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VLA Observations of the Extended Radio Core in 3C 236

E. B. Fomalont[1], G. K. Miley[2], and A. H. Bridle[3]

[1] National Radio Astronomy Observatory,* VLA Project, Socorro, NM 87801, USA
[2] Sterrewacht, Leiden, Netherlands, and Lick Observatory, Santa Cruz, CA 95064, USA
[3] Queen's University at Kingston, Ontario, Canada K7L 3N6

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Summary. Observations of the extended radio core in the giant radio galaxy 3C 236 were made at the VLA at 4.9, 14.8, and 22.5 GHz with a 10.6 km four-element array. We find that the spectral index distribution across the 2 kpc radio core is remarkably uniform and follows a power law. A flat-spectrum compact radio core was *not* detected at the 100 mJy level, hence the precise location of the nuclear region in the extended core is not known.

The absence of a cut-off in the spectrum of the 2 kpc core at frequencies below 22.5 GHz implies that the electron age of $< 10^7$ yr is much less than the light travel time across the extended emission associated with 3C 236. This 2 kpc emission may be associated with the energy transport from the galactic nucleus to the outer lobes.

Key words: extended radio cores — giant galaxies — energy transport and collimation

I. Introduction

The giant double radio source 3C 236, of linear size ~6 Mpc (Willis et al., 1974) ($H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$), contains an extended radio core of angular size about one arcsec (linear size ~2 kpc). High resolution studies by Wilkinson (1972), Fomalont and Miley (1975, hereafter FM), and Preuss et al. (1977) have shown that the radio structure of the core is bifurcated into two unequal parts within which there is some fine-scale structure at the milliarcsec level. The axis of extension of the core aligns with that of the giant double, and with the minor axis of the optical galaxy, to within ~2°. These alignments are in agreement with the expectations of relativistic beaming models in which the source's energy supply is produced within $\lesssim 10$ pc of the nucleus of the galaxy, is collimated into two narrow beams, and is then transported with little or no loss to the distant radio lobes.

The detailed role of the 2 kpc radio core in 3C 236 in such beam models is unclear however. If the ultimate energy reservoir of the source is associated with activity close to the galactic nucleus, the extended core emission is more likely to be associated with the interactions between the beams and the non-relativistic gas around the nucleus than with the primary energy release. Two questions must be answered before the radio core of 3C 236 can be properly interpreted: (1) What is the detailed morphology of the source; does it resemble a miniature double source in its radiative characteristics? and (2) Where is the nucleus of the galaxy within the extended radio core? It will be difficult to determine the position of the nucleus to the necessary accuracy by optical measurements, but it may be possible to locate the nucleus indirectly by detection of a milliarcsec, flat-spectrum radio component within the extended radio core.

The VLBI observations by Schilizzi et al. (1979) indicate that the radio core has a relatively complex structure containing five small-diameter components. Such internal complexity is uncommon in the larger-scale double sources, and suggests that the core is not simply a "miniature double." The new VLBI data confirm that the overall alignment of the small components is near that of the large (39′) double but also show variations of about ten degrees in the internal alignment of the components.

In order to complement these new VLBI observations, we have observed the source with the VLA with a resolution of several tenths of an arcsec. The goals were to extend information about the spectral distribution across the source to high frequencies and also to search for a flat-spectrum component which might indicate the location of the nucleus of the galaxy.

II. Observations and Reductions

The radio core in 3C 236 was observed with four antennas of the VLA in December 1977 at 4.9, 14.8, and 22.5 GHz. The 25 m antennas were located on the southwest arm of the VLA (orientation 34 degrees South of West) with relative positions of 0.0, 1.8, 7.2, and 10.6 km. Each antenna used two independent receivers sensitive to right and left circular polarizations, with a bandwidth of 50 MHz, and with system temperatures of 70°K at 4.9 GHz and 400°K at 14.8 and 22.5 GHz (Weinreb et al., 1977). In order to lessen the effect of tropospheric refraction variations and to calibrate the instrumental gain and phase fluctuations, we observed the nearby unresolved calibrator 0923+392 (=DA267 = 4C39.25) alternately with 3C 236 in fifteen-minute cycles, spending five minutes on the calibrator and ten minutes on the source. A total of fourteen

Send offprint requests to: E. B. Fomalont, National Radio Astronomy Observatory, P.O. Box 2, Green Bank, WV, 24944 USA

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hours' observing was apportioned among the frequencies as follows – 8 h at 22.5 GHz, 4 h at 14.8 GHz, and 2 h at 4.9 GHz. Maps of 3C 236 were made by Fourier transforming the calibrated data and then reducing the effects of the ~30% sidelobes of the synthesized beam using the CLEAN algorithm (Högbom, 1974).

