THE ASTROPHYSICAL JOURNAL, 326:L5–L8, 1988 March 1

SUPERLUMINAL MOTION TOWARD A STATIONARY KNOT IN THE RADIO CORE OF THE QUASAR 3C 395

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Received 1987 February 3; accepted 1987 November 25

ABSTRACT

We have recently confirmed that the quasar 3C 395 (1901+319) is a superluminal radio source, based upon one 18 cm and three 6 cm VLBI images of the compact radio emission in 3C 395 obtained over a 5.5 yr period. The compact structure in 3C 395 (at 6 cm with a convolving beam of 2.4 × 1.8 mas, position angle 162°) is dominated by three components: (1) A bright, unresolved component to the northwest, almost certainly the central core of 3C 395. It has apparently brightened by about 0.4 Jy between 1983.3 and 1985.4, from 0.6 Jy to 1.0 Jy. (2) A moderately resolved component 15.8 ± 0.2 mas to the southeast along position angle 118°. The position of this component relative to the core has changed by less than 0.2 mas in 6 yr. The flux density of this component has remained nearly constant over the past 6 yr. (3) A component whose flux density has remained constant between 1983.3 and 1985.4 moving rapidly away from the core toward component 2 with a proper motion of 0.64 ± 0.1 mas per year. At the distance of 3C 395 ($z = 0.635$), this corresponds to an apparent velocity of $\sim 15h^{-1}$ c for $H_0 = 100h$ km s^{-1} Mpc^{-1} and $q_0 = 0.05$.

The object 3C 395 is unique among the dozen or so superluminals, in that on milliarcsecond scales it has a superluminal component moving between two relatively stationary components.

Subject headings: galaxies: jets — interferometry — quasars

I. INTRODUCTION

The object 3C 395 (1901+319) is a compact radio quasar with a visual brightness of 17th mag (Véron, Véron, and Witzel 1974) and a redshift of 0.635 (Wills and Wills 1979). It has been observed with the Very Large Array at 6 cm by Perley, Fomalont, and Johnson (1980), 6 cm and 20 cm by Perley (1982), 2 cm and 6 cm by van Breugel, Miley, and Heckman (1984), and again at 6 cm by Pearson, Perley, and Readhead (1985). These radio observations, which were made with synthesized beamwidths of order 1″, all used the Very Large Array in its "snapshot" mode. They show that 3C 395 consists of two components on the ~arcsecond scale: a bright, unresolved component with 1.43 Jy flux density at 6 cm, and a fainter component (0.32 Jy at 6 cm) to the northwest along position angle ~307° (Pearson, Perley, and Readhead 1985). The observations of van Breugel, Miley, and Heckman (1984) show that the brighter component is variable in flux density and has a rising spectrum between 6 cm and 2 cm.

All early VLBI observations of 3C 395 (Phillips and Mutel 1980; Johnston *et al.* 1983; Phillips and Shaffer 1983) show that the core of 3C 395, corresponding to the brighter of the components observed on arcsecond scales, is a compact double whose structure was dominated by two components separated by 15.6 mas along position angle 118°. Since these VLBI observations were at different frequencies, Johnston *et al.* (1983) were able to show that the component in the compact double to the northwest (component 1) was both unresolved and had a spectral index of -0.2 [$S_\nu(\mathrm{Jy}) \propto \nu^{+\alpha}$], while the component to the southeast (component 2) was partially resolved and had a steeper spectrum, with a spectral index of -0.6; Phillips and Shaffer (1983) suggested spectral indices for components 1 and 2 of -0.2 and -1.7, respectively. Johnston *et al.* (1983) pointed out that the asymmetry in the small-scale structure is reversed from the arcsecond structure in 3C 395, so that the partially resolved component 2 is on the opposite side of the unresolved core from the large ~arcsecond component.

Waak *et al.* (1985) presented new VLBI observations of 3C 395 at 6 cm which, when combined with a re-analysis of the data used by Johnston *et al.* showed that structural changes were occuring in 3C 395 between the 1979.93 epoch of the observations presented by Johnston *et al.* (1983) and the 1983.26 epoch of the observations presented by Waak *et al.* (1985). They interpreted these changes as superluminal motion of a component (which we denote as component 3) in 3C 395 away from component 1 and toward component 2, with a proper motion 0.7 mas per year. This corresponds to an apparent superluminal motion of $16.6h^{-1}c$ (we assume throughout that $H_0 = 100h$ km s^{-1} Mpc^{-1} and $q_0 = 0.05$).

