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The Ooty Synthesis Radio Telescope: First Results

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(*Invited article*)

Abstract. A 4-km synthesis radio telescope has recently been commissioned at Ootacamund, India for operation at 327 MHz. It consists of the Ooty Radio Telescope (530 m × 30 m) and 7 small antennas which are distributed over an area of about 4 km × 2 km. It has a coverage of about ± 40° in declination δ. The beam-width is about 40 arcsec × 90 arcsec at $\delta = 0°$ and about 40 arcsec × 50 arcsec at $\delta = 40°$. The sensitivity attained for a 5:1 signal-to-noise ratio is about 15 m Jy after a 10-hour integration.

The observational programmes undertaken and some of the results obtained recently are summarized. The radio halo around the edge-on spiral NGC 4631 is found to have a larger scale-height at 327 MHz than is known at higher frequencies. Mapping of interesting radio galaxies at 327 MHz is being carried out; preliminary results for 0511–305 (~2 Mpc) and 1333–337 (~ 750 kpc) are summarized. The very-steep-spectrum radio source in the Abell cluster A85 is found to be resolved; since it has no obvious optical counterpart, it is conceivable that it is a remnant of past activity of a galaxy that has drifted away in about 10^9 years.

Key words: radio telescopes—galaxies, radio—galaxies, spiral

1. Introduction

Many galactic and extragalactic radio sources have extended features of low surface brightness which arise from the oldest relativistic electrons in the universe. Studies of such diffuse features offer a powerful means of understanding the evolution of radio sources, particularly concerning the sites of particle acceleration and energy losses. As these components generally have steep spectra, they become increasingly more prominent at longer wavelengths. Hence, their detailed study requires a radio telescope operating at wavelengths of a metre or more and having sufficiently high resolving power, sensitivity and dynamic range. Such a telescope is also useful for many other types of studies, such as, undertaking radio source surveys, monitoring metre-wavelength variable sources, studying flare stars, observing radio recombination lines *etc.*

In this paper, we briefly describe a 4-km aperture synthesis radio telescope recently set up at Ootacamund, India, for operation at 326.5 MHz. Several observational programmes that have been initiated and some of the results obtained are also described.

2. The Ooty Synthesis Radio Telescope

As shown in Fig. 1, the Ooty Synthesis Radio Telescope (OSRT) consists of 8 antennas located in an area of about 4 km × 2 km (Bagri *et al.* 1984). This configuration was chosen to take advantage of the large collecting area and the long north-south aperture of the Ooty Radio Telescope (ORT) which is described below. As the ORT is 530 m long, it was necessary to install only a small number of remote antennas to achieve a good coverage in the spatial-frequency (u, v) plane of the synthesis telescope. For a 10-hour observing run with the 4-km OSRT, the maximum level of positive or negative sidelobes of the synthesized beam is below 15 per cent (depending upon the declination), thus permitting a reasonable CLEANing of the dirty maps (Högbom 1974). Though the remote antennas are of much smaller size than the ORT, the sensitivity attained with the OSRT in 10 hours is ~ 15 mJy (for a 5:1 signal-to-noise ratio). The beamwidth of the OSRT is about 40 arcsec × 90 arcsec at declination $\delta = 0°$ and about 40 arcsec × 50 arcsecat $\delta = 40°$. The system parameters are summarized in Table 1.

The ORT consists of a 530 m long and 30 m wide steerable parabolic cylindrical antenna mounted equatorially (Swarup *et al.* 1971; Sarma *et al.* 1975). Its effective collecting area is about 8000 m^2. The antenna can be steered mechanically in hour angle (HA) from -04^h07^m to $+05^h26^m$. An array of 1056 co-linear dipoles is placed along the focal line of the cylindrical antenna, and is grouped into 22 modules containing 48 dipoles each. The antenna beam is steered in declination by appropriately phasing the dipole array. A 4-bit diode-controlled phase-shifter with a loss of about 0.7 dB is placed after each dipole. A branched transmission line system with a loss of 0.3 dB connects the 48 dipoles. An RF amplifier of noise temperature around 120 K follows each of the modules of 48 dipoles. The system temperature of the ORT is about 250 K. The outputs of the 22 modules of the ORT are brought to a central receiver room at an IF of 30 MHz and combined there.

