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EVOLUTION OF THE SUB-MILLIARCSECOND NUCLEUS OF 3C 84 AT 100 GHz

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ABSTRACT

VLBI observations of 3C 84 at 3 mm indicate that the narrow jet detected in 1985 has evolved into a resolved component, 0.2 × 0.1 pc, separated from the nucleus by 0.2 pc. The position angle of the new component is close to that of the 1985 jet but differs from that of the 5 pc scale structure seen at lower frequencies. An unresolved nuclear source, <0.05 pc in size, has decayed monotonically from 14 Jy in 1982 to <0.5 Jy in 1987, corresponding to the decay in total flux density which followed a millimeter-wave outburst in 1980. The changes in source structure can be understood in terms of the diffusion of high-energy electrons with synchrotron lifetimes of ~ 2 yr from the radio nucleus into the halo.

Subject headings: galaxies: individual (NGC 1275) — galaxies: jets — galaxies: Seyfert — galaxies: structure — interferometry

I. INTRODUCTION

The source 3C 84 is a variable radio source associated with the Seyfert-like galaxy NGC 1275 at a distance of 108 Mpc ($z = 0.018$; $H_0 = 50$ km s^{-1} Mpc^{-1}). Its total flux density at millimeter wavelengths has decayed following an outburst in 1980 (Ennis, Neugebauer, and Werner 1982; Dent *et al.* 1983).

VLBI observations at 10 and 22 GHz (Romney *et al.* 1982; Readhead *et al.* 1983*a*) have shown that the compact radio emission in 3C 84 is distributed along a north-south axis with the most compact light-year–sized component located at the north end. The size, inverted spectrum, and variability of this component suggest strongly that it is the nucleus of NGC 1275.

VLBI observations at millimeter wavelengths are required to map the compact radio structure because emission at centimeter wavelengths is optically thick. We interpreted previous 3 mm VLBI observations of 3C 84 from 1981 to 1985 in terms of a slowly varying core-halo model that is consistent with the slow decay of flux density following the 1980 outburst (Backer *et al.* 1987, hereafter B87). Data obtained in 1985 on transcontinental baselines indicated the presence of a narrow jet in position angle 205° (B87). In this *Letter* we describe the subsequent evolution of the structure of 3C 84 based on new observations obtained in 1987 March.

II. OBSERVATIONS

The station parameters and sources observed are summarized in Table 1. Observations were made simultaneously at 100 GHz and at 5 GHz at all four stations. The 5 GHz observations were used to check the baseline and clock parameters, and as an aid to detecting hardware problems. We used the Mark III recording system (Rogers *et al.* 1983) with a 52 MHz bandwidth for the 100 GHz data and a 4 MHz bandwidth for the 5 GHz data. System temperatures at each station were measured using the chopper wheel method. Additional hot/cold load measurements and planet observations were made at KTPK to calibrate the flux density of all the program sources. At HCRO two of the three antennas were phased together for increased sensitivity; the local fringe amplitude between the phased pair and the third antenna was used to calibrate the effective antenna temperature for the VLBI observations.

Following correlation of the data at the Haystack Observatory, amplitudes and closure phases were derived from 10 s coherent integrations averaged incoherently over each 360 s scan. The data were calibrated using the measured antenna and system temperatures and converted to flux densities. The consistency of the flux calibrations between the stations suggests that the flux density scale is correct to 10%.

III. DISCUSSION

Figure 1 shows the measured visibility amplitudes and closure phases. A simple two-component model having 10 parameters fits both amplitude and closure phases within 1.5 σ. Table 2 shows the range of these parameters that fit the data within 2 σ. These components have been labeled "halo" and "J" for comparison with earlier epochs (B87). The transcontinental baselines set an upper limit of 0.5 Jy for any components smaller than 0.1 mas. The total flux density was 30 Jy in 1987; the measured visibility flux of 12 Jy leaves 18 Jy undetected, corresponding to structure larger than ~ 0.7 mas.

