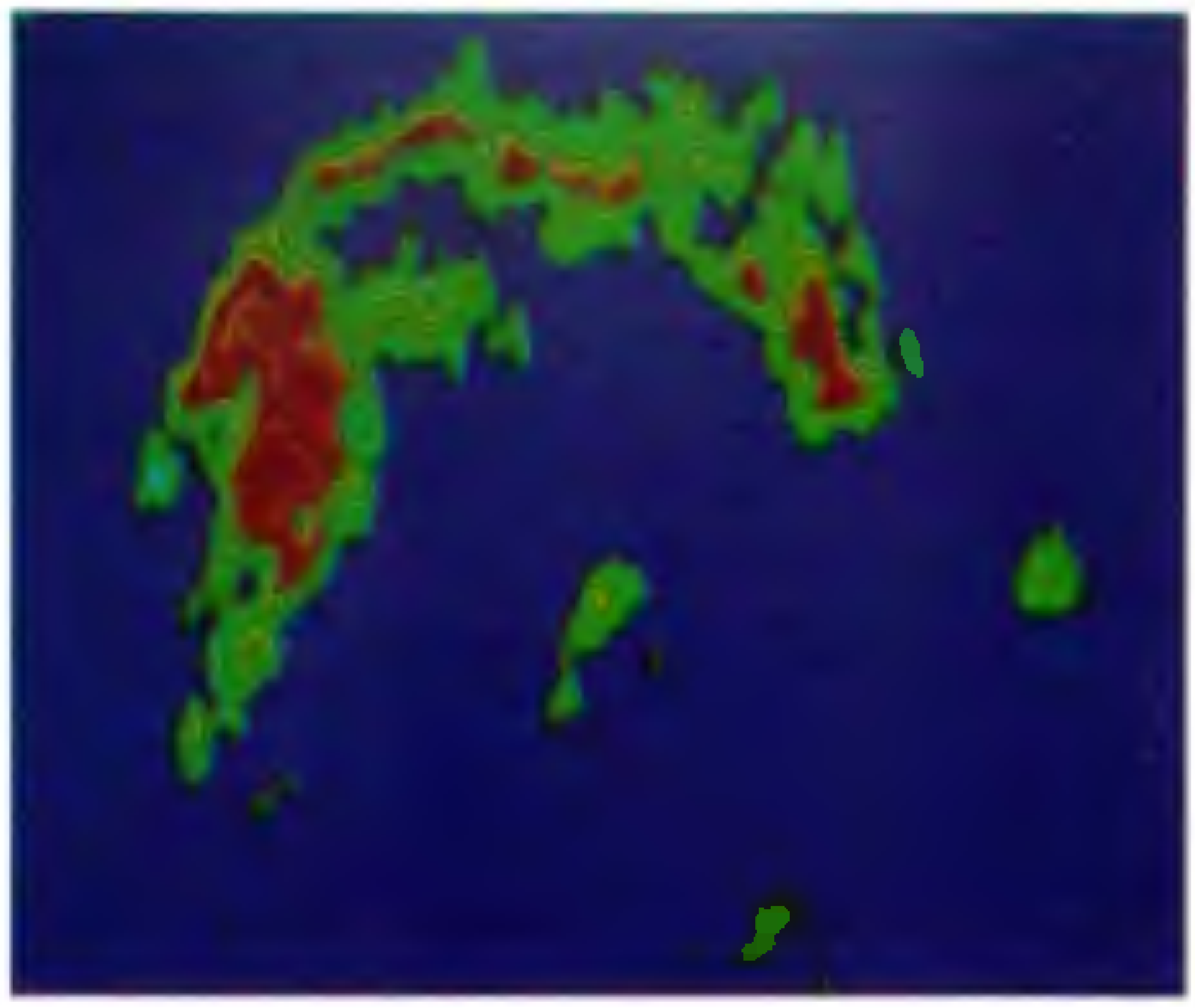

Figure 12. 327-MHz OSRT image of supernova remnant W28. [Observer: T. Velusamy]

Morphologically, there are three kinds of SNRs—ordinary remnants that are expanding shells, 'plerions' that are Crab-like nebulae without any shell, and combination-type SNRs that contain both shell and 'plerion' structure. As very few combination-type SNRs are known, a survey of the Galactic plane was made with OSRT, in order to detect more of that class[120]. An example of a combination-type SNR is G16.73+0.1 (ref. 121). Such a survey, combined with observations in the optical, X-ray and higher radio frequencies, will throw light on some of the basic problems of supernovae and their remnants.

