36 Goodman, J and Narayan, R, *Mon. Not R Astron Soc*, 1985, **214**, 519
37 Vijayanarasimha, U., Ananthakrishnan, S and Swarup, G, *Mon. Not. R Astron Soc*, 1985, **212**, 601
38 Linfield, R P *et al*., *Astrophys J*, 1989, **336**, 1105.
39. Blandford, R D, Narayan, R. and Romani, R W, *Astrophys J*, 1986, **301**, L53.
40 Sarazin, C. L., *Rev. Mod Phys*., 1986, **58**, 1.
41. Crawford, C. S, Crehan, D A., Fabian, A C. and Johnstone, R. M, *Mon Not. R Astron Soc*, 1987, **224**, 1007.
42. Ananthramaiah, K. R and Narayan, R., in *Radio Wave Scattering in the ISM* (ed Cordes, J. M, Rickett, B J and Backer, D C), AIP Conf Proc. 174, 1988, pp 185–189.
43. Thomas, P. A, Fabian, A C and Nulsen, P. E. J, *Mon Not. R Astron Soc*., 1987, **228**, 973
44 Canizares, C. R, Markert, T H and Donahue, M. E., in *Cooling Flows in Clusters of Galaxies* (ed. Fabian, A C.), Kluwer, 1988, pp 63–72.
45. Mushotzky, R F. and Szymkowiak, A E, in *Cooling Flows in Clusters of Galaxies* (ed Fabian, A. C), Kluwer, 1988, pp 53–62.
46. Arnaud, K. A., in *Cooling Flows in Clusters of Galaxies* (ed. Fabian, A C), Kluwer, 1988, pp 31–40
47. Balbus, S. A, *Astrophys. J*, 1988, **328**, 395
48. Tribble, P C., *Mon. Not. R Astron. Soc*., 1989, **238**, 1.
49 Nulsen, P. E. J., in *Cooling Flows in Clusters of Galaxies* (ed. Fabian, A. C.), Kluwer, 1988, pp 175–187.
50. Loewenstein, M, *Mon. Not. R. Astron. Soc*., 1989, **238**, 15–41

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High-resolution radio images of the Crab nebula

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High-resolution images of the Crab nebula at a wide range of radio frequencies from 327 MHz to 5 GHz have been made using the Very Large Array. The image at 327 MHz shows the pulsar and the radio jet very prominently. The emission from the jet has a radio spectrum steeper than the nebular emission.

THE Crab nebula is one of the most interesting and fascinating astronomical objects. It is the remnant of the supernova explosion 1054 AD. It is basically a pulsar-driven synchrotron nebula, where the relativistic electrons generated by the pulsar emit radiation by synchrotron process. Bright filaments emitting optical lines are also embedded within this nebula. About 20% of the Crab pulsar's spin-down energy is converted into synchrotron radiation in the radio to X-ray wavelengths. Indeed, it provides an excellent astrophysical battleground for testing high-energy plasma processes. In spite of the fact that it has been one of the most well-studied objects over several decades, modern imaging techniques have continued to reveal more and more intriguing details. For example the jet-like feature protruding outside the nebular boundary, first noted by van den Bergh[1] in 1970, has been recently studied in detail in [OIII] (ref. 2); radio emission from this feature was detected by Velusamy[3] at 20 cm. Although several radio images of the Crab nebula have been made in the last two decades[4,5], there are many unresolved questions: for example the existence of a low-surface-brightness shell characteristic of typical supernova remnants, the magnetic field structure in the filaments, the energy distribution of the relativistic electrons in the filaments vs the nebular regions, interaction of pulsar wind with the surrounding nebula. Detailed study of such problems requires high-resolution images with high dynamic range over a wide range of frequencies. For example, the present upper limits are not low enough to rule out the existence of any shell around the Crab with surface brightness comparable to that in the remnant of supernova AD 1006 (ref. 6). In view of the above, we have been observing the Crab nebula at radio frequencies using the Ooty synthesis radio telescope (OSRT)[7] and the Very Large Array (VLA)[8]. In this paper we present an OSRT map at 327 MHz and high-resolution (4 to 5 arcsec) images of the Crab nebula at 327 MHz, and 1.5 and 5 GHz obtained with the VLA.