At 4.9 GHz the source was slightly resolved. A fit to the visibility function using a one-component Gaussian model produced the angular size and orientation of the source, in good agreement with FM. At the two higher frequencies the radio maps were limited in quality by phase fluctuations caused by tropospheric irregularities and local oscillator phase variations rather than by receiver signal-to-noise. Both radio maps and fitting of the visibility data (amplitude and phase or amplitude alone) were therefore used in deriving parameters for the source spectrum and structure at these frequencies.

III. Results

The main result is that the spectral index distribution across the radio core of 3C 236 is remarkably uniform and follows a power law. Figure 1 displays the radio maps obtained at 14.8 GHz at the VLA and at 2.7 GHz at Green Bank (FM) to illustrate the uniformity. Within the errors on these maps, there is no appreciable change in spectral index between 2.7 GHz and 14.8 GHz over the extent of the radio core of 3C 236. Both maps were convolved to a resolution of 0″.50 × 0″.25 (major axis in position angle 124°); the dynamic range is about 6:1 and 20:1 at 14.8 and 2.7 GHz, respectively. There was an offset of unknown origin of 0″.2 between the maps derived from the VLA observations and the Green Bank observations. The maps were put on the same coordinate system by assuming that the peak of the two maps coincided, and the VLA coordinates were arbitrarily chosen for display of the data.

The flux densities of the various core components resolved with the VLA observations are shown in Table 1. The locations of the three major components *A*, *B*, *C*, defined in FM, are also shown in Fig. 1b. The adopted flux-density values and their estimated errors were derived by fitting Gaussian models to the visibility amplitudes (rather than directly from the maps); we have verified that the maps and models agree satisfactorily. Component A is resolved at the higher VLA frequencies and has an angular size of ~0″.5, in agreement with that found by FM. Thus, the integrated flux density in Table 1 for this component is much larger than the peak flux density shown in Fig. 1a. Components *B* and *C*, separated by only 0″.15, were not resolved even with the VLA observations at 22.5 GHz.

The radio spectra of two main regions of the radio core, *A* and (*B* + *C*), are now known over a factor of 60 in frequency (see Fig. 2). Both have exceedingly straight (i.e., power-law) spectra with indices ~0.5 and there are only slight differences in spectral index between them despite the relatively complex fine structure of the source shown by the VLBI data (Schilizzi et al., 1979). Furthermore, the spectrum of component *C* between 1.4 and 2.7 GHz differs little from that of (*B* + *C*).

It is known from transcontinental VLBI observations (Preuss et al., 1977) that a milliarcsec nuclear component with ~80 mJy at 5 GHz exists somewhere within the radio core. The resolution of the VLA data was not sufficient to locate this component to a limit of about 100 mJy either directly from the maps or by the spectral comparison of the 14.8 and 22.5 GHz data. The location of any "nuclear component" within the radio core therefore remains unknown.

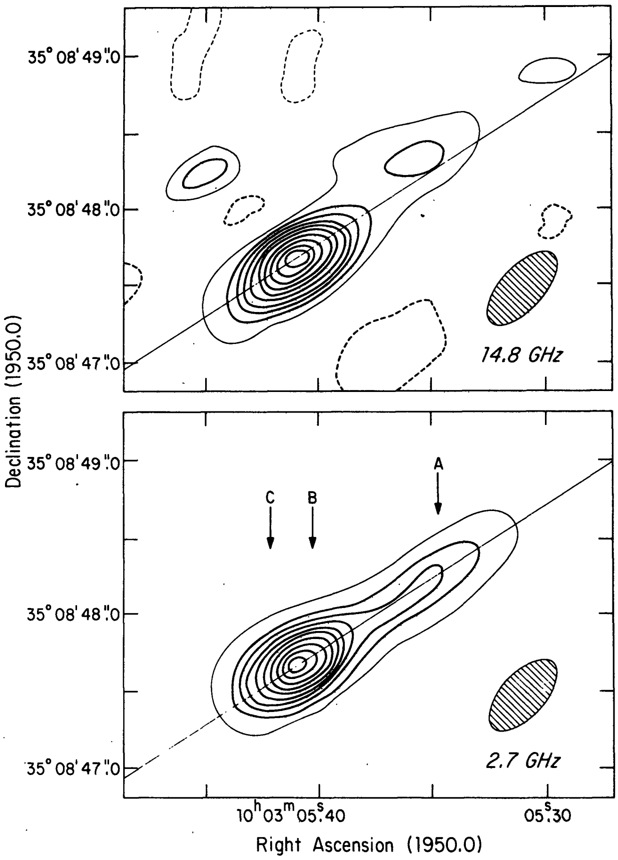

Fig. 1. Cleaned contour maps of the radio core of 3C 236. Contour levels are at 5% (light line), then every 10% to 95%. The dashed contours are at −10% level. The shaded ellipse indicates the synthesized beam and the line drawn through the source in position angle 122.5 deg indicates the orientation of the 39′ extended source. (**a**) The map at 14.8 GHz. The peak of the map is 0.44 Jy/beam. (**b**) The map at 2.7 GHz. The peak of the map is 1.33 Jy/beam. The approximate right ascensions of the three major components (FM) are designated