Hybrid maps were made from the observed amplitudes and

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[1] This *Letter* is dedicated to the memory of Alan T. Moffet, a valued colleague and friend, who did much to make VLBI at mm-wavelengths possible.

TABLE 1

SUMMARY OF 100 GHz VLBI EXPERIMENT

Parameters and Sources	Value
Epoch	1987 March 30
Sources	3C 84, 3C 273, 3C 279, 3C 345, OJ 287, and NRAO 530
Stations	HCRO (2 × 6 m) Hat Creek Radio Observatory, University of California at Berkeley. KTPK (12 m) Kitt Peak, National Radio Astronomy Observatory. OVNO (10 m) Owens Valley Radio Observatory, California Institute of Technology. QBBN (14 m) Quabbin, Five College Radio Astronomy Observatory, University of Massachusetts.

closure phases by adjusting the visibility phases to agree with the model. At the full resolution, 80 micro-arcsec, much of the substructure is not well constrained because the signal-to-noise ratio was insufficient to determine closure phases on all the long baselines. A consistent map (Fig. 2) is obtained at a resolution of 0.2 × 0.1 mas for a range of starting models. The peak on the map corresponds to the halo component, while the resolved structure to the southwest coincides with component J.

Based on the data available in 1985, Backer *et al.* (1987) suggested a model for 3C 84 consisting of a compact nucleus and a jet of unresolved width at a position angle of 205°,

TABLE 2

MODEL COMPONENTS FOR 3C 84

Component	Flux Density (Jy)	Radius (mas)	Position Angle	Major Axis (mas)	Axial Ratio	Position Angle
Halo	4.7 (0.3)	0.0000	0°0000	0.3 (0.1)	(0.3–1)	126° (30°)
J	6.8 (0.8)	0.4 (0.1)	225 (15)	0.4 (0.1)	(0.4–1)	(15–90)

NOTE.—The fitted functions are elliptical Gaussian components with the given major axis (FWHM), axial ratio, and position angle, located with respect to the core by a radius vector and position angle. The error or range of parameters which fit the data within 2 σ are given in parentheses.