The observations at 327 MHz were first made with OSRT[7] during 1986. The OSRT contour map of the Crab obtained with a resolution of 56×33 arcsec^2 is shown in Figure 1. The overall structure is consistent with the high-resolution maps at higher frequencies, e.g. at 1.5 GHz (ref. 9). The jet protruding out of the northern boundary is seen very prominently at 327 MHz. A comparison of this map with the 1.5-GHz map[9] suggests a steepening of the spectrum outward along the jet, with spectral index $\alpha \sim -0.25$ (where $S_\nu \sim \nu^\alpha$) near the nebula to -0.7 near the tip of the jet. However, in view of the low dynamic range in this OSRT map, observations at 327 MHz were also made with the VLA to confirm this.

The VLA is best suited for multifrequency high-

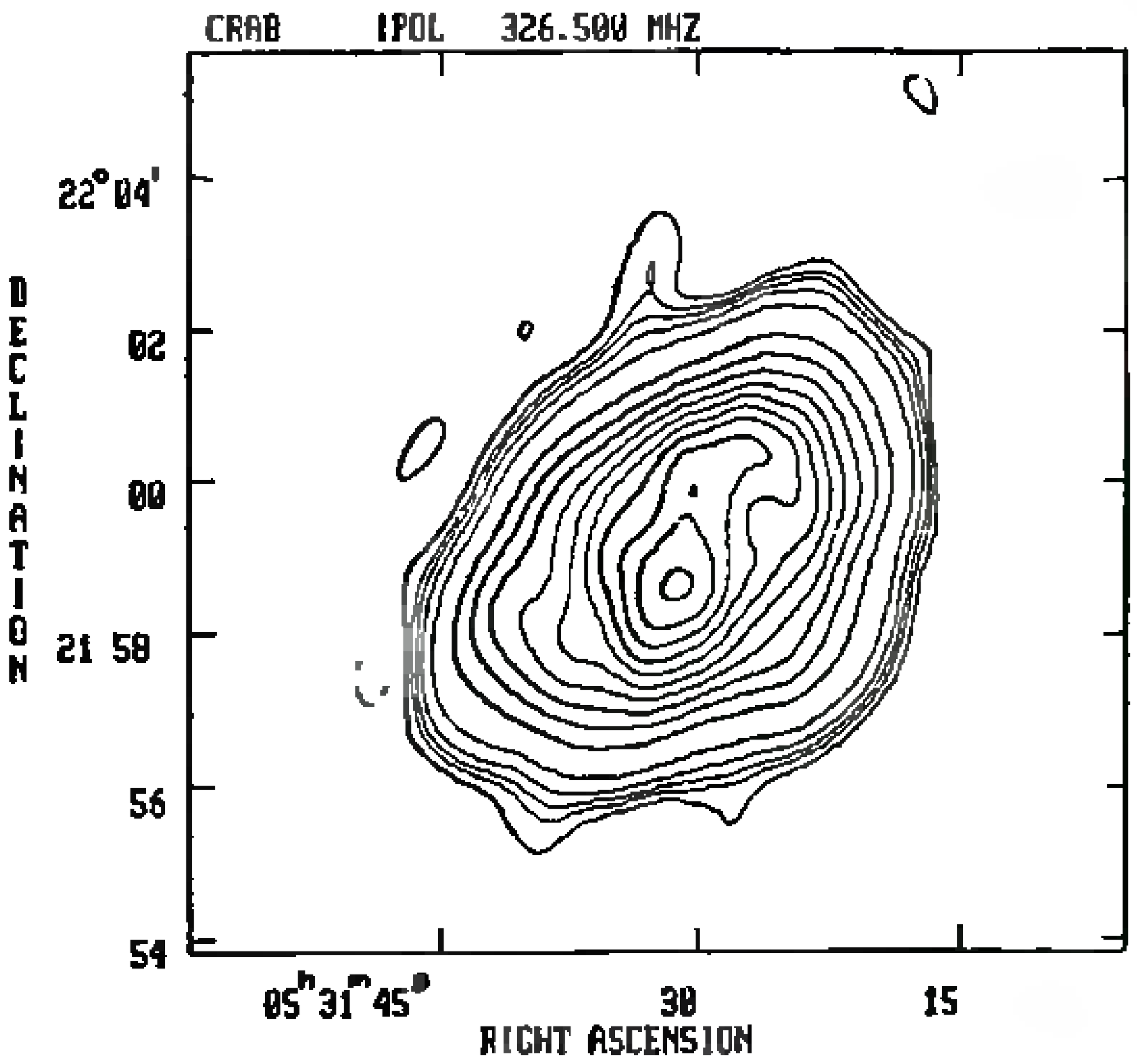

Figure 1. Contour map of the Crab nebula at 327 MHz observed with the OSRT. The restoring beam was 56″ × 33″ at a position angle of −12°. The contour levels are −0.3, 0.3, 0.6, 0.9, 1.5, 3, 9, 15, 21 Jy/beam, etc.

