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14.8-GHz mapping of the extended radio core in NGC 1167

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Summary. The radio source in the 12 mag S0 galaxy NGC 1167 has been mapped at 0.8 arcsec by 0.35 arcsec resolution using seven antennas of the VLA at 14.8 GHz. The source has an asymmetric structure similar to that in the 2-kpc core of the giant radio galaxy 3C 236. Physical properties of the components of the two extended sources are compared.

In a recent study of small-diameter components in extended radio galaxies (Bridle & Fomalont 1978) we introduced the term 'extended radio core' to describe a class of radio structure found within some elliptical radio galaxies. These extended cores have radio continuum spectra steeper than $\nu^{-0.4}$ and linear sizes generally $\gtrsim 1$ kpc; they also appear to exhibit a spectrum–luminosity correlation analogous to that evidenced by straight-spectrum radio galaxies and quasars (Bridle, Kesteven & Guindon 1972b; Véron, Véron & Witzel 1972; MacLeod & Doherty 1972). The extended cores described by us previously are all associated with larger-scale radio structures outside their parent galaxies. We report here new high-resolution 14.8-GHz observations of NGC 1167 which show that it contains an extended core 'in isolation', i.e. without detectable large-scale emission.

NGC 1167 (= 0258 + 350) has been recognized as a radio galaxy since its identification with 4C 39.04 (Aizu 1966; Caswell & Wills 1967; Wills 1967a; Olsen 1970). It has consistently been reported as a small-diameter radio source without halo emission (e.g. Bridle *et al.* 1972a; Colla *et al.* 1975). We first observed it with the NRAO four-element interferometer at 2.695 and 8.085 GHz during a study of elliptical and S0 galaxies over 35-km baselines (Bridle & Fomalont 1978). We found that all of the 2.7-GHz flux density detected by Kesteven, Bridle & Brandie (1976) at the NRAO 91-m telescope was confined to an angular scale $\lesssim 4$ arcsec, and that most of this emission originated in two components with angular scales of order 1 and 2 arcsec. We therefore included the source in a program to test 14.8-GHz mapping procedures at the Very Large Array (VLA) now being brought into operation in New Mexico.

The 14.8-GHz observations were made with seven antennas of the VLA during 1978 April 14–16. The 25-m antennas were stationed on the south-west arm (34° south of west) at 44.85, 147.33, 484.00, 970.50, 1589.92, 3188.09 and 7659.48 m from the Wye centre. The observing frequency was 14.765 GHz and two independent 50-MHz channels sensitive to the two circular polarizations were used. System temperatures of ~350 K were obtained with the front-end configuration described by Weinreb *et al.* (1977). All antenna outputs were correlated, providing 21 interferometer pairs.

Twenty-six 13-min observations were made, distributed in hour angle to optimize (u, v) coverage. Gain and phase fluctuations due to the instrument and to tropospheric irregularities were monitored by interspersing the 13-min observations of NGC 1167 with 5-min observations of the compact source in NGC 1275 (3C 84), which is ~7°.2 away. Data obtained during periods when the monitoring of NGC 1275 showed excessive phase fluctuations were discarded; the remaining 13 scans of NGC 1167 (~160 min of data) span the hour-angle range from $-4^h 10^m$ to $+6^h 50^m$. The theoretical antenna pattern resulting from our edited (u, v) coverage and weighting functions has a main lobe with FWHM of 0.75 × 0.35 arcsec in pa 130°, and ≈ 20 per cent side lobes at about 1 arcsec from the peak. We reduced the effects of these side lobes on the final map using a CLEAN deconvolution algorithm (e.g. Högbom 1974).

