THE ASTROPHYSICAL JOURNAL, 319:L69–L72, 1987 August 15

MULTIFREQUENCY VLBI OBSERVATIONS OF 4C 39.25: A SUPERLUMINAL SOURCE WITHOUT A WELL-DEFINED CORE

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Received 1987 April 20; accepted 1987 June 1

ABSTRACT

The radio source 4C 39.25 has been shown by Shaffer *et al.* to contain both superluminally moving and stationary components. We present the results of VLBI observations of 4C 39.25 at 1.35 cm at epoch 1983.77. Comparison with the 2.8 cm maps of Shaffer *et al.* indicates that none of the components possesses the characteristics normally associated with the compact core of a superluminal source. When combined with the steep spectrum at frequencies above 10 GHz and the two-sided arcsecond-scale jet, we infer from the lack of a well-defined core that 4C 39.25 represents a source intermediate between more typical superluminal sources and symmetric extended radio sources with weak cores. A relativistic jet model is possible only if the jet bends by over 50° or decelerates as it moves outward, or both.

Subject headings: galaxies: jets — interferometry — quasars — relativity

I. INTRODUCTION

The quasar 4C 39.25 ($z = 0.699$; see Hewitt and Burbidge 1980) has been shown by Shaffer *et al.* (1987) to contain two components which remain stationary relative to each other on either side of a third component which is moving superluminally relative to the other two. The source had previously been reported to be a double with no relative motion (e.g., Shaffer *et al.* 1977; Bååth *et al.* 1980; Pauliny-Toth *et al.* 1981), thus providing a counterexample to the superluminal sources which are more common among strong compact radio sources. One possible explanation for the lack of relative motion is that the components are in fact separating superluminally with identical velocities from a core which could not be detected at a wavelength of 2.8 cm owing to self-absorption. In order to test this possibility, the authors observed 4C 39.25 at 1.35 cm using very long baseline interferometry (VLBI). As is discussed below, the resultant map, when compared with maps at longer wavelengths, reveals that none of the three compact components possesses the spectrum and/or compactness typical of the compact cores found in other superluminal radio sources, nor is any other corelike structure apparent. In addition, the overall spectrum and arcsecond-scale morphology of 4C 39.25 differ from those of most other superluminal sources. We place these results in the context of the general classification of radio sources, and find that 4C 39.25 possesses the properties of more than one class. It therefore may be an important link which connects the superluminal sources with the extended sources containing weak cores.

II. OBSERVATIONS

4C 39.25 was observed on 1983 October 8 between 0600 and 2000 UT at a wavelength of 1.35 cm using a VLBI array consisting of the 20 m antenna at Onsala Space Observatory; the Max-Planck-Institut für Radioastronomie 100 m antenna at Effelsberg, West Germany; the Haystack Observatory 37 m antenna at Westford, Massachusetts; the 26 m antenna operated by the Naval Research Laboratory at Maryland Point, Maryland; the National Radio Astronomy Observatory (NRAO) 43 m antenna at Green Bank, West Virginia; one of the 25 m antennas of NRAO's Very Large Array (VLA) near Socorro, New Mexico; and the Owens Valley Radio Observatory 40 m antenna at Big Pine, California. A receiver failure at the VLA limited the useful data from that station to about 4 hr. The experiment recorded a 1.8 MHz wide band, centered on 22,231 MHz and sensitive to left circular polarization, with the Mark II VLBI system (Clark 1973). The data were processed on the JPL-CIT correlator at Caltech. The post-processing, editing, calibration, and mapping were performed on the Boston University Astronomy VAX 11/750 computer system using a combination of the AIPS software written by the NRAO staff and the Caltech VLBI software written by Caltech and JPL staff, most notably T. J. Pearson.

The nominal calibration parameters as supplied by the individual stations were applied to the data. Crossovers in the *u-v* tracks were then used to adjust the gains at each telescope by constant factors to achieve consistency. The signal-to-noise ratio was low on most baselines for at least some fraction of the time. The resultant map (not shown here) is therefore of relatively low dynamic range, approximately 15:1 as judged by the highest level of negative contours. Also, variable atmospheric opacity and receiver instability are more pronounced at 1.35 cm than at longer wavelengths. Hence, it is difficult to determine the absolute flux densities of features appearing in the map.