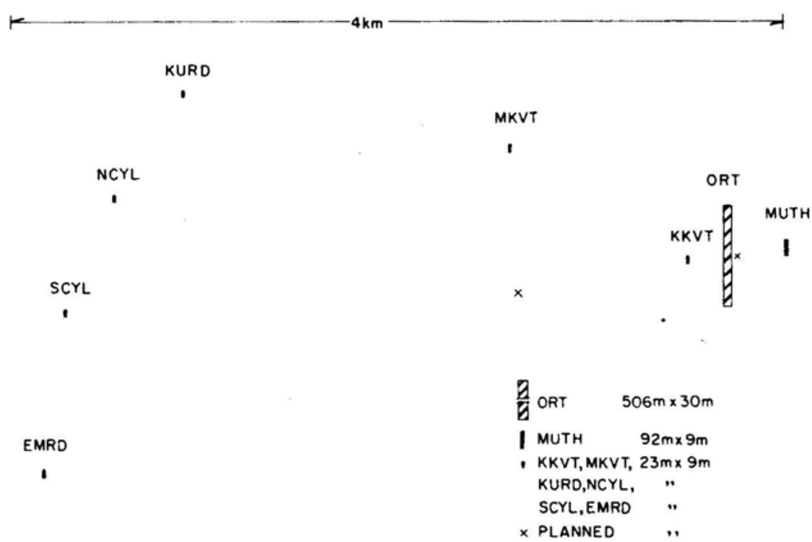


Figure 1. Configuration of the 4-km Ooty Synthesis Radio Telescope (OSRT).

Table 1. Parameters of the Ooty Synthesis Radio Telescope.

Antennas (Illuminated aperture)	ORT (506 m × 30 m) One parabolic cylinder (92 m × 9 m) Six parabolic cylinders (23 m × 9 m)
Baseline	4 km (EW), 2 km (NS)
Frequency	326.5 MHz
Bandwidth	3.5 MHz
Sky coverage HA	-04^h07^m to 05^h26^m (ORT) -05^h30^m to 05^h30^m (other antennas)
DEC	$\pm 40°$
Field of view (FWHP)	$3° \times 0°.6$ (EW × NS); $3° \times 3°$ with declination scanning
Synthesized beamwidth ($\beta_\alpha, \beta_\delta$)	40 arcsec × 90 arcsec at $\delta = 0°$ 40 arcsec × 50 arcsec at $\delta = 40°$
Sensitivity	15 mJy (S/N ratio = 5 : 1) for 10-hour integration

The antenna located about 360 m to the east of ORT (Fig. 1) is a 92 m long × 9 m wide equatorially-mounted parabolic cylinder, containing 4 modules of 48 dipoles each. All the other 6 antennas, which are located at distances ranging from 200 m to about 4 km west, are 23 m × 9 m parabolic cylinders. These are steered mechanically from about -5^h30^m to $+5^h30^m$ (some of them from -6^h to $+6^h$). The dipole array and RF electronics for these antennas are similar to those of the ORT. The pointing of the OSRT antennas in hour angle and declination is done using a telemetry system (Sankararaman, Subramanian & Balasubramaniam 1982).

Local oscillator signals are transmitted to antennas located up to about 300 m distance by cables buried underground. For more distant antennas, the local oscillators are phase-locked to a central oscillator and any path variations are measured using a round-trip phase measurement scheme (Bagri, Narayana & Venkatasubramani 1984). The 30-MHz IF signals from the remote antennas are brought to the central receiver room, converted to video signals, and correlated with the output of the ORT. The observations described in this paper have been made over the last few months using only a 5-baseline digital correlator system, which correlates the output of the entire ORT with those of 5 other antennas at a time.

