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Radio observations of the S0 galaxy NGC 1218 (3C 78)

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Summary. We present VLA observations of the S0 galaxy NGC 1218 at $\lambda 20$ and 6 cm with both the A and D arrays, at $\lambda 20$ cm with the B array and at $\lambda 2$ and 1.3 cm with the A array. We also present VLBI observations at $\lambda 6$ cm with the European Network. The high-resolution radio observations reveal a flat-spectrum core and a one-sided jet whose width increases with distance from the nucleus. Assuming Faraday rotation to be small at $\lambda 6$ cm, the magnetic field lines in the outer region of the jet are inclined to its axis and appear to diverge. The large-scale structure does not exhibit well-defined lobes but forms an extended halo with a largely circumferential magnetic field. We suggest that the observed one-sidedness of the jet could perhaps be due to a difference in the collimation of the jets on opposite sides of the nucleus, in addition to any possible effects of relativistic beaming.

1 Introduction

The radio source 0305+039 (3C 78) associated with the S0/a galaxy NGC 1218 (m_p=14 and z=0.0289) has been observed at radio frequencies by a number of authors (*cf.* Unger, Booler & Pedlar 1984, and references therein). These observations span a large range in angular resolution and cover both low and high frequencies. The large-scale structure ($\gtrsim$1 arcmin) has been

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determined by Fomalont (1971) and Slee (1977) at 1415 and 160 MHz respectively. Fomalont found the source to be of the core–halo type with an angular extent of ~80×55 arcsec^2, while Slee's observations showed that, in addition to this structure, there appeared to be an extension towards the north-west. At resolutions of ~1 arcsec or so, the radio core and a one-sided jet have been observed by the VLA at λ6 and 20 cm (Jones, Sramek & Terzian 1981b; Perley 1982), and by MERLIN at λ73, 18 and 6 cm (Unger *et al.* 1984). On VLBI scales, the nucleus has a core-jet structure with the milliarcsec-scale jet roughly aligned with the larger-scale one (Jones, Sramek & Terzian 1981a; Jones 1984). The rotation measure of 3C 78 (l=174°.9, B=−44°.5) has been reported to be 14±2 rad m^{-2} with an intrinsic position angle of 85°±3° by Simard-Normandin, Kronberg & Button (1981), and 8.7±1.9 rad m^{-2} with an IPA 87°±4° by Tabara & Inoue (1980). Heckman *et al.* (1983a) have made neutral hydrogen observations of this source and find $M_{\rm H\,I}$ to be <36×10^9 $M_\odot$.

In this paper we present VLA observations of this source at λ20 and 6 cm with both the A and D arrays, at λ20 cm with the B array and at λ2 and 1.3 cm with the A array. We also present VLBI observations with the European Network. This is followed by a brief discussion.

2 Observations

The VLA A-array observations were made on 1982 June 18 along with a sample of 29 other galaxies which were observed to study the spectra of their cores (Saikia, Cornwell & Kapahi, in preparation). The source was observed for ~3 min each at 1465 (20 cm) and 4885 MHz (6 cm), and for ~10 min each at 14 965 (2 cm) and 22 485 MHz (1.3 cm). The source was observed with the D-array on 1983 June 29 for ~10 min each at 1465 and 4885 MHz, and with the B-array on 1984 January 30 for about 30 min at 1420 MHz. In all these observations the bandwidth used was 50 MHz. The primary flux density and polarization calibrators were 3C 48 and 3C 386. The radio