The present *Letter* was motivated by our desire to confirm, if possible, the existence of superluminal motion of component 3, and to test for lack of motion between components 1 and 2.

II. OBSERVATIONS AND RESULTS

a) 5 GHz Observations

The object 3C 395 was observed on 1985 June 1 at 4990 MHz with an eight-station VLBI experiment. In Table 1 we summarize the parameters of the observations for each of the stations used in this experiment. The effective observing bandwidth was 1.8 MHz using the Mark II VLBI recording system (Clark 1973). The data were processed by the NRAO VLBI Mark II correlator, using multiple passes so that all baselines were correlated. Except for brief scans on calibrator sources, 3C 395 was observed continuously for 14 hr (the

TABLE 1

5 GHz Observational Parameters

Antenna (abbreviation)	Location	UT Observed Time (hr)	System Temperature (K)	Sensitivity (K Jy^{-1})
Max-Planck-Institut 100 m (B)	Effelsberg, FRG	02–09	57	0.97
Haystack 46 mm (K)	Westford, Mass.	02–12	140	0.15
NRAO 43 m (G)	Green Bank, W.Va.	02–15	46	0.26
University of Iowa 20 m (I)	Iowa City, Iowa	04–16	101	0.046
G.R. Aggasiz Station 25 m (F)	Fort Davis, Tex.	04–15	96	0.095
VLA (single 25 m) (Y)	Datil, N.M.	03–16	53	0.099
OVRO 40 m (O)	Big Pine, Cal.	04–16	68	0.22
U.C. Berkeley 25 m (H)	Hat Creek, Cal.	05–16	55	0.095

actual UT observing times for individual antennas are summarized in Table 1).

Global fringe-fitting (Schwab and Cotton 1983; Benson 1985; Walker 1986) was used to find the fringes and correct for residual phase errors in the data. The data were calibrated with the techniques of Cohen *et al.* (1975), using the measured system temperatures at the individual antennas and a flux density for 3C 395 of 2.7 Jy, as measured by the Max-Planck-Institut 100 m antenna. Antenna-based calibration corrections were derived using self-calibration techniques (e.g., see Pearson and Readhead 1984 and references therein). Gain corrections for the complex antenna phases were derived for each 1 minute integration of the data; amplitude corrections (presumably due to calibration errors) were averaged over the entire data set before being applied. On the final image the rms noise level was ~ 1.9 mJy per beam.

In Figure 1 we present our final 5 GHz image of 3C 395. Our observations were insensitive to the arcsecond scale emission in 3C 395 and show that the compact structure was dominated by three components. Component 1 (the most northwesterly of the three components shown in Fig. 1) is unresolved by our observations. The peak brightness in component 3 is located 4.7 ± 0.3 mas away from component 1 along position angle $120° \pm 3°.7$. Component 2 is 15.7 ± 0.3 mas away from component 1 along position angle $118°.4 \pm 1°.1$. There is also some low-level emission between components 1 and 3 so that components 1 and 3 are apparently joined by a bridge of radio emission.

