3C454.3: A NEW KIND OF SUPERLUMINAL SOURCE?

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ABSTRACT. The quasar 3C454.3 has a "core-jet" structure, on scales ranging from 50 kpc to 100 pc. VLBI observations made during the last 5 years show that the structural variations within the core region are very different from those seen in the "classical" superluminal sources. After a period of very rapid expansion (apparent velocity $v_a \geq 30c$), the brightest features in the core region showed little relative motion ($v_a < 3c$), although at least one weak, more distant component appears to have separated from the others with $v_a \sim 19c$. The most likely interpretation of the stationary features involves stationary shocks excited by a relativistic flow.

INTRODUCTION

The radio source 3C454.3 is identified with a 16th magnitude quasar at a redshift $z = 0.859$. It is an optically violent variable and varies strongly at centimetre (e.g. Kellermann and Pauliny-Toth 1967) as well as decimetre (e.g. Hunstead 1972, Fanti et al. 1979) wavelengths.

The time-scale of the variations at decimetre wavelengths led Jones and Burbidge (1973) to suggest that bulk relativistic motion should be present. These low-frequency variations may not be intrinsic, but due to the interstellar medium (Rickett et al. 1984). Nevertheless, the short time-scale and large amplitude of the variations at centimetre wavelengths suggest that bulk relativistic motion is required to reduce the brightness temperature in the source frame below the limit set by inverse Compton losses (Kellermann and Pauliny-Toth 1969).

A large outburst at centimetre wavelengths in 3C454.3 (the second in the last 10 years) reached its peak at λ2.8 cm in mid-1981, and we began our VLBI measurements of the source at that time.

THE OBSERVATIONS

Most of our VLBI observations were made at λ2.8 cm with transatlantic baselines, giving an angular resolution of 0.36 milliarcsec (mas). We

E. Ye. Khachikian et al. (eds.), Observational Evidence of Activity in Galaxies, 295–300.

have also made observations at λ6 cm and λ18 cm, in order to map features of low surface brightness, and at λ1.3 cm, in order to improve the angular resolution. We report here mainly on the results of the observations at λ2.8 cm, which span the range of epochs 1981.4 to 1985.9 and typically include at least 5 of the following antennas:

Diameter (m)	Location
100	Effelsberg, FRG
32	Medicina, Italy
37	Haystack Observatory, Westford, MA, USA
43	National Radio Astronomy Obs., Green Bank, WV, USA
25	George Agassiz Station, Ft. Davis, TX, USA
40	Owens Valley Radio Obs.,Big Pine, CA, USA
25	Hat Creek Radio Obs., Hat Creek, CA, USA

The data were recorded with the "Mark II" recording system (Clark 1973), which has an effective bandwidth of 1.8 MHz, and were correlated with the 3-station VLBI processor of the MPIfR.

In order to improve the signal-to-noise ratio, use was made of a new fringe-fitting algorithm (Alef and Porcas 1986) following the processing, which utilises antenna-based residuals in fringe-rate and delay. The calibration of the data followed the procedures of Cohen et al. (1975) and the subsequent production of the maps employed the usual procedures of Fourier inversion, CLEAN and self-calibration (e.g. Pearson and Readhead 1984), using software developed by J. Romney and W. Alef at the MPIfR.

RESULTS AND DISCUSSION

On the arcsec scale, the structure of 3C454.3 shows a strong core feature, and a weaker, slightly curved "jet", pointing towards a "hot-spot" some 5 arcsec away in P.A. -48° (Browne et al. 1982). Our VLBI observations at λ18 cm show a similar structure, on a much smaller scale; the jet here is only about 20 mas (180pc; we adopt $H_0 = 55$ km s^{-1} Mpc^{-1}, $q_0 = 0.05$ throughout) long and its P.A. is -65° near the core and -53° at its end. At λ6 cm, the jet can be traced to about 10 mas (90pc) from the core, and for $\lambda \leq 2.8$ cm, it is difficult to map reliably, owing to its low surface brightness.

A comparison of VLBI maps made over a range of λ from 2.8 to 18 cm near the same epoch (∿ 1981.5) shows that the core was then self-absorbed below λ2.8 cm, with a spectral index $\alpha \sim +0.9$ (flux density $S \propto \nu^{\alpha}$), while the mas jet was transparent, with $\alpha \sim -0.7$. An extrapolation of the spectra to λ75 cm, where variations of the total flux density of up to 4 Jy are observed (e.g. Padrielli 1984), gives a flux density of the core of only 1 Jy, whereas that of the mas jet is about 10 Jy. This suggests that the long-wavelength variations arise from the mas jet, and, in view of its large extent, must be extrinsic, as suggested by Rickett et al. (1984).