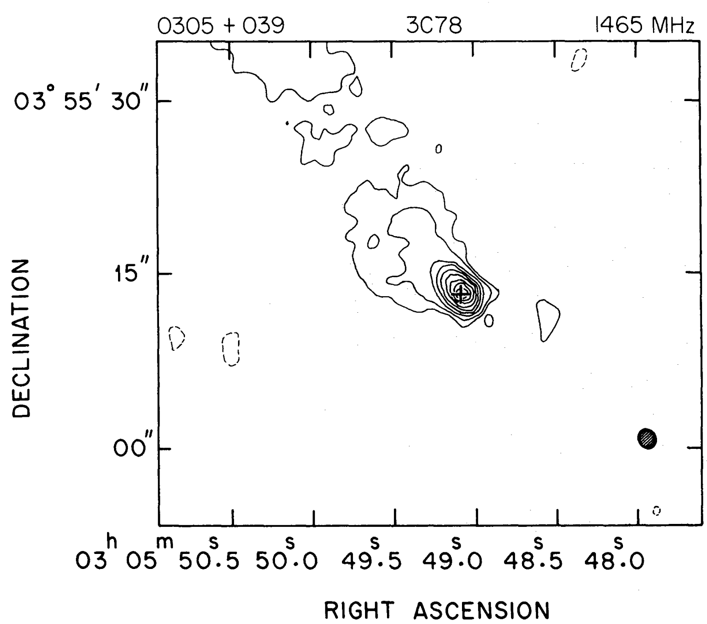


Figure 1. The λ20-cm map of the nuclear region of 3C 78 (NGC 1218) with a resolution of 1.55×1.44 arcsec^2 along PA 31°. Peak brightness=752 mJy/beam. Contours: 7.52×(−0.5, 0.5, 1, 3, 5, 10, 20, 40, 60, 80) mJy/beam. In Figs 1–5, the cross marks the position of the centre of the optical galaxy (RA: 03^h 05^m 49^s.08; Dec: 03° 55′ 13″.2) measured by Palimaka, Bridle & Fomalont (1980), while the beams are shown by hatched ellipses.

data were calibrated via standard VLA DEC-10 computer programs. All the maps presented here have been made from a self-calibrated data base (Schwab 1980).

The VLBI observations of NGC 1218 were made on 1983 June 6 using the telescopes at Jodrell Bank, Effelsberg, Westerbork & Onsala. The Mk II recording system was used at an observing frequency of 5 GHz and bandwidth of 2 MHz. The total duration of the observations was ~10 hr.

3 Results

3.1 RADIO STRUCTURE

In Figs 1 and 2 we show the A-array maps at λ20 and 6 cm made with resolutions of 1.55×1.44 arcsec^2 along PA 31°, and 0.48×0.41 arcsec^2 along PA 20°.5 respectively. The rms noise in the maps are about 0.70 and 0.60 mJy/beam respectively. There is a prominent radio jet towards the north-east, with its width increasing with distance from the nucleus. To investigate whether there is a weak counter-jet visible in the A-array data we made several maps at λ20 cm, editing the data at various stages and also varying the self-calibration parameters. Although there is a suggestion of weak radio emission on the opposite side, a better map is required to confirm it. Assuming Faraday rotation to be small at λ6 cm, the magnetic field lines in the outer regions of the jet are inclined to its axis and appear to diverge. If there is outflow of radio-emitting material along the assumed field lines, the width of the jet could increase significantly with distance from the core. The polarization of the core at λ6 cm is ~1 per cent along PA~45°.

In Fig. 3 we show our λ2-cm map along with the VLBI map made by Jones (1984). Our VLBI