The field of view of the OSRT is determined by the voltage radiation pattern of the entire ORT, which is 170 arcmin (EW) × 8 arcmin (NS). However, for mapping a large field of view (up to 170 arcmin × 170 arcmin) with the existing 5-baseline correlator system, a declination scanning technique has been developed by Pramesh Rao & Velusamy (1983). Using diode phase shifters, the declination of the ORT is changed in steps of about 3 arcmin every 200 ms. For a 170 arcmin field of view, the declination scanning is completed in 12 s, during which period there is negligible change of the u and v Fourier components of the source brightness distribution being observed. The Fourier transform of the visibilities measured during every scan gives the true visibility function of the source at Δv intervals, equal to the width of the ORT divided by the number of declination settings. This scheme also allows calibration of the OSRT using any relatively compact source located in the field for determining instrumental and ionospheric phase variations.

For the purpose of measuring low spatial frequency components, it is planned to install a 28 m × 9 m cylinder about 50 m to the east of ORT. Another antenna is to be installed a kilometre away for improving the (u, v) coverage. A 256-channel correlator system is presently being installed for intercorrelating 14 antenna-outputs, *e.g.* 5 outputs of the ORT (each from 4 of the 22 modules) and 9 of the small antennas. The division of the ORT would widen the NS field of view of the OSRT to about 0°.6. These additions will improve the capability of OSRT considerably.

3. Scientific programmes and results

A summary of the observational programmes being undertaken currently with OSRT and some of the results obtained so far are given below.

3.1 *Galactic Radio Sources*

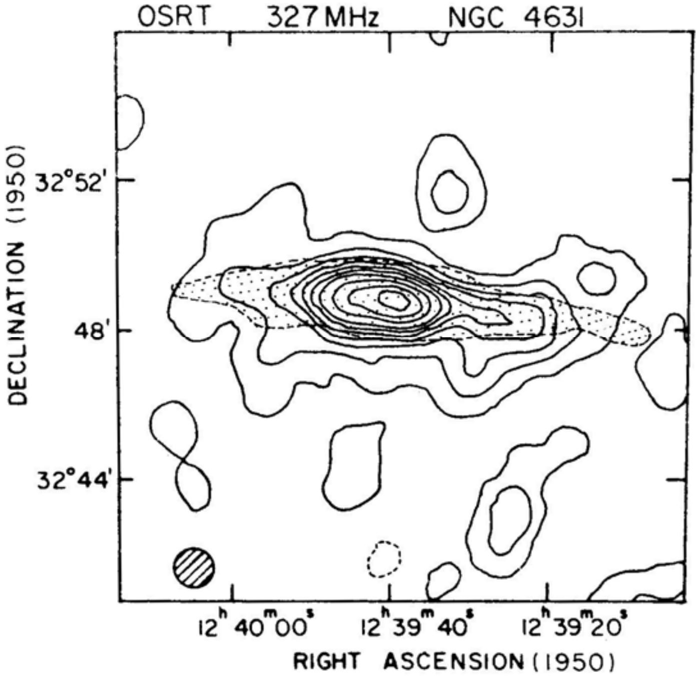
The wide-field mapping technique described above has been used for mapping many galactic sources, including the galactic centre. Velusamy & Pramesh Rao (1982) have mapped W 50 at 327 MHz and have examined the radio emission from the distant lobe-like features separated by ~ 2° along the jet axis of SS 433. Map of IC 443 at 327 MHz was presented by Pramesh Rao & Velusamy (1983). Recently, P. D. Jackson & T. Velusamy have observed a 6° × 6° region to detect any continuum emission at 327 MHz associated with an expanding HI shell in Puppis (Stacy & Jackson 1982). However, the OSRT maps of several of these galactic sources suffer from the missing short spacings (< 80 λ) and can be completed only after the nearby antenna (at 50 m from the ORT) becomes available.