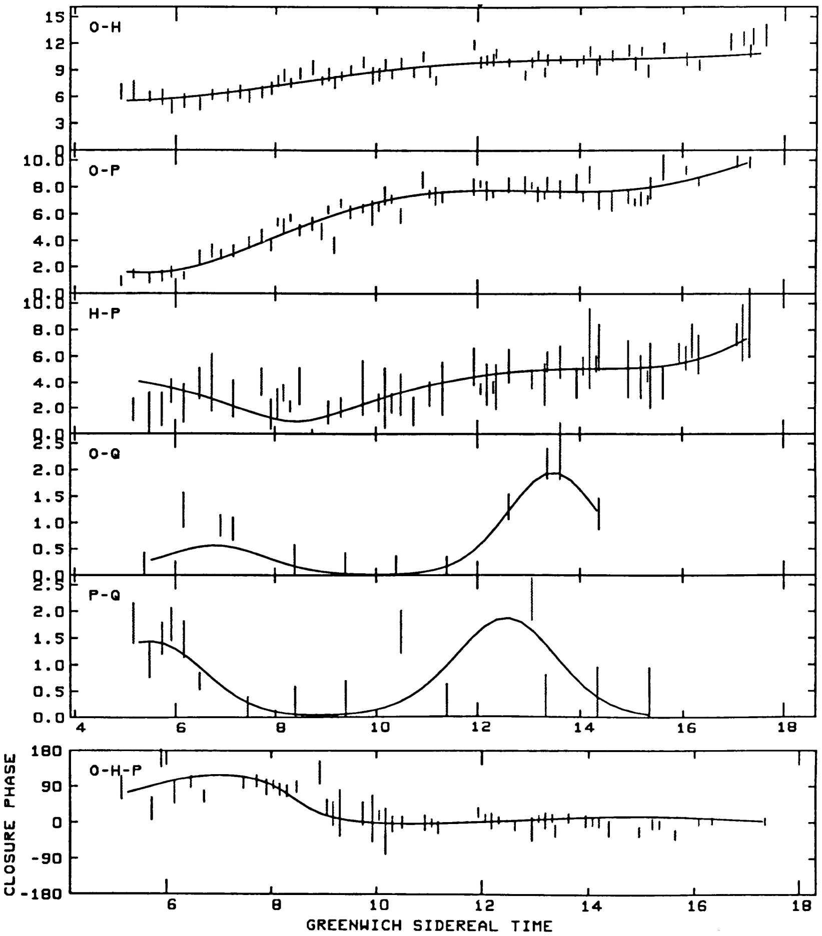

FIG. 1.—Observed visibility flux density and closure phase. The rms errors are indicated by the vertical bars. The fitted curve corresponds to the model in Table 2. The stations are indicated in the upper left corner: O = OVRO, H = HCRO, P = KTPK, and Q = QBBN (see Table 1).

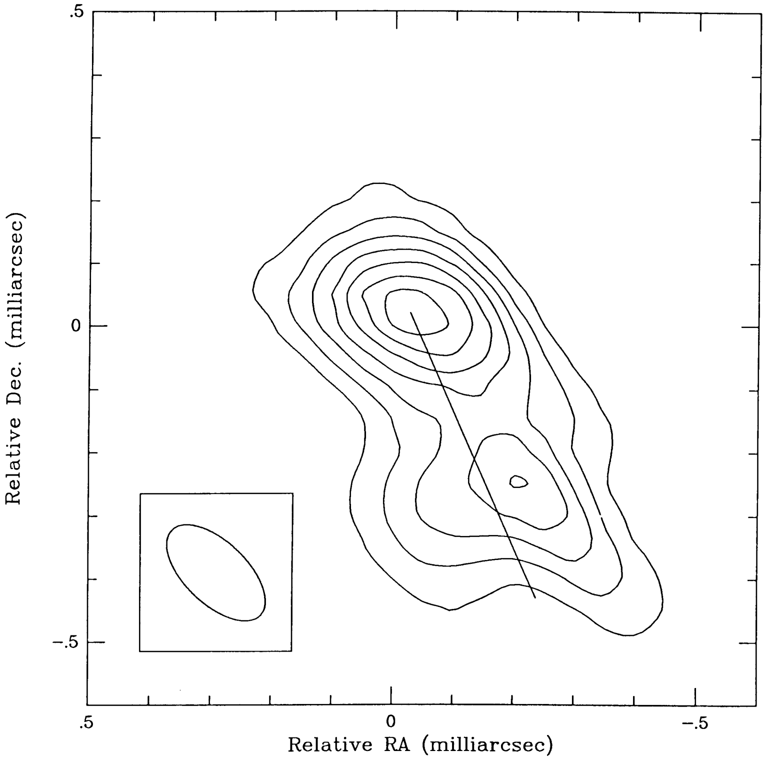

FIG. 2.—Hybrid map of 3C 84 at 100 GHz (1987 March) smoothed to a resolution 0.2 × 0.1 mas, indicated in the lower left-hand corner. The vector shows the position angle of the jet in 1985. Contours at intervals 250 mJy per beam (1.5×10^9 K).

embedded in a more extended halo. The data in 1985 and 1987 are not consistent with a single unchanged model. This is readily apparent if one compares the present OVRO-HCRO visibility with that in 1985 (B87). The change in the OVRO-HCRO visibility corresponds to the appearance of component J in the present model. Component J is displaced from the smaller halo component in a position angle 225°, close to that of the 1985 jet. This alignment suggests that the 1985 jet has evolved to produce component J in 1987.