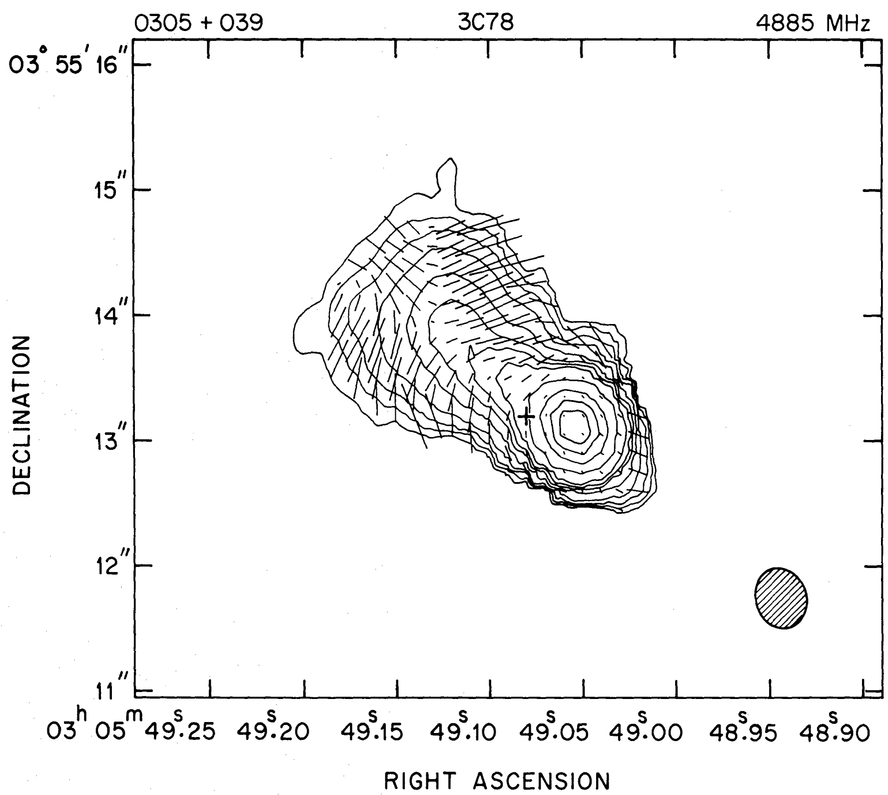


Figure 2. The λ6-cm map of the nuclear region with a resolution of 0.48×0.41 arcsec^2 along PA 20°.5. Peak brightness=628 mJy/beam. Contour levels: 6.28×(−0.4, 0.4, 0.6, 0.9, 1.5, 3, 5, 7, 10, 20, 40, 60, 80) mJy/beam. Polarization: 1 arcsec=55 per cent polarization.