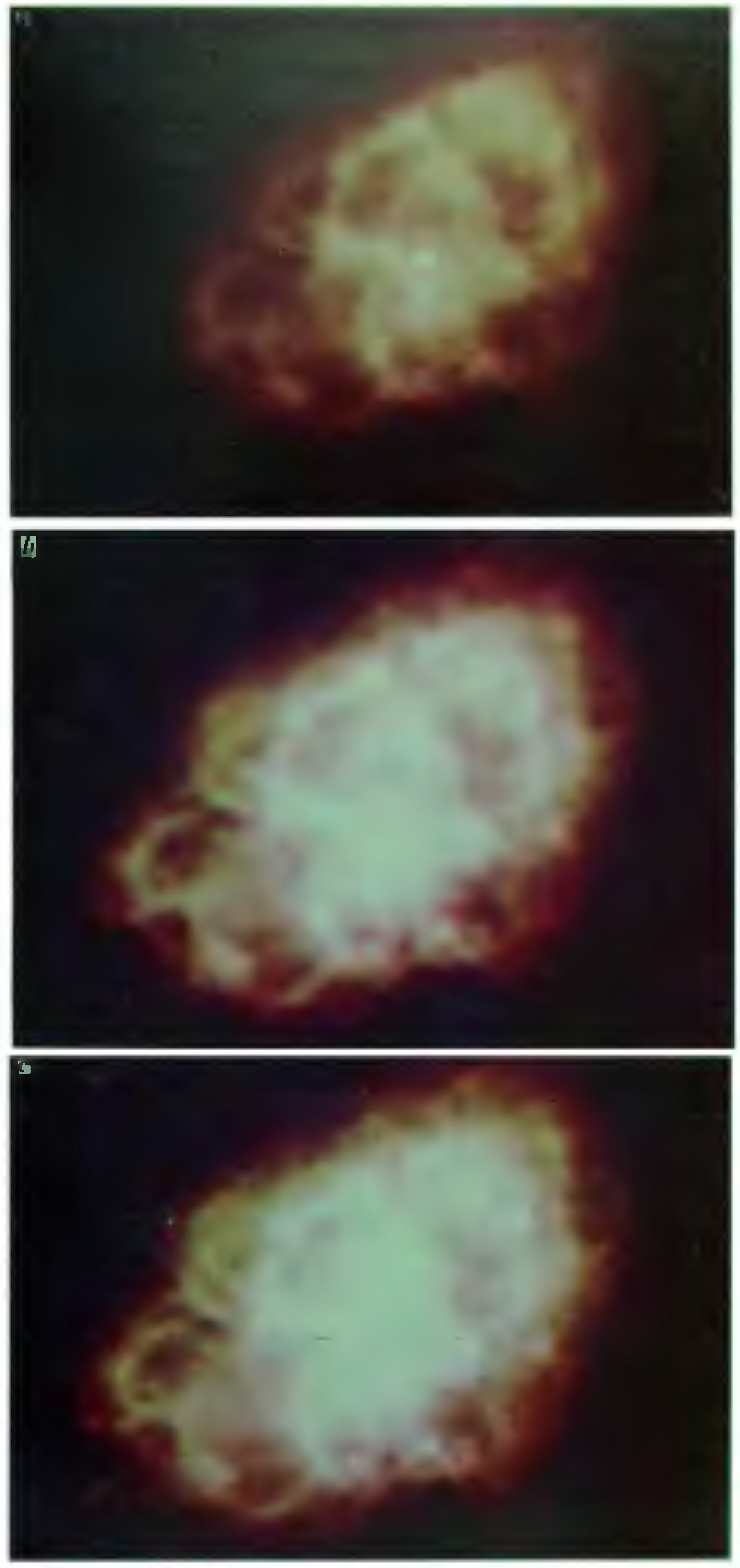

Figure 2. Photographic representation of the radio brightness distribution of the Crab nebula (*a*) at 327 MHz with a resolution of 5″ × 5″, (*b*) at 1.5 GHz (reproduced from Velusamy[6]) and (*c*) at 5 GHz with a resolution of 4″ × 4″ (this paper).

resolution observations. The VLA observations at 327 MHz were made in the D, B and A configurations. The D-array observations were made during May 1987 in the spectral-line mode for a total of 4 h at 332 MHz with a bandwidth of 0.6 MHz. The B- and A-array observations were made during March 1989 and December 1989 respectively in continuum mode using both IFs with bandwidths of 3 MHz. The duration of the observation was about 2 h in the B and 6 h in the A configurations. Self-calibrated maps were made using the standard techniques. Figure 2 shows the photographic representation of maps of the Crab nebula at 327 MHz with a resolution of 5×5 arcsec^2; also shown are the VLA images of the Crab at 1.5 and 5 GHz with 4×4 arcsec^2 resolution. The VLA 1.5-GHz image is reproduced from Velusamy[6]. The observations for the 5-GHz image were made in C array for 6 h during May 1984. We have also used D-array data obtained in snapshot observations (10 min) during August 1984 and in 6 h of observations during November 1982 from the archives.