Fig. 1 shows a CLEANed map of NGC 1167 at 14.8 GHz, restored with a Gaussian antenna pattern having FWHM 0.8 × 0.35 arcsec in pa 130°. The peak (B) on this map is 130 mJy at $\alpha(1950) = 02^h 58^m 35^s.37$, $\delta(1950) = +35° 00' 32''.0$ (relative to our adopted position of $03^h 16^m 29^s.56$, $+41° 19' 51''.86$ for the core of NGC 1275). This peak has an intrinsic FWHM of 1.2 arcsec in pa 123 ± 5° and an integrated flux density of 260 mJy. North-preceding this peak is a well-resolved feature (A) extending ~2 arcsec along pa ~140°. The total intensity in (A) and in low-level emission around (B) is 300 ± 100 mJy, the large uncertainty arising from the integration of the low-brightness emission. The largest angular size of the source, measured across the 10 per cent peak intensity contours, is ~4 arcsec.

The redshift of NGC 1167 is ~0.0165 (Sargent 1973; Wills & Wills 1976). Taking $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, the distance to the system is 99 Mpc, the linear half-widths of features (A)

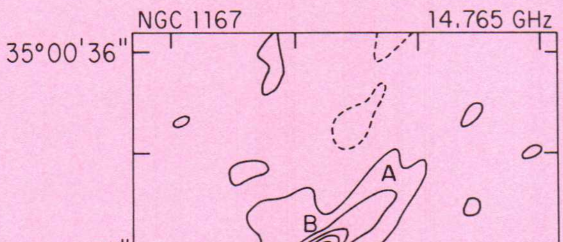

Figure 1. Radio map of NGC 1167 at 14.8 GHz. The bold contour levels are at +13, 39, 65, 91 and 117 mJy/beam. The dashed contours are at −13 mJy/beam. The cross-hatched ellipse shows the FWHM of the clean beam (0.8 × 0.35 arcsec in pa 130°). The bold cross depicts the optical position of the centre of the galaxy, as measured by Wills & Wills (1976). The two components A and B are indicated.

Table 1. Flux densities of NGC 1167 at various frequencies.

Frequency (GHz)	Flux density (Jy)	Reference
0.178	$5.1^{+1}_{-0.7}$	Pilkington & Scott (1965)*
0.408	3.91 ± 0.31	Colla *et al.* (1973)
1.400	1.88 ± 0.06	Bridle *et al.* (1972a)
2.695	1.29 ± 0.02	Kesteven *et al.* (1976)
2.695	1.31 ± 0.01	Pauliny-Toth *et al.* (1978)
4.900	0.926 ± 0.012	Pauliny-Toth *et al.* (1978)
8.085	0.70 ± 0.03	This paper, NRAO data
10.690	0.65 ± 0.04	Pauliny-Toth *et al.* (1978)
14.765	0.56 ± 0.10	This paper, VLA data

* Adjusted to the flux-density scale of Bridle *et al.* (1972b).

and (B) are 0.55 and 0.95 kpc and the overall extent of the source is 1.9 kpc. The continuum radio spectrum of the entire core (Table 1 and Fig. 2) is consistent with a power law $S(\nu) \propto \nu^{-0.54 \pm 0.01}$ over the frequency range 0.178–14.8 GHz, although a slight flattening of the spectrum above ~10 GHz is also possible. The ≈ 2-kpc linear scale of the source and its spectral index of 0.54 place it in the category of 'extended radio cores' defined by Bridle & Fomalont (1978).

It is of interest to compare the physical properties of this extended core with those of one associated with large-scale emission outside its galaxy. Table 2 compares parameters of NGC 1167 with those of 3C 236, the only other system whose core has been mapped in comparable detail (Fomalont & Miley 1975; Fomalont, Miley & Bridle 1978). The energy densities and equipartition field strengths *within the resolved subcomponents* of the two extended cores are very similar, despite the > 60:1 difference in overall 2.7-GHz luminosities. Comparison of Fig. 1 with the 2.7- and 14.8-GHz maps of 3C 236 (Fomalont & Miley 1975; Fomalont *et al.* 1978) shows that both cores are *asymmetric* 'double' structures in which the component with the greater flux density has the larger angular scale.