Of even more concern is the question of uniqueness of the map. Given the low signal-to-noise ratio of many of the data, the standard self-calibration–hybrid mapping procedure (Cornwell and Wilkinson 1981) is poorly constrained. Unfortunately, some form of self-calibration is necessary at 1.35 cm owing to the calibration uncertainties. In order to limit the number of free parameters, and thereby restrict the freedom of the self-calibration routines, the hybrid maps were used only to determine the number and placements of the major components of the source. The 2.8 cm maps (suitably interpolated in time) were also used for the same purpose. A first-order model was thus produced to serve as the starting point in the model fitting routine. This model contained four elliptical Gaussian components (cf. the 1984 August map of Fig. 1). The model fitting produced a best-fit model, which was then used in the self-calibration routine AMPHI (from the Caltech VLBI software package) to adjust the telescope gains by constant factors. Another round of model fitting to the data thus adjusted produced a final model. The data were then once again adjusted for gain errors on a 2 hr time scale by AMPHI for the purpose of determining whether the model is capable of producing an acceptable fit to these "corrected" data. The fit thus produced has a reduced χ^2 of 0.88, with no significant systematic deviations from the data. The model consists of 20 parameters which are allowed to vary, in contrast with the > 100 parameters typically involved in hybrid mapping. Within the context of this procedure, the overall model, i.e., a point source in between two more diffuse components, is insensitive to the starting model. For example, the same basic structure is obtained if one uses a single point source in the first iteration.

III. RESULTS

The 1.35 cm model of 4C 39.25 is shown in Figure 1, along with the 2.8 cm maps of Shaffer *et al.* (1987). The model clearly shows a strong, unresolved component which lies between two weaker, partially resolved components. (The fourth component in the model contains an insignificant fraction of the total flux density.) While the model is certainly not unique, the presence of these three main components is clearly required by the data. We identify the strong, compact component in the middle with the superluminal component ("b") of Shaffer *et al.* and Marcaide *et al.* (1985). The outer two components are more poorly defined, since they are heavily resolved by our array. Still, the emission appears in the approximate locations of components designated "a" and "c" by the above authors.

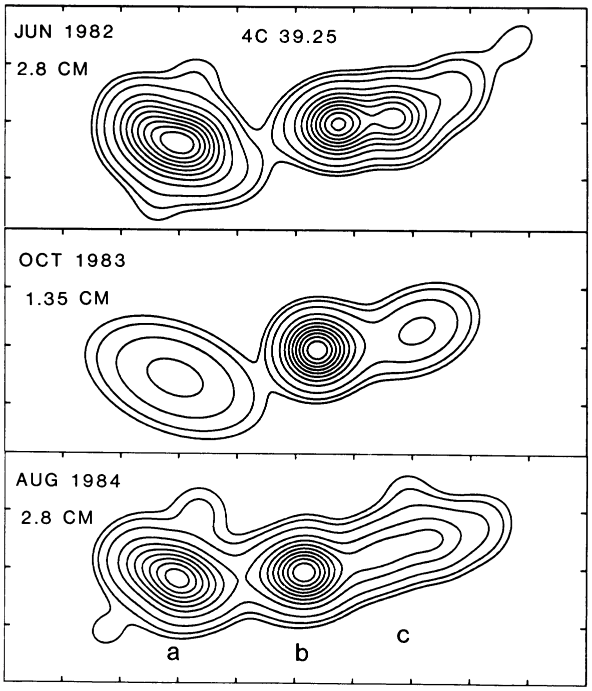

FIG. 1.—VLBI maps (2.8 cm) and model (1.3 cm of 4C 39.25 at the given wavelengths and epochs. Restoration beam is a circular Gaussian of FWHM = 0.4 mas, which corresponds to the resolution along the source axis. East is to the left, and north is up. Tick marks are 0.5 mas apart. The component designations are given in the bottom panel. Maps are registered such that components a and c are roughly stationary. Contour levels are 3, 5, 10, 20, ..., 90% of peak brightness temperature of (a) 3.35×10^{11} K, (b) 7.0×10^{9} K, and (c) 6.0×10^{10} K.

Because of variable atmospheric absorption and the lack of known 1.35 cm VLBI calibrators in 1983 (a limited number of such calibrators are now known), the overall flux density calibration is uncertain. Nevertheless, since fringes disappear when the BONN-HSTK and BONN-NRAO correlated flux densities dip below the expected limit of about 0.3 Jy, it is unlikely that the flux densities are off by more than about 30%.