The most striking feature in the 327-MHz image shown in Figure 2 is the pulsar seen as a point source. The filaments and overall structure of the Crab at the three frequencies show remarkable resemblance. It may be noted that such an image, bringing out the details of the filaments and also the pulsar, is being presented for the first time. As pointed out by Velusamy[6], the distribution of the radio filaments in Figure 2 is consistent with an inner shell of diameter ~3 arcmin formed by the bright filaments and knots and a system of filaments filling the outer volume. Some of the outer filaments are connected to this inner shell by loop-like features representing the magnetic field structure. The inner shell may represent the region of interaction of the pulsar wind with the stellar ejecta. The images in Figure 2 have been enhanced to bring out the sharp features more clearly, and therefore the underlying smooth brightness distribution is not fully represented. Although the jet is not obvious in these images, it is seen clearly when the low surface brightness is enhanced. These images are extremely valuable for a detailed multifrequency investigation of the individual filaments and the diffuse nebular emission. However, the dynamic range in the 327-MHz image is rather low (~200), compared to that in the higher-frequency images (> 1000). This has been caused by poor UV coverage due to lack of data in B and C configurations. Observations in the B/C configuration have been made very recently and the data are being processed. The detailed analysis of the radio emission from the nebula, filaments, etc. will be presented later. In this paper we highlight only the emission from the pulsar and the jet.