3.2 *Nearby Spiral Galaxies*

S. Sukumar & T. Velusamy are observing systematically several edge-on and face-on nearby spiral galaxies, particularly at low or southern declinations. The aim of this programme is to (i) separate the thermal and nonthermal emission in the disk unambiguously, (ii) study the synchrotron emission as a function of distance (z) from the plane of the galaxy, and (iii) derive detailed models for the origin and propagation of relativistic electrons in the disk and halo of nearby spiral galaxies. Fig. 2 shows a 327-MHz map of NGC 4631, a well-known edge-on galaxy. The radio map has been restored with a beam of 60 arcsec × 60 arcsec. The optical image of NGC 4631 is marked by a broken line and is shaded by dots. Sukumar & Velusamy (1984) have made a comparison of the 327-MHz map with the Westerbork maps at 610 MHz and 1412 MHz (Ekers & Sancisi 1977), and with the Effelsberg map at 10.7 GHz (Klein & Wielebinski, personal communication), smoothing all the four maps to similar resolutions. Their results show a halo of larger scale height at 327 MHz than seen at higher frequencies. The spectral index α between 327 MHz and 10.7 GHz steepens from about –0.6 ($S \propto \nu^{\alpha}$) over the galactic disk to – 1.5 at about 6 kpc above the disk.

3.3 *Extended Radio Galaxies*

Several strong and nearby radio galaxies such as Fornax A are being mapped for studying the interaction of their outer components with the circumgalactic material. Gopal-Krishna, S. Lakshmi, A. K. Singal & S. Krishnamohan are making a search for giant radio galaxies and are also mapping radio galaxies with size > 500 kpc.



Figure·2. A327-MHz map of NGC 4631 made with a 60-arcsec Gaussian beam. The contour levels are – 15,15,45,75,105,135,165,195,245,295 and 345 mJy/beam. The optical image of the galaxy is marked by a broken line and is shaded by dots.

In Fig. 3 is shown a 327-MHz OSRT map of the radio source 0511 – 305 made with a 60-arcsec beam, revealing a complex structure. The source was mapped earlier at 408 MHz with a 2.8-arcmin beam (Schlizzi & McAdam 1975). The present observations resolve each lobe into a few peaks lined up along a curved ridge. These ridges show an inversion symmetry about the 18.5-mag galaxy 'c' which, therefore, might be the correct optical identification. Also, this galaxy lies almost exactly midway between the outermost radio peaks. For an estimated redshift of 0.25 based on the apparent magnitude, the overall size of the source would be more than 2 Mpc.

An OSRT map of another large radio galaxy 1333–337 is shown in Fig. 4. The parent galaxy IC 4296 is elliptical with $m_r \sim 11$ and a redshift $z = 0.0129$ (Evans 1963). Earlier, this source has been mapped at 1415 MHz with 50-arcsec resolution (Goss *et al.* 1977) and at 408 MHz with a 2.8-arcmin beam (Schlizzi & McAdam 1975). The outermost peaks are seen to be separated by 33 arcmin which corresponds to ~ 750 kpc. The south-eastern lobe has a complex structure. The inner radio double is embedded within the main body of the galaxy, and has a notably sharp boundary to the north-eastern side as seen in the 327 MHz map. This is consistent with the motion of the galaxy against the intergalactic medium, as proposed by Goss *et al.* (1977) in order to account for the bend in the large-scale structure.