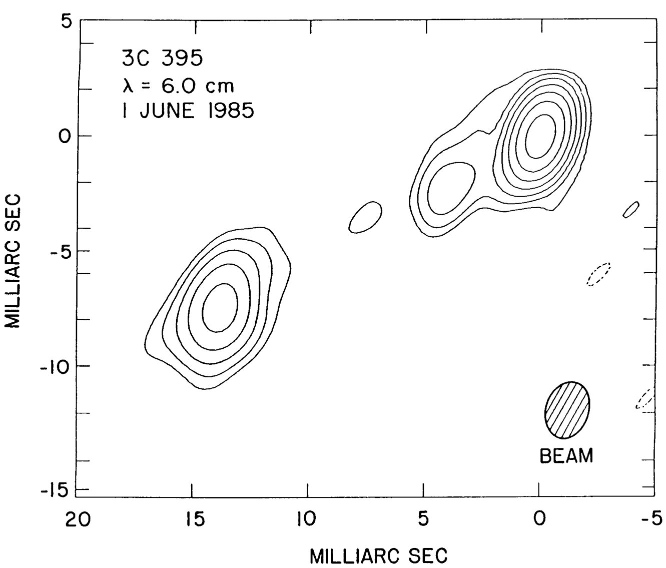

Fig. 1.—Image of 3C 395 from 1985.4. This image has been convolved with the nominal restoring beam, an elliptical Gaussian with major axis 2.4 mas along position angle 162° and minor axis 1.8 mas (the restoring beam is indicated by the hatched area in the lower left of the figure). The contours represent −1, 1, 2, 4, 8, 16, 32, and 64% of the peak brightness of 1.01 Jy per beam.

b) 1.66 GHz Observations

The 1.66 GHz observations took place at epoch 1984.93 using the array BKGFYOH (see Table 1 for telescope abbreviations). The observing system was very similar to the 5.0 GHz observations described above. We mapped the source using both the Caltech VLBI hybrid mapping algorithms (Pearson and Readhead 1984) and the NRAO AIPS mapping programs. Both algorithms use self-calibration to correct for station-based amplitude and phase errors (Pearson and Readhead 1984). The images produced by each of the two techniques were very similar—Figure 2*d* is a contour plot of the final image (rotated by −28°). The image contains 1.72 Jy of flux density, whereas the total measured by the MPI 100 m antenna was 2.65 Jy. The remaining 930 mJy apparently are contained in the arcsecond structure in 3C 395 which has been completely resolved by the VLBI array.

In order to provide quantitative estimates of component sizes, fluxes, and separations for comparison with the 5.0 GHz maps, we fit elliptical Gaussian model components to the visibility data using a least-squares fitting algorithm. Three components were needed to provide a satisfactory fit, corresponding to the two outer components (1 and 2) and the superluminal component (3). The model parameters are given in Table 2. Although the 1.66 GHz and 5.0 GHz maps are similar in appearance, they do not agree in detail. For example, the separations between components 1 and 2 are 15.1 ± 0.1 mas and 15.8 ± 0.2 mas at 1.66 and 5.0 GHz, respectively. Also, the separations between the "core" (component 1) and the superluminal component (3) is 3.6 ± 0.2 mas versus 4.4 ± 0.3 mas at 1.66 and 5.0 GHz, respectively (the 5.0 GHz separation has been interpolated to 1984.92 using a linear least-squares fit to the observed separations at 5 GHz. Both of these differences are significantly greater than the measurement errors. They are probably due to spectral index gradients in each component, as can be expected if the components represent emission from bulk relativistic flows. Similar effects are seen in the superluminal sources 3C 345 (Biretta, Moore, and Cohen 1986) and BL Lac (Phillips, Mutel, and Bucciferro 1988).

III. DISCUSSION

Our observations confirm the inference of Waak *et al.* (1985) that the quasar 3C 395 displays apparent superluminal