We show the results of our VLBI observations at λ2.8 cm in Fig. 1 as a series of maps of the core region. The structural changes seen are quite unlike those which have been observed in the "classical" superluminal sources, such as 3C120, 3C273, 3C345 (e.g. Cohen and Unwin 1984).

The first two sets of observations (1981.4, 1982.1), near the peak of the outburst at λ2.8 cm, show the core as only slightly resolved. At both epochs, the data were well fitted by an unresolved component $\lesssim$ 0.2 mas (1.8pc) and a larger component, about 0.5 mas (5pc) in diameter, centred on the same position. Between 1981.4 and 1982.1, the flux density of the core region increased by about 2 Jy, and this increase occurred in the larger component, which brightened by ∼50 percent. This brightening, of a region 5pc in size, in a period of only 0.7 years, must be described as "superluminal" with an apparent propagation rate of the exciting signal (if originating at the centre) $\gtrsim$ 22c.

The map for epoch 1983.8 shows a dramatic change: the core became elongated in P.A. -95° (a direction differing by 30° from that of the mas jet), and showed three distinct brightness peaks, with an overall separation between the extreme peaks of 1 mas (9pc). There is an indication of a further component 1.4 mas West of the easternmost feature. We refer to these features by number, starting from the East. If these features were ejected from a region < 0.3 mas in extent at epoch 1982.1, in one direction, the apparent velocities of components 2, 3 and 4 between 1982.1 and 1983.8 must have been $\gtrsim$ 10c, 28c and 40c, respectively!

Surprisingly, following this apparent rapid expansion, the separations of the brightest features remained nearly constant: the apparent velocities of

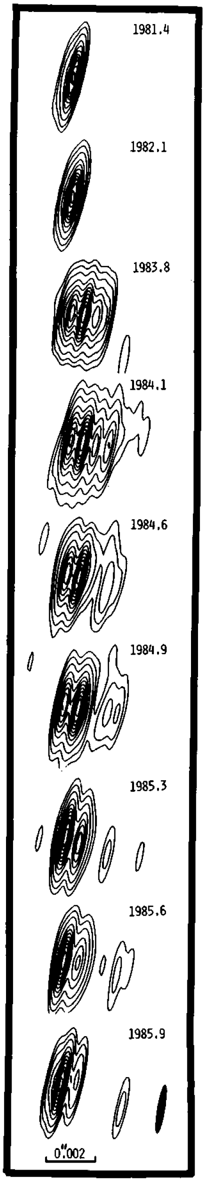

Figure 1: VLBI maps of the core region of 3C454.3 at λ2.8 cm. The restoring beam, of 2 x 0.3 mas is shown in the lower right corner. Contour intervals are 2.5, 5, 10, 20 ... 100 percent of the maximum brightness temperature, which is 1.9, 1.9, 0.38, 0.33, 0.41, 0.44, 0.63, 0.72, 0.84 x 10^{11}K, in order of epoch. There is no absolute position information, and the maps are aligned on the assumption that the easternmost component is the core, and that this is the only component visible in the first two epochs.

components 2 and 3 relative to component 1 were $< 3c$.

Nevertheless, component 4, which became distinctly visible on the western side of the core region by 1984.1, did show the "classical" superluminal motion between 1983.8 and 1984.9, when it separated from component 1 at a rate of 0.35 mas/yr, or 19c. A weaker feature (component 5?) which appeared distinct at epoch 1984.9, had a similar rate of separation. After 1984.9, these outer components faded, and the presence of any motion became difficult to establish.

This fading has occurred in all components, with the exception of 1: component 3 had disappeared by 1984.9, and even component 2 has become steadily fainter since 1984.9. Component 1, however, has brightened steadily since 1984.1, when the total flux density at $\lambda 2.8$ cm also began to increase again. This suggests that component 1 is the true core, or at least, most closely connected with it, and that the alignment of the maps in Fig. 1 is correct. Our data at $\lambda 1.3$ cm, which show the easternmost component to be the brightest, support this interpretation.