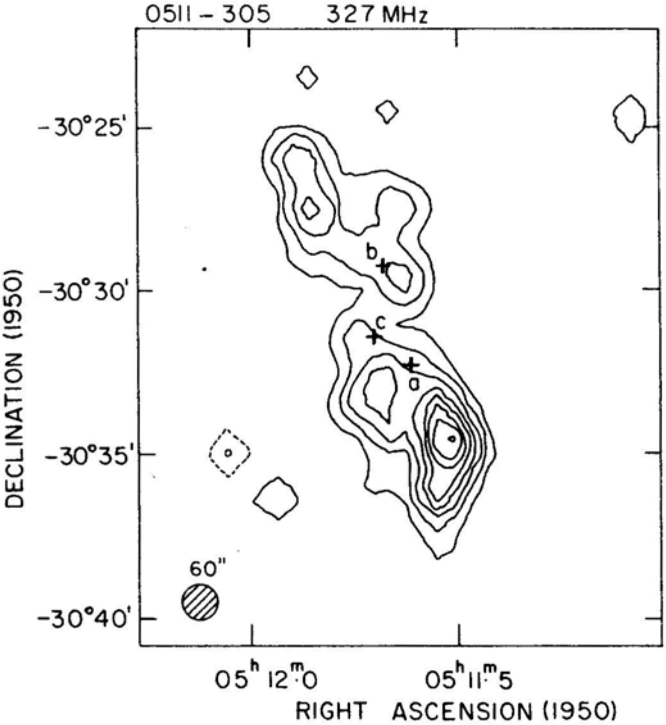


Figure 3. The OSRT map of the source 0511–305, restored with a 60-arcsec beam. The contour levels are – 60, –30, 30, 100, 200, 350, 500, 700, 900 and 1200 mJy/beam. The three plus marks denote the positions of optical objects (a) 17-mag N galaxy; (b) 17.5-mag galaxy and (c) 18.5-mag galaxy (Schlizzi & McAdam 1975).

3.4 *A Very-Steep-Spectrum Source in Abell 85*

It is known that radio sources with a very steep spectral index ($\alpha \lesssim -1.2$) tend to occur in rich clusters of galaxies (Baldwin & Scott 1973), predominantly of Bautz-Morgan (BM) class I which are dominated by a giant cD galaxy (Slee, Wilson & Siegman 1982). Such clusters are also found to be X-ray emitters, implying the presence of hot thermal gas which can confine relativistic electrons for a long period of time and thereby allow synchrotron losses to steepen the radio spectrum. There are only a limited number of known, very-steep-spectrum sources, which have been found either from the association of 4C sources with rich clusters (*e.g.* McHardy 1979), or from Culgoora observations at 80 and 160 MHz of sources known to be associated with clusters from work at higher frequencies (*e.g.* Slee & Siegman 1983). With the high sensitivity of the OSRT, it is proposed to search for steep spectrum sources by surveying a large number of clusters of BM-I type.

In Fig. 5(a) is shown a radio map of the A bell cluster A 85 made by V. K. Kapahi & Ravi Subrahmanyan at 327 MHz with a 3-arcmin gaussian beam. For comparison, a 2695 MHz Effelsberg map made with a 4.4 arcmin beam (Waldthausen *et al.* 1979) is shown in Fig. 5(b). The source 1 is coincident with the brightest elliptical cD galaxy of 12.8 mag. Bright elliptical galaxies are also seen near radio sources 2 and 5. The source 4 is not seen at 327 MHz, and may be a background fiat spectrum source.