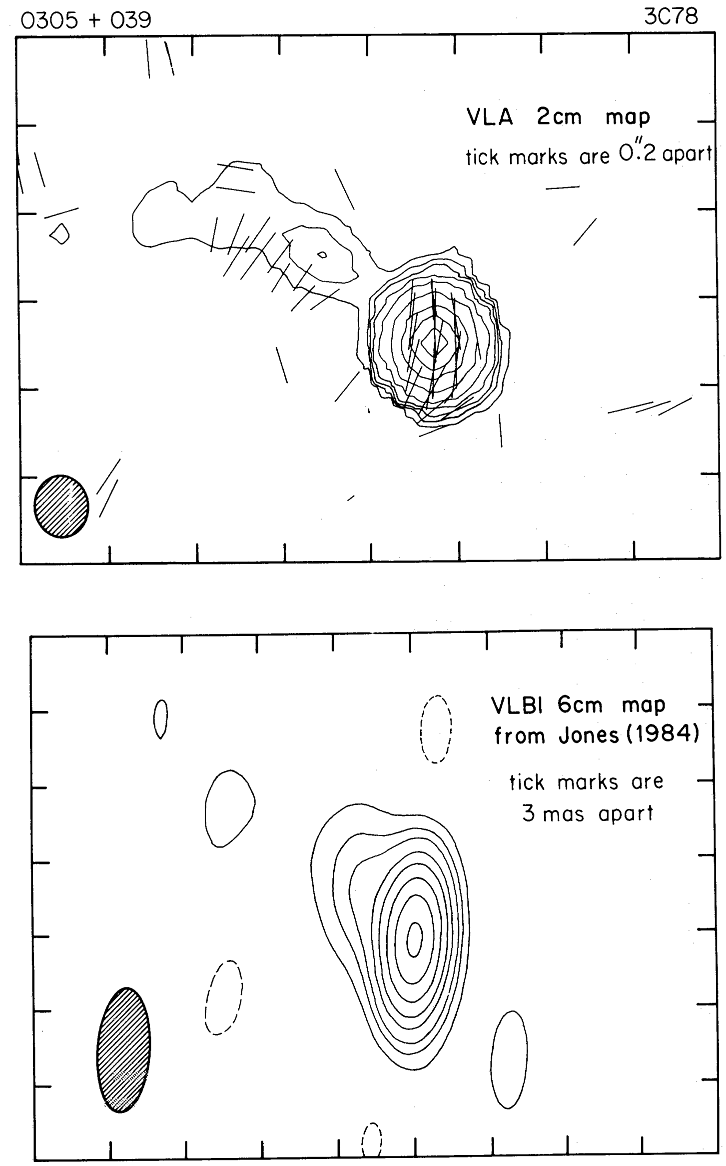


Figure 3. The λ2-cm VLA map, and the λ6-cm VLBI map made by Jones (1984). The parameters for the VLA map are as follows. Beam size: 0.145×0.128 arcsec^2 along PA 1°. Peak brightness=689 mJy/beam. Contour levels: $6.89\times(-1, 1, 2, 3, 5, 10, 20, 40, 60, 80)$ mJy/beam. Polarization: 1 arcsec=37 mJy/beam. The peak brightness in the VLBI map which has a resolution of 5×2 mas^2 along PA $-5°$ is 400 mJy/beam, and the contours are $4\times(-5, 5, 10, 15, 25, 35, 50, 70, 95)$ mJy/beam.

map at λ6 cm made with a restoring beam of 10×10 milliarsec^2 has a dynamic range of ~30–1, but shows only a point source with a flux density of 680 ± 60 mJy. The λ2-cm map made with a resolution of 0.145×0.128 arcsec^2 along PA 1° has an rms noise of about 1.5 mJy/beam. The data for this map were self-calibrated assuming a point source model with flux density 700 mJy. The polarization in the jet is only very marginally significant, but its PA appears to be close to the vectors seen near the core in the λ6-cm map. The core appears to be ~1.5 per cent polarized at λ2 cm. The jets seen at all scales ranging from the arcsec to the milliarcsec scale are inclined at a PA of ~50°. At λ1.3 cm, we detect only the core which appears to be <2 per cent polarized.

The B-array λ20-cm map (Fig. 4) made with a resolution of 4.2×4.2 arcsec^2 shows that, in addition to the core and the jet towards the north-east, there is also a counter-jet and a diffuse

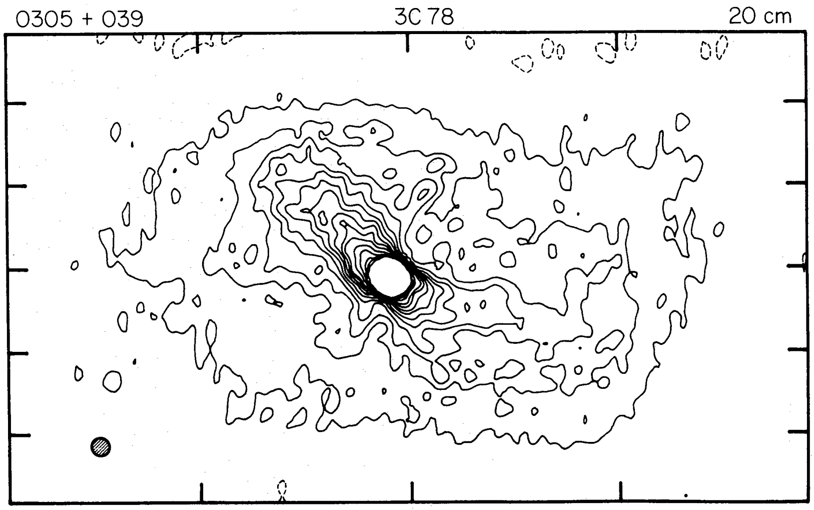


Figure 4. Map of 3C 78 (NGC 1218) using the VLA B configuration at 1420 MHz. The angular resolution is 4.2×4.2 arcsec^2. Contour levels are −4.8, 4.8, 9.5, 14.3, 19.1, 23.8, 28.6, 33.4, 38.1, 42.9, 47.7, 57.2, 66.8, 76.3, 85.8 and 95.4 mJy/beam. The peak brightness is 1192 mJy/beam. The tick marks are at intervals of 50 arcsec along the x-axis and at intervals of 20 arcsec along the y-axis.