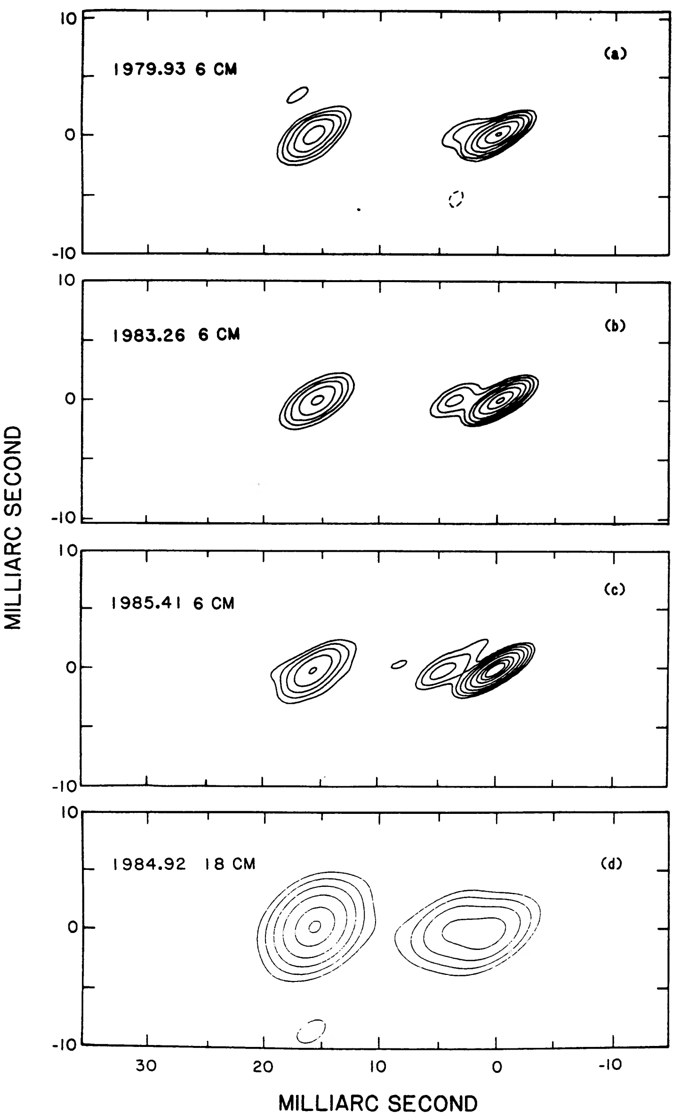

FIG. 2.—Images of 3C 395 at four epochs: 1979.93, 1983.26, and 1985.41 (from 6 cm observations), and 1984.92 (from 18 cm observations). All four maps have been rotated clockwise by 28°. The three 6 cm images have been convolved with a beam 3 × 1 mas in size extended along position angle −30°; the 18 cm image has been convolved with a 4.6 × 2.8 mas beam along position angle −22.5°. (*a*) and (*b*) Contour levels represent −2, 2, 4, 8, 16, 32, 64, and 96% of 415 mJy per beam and 576 mJy per beam for the 1979.93 and 1983.26 maps, respectively. (*c*) In the 1985.41 map, contours represent −11.5, 11.5, 23, 46, 92, 184, 369, 553, and 737 mJy per beam, so that the 1983 and 1985 contours are at the same absolute level even though the core has brightened considerably between 1983 and 1985. (*d*) In the 1984.92 map, contour levels represent 4, 8, 16, 32, 64, and 96% of 660 mJy per beam.

motion. In Figure 2 we present four images of the core of 3C 395 (Johnston *et al.* 1983; Waak *et al.* 1985; and this work). The three 6 cm images have been convolved with a restoring beam of 3 × 1 mas (position angle −30°); the single 18 cm image has been convolved with a 4.6 × 2.8 mas beam (position angle −22.5°). These images are all dominated by the same three components. In Table 2 we summarize the components observed in 3C 395 and their positions relative to the assumed core of 3C 395 (the 18 cm positions and fluxes are derived from model fitting as described above).

In the discussion which follows, we assume that component 1 is stationary and that it is the active core of 3C 395. This assumption is reasonable because component 1 is essentially unresolved and has a flatter radio spectrum than component 2. Further justification for assuming component 1 is the core of 3C 395 is that it has brightened substantially, from 0.6 Jy in 1983 to 1.0 Jy in 1985.

In all four images, component 2 appears to be moderately resolved with a size of ∼2–3 mas. It is located ∼15.6 mas southeast of the core (component 1) along position angle 118°. The 6 cm position of this component relative to the core has changed by *less* than 0.2 mas in 6 yr (see Table 2). The flux density of this component has remained ∼ constant over the past 6 yr.

Finally, component 3 appears to be moving rapidly away from the core towards component 2 with a velocity of 0.64 ± 0.1 mas per year, based on a linear least-squares fit to the 6 cm data. At the distance of 3C 395, this corresponds to an apparent velocity of $\sim 15.2h^{-1}c$. The flux density of this component has remained constant between 1983.3 and 1985.4.

There are also indications of other, fainter structure in 3C 395, based on analysis of the visibility and map residuals. From the 1983.3 data, there was some hint of emission to the north and west of component 2. We were unable to confirm this with our 1985.4 observations due to the failure of our shortest baseline. With improved receivers, more antennas, and better calibration techniques, the 1985.4 map has a significantly higher dynamic range than the earlier maps. There is the possibility of faint emission between components 3 and 2, but we are not able to confirm this with the 1985.4 observations alone.