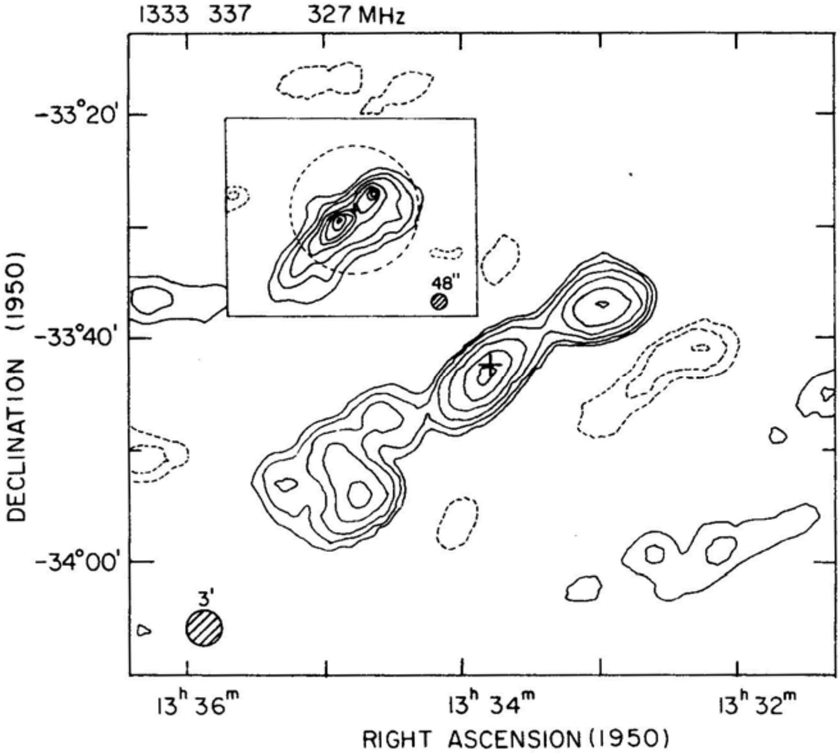


Figure 4. The OSRT map of the source 1333–337 restored with a 3-arcmin beam. The contour levels are –500, –250, –120, 120, 250, 500, 1000, 1800 and 3000 mJy/beam. The plus sign marks the position of the centre of the optical galaxy IC 4296 (Goss *et al.* 1977).The inset is a 327-MHz map of the central component, made with a resolution of 50 arcsec, using mainly the larger antenna spacings of the OSRT. The contours are drawn at –75, –40, 40, 100, 200, 350, 500, 650, 800 and 900 mJy/beam. The outline of the optical galaxy with a diameter 160 arcsec (= 60 kpc) is indicated with a circle encompassing the inner double source.

The 327-MHz map shows a very-steep-spectrum source (VSSS) coincident with the Molonglo position of radio source 0038–096 (Mills & Hoskins 1977). Its spectral index $\alpha = -1.94$ between 80 and 408 MHz, which is consistent with its being absent (<20 mJy) in the Effelsberg map at 2695 MHz. A preliminary 327-MHz map with a 40-arcsec resolution shows that the source is considerably resolved.

Abell 85 is a distance class 4, Richness class 1, BM class I cluster with a redshift of 0.0518 (Sarazin, Rood & Struble 1982). The X-ray emission is smooth and centrally peaked around the galaxy with an X-ray core radius of 3.25 arcmin (Jones *et al.* 1979). Assuming $\alpha = -2$ between 10 MHz and 10 GHz for the VSSS, the total radio luminosity $L = 6 \times 10^{42}$ erg s^{-1} (for $H_0 = 50$ km s^{-1} Mpc^{-1}). This gives an estimated equipartition field $B \sim 3.5 \times 10^{-6}$ gauss and source age $> 8.4 \times 10^{8}$ yr, assuming that the frequency of break in the spectrum $\nu_c < 30$ MHz and the ratio of the energy of protons to that of electrons is unity.

The tenth brightest galaxy in the cluster is of 15.7 mag. Since strong radio sources are generally associated with the brightest galaxies in a cluster, it is curious that there is no obvious optical identification for this very-steep-spectrum source. The source is