Pulsars

The ORT, with its large collecting area, has been used for several studies and searches for pulsars[122–127]. Pulsars, first discovered by Cambridge astronomers in 1967, are rapidly rotating neutron stars with strong dipole magnetic fields in which the radio emission arises in a narrow cone around the magnetic field lines owing to curvature radiation. This cone sweeps past the observer like a lighthouse beacon with each rotation of the neutron star. The periods of pulsars range all the way from a millisecond to a few seconds. Of the few hundred pulsars known so far, eight were discovered with the ORT. One of these, PSR 1911+03, had an unusually large pulse width amounting to about 21% of the period[124].

Fluctuations in the intensity of pulsars take place on time-scales ranging from microseconds to years and are of considerable astrophysical interest. While fluctuations with intermediate time-scales of several minutes to hours can arise owing to electron-density irregularities in the interstellar medium along the line of sight, variations with both shorter and longer time-scales are thought to be intrinsic to the pulsars. Extensive studies with ORT have shown that the intrinsic intensity variations (IIV) with high fluctuation indices also exist in many pulsars on the intermediate time-scales. For this study, a technique for separating the fluctuations due to the ISM from IIVs with similar time-scales was developed at Ooty[125]. From measurements of temporal and radio-frequency correlations of a few dozen pulsars of low dispersion measure, it was inferred that the local ISM has rather homogeneous properties out to a distance of about 2 kpc (ref. 126).

Simultaneous observations of a few pulsars at 327 MHz using ORT and the Parkes radio telescope in Australia revealed[127] the existence of multiple diffracting plasma screens in the ISM in some directions. For other cases it enabled the determination of stable interstellar diffraction-pattern velocities in the range of 40 to 120 km sec^{-1}. Subsequently, an analysis of the spatial distribution of a large sample of pulsars from the Molonglo Survey was used to infer the presence of a high-electron density layer about 150 light years below the plane of the Galaxy[128].

The mean pulse profile of a pulsar obtained by averaging several hundred consecutive pulses is quite stable and has a characteristic shape for a particular object. This mean pulse shape is like a modulating window for the bursts within individual pulses which are emitted over a shorter duration. Investigations on the details of subpulse emission carried out on PSR 0031–07 and PSR 0833–45 were used to constrain the pulsar emission mechanisms[129].

HII regions

Wide field maps of Orion A, a nearby bright HII-region, have been made with a resolution of 1 arcmin at 90 cm, where the central region is highly opaque, and at 2.8 cm, where the nebula is fully transparent. These observations have provided the first evidence from radio continuum data alone for a large systematic gradient of electron temperature within the nebula[130], which is vital for interpretation of the radio recombination line observations and for understanding the details of physical processes taking place within the nebula.

Radio stars

A variety of stars have in recent years been detected as weak radio sources with large radio telescopes. One of the strongest of these is the well-known X-ray source Sco X-*l*, which exhibits a remarkable triple structure in the radio with a central source coincident with the optical star and two outer lobes similar in appearance to those found in extragalactic radio sources. OSRT observations of Sco X-1 have revealed the presence of a possibly associated additional pair of outer radio components, raising interesting scenarios for magnetic focusing of the jets[131,132]. Observations of the hydrogen-deficient binary Upsilon Sagittarii using the VLA at 2 and 6 cm have set upper limits to the mass-loss rate via a high-temperature wind[133].

The interplanetary medium

Radio waves from a compact source are scattered by electron-density irregularities in the solar-wind plasma, producing random intensity patterns on the Earth. These patterns sweep past at the velocity of the solar wind (400 km sec^{-1}) leading to intensity fluctuations on time-scales of about 0.1 second. This phenomenon of interplanetary scintillation (IPS) provides useful information on both the interplanetary medium (IPM) and the angular size of the source (in the range of about 0.05 to 1 arcsec). With its high sensitivity, ORT is well suited for IPS studies and a number of compact sources have been observed since the early seventies to derive scintillation indices (i.e. the normalized root mean square of the intensity fluctuations), power spectra, and the second moments of the spectra for a wide range of solar elongation. Based on this a simplified model was proposed for the variation of scale sizes of irregularities with radial distance from the Sun[20]. Using these IPM parameters, information on the fine structure in hundreds of compact radio sources was derived[20,21].