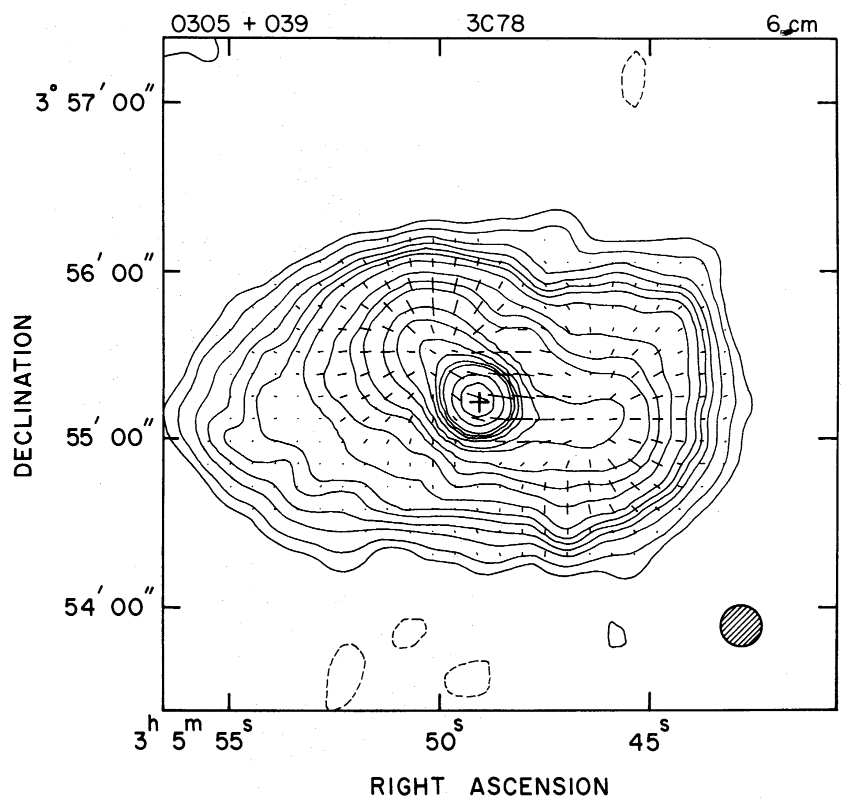


Figure 5. The large-scale structure of 3C 78 (NGC 1218) at λ6 cm with a resolution of 15×15 arcsec^2. Peak brightness = 1175 mJy/beam. Contours: −1.5, 1.5, 3, 6, 9, 12, 15, 20, 30, 40, 50, 75, 100, 150, 200, 250, 300, 500, 800 mJy/beam. Polarization: 1 arcsec = 4.1 mJy/beam.

halo in which all these features are embedded. The extent of the halo can be seen clearly in the lower resolution D-array maps at λ6 and 20 cm. The λ6 cm map, which has a resolution of 15×15 arcsec^2 and an rms noise of ~0.5 mJy/beam, shows that the radio emission extends to about 3.5×2 arcmin^2 (Fig. 5). This is much larger than the size of the halo suggested by Fomalont