The unresolved core detected in previous epochs has decayed in flux density from a peak 45 Jy at the time of the 1980 flare to 14 Jy in 1982, and to less than 0.5 Jy in 1987. In 1980 a minimum source size of 0.1 mas is set by the inverse Compton limit. As the flux density has decayed from 14 Jy in 1982 to <0.5 Jy in 1987, the observed size has remained smaller than 0.1–0.2 mas, depending on which long baselines were observed (B87). Thus, the core does not fit an expanding source model (Pauliny-Toth and Kellermann 1966). The magnetic field, estimated from the source parameters in 1982, is 0.8 G. The synchrotron lifetime of electrons radiating at 100 GHz is then less than 1 yr, and a continuing, but decreasing, injection of energy is required in the nucleus if this field is maintained. However, if the magnetic field has decreased, then the observed decay of the nuclear source could correspond to a single injection of particles in 1980. In either case the decay of electron energies in the core leads to a population of lower energy electrons which diffuse into the halo.

The halo component has changed considerably since 1985; it is reduced both in flux density (from 12 to 5 Jy), and size (from 0.6 to 0.3 mas). This change contrasts with the period from 1982 to 1985 where the shape of the halo, determined from the OVRO-HCRO visibility, remained unchanged as the halo slowly decreased in flux density. The change in the halo occurring at the time when the central source has become inactive suggests a model in which the halo is maintained by electrons from the central source. If the decay over a 2 yr period in the halo is due to the synchrotron lifetimes of the electrons then a field ~0.14 G is implied. Comparison with maps at 43 GHz for epoch 1986 May (Dhawan 1987), and 22 GHz for epoch 1986 February suggests that the halo has a spectral index ~0 ($S \approx \nu^\alpha$) and becomes optically thick between 43 and 22 GHz implying a field strength ~ 0.2 G. Thus the change in source structure at 100 GHz is probably not due to opacity changes. Electrons radiating at 100 GHz in a field ~0.14 G have energies ~0.2 GeV. Using a distance 108 Mpc, the luminosity of the halo is 10^{43} ergs s^{-1} and the energy in relativistic electrons ~ 10^{51} ergs. The field energy in the halo ~ 10^{50} ergs. Thus the particle energy dominates and relativistic electrons will diffuse through the halo. If the size of the halo is determined by the synchrotron lifetimes of the electrons then the diffusion velocity ≈0.25*c*. The halo is now smaller because the supply of high energy electrons from the nucleus has ceased.

The jet modeled in the 1985 data suggests a preferred direction of migration from the nucleus. We note that this direction has been maintained for at least 2 yr and differs significantly from that of the 10 mas scale structure observed in a position angle ~170° at 10.5 GHz (Romney *et al.* 1982) at at 22 GHz (Marr *et al.* 1988).

There is no evidence in the present data for the unresolved component, located ~10 mas to the south, seen at 22 GHz (Readhead *et al.* 1983*a*; Marr *et al.* 1988), and for which there was evidence in data from previous epochs at 90 GHz (B87). The 22 GHz maps suggest that this compact component is moving away from the core and, at this epoch, has caught up to the leading edge of the southern extended component (Marr *et al.* 1988).

IV. CONCLUSION

The 3 mm data show that significant changes in source structure occur on a sub-milliarcsecond scale during a quiescent phase of the compact radio source in NGC 1275. The changes can be understood in terms of the migration of high-energy electrons from a $\sim < 0.1$ pc radio nucleus into a ~ 0.3 pc halo. The decay of flux density from the nucleus is due to the finite synchrotron lifetimes of the high-energy particles and a decreasing rate of generation. The decaying particles migrate into the lower magnetic fields in the halo. The preferred direction on a sub-milliarcsecond scale, 205°–225°, is, however, significantly different from that of the 10 mas structure seen at lower frequencies in position angle $\sim 170°$. Changes in source structure are expected to propagate to lower frequencies and appear as changes in the core component at 22 GHz.

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