3C 395 is thus seen to be unique among the dozen or so superluminals, in that it has a superluminal component moving between two relatively stationary components. If the (highly variable) core of 3C 395 were to fade out, the other two components in 3C 395 would be seen to be contracting superluminally!

A possible interpretation of these observations is that 3C 395 is a core-jet compact radio source in which a jet nearly along the line of sight bends back through the line of sight. In this interpretation, material ejected into the jet at first moves superluminally outward from the core, as component 3 seems to be doing. As in other superluminal sources such as 3C 345 (e.g., see Biretta, Moore, and Cohen 1986), the moving component should fade with time as it moves out, perhaps disappearing completely in the next 5 yr or so. An underlying, continuous jet acts as a channel for the relativistically moving material to make its way to the region near the 1″ component. In this interpretation, the stationary hot spot must be a region where the physical characteristics of the jet change substantially. An alternative interpretation for the morphology of this radio source is that it is a two-sided radio quasar, since two-sided emission is seen in many superluminal radio sources (Browne 1987; Johnston *et al.* 1987; Simon *et al.* 1987).

These interpretations suggest questions which may be resolved by further VLBI observations. Is the velocity of the moving component constant? The above would suggest that component 3 will eventually decelerate as it moves along the jet back toward the line of sight. Is component 2 truly stationary? Our present limit to its velocity is less than about $1h^{-1}c$. Finally, is the supposed underlying jet detectable if we improve our sensitivity to faint structure on the 10–20 mas scale? We have only supposed the existence of a jet, not actually observed it. However, in each of these maps there is evidence of 100–600 mJy which is unaccounted for when comparing the sum of

TABLE 2

COMPONENTS IN 3C 395

Component	Description	Position Relative to Core: Distance (mas)	Position Relative to Core: Position Angle (degrees)	Epoch	Wavelength (cm)	Flux Density (Jy)	Reference
1	Assumed core	...	...	1978.39	18	1.0	1
				1979.93	6	0.4	2
				1980.59	13	~0.8	3
				1983.26	6	0.6	2
				1984.92	18	0.33	4
				1985.41	6	1.1	4
2	Stationary	15.6 ± 0.2	118.5 ± 0.5	1978.39	18	1.5	1
		15.6	118	1979.93	6	0.4	2
		~15	~120	1980.59	13	~1.6	3
		15.6	118	1983.26	6	0.4	2
		15.1 ± 0.1	118.6 ± 0.5	1984.92	18	0.94	4
		15.7 ± 0.3	118.4 ± 1.1	1985.41	6	0.44	4
3	SL component	1.2 ± 0.3	118	1979.93	6	0.09	2
		3.7 ± 0.8	118	1983.26	6	0.12	2
		3.6 ± 0.2	117.5 ± 3.5	1984.92	18	0.30	4
		4.7 ± 0.3	119.7 ± 3.7	1985.41	6	0.09	4
	Arcsecond	~700	−153	1979	6	0.3	5
				1981.12	6	~0.3	6

REFERENCES.—(1) Phillips and Mutel 1980; (2) Waak *et al.* 1985; (3) Phillips and Shaffer 1980; (4) This *Letter*; (5) Perley *et al.* 1980; (6) Pearson *et al.* 1985.

the three VLBI components plus the arcsecond component to the total flux density. We may be observing for the first time the resupply of a stationary hotspot in an extragalactic radio source.

We wish to acknowledge the Max-Planck-Institut für Radioastronomie, the US VLBI network, and the staffs of the various observatories for their contributions to these observations. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation. Radio Astronomy at the Owens Valley Radio Observatory of the California Institute of Technology, at the George R. Aggasiz Station of the Harvard College Observatory, at the North Liberty Radio Observatory of the University of Iowa, and at the Haystack Observatory of the Northeast Radio Astronomy Observatory Corporation (NEROC) is supported by grants from the National Science Foundation. We wish to thank R. B. Phillips for useful discussions about the nature of 3C 395. We are especially indebted to Mr. Robert Vernon at the National Radio Astronomy Observatory for his diligent and invaluable efforts at operating the NRAO VLBI correlator. We thank R. P. Linfield for making critical comments on the manuscript.

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