In the mid-seventies, it was realized that there were better point sources than had been used for calibrating the IPS observations. The quasar 1148–00 was found to be one of the most compact and relatively strong (3 Jy) radio sources at 327 MHz from two-frequency IPS observations[134] made at Ooty and Puschino (USSR) and from VLBI observations[75] between Ooty and

Europe. IPS observations of 1148–00 have been made for more than one solar cycle and have given a good picture of the IPM. Detailed fitting of the observed power spectra shows[135] that the spectrum of the turbulence in the solar wind is best described by a power law with an 'inner scale' rather than a gaussian as had been assumed earlier. The quality of the fits to the observed spectra is generally so good (Figure 13) that it has been possible to estimate the values of solar wind velocity directly from single-station observations[136], which are in close agreement with those derived from the conventional 3-station measurements (Figure 14). This technique is currently being used to study transients in the solar wind and the dependence of solar wind velocity on heliographic latitude and on the solar cycle.

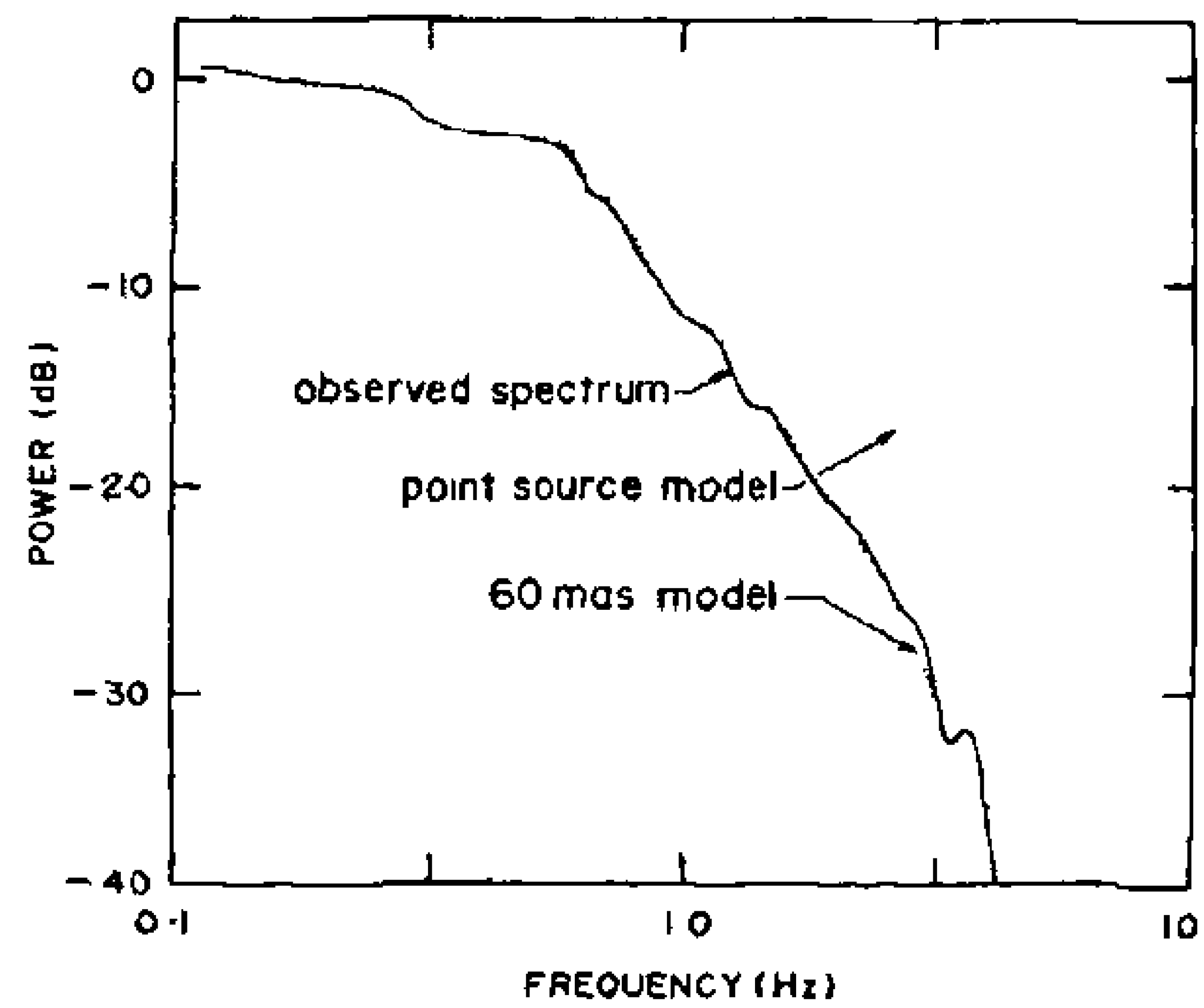

Figure 13. The power spectrum of interplanetary scintillation of 3C273 observed using the Ooty Radio Telescope at 327 MHz compared with a point source and an extended source model. Based on ref. 136.