The pulsar is detected as a point source with a flux density of 2.3 Jy at 327 MHz; it was not detected at 1.5 and 5 GHz. The pulsar is located in a local minimum between two bright filaments. The upper limit to the pulsar flux at 1.5 GHz is 10 mJy. The continuum flux at 327 MHz is quite consistent with the spectrum given by Rankin *et al.*[10]

Although the jet is clearly seen in the high-resolution images, the signal-to-noise ratio over the jet, especially at 327 MHz, is not adequate for any quantitative study. Therefore we have smoothed the images at 327 MHz and 1.5 GHz to a lower resolution of 14.7×12.7 arcsec^2, and in Figure 3 is shown the brightness distribution over the jet. The rms noise in these low-resolution maps are 12 and 3 mJy/beam respectively at 327 MHz and 1.5 GHz. Because of the higher sensitivity at 1.5 GHz, the brightness is seen at much lower levels at this frequency than at 327 MHz. In the 327-MHz map there is a residual negative 'bowl' along the nebular boundary at levels of 20–50 mJy/beam. This is possibly due to imperfect cleaning caused by poor UV coverage. The new VLA observations in B/C configuration should improve the 327-MHz map considerably and enable reliable investigation at very low brightness. Nevertheless, the present data show the prominence of the radio jet at low frequencies, confirming the OSRT results. Furthermore, there is a clear correlation between the maps in Figure 3: the extension of the jet far out to the north, up to declination 22°04′00″ with a slight tilt to the west, is clearly seen at both frequencies. A detailed comparison of these low-resolution maps at 327 MHz and 1.500 GHz shows that the spectral index within the nebula is typically in the range -0.2 to -0.3. As seen from the intensity contours in Figure 3, the spectral index varies significantly outward along the jet, reaching a value of ~ -0.6 at the outer edge. As mentioned earlier a detailed and more reliable multifrequency investigation will be presented later with the full synthesis VLA map at 327 MHz.

The origin of the jet is not fully understood yet. The most obvious model would be that it is the result of a high-velocity flow originating from the pulsar. However, this seems unlikely, because of the absence of counter-jet, any geometrical relation to the pulsar and its rotation axis, and inconsistency with the observed magnetic field structure over the jet[11]. Furthermore, the steeper spectral index, in the range ~ -0.4 to -0.6, for the radio emission as suggested in this paper indicates that the electron energy spectrum in the jet is steeper than inside the nebula. The relativistic electrons in the jet may have a different origin from those within the nebula. This supports the models in which the jet is a result of instability in the filamentary shell or represents a 'shadow flow' where a gas cloud is overtaken by the ballistic flow of the stellar envelope ejected in supernova explosion[12]. The latter model is quite