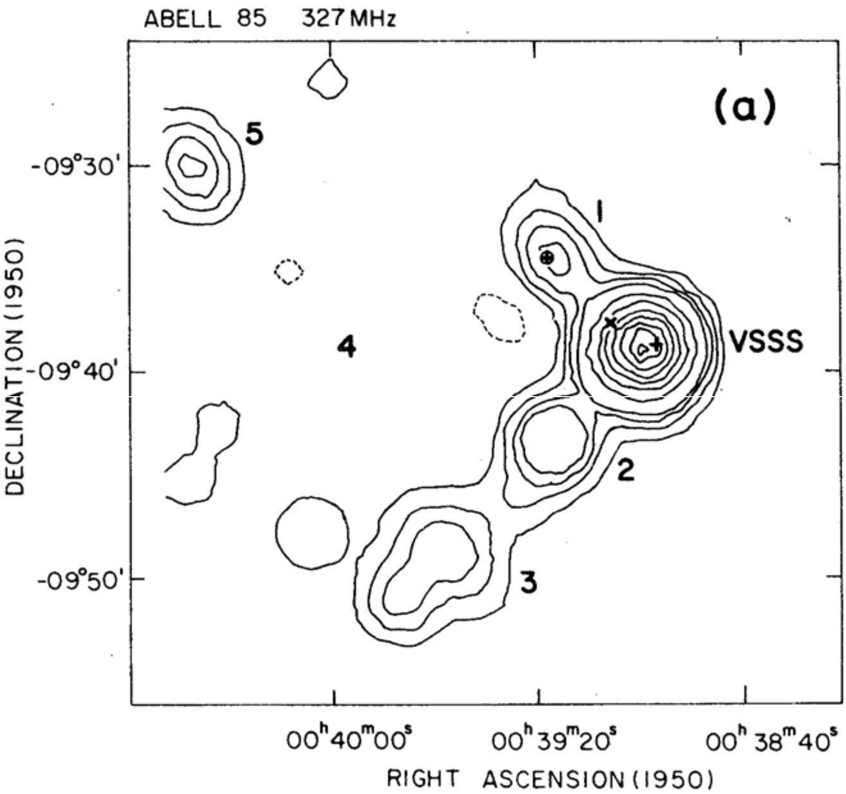


Figure 5. (a) A 327-MHz map of the cluster A bell 85 made with a 3-arcmin beam. The contour levels are: –50, 50, 100, 150, 200, 400, 600, 800, 1000, 1200, 1400 and 1600 mJy/beam. The symbol × shows the estimated centre of the cluster (Waldthaussen *et al.* 1979), ⊕ the position of the cD galaxy and + the Molonglo position of 0038–096. (b) A 2695-MHz map of Abell 85 with a 4.4-arcmin beam made by Waldthaussen *et al.* (1979). Symbols are same as in Fig. 5(a). The contour levels are: 0, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90 mJy/beam.

separated from the cD galaxy by 6 arcmin corresponding to ~ 550 kpc. If the radio source was created by the cD galaxy, the speed of the cD galaxy would have to be about 550 km s^{-1} to travel a distance of 550 kpc in 10^9 yr, the estimated age of the source. This speed is considerably higher than generally estimated for cD galaxies. Kapahi & Subrahmanyan have considered therefore the possibility that the radio source was caused by another bright elliptical galaxy which may have since moved away, or even been cannibalized by the dominant cD galaxy in the potential well of the cluster. Higher resolution observations of this and other similar clusters could throw more light on this question.

4. Conclusions

Observations have been summarized of some of the radio sources mapped with a 4-km synthesis radio telescope which has recently been completed for operation at 327 MHz. The dynamic range of the maps is usually limited to about 20 to 30 due to phase

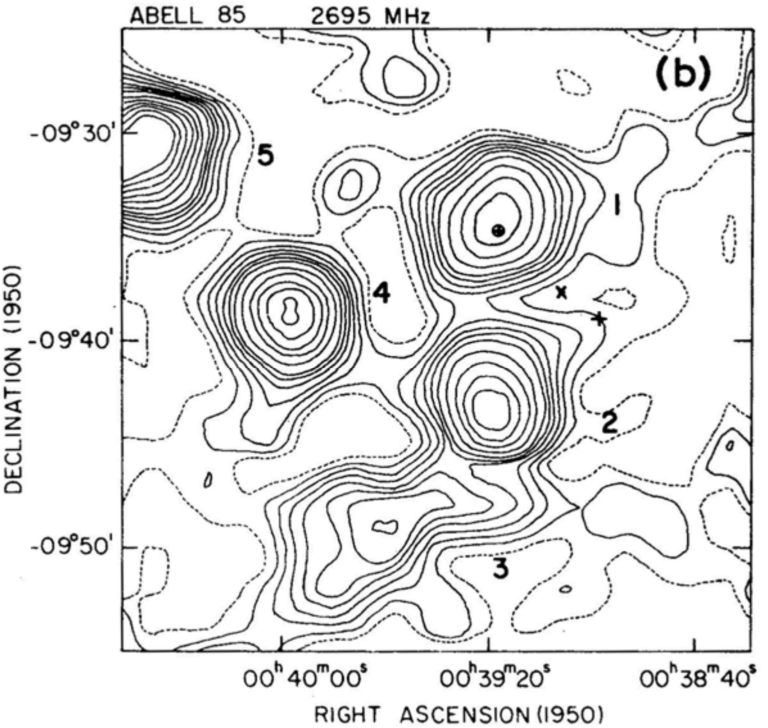


Figure 5. Continued.

variations caused by ionospheric irregularities. Because of the relatively small collecting area of most of the antennas, 'self-calibration' schemes cannot in general be applied except for a few strong sources. To improve the dynamic range, suitable calibration schemes are therefore being evolved utilizing the rapid steering capability of the antennas in declination. With an improved dynamic range, the 40-arcsec beam would be valuable for studying diffuse features in a variety of galactic and extragalactic radio sources.

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