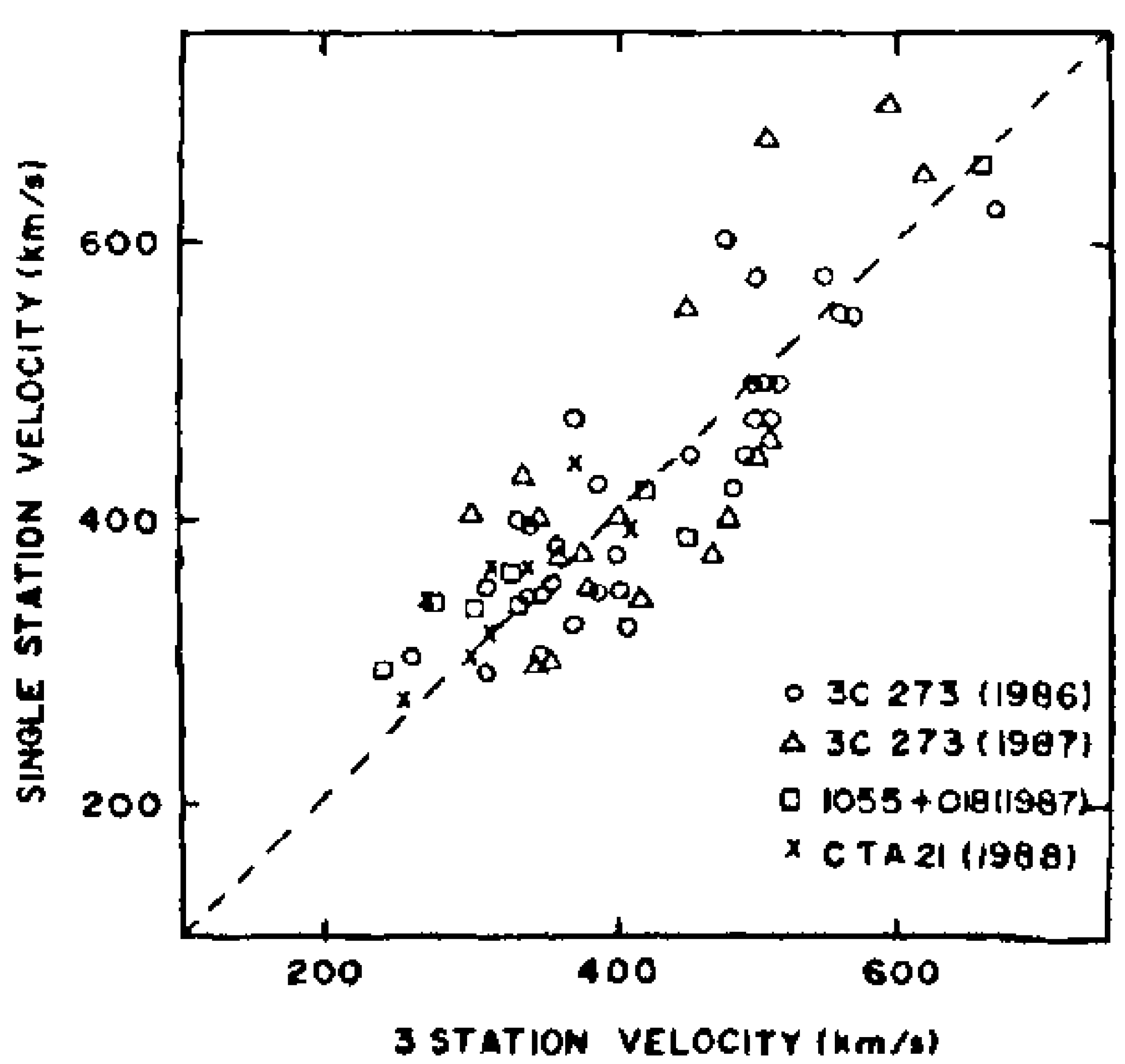

Figure 14. Comparison of solar wind velocities derived from 3-station IPS observations of some radio sources with those derived from the single-station spectral-fitting technique using the Ooty Radio Telescope[136].