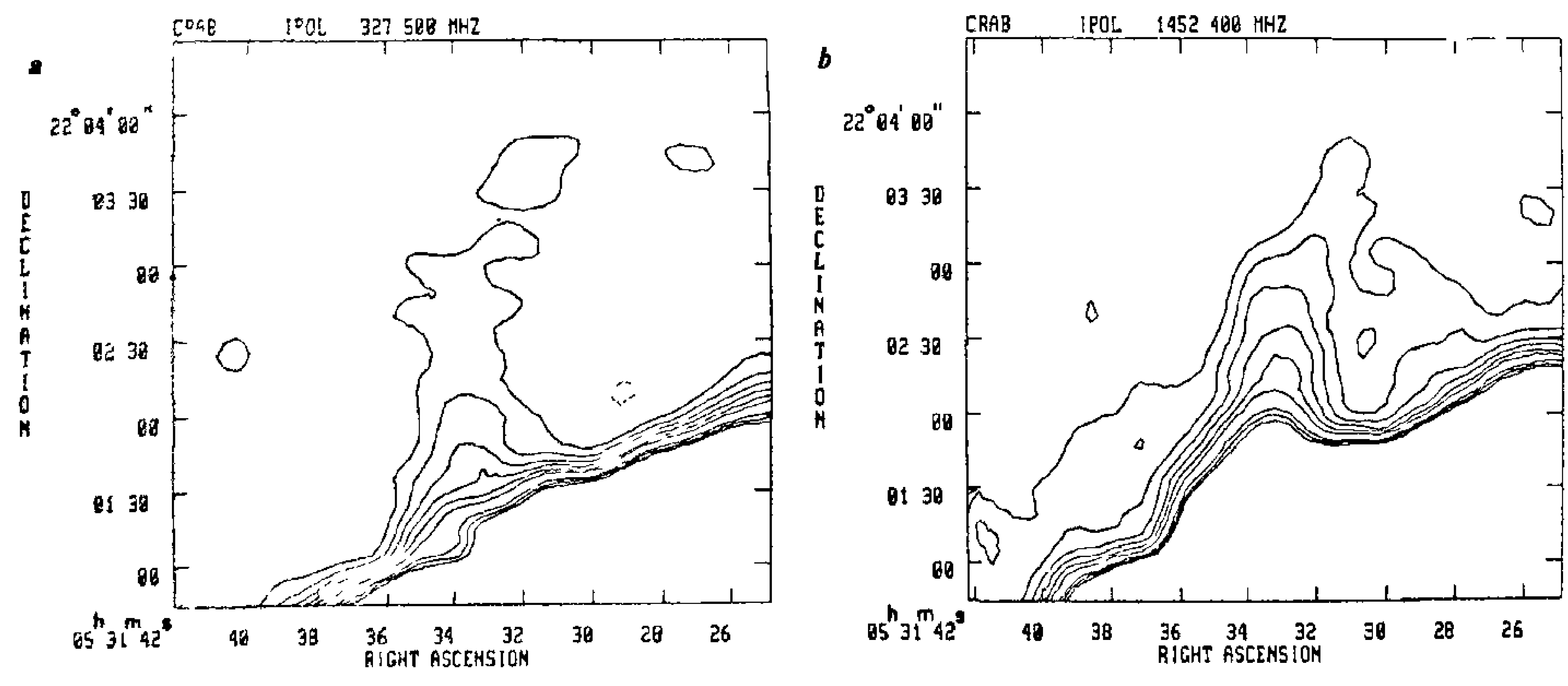

Figure 3. Low-resolution contour map of the jet region with a restoring beam of 14.7″ × 12.7″ at a position angle of −68° (*a*) at 327 MHz (contour intervals are 60 mJy/beam) and (*b*) at 1.5 GHz (contour intervals are 10 mJy/beam).

attractive since it explains the geometry and kinematics of the jet and is also consistent with a radio spectrum that is distinct from the nebular spectrum.

1. van den Bergh, S., *Astrophys. J. Lett.*, 1970, **160**, L27.
2. Gull, T. R. and Fesen, R. A., *Astrophys. J. Lett.*, 1982, **260**, L75.
3. Velusamy, T., *Nature*, 1984, **308**, 251
4. Wilson, A. S., *Mon. Not. R Astron. Soc.*, 1972, **157**, 229.
5. Swinbank, E. and Pooley, G., *Mon. Not. R. Astron. Soc.*, 1979, **186**, 775.
6. Velusamy, T., in *Proc. Workshop on 'Crab Nebula and Related Supernova 'Remnants'* (eds. Kafados, M. and Henry, R. B.), Cambridge University Press, 1984.
7. Sukumar, S., Velusamy, T., Pramesh Rao, A., Swarup, G., Bagri, D. S., Joshi, M. N. and Ananthakrishnan, S., *Bull. Astron. Soc. India*, 1988, **16**, 93.
8. Napier, P. J., Thompson, A. R. and Ekers, R. D., *Proc. IEEE*, 1983, **77**, 1295.
9. Velusamy, T., *Mon. Not. R. Astron. Soc.*, 1985, **212**, 359.
10. Rankin, J. M., Comella, J. M., Craft, Jr, H. D., Richards, D W and Campbell, D. B., *Astrophys. J.*, 1970, **162**, 707
11. Bietenholz, M. F. and Kronberg, P. P., *Astrophys. J.*, 1990, **357**, L13.
12. Morrison, P. and Roberts, D., *Nature*, 1985, **313**, 661.

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