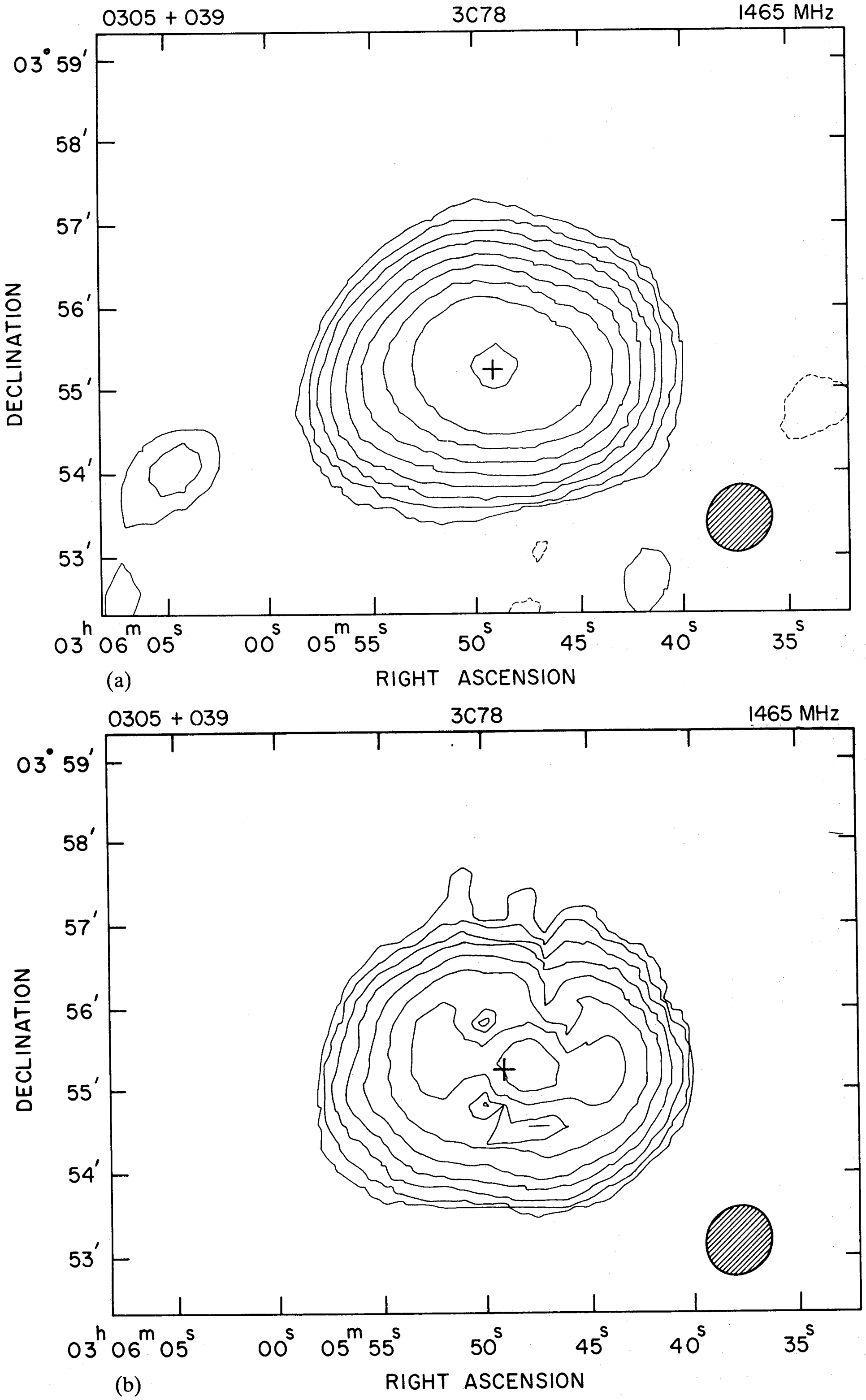
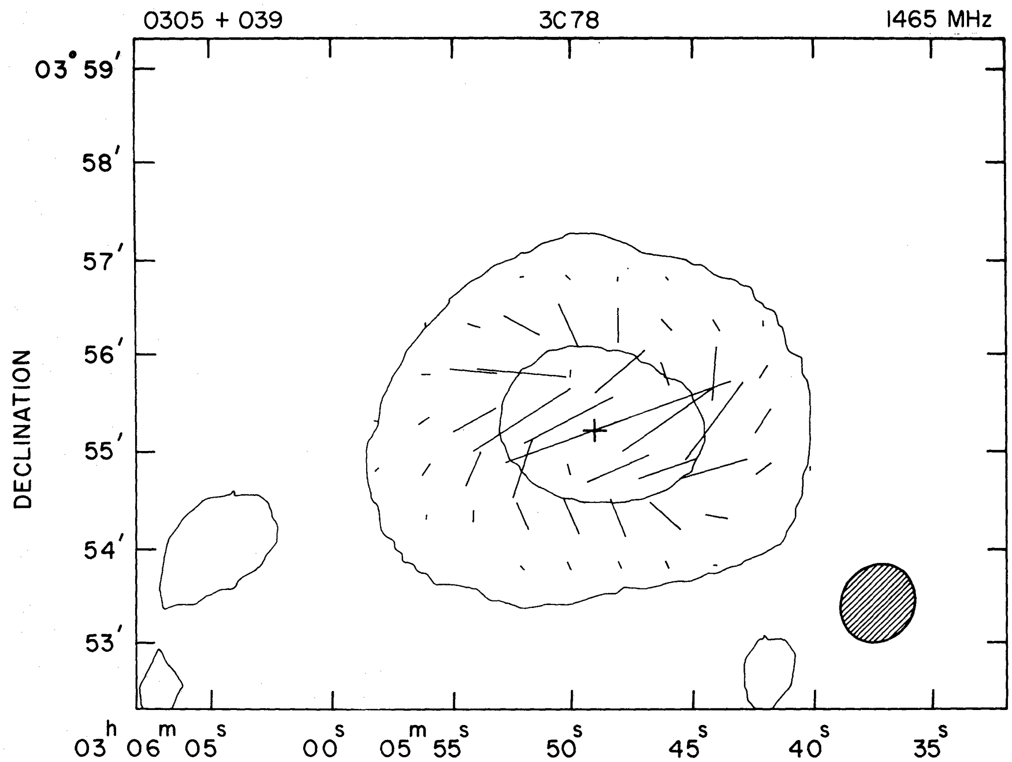