The first observations[137] of scintillation through the plasma tail of a comet were made with the ORT during the occultation of the source 2025–15 by the coma and tail of comet Kohoutek (1973f) on 5 January 1974. However, similar observations to detect radio-source scintillations through the tail of comet Halley, along with observations of a grid of control radio sources, have not confirmed[138] the earlier results. Clearly, more such observations are needed.

Interstellar medium

The properties of the ionized component of the interstellar medium can be inferred from the effects of propagation of radio waves through the medium, e.g. from (i) the angular broadening of extragalactic radio sources, and (ii) intensity modulation due to refractive scintillations. Two major programmes have been undertaken for investigating these aspects:

(i) *IPS survey of the Galactic Plane.* An extensive IPS survey of the Galactic plane was made using ORT to detect sources with compact components at small galactic latitudes ($b < 10°$). The absence of sources with components smaller than 0.5 arcsec in the Galactic Centre region indicated[139] larger interstellar scattering in these directions than expected from earlier work, which did not include this region. The enhanced scattering varies with both galactic latitude and longitude. A two-component model for the distribution of scattering plasma was proposed. Using IPS, pulsar and VLBI data, an estimate for the scattering angle as a function of latitude was also derived[140].

(ii) *Observations of low-frequency variables.* The flux densities of many compact radio sources are known to vary at metre wavelengths by $\lesssim 20\%$ on time-scales of about one year. The angular sizes of these sources, derived using the time-scales of variations, suggest that the brightness temperatures are of the order of 10^{15} K, well above the inverse Compton limit of 10^{12} K. Two major models that can explain this phenomenon are: (a) relativistic bulk motion in the emitting components and (b) refractive interstellar scintillations (RISS) in the intervening medium.

The first model would be applicable if low-frequency variability (LFV) correlates with intrinsic properties of the sources, such as optical activity or apparent superluminal motion. In the second model, the amplitude and scales of flux variations should be a function of galactic coordinates. With this in view it was decided to monitor the flux density of a well-defined sample of about 100 flat-spectrum radio sources at 327 MHz using the OSRT. It was found that LFV does not correlate with degree of optical polarization in contrast to the high-frequency variability[61]. A definite dependence on galactic latitude was found, supporting the RISS interpretation[141]. A similar latitude dependence was found both in the Galactic centre and the Galactic anticentre directions. Detailed modelling of the observed latitude dependence suggests that interstellar scattering could be influenced by the spiral arms of our galaxy.

VLBI observations at 6 and 18 cm of a number of the low-latitude sources have also been carried out. Angular broadening (~40 mas at 18 cm) due to interstellar scattering was detected towards 1748–253 (l=3.7, b=0 6). These observations, combined with the estimated scattering angle towards the Galactic centre and towards the OH maser sources close to the Galactic centre, suggest[141] that there is an extremely narrow (scale size ~55 pc) region of enhanced scattering close to the Galactic centre.

The Galactic centre

The radio source Sgr-A associated with the centre of our galaxy is one of the strongest radio sources in the sky. Its lunar occultation[142] in September 1970 was one of the first major observations with ORT. Being located at least 70 times nearer than the centre of any other galaxy, Sgr-A provides a much more detailed view of the energetic phenomena occurring inside the dense stellar cores of galaxies. With a resolution of 1 arcmin at 327 MHz, the Ooty occultation observations of Sgr-A provided the first details of its synchrotron radiation, revealing a multicomponent structure at metre wavelengths, superposed on a halo of ~20-pc diameter. These observations were combined with available high-resolution observations at shorter wavelengths to yield the first two-dimensional separation of the thermal and nonthermal emission within Sgr-A. It was shown[143] that the nonthermal emission traced a shell-like structure with a diameter of ~8 pc, marked by several peaks superposed on a broader nonthermal source of flatter spectrum. Recent observations by various groups have confirmed (e.g. Ekers *et al.*[144]) these findings (Figure 15) and have further revealed a unique complex of magnetized plasma filaments threading the nonthermal halo (Anantharamaiah *et al.*[145]). The multi-frequency radio maps of both continuum and recombination line emission suggest that the nonthermal shell and the halo are two clouds of relativistic plasma, ejected from a mini-quasar (possibly a black hole) active at the nucleus of our galaxy[145]. VLBI observations have in fact revealed a compact radio source identified with the mini-quasar. The picture emerging from all these studies seems to be that the basic nature of the nuclear activity in our galaxy might be quite similar to the far more violent phenomena witnessed in quasars.