Owing to the heavily resolved structures of components a and c, we cannot determine their flux densities at 1.35 cm. (The same problem might also exist at 3.8 and 2.8 cm, since Shaffer *et al.* 1987 report that a significant fraction of the total flux density is resolved out by the VLBI arrays at these wavelengths.) Component b, however, is unresolved at 1.35 cm. This limits its extent to $\lesssim 0.1$ mas along the narrow axis of the beam (position angle 78°) and to $\lesssim 0.25$ mas along the long axis of the beam. The flux density of component b is 0.45 ± 0.15 Jy, with the major source of uncertainty being the flux density calibration of the experiment. This flux density lies well below the values observed at earlier and later epochs at longer wavelengths: 1.2 Jy at 2.8 cm in 1982 June; 1.2 Jy at 3.8 cm in 1984 July; and 1.3 Jy at 2.8 cm in 1984 August (Shaffer *et al.* 1987). Since the total flux density of 4C 39.25 at centimetric wavelengths monotonically decreased by less than about 0.3 Jy during this period (Aller *et al.* 1985), it is very unlikely that the 2.8 cm flux density of component b decreased to a value much less than 1.2 Jy at the epoch of our

1.35 cm observations. Using 1.2 Jy as the 2.8 cm flux density, we obtain a two-frequency spectral index of $\alpha = -1.3 \pm 0.3$ between 10.65 GHz (2.8 cm) and 22.23 GHz (1.35 cm). (The spectral index α is defined here such that, for a power-law dependence of flux density S_ν, $S_\nu \propto \nu^\alpha$.)

IV. DISCUSSION

These 1.35 cm observations show that 4C 39.25 is unusual among superluminal radio sources: none of the components possesses all three of the basic properties of the compact "core" found in VLBI maps of other superluminal sources. The "classical" superluminal source contains a component which is at most barely resolved, has a flat or inverted spectrum, and is situated at one end of the brightness distribution. The superluminal motion is traditionally measured relative to this "core," an interpretation which is supported by the lack of motion (relative to an external reference frame) of the core in 3C 345 (Bartel *et al.* 1986). In the case of 4C 39.25, component c lies at one end of the brightness distribution, and component b's motion is away from c. It is therefore tempting to identify component c as the core. However, its spectrum is not flat or inverted, and it is heavily resolved by VLBI arrays at centimetric wavelengths. Component b is unresolved at 1.35 cm but does not lie at the end of the brightness distribution and also does not have the spectrum expected of a compact radio core. Component a contains none of the properties of a core: its spectrum is neither flat nor inverted above 10 GHz; it is heavily resolved; and, despite its location at one end of the VLBI brightness distribution, the superluminal motion of component b is toward rather than away from it.

4C 39.25 differs from most other known superluminal sources in other ways, as well. The arcsecond-scale map of Browne *et al.* (1982) reveals a two-sided, although asymmetric, jet. Most other superluminal sources mapped by Browne *et al.* contain one-sided jets. (Another superluminal source, 1928+738, has been found by Johnston *et al.* 1987 to also contain a two-sided jet.) Furthermore, the spectrum of 4C 39.25 does not fit the pattern found by Landau *et al.* (1986). Nearly simultaneous multifrequency observations of active extragalactic sources by these authors yielded spectra whose slopes change smoothly with frequency for the most active (i.e., variable) sources. 4C 39.25, in contrast, has a spectrum which displays a sharp peak near 10 GHz. This object, along with three others with peaked radio spectra, was used as part of a control sample by Landau *et al.* Rudnick and Jones (1982) had previously found that sources with peaked radio spectra tend to have less pronounced variability than do flat-spectrum radio sources. It is interesting that another peaked-spectrum source, PKS 2134+004, has also been found to contain VLBI components whose relative positions have remained constant (Pauliny-Toth *et al.* 1984).

4C 39.25 has not been well monitored for brightness variations at optical wavelengths. In the radio, Medd *et al.* (1972), Altschuler and Wardle (1976), and Aller *et al.* (1985) have found 4C 39.25 to be variable over a time scale of a few years in both flux density and polarization, similar to other superluminal radio sources. Hence, 4C 39.25 has some of the properties of superluminal radio sources, but differs from the others in both structure and spectrum.