Figure 6. (a) The large-scale structure of 3C 78 (NGC 1218) at λ20 cm with a resolution of 50.7×45.6 arcsec^2 along PA −31°. Peak brightness=3130 mJy/beam. Contours: 5×(−2, −1, 1, 2, 4, 8, 16, 32, 64, 128, 512) mJy/beam. (b) The polarized intensity distribution of 3C 78 (NGC 1218) at λ20 cm with a resolution of 50.7×45.6 arcsec^2 along PA −31°. Peak brightness =213 mJy/beam. Contours: −2, −1, 1, 2, 4, 8, 16, 32, 64, 128 mJy/beam. (c) The total-intensity map of 3C 78 (NGC 1218) at λ20 cm with the polarized intensity vectors superposed. Peak brightness=3130 mJy/beam. Polarization: 1 arcsec=1.42 mJy/beam. Contour levels: 5, 640 mJy/beam. The resolution is again 50.7×45.6 arcsec^2 along Pa ×31°.



(c)

Figure 6 – *continued*

(1971) and extends significantly beyond the size of the galaxy seen on the Palomar Sky Survey prints. The large-scale structure exhibits no well-defined lobes, let alone hot- or warm-spots, but appears to form an extended halo. Assuming the rotation measure to be small at this frequency, the magnetic field lines appear to be largely circumferential. The λ20 cm total intensity map, Fig. 6(a), with a resolution of 50.7×45.6 arcsec^2 along PA $-31°$ and rms noise of ~2 mJy/beam, shows no new features. In particular, we do not see the extension towards the north-west in Slee's (1977) map. The λ20 cm polarization maps of resolution 50.7×45.6 arcsec^2 along PA 31° and rms noise of ~0.3 mJy/beam are shown in Fig. 6(b) and (c). The orientation of the **E**-vector at the pixel of maximum polarized intensity is close to the integrated values listed by Tabara & Inoue (1980).

3.2 RADIO SPECTRUM OF THE CORE

In Fig. 7 we show the spectrum of the entire source adapted from Kühr *et al.* (1981), and the spectrum of the core using our VLA measurements and the MERLIN values determined by Unger *et al.* (1984). Our VLA core flux densities, which are peak values estimated from the maps, are 752, 628, 689 and 640 mJy at λ20, 6, 2 and 1.3 cm respectively. Comparing our values at λ20 and 6 cm with those determined by Perley in late 1980 and early 1981, we find his values to be only slightly higher at both frequencies, indicating no large variations of core flux density over a period of ~1½ yr. However, Jones *et al.* (1981b), who observed this source with the VLA in 1980 June, found the maximum brightness at λ6 cm to be only ~350 mJy/beam. Unger *et al.* (1984), on the other hand, found the core flux density at λ6 cm to be ~700 mJy on 1982 May 7. The VLBI observations by Jones (1984, and references therein), Preuss *et al.* (1977) and the present observations also suggest that the core might be variable. Careful monitoring is, however, required to determine its variability characteristics. The VLA λ20 cm flux density appears to be