The kinematics in 3C454.3 thus appear much more complex than in the "classical" superluminal sources; a period of rapid apparent expansion with $v_a \gtrsim 30c$ is followed by a period in which some features are nearly stationary, while others move with $v_a \sim 20c$. On the standard models, the initial expansion requires relativistic bulk motion with Lorentz factor $\gamma \gtrsim 30$ and an angle of the motion to the line of sight $\theta \lesssim 1\overset{\circ}{.}9$. How is the subsequent lack of motion of some features to be explained? We may consider:

1) A decrease in the bulk velocity. For $\gamma = 30$, $\theta = 1\overset{\circ}{.}9$, a change in velocity $\lesssim 3000$ km s^{-1} is required to reduce v_a from $\gtrsim 30c$ to 3c. It is, however, not clear why this should occur for two features (2 and 3) at different distances from the core, and the loss in energy ($\Delta E/E = \Delta\gamma/\gamma \sim$ 75 percent) is substantial.

2) A bend in the trajectory, e.g. a decrease in θ from $1\overset{\circ}{.}9$ to $\lesssim 0\overset{\circ}{.}1$ also would reduce v_a to $\lesssim 3c$. If the bend occurs at the same place in space for all components, then the observed separations of 1 and 2, 1 and 3 are not explained, since the change in θ causes a "piling up" of components at the bend. On the other hand, if the bend occurs at successively larger distances from the core for 2, 3, etc., then identical degrees of bending are required, which seems contrived.

3) The true core is invisible, either because it is always opaque, or because its axis is at a large angle (say $> 5^{\circ}$) to the line of sight, and the "stationary" features are all moving at the same rate with respect to it. The initial apparent expansion then marks the emergence of successive components from the opaque region, or their motion past a suitable bend in the trajectory. Then, however, the emission between outbursts must arise from some feature that is always present, e.g. the point of emergence of the jet from an opaque region, or the location of the bend. In this case, this point is effectively the "core" and the postulate of an invisible core is superfluous. Furthermore, the separation of, say component 1 from the mas jet should decrease with time, and there is no evidence for this.

4) The features in the $\lambda 2.8$ cm maps mark regions of increased emission, caused, for example,by stationary shocks. Lind and Blandford (1985) have

shown that the velocity of shock fronts (the "components") may differ from that of the underlying fluid (the cause of the Doppler boosting of the emission), and that stationary emission patterns are possible.

This last explanation seems the most likely one to explain the complex behaviour of 3C454.3: the relativistic fluid excites shocks at progressively larger distances from the centre of activity. This effect appears superluminal and hence requires $\gamma \gtrsim 30$ and $\theta \lesssim 2^\circ$, but gives rise to a stationary shock pattern. A change in physical conditions at larger distances produces a moving pattern, and the "classical" superluminal behaviour of the outer components (4 and 5).

It is not clear why most of the "classical" superluminal sources do not also show this behaviour. Nevertheless, 3C454.3 is not unique in this respect. For example, in the quasar 4C39.25, a pattern of two strong, stationary features was observed over several years (e.g. Shaffer et al. 1977; Bååth et al. 1980), but more recent observations have revealed the appearance of a weaker, probably superluminal feature between the stationary components (Marcaide et al. 1985; Shaffer and Marscher 1985). The radio galaxy 3C111 shows a similar behaviour, but observed in reverse: following a period when no motion of a jet feature with respect to the core was observed, all the features faded, leaving only the core (Götz et al. 1986). This corresponds closely to the behaviour of 3C454.3 after the initial expansion.

Clearly, simple models, which rely only on geometrical alignment, and a single value of γ and the (unbeamed) core luminosity (e.g. Orr and Browne 1982) are inadequate in explaining all the phenomena observed in superluminal sources in general, and in 3C454.3 in particular. The latter is in a different class from that of the "classical" superluminal sources.

ACKNOWLEDGEMENT

The work described here has been carried out in collaboration with R.W. Porcas (MPIfR), J.A. Zensus (California Institute of Technology), S.Y. Wu (Beijing Observatory), K.I. Kellermann (National Radio Astronomy Observatory*), G. Nicolson (NITR) and F. Mantovani (Laboratorio di Radioastronomia, Bologna). Thanks are also due to the support of the staff at the various antennas, and at the MPIfR processor.

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* The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under contract with the National Science Foundation.

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