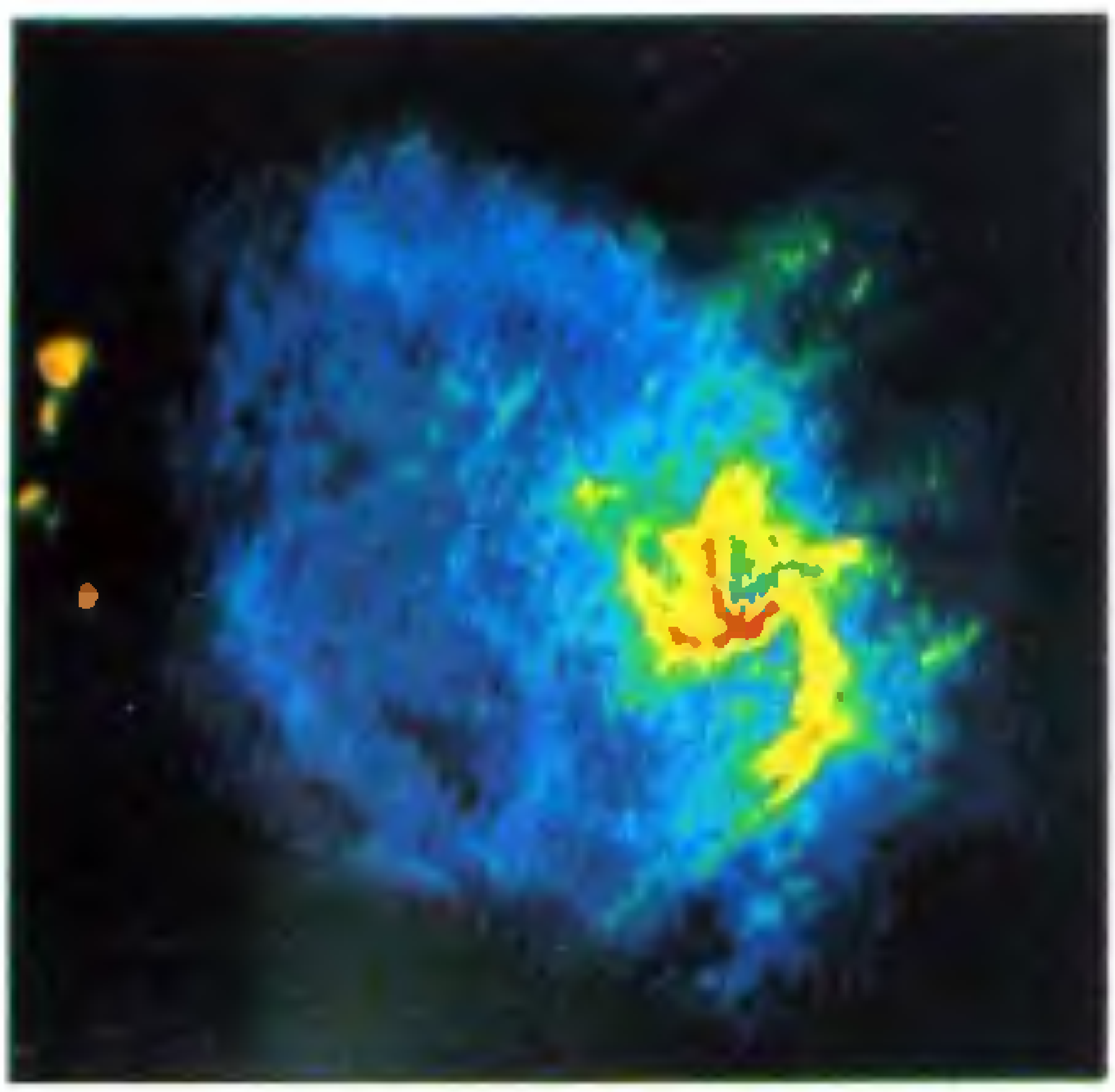

Figure 15. VLA image of the Galactic centre at 6 cm [Courtesy NRAO/AUI observers R D Ekers, U J Schwarz and W M Goss]

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A more detailed account of the work summarized here is given in the brochure *25 Years of Radio Astronomy* (available from TIFR, Poona University Campus, Pune 411 007), which lists about 350 research publications of the Radio Astronomy Group published between 1963 and March 1989 and about 23 Ph D theses based on work carried out in the Group or using the observational facilities developed by it. About 30 more research papers have since been published and three more Ph D theses completed.