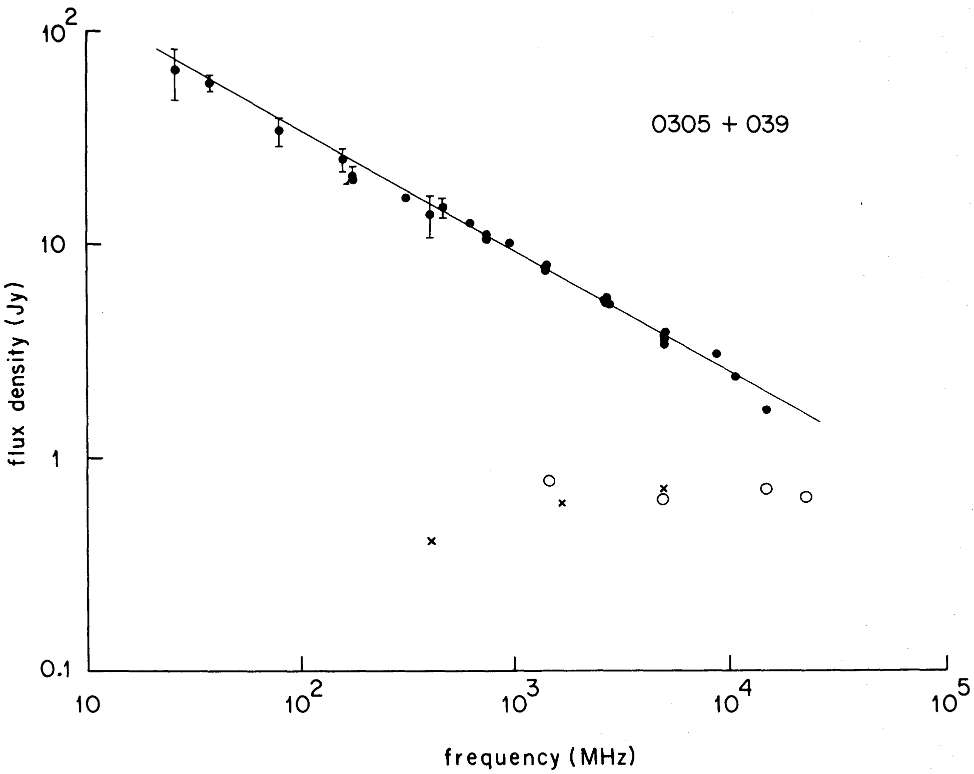


Figure 7. Integrated spectrum of the source using the total flux densities listed by Kühr *et al.* (1981), and the spectrum of the core. Our VLA measurements of core flux densities are shown by open circles while the MERLIN measurements by Unger *et al.* (1984) are shown by crosses.

significantly higher than the MERLIN value at λ18 cm. This is probably due to the larger VLA beam at this frequency. The core spectrum is flat from ~2–22 GHz, but appears inverted below ~2 GHz.

4 The optical nucleus

A *V*-band photograph obtained with the 1-m reflector of Kavalur Observatory at an image scale of 16 arcsec mm^{-1} shows that the nucleus is distinct and starlike. The full width at half maximum of the nucleus is 3.0 arcsec after correcting for the 2.2-arcsec seeing. No asymmetry or structure is evident. Heckman *et al.* (1983b) find weak emission lines, and significant non-stellar continuum flux at 3850 Å, suggesting mild activity of the optical nucleus. From their *HKLN* photometry, Heckman *et al.* also find evidence of an excess in the near-infrared, although this excess is not as high as in other nuclei in their sample.

5 Discussion

The increase in width of the jet with distance from the nucleus, the absence of any prominent hot- or warm-spots and the structure of the extended emission suggest that the jet expands into the extended halo, perhaps decollimating as it traverses the density gradients of the external medium. In addition to the prominent jet towards the north-east, there is a counter-jet which can be clearly seen in the B-array map. Besides any possible effects due to relativistic beaming, the apparent asymmetry of the arcsec-scale radio jets is perhaps due to differences in collimation of the oppositely directed jets. In the high-luminosity sources, such as in quasars, where prominent hot-spots are usually, though not always, seen on both sides of the nucleus, and the jets generally appear well-collimated, the collimation is perhaps similar for the oppositely-directed jets. Here, the apparent one-sidedness could be largely due to relativistic beaming (Saikia 1984). There are, however, examples such as in the quasar 1004+13 (Fomalont 1981), where the jet appears to broaden into a diffuse lobe without forming any high-brightness feature. In the low-luminosity sources, the jets are broader, smoother and often appear just to fade away. In such sources, jets might appear one-sided even with moderate resolution if the collimations of the fluid on opposite sides of the nucleus are very different. We suspect that this might be the reason, at least partly, for the observed asymmetry in the arcsec-scale jets in 3C 78.

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