IV. Discussion

The absence of a bend in the spectrum at frequencies below 22.5 GHz implies that the electrons cannot have been radiating for more than 10^7 yr (e.g., van der Laan and Perola, 1969).

Table 1. Flux densities of 3C 236 core components at three VLA frequencies

Frequency (GHz)	Flux Density (Jy)		
	A	*B* + *C*	Total
4.885			1.50 ± 0.02
14.765	0.31 ± 0.03	0.49 ± 0.04	0.80 ± 0.05
22.485	0.25 ± 0.05	0.35 ± 0.05	0.60 ± 0.07

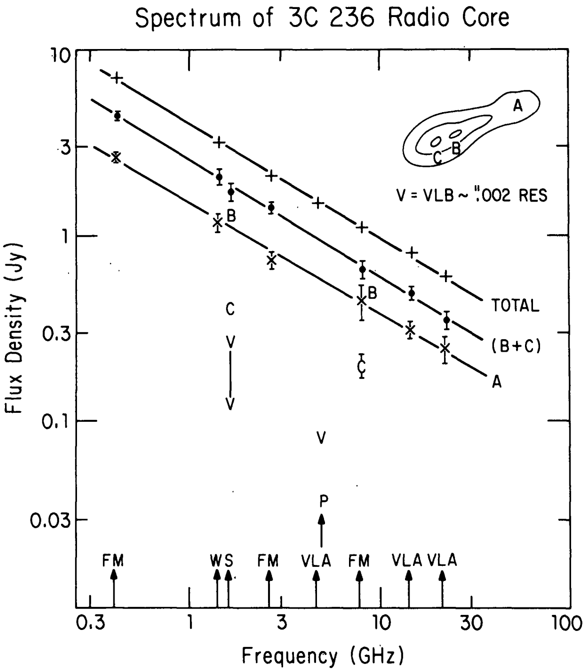

Fig. 2. The spectrum of the radio core in 3C 236. The flux density and error for the total and various components in the radio core are indicated. References to the data are given at the bottom: W (Wilkinson, 1972), FM (Fomalont and Miley, 1975), P (Preuss, et al., 1977), S (Schilizzi et al., 1978), VLA (present paper)

This is a maximum age assuming a core magnetic field of $H \sim H_R/\sqrt{3}$ where $H_R \approx 4.8\ 10^{-6}$ g is the equivalent magnetic field of the microwave background. A more realistic field would be the equipartition value of $H \sim 10^{-4}$ g which would give 10^5 y for the radiative lifetime. This is much shorter than the $\sim 2\ 10^7$ yr light travel time across the giant source; hence the 2 kpc radio core cannot be the relic of the initial explosion which produce the outer lobes, but must be a relatively recent event (FM).

If, as seems likely, energy is beamed quasi-continuously (Blandford and Rees, 1974) from a compact ($\lesssim 10$ pc) active region in the nucleus to the giant outer lobes of the source, we may associate the radio core with dissipative processes in this energy transport. The 2 kpc scale of the core, together with the absence of similar emission elsewhere along the presumed path of the beam, argue that the core emission arises from an interaction between the energy flow and the large densities and temperatures assumed to exist in the inner region of the galaxy. Since the properties of the ambient medium should vary considerably over a region 2 kpc in extent the observed uniformity of the spectral index across the core is surprising. A mechanism is needed which can generate synchrotron radiation whose strength is very dependent on the surrounding physical conditions but whose spectrum is relatively independent of them. An equilibrium Fermi-type acceleration process (e.g. Pacholczyk, 1970) is a possibility.

The precise location of the galactic nucleus in 3C 236 is crucial to the further understanding of the role of the radio core. If the nucleus is toward one end of the core, the core structure may be similar to the one-sided jets recently found in several large-scale radio sources (Bridle et al., 1976; Waggett et al., 1977; van Breugel and Miley, 1977). If, however, the nucleus proves to be near the centroid of the core, the core may be similar to ordinary double sources at a much reduced linear scale. Further observations at 22.5 GHz are planned at the VLA at somewhat higher resolution to detect the flat-spectrum nuclear component, if it is stronger than about 30 mJy, and to determine its precise position in the extended radio core.

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