The two-sidedness of the arcsecond-scale jet implies that the outer jet is not strongly beamed. (The intensity ratio of the eastern to western side is difficult to determine from the map of Browne *et al.* 1982; a rough estimate gives a value ~ 4, which suggests weak beaming.) In standard relativistic jet models (e.g., Blandford and Königl 1979), the superluminal motion requires that the jet lie within $\lesssim 27h$ degrees of the line of sight, where h is Hubble's constant in units of 100 km s^{-1} Mpc^{-1}, and $q_0 = 0$ has been assumed. For a spectral index $\alpha \approx -1$, the flux density of the entire jet is boosted by a factor δ^3, while the flux density of a feature in the jet is enhanced by a factor δ^4, where δ is the Doppler factor. The weakness of the core and its relatively low turnover frequency imply that the emission from the core is not as strongly beamed as for other superluminal sources. For $h = 1$, for example, the observed superluminal motion can be explained with a relatively low Doppler boosting by a jet with a flow velocity of $0.993c$ (Lorentz factor of 8.5) directed at an angle 25° to the line of sight. The corresponding Doppler factor would be 1.2 in this case, compared with a value $\sim$ 5–10 for most superluminal sources. The core would then be expected to be relatively weak with a lower than normal turnover frequency, as observed. It is then, however, difficult to explain why 4C 39.25 is such a bright radio source. (Its luminosity would need to be much higher than that of other compact radio sources, which are typically thought to be highly beamed.) The above limit on the angular size of component b, combined with the observed turnover frequency and flux density, can be used to estimate the expected self-Compton X-ray flux density (see, e.g., Marscher 1983). The value thus derived, $\sim 9\ \mu$Jy at 1 keV, is roughly 20 times that observed (Tananbaum *et al.* 1979). Since the derived X-ray flux depends on the values of the observed parameters of the radio source raised to high powers, the discrepancy is insignificant given the uncertainties of our analysis of the radio spectrum. Hence, a high degree of relativistic beaming is neither required nor ruled out for the core using this method.

Under the same scenario, the arcsecond-scale jet:counterjet ratio of ~ 4 requires that the jet axis lie at an angle $\sim 77°$ to the line of sight. The observed apparent bending is 17° between the milliarcsecond-scale and arcsecond-scale jets, compared with the required 52°. Since the projection angle is unknown, these two values are not inconsistent. The amount of bending required would be less if the jet were allowed to decelerate between the milliarcsecond and arcsecond scales.

The above model does not explain why component a appears stationary relative to component c. Variations of the standard relativistic jet model, as discussed by Shaffer *et al.* (1987), are required to accommodate this phenomenon.

Another possibility is that the jet in 4C 39.25 is only sometimes relativistic. Component b would then be a product of a recent stage in which the flow was accelerated from nonrelativistic to highly relativistic speeds. If this is the case, then one would expect component b to be significantly decelerated when it encounters the region now occupied by component a (in the year 1991).

V. CONCLUSIONS

The radio spectrum, VLBI structure, and arcsecond-scale structure of 4C 39.25 lead to the impression that this source possesses some of the characteristics of each of two distinct classes of radio source. One of the compact components is moving superluminally, while two others are stationary relative to each other. As opposed to other superluminals, the arcsecond-scale jet is two-sided. Furthermore, the 1.35 cm VLBI observations given here show that source does not contain any compact component which has the characteristic typical of a compact radio core.

Taken together, these properties indicate that 4C 39.25 is an intermediate class of radio-loud quasar. The two-sidedness of the arcsecond-scale jet is consistent with the standard relativistic jet model for superluminal motion only if the compact jet is more strongly beamed than the more extended jet. This could occur if either the speed of the jet flow were to decrease with distance from the center of activity, or if the apparent bending of the jet of 17° were to correspond to an actual bending of at least 50° (or some combination of deceleration and bending). The absence of a component with the properties typical of a compact core could result from weaker beaming of the compact jet compared with other superluminal sources. In addition, some variation of the standard relativistic jet model must be invoked to account for the lack of apparent motion of component a.

It can be argued that the nonstandard mixture of properties in 4C 39.25 is evidence against the relativistic jet model for superluminal motion. Indeed, it is only the superluminal motion and the one-sidedness of the compact structure which suggest that the jet is relativistic. If the jet is allowed to lie well outside the line of sight, and the compact jet is assumed to be intrinsically one-sided, then alternatives to relativistic bulk motion must be found to explain the superluminal motion of component b. One possibility is a phase effect, which causes a bright spot generated by an upstream disturbance to appear to move superluminally through the jet (Blandford 1987).

There are other possible explanations for the behavior of 4C 39.25 (see also Shaffer *et al.* 1987), but the observations do not currently allow a distinct choice to be made among these. Continued observations of 4C 39.25 should help to further define its characteristics. Of most interest will be the interaction between components b and c when they "collide" in 1991.

The authors thank the staffs at all the observatories for their effort in successfully observing 4C 39.25 during our experiment. Much assistance was also received from the staff scientists and engineers at the correlator at Caltech, especially S. Unwin and G. Dvorak. NRAO is operated by Associated Universities, Inc., under contract with the National Science Foundation. VLBI at Haystack Observatory and Owens Valley Radio Observatory is funded through the National Science Foundation. A. P. M. was supported in part through NSF grant AST-8315556.

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