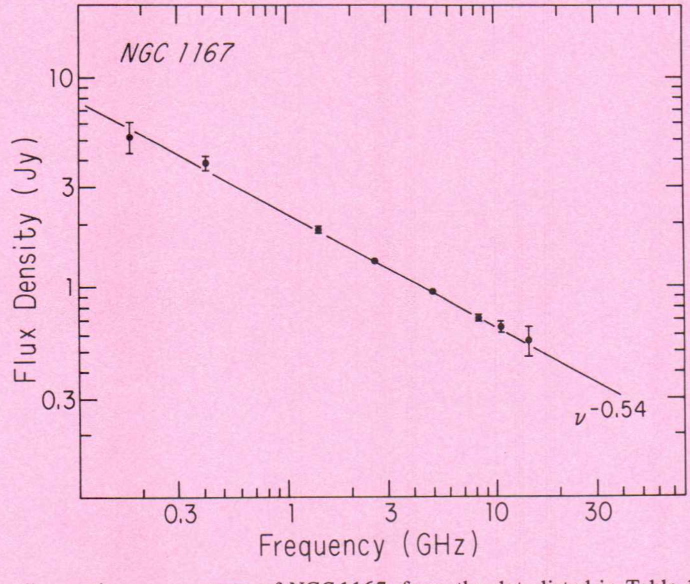

Figure 2. The radio continuum spectrum of NGC 1167, from the data listed in Table 1. A power law of slope $\nu^{-0.54}$ is drawn through the data.

Table 2. Physical parameters of the extended radio cores in NGC 1167 and in 3C 236.

	NGC 1167	3C 236
Overall linear size of core (kpc)	1.9	1.95
Monochromatic luminosity at 2.7 GHz ($W Hz^{-1}$)	1.4×10^{24}	9.3×10^{25}
Spectral index	0.54 ± 0.01	0.67
Absolute visual magnitude of galaxy	−23.0 mag	−23.1 mag
Energy density in core components ($J m^{-3}$)★	$\sim 9 \times 10^{-10}$	$\sim 3 \times 10^{-9}$
Equipartition magnetic field in core components★ (gauss)	$\sim 3 \times 10^{-4}$	$\sim 5 \times 10^{-4}$

★ Assuming equipartition of energy between relativistic electrons, relativistic protons and magnetic energy with a power-law radio spectrum from 10 MHz to 100 GHz. Estimates for 3C 236 are for component A only; for NGC 1167 values quoted are average of values for two main emission peaks, A and B. $H_0 = 50\ km\ s^{-1}\ Mpc^{-1}$ has been assumed.

It should be emphasized that we do *not* know that these two broadly double extended cores are symmetrically placed within the optical galaxies, i.e. that they are 'miniature double sources' around the galactic nuclei. Their asymmetrical structures could be 'one-sided jets' whose angular scale increases towards the north-west in each source. Indeed, the best available estimate for the position of the optical centre of NGC 1167, measured from a glass copy of the *Palomar Sky Survey* by Wills & Wills (1976) places this centre 0.6 arcsec following and 0.6 arcsec south of peak (B) on our map (see Fig. 1). Confirmation of this position as that of the 'bright nucleus' reported by Wills (1967b) would imply that the extended core of NGC 1167 is in fact a 'one-sided jet' structure.

It has been postulated (Fomalont & Miley 1975; Bridle & Fomalont 1978) that the extended cores of radio galaxies are related to the processes resulting in the collimation of the energy flow to extended radio structures from galactic nuclei. If this were generally true, NGC 1167 may be an example of a 'collimating engine' whose ejecta have not accumulated outside the galaxy to make a detectable large-scale source. This could be due to a recent turning-on of activity in NGC 1167, to inefficiency of energy transport out of the galaxy, or to failure to cross some threshold required for continuing energy transfer to large distances. Detection and mapping of other 'lobe-less' extended cores may clarify the relationship between NGC 1167-type systems and the cores with well-developed outer lobes, as in 3C 236.

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