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# SUPERLUMINAL MOTION IN THE GIANT QUASAR 4C 34.47

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## ABSTRACT

We have detected superluminal motion in the core of 4C 34.47, the largest radio source associated with a QSO. Our data indicate an apparent superluminal core expansion speed of  $(2.5 \pm 0.2)h^{-1}c$  ( $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0.5$ ). The superluminally expanding core of 4C 34.47 is embedded in a double-lobed radio source which is extended by  $560h^{-1} \text{ kpc}$ . Explanation of the superluminal character of 4C 34.47 in the framework of relativistic beaming is considered.

*Subject headings:* interferometry — quasars — radio sources: general

## I. INTRODUCTION

Superluminal velocities in extragalactic radio sources have been conventionally explained in the relativistic beaming model (e.g., Pearson and Zensus 1987). This model explains superluminal motion and the apparent one-sidedness of radio jets as being due to bulk relativistic motion of the emitting plasma along a direction close to the line of sight. Because of this preferred orientation, superluminal quasars should therefore appear small in overall linear extent. Schilizzi and De Bruyn (1983) and more recently Barthel *et al.* (1986) demonstrated that this is not always the case, and decoupling of the pattern speed and the bulk flow (Barthel *et al.* 1986), or jet precession (Schilizzi and De Bruyn 1983) was proposed as a possible cause. A critical test of the simple relativistic beaming model (uniform velocity, unidirectional bulk relativistic motion) is provided by the search for structural changes in the cores of extended lobe-dominated quasars (e.g., Scheuer 1984). In a complete sample of sources selected on the basis of the existence of extended, presumably unbeamed structure, the orientation bias is expected to be minimal, and superluminal motion should be comparatively rare. Three superluminal sources have been found in such investigations so far: 3C 179 (Porcas 1981), 3C 263 (Zensus, Hough, and Porcas 1987), and 3C 245 (Hough and Readhead 1987). Because these sources all have relatively modest projected linear sizes, explanation of the changes in their core structures by the relativistic beaming model does not lead to extreme difficulties. We are engaged in a study of the milliarcsecond structure and evolution in the cores of a sample of large, double-lobed quasars (Barthel *et al.* 1984), and report here the discovery of superluminal motion in

an extreme case, namely, the core of 4C 34.47, the largest known radio source associated with a QSO.

## II. THE QUASAR 4C 34.47

4C 34.47 (1721+343) is a classical triple radio source (Fanaroff and Riley 1974, class II) of 4:3 overall angular extent, identified with a 16.5 mag QSO at a redshift of 0.206 (e.g., Hewitt and Burbidge 1980). Radio maps of the overall morphology of 4C 34.47 can be found in Jägers *et al.* (1982), Barthel (1987), and Barthel and van Breugel (1989). With its projected linear size of  $560h^{-1} \text{ kpc}$  ( $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$  and  $q_0 = 0.5$ , used throughout) 4C 34.47 is the largest known radio source associated with a QSO. A straight and narrow radio jet extends over more than  $200h^{-1} \text{ kpc}$  from the bright core to the southern hotspot. No counterjet is observed, with a lower limit to the jet-counterjet ratio of 10:1. At 5 GHz the compact core has a flux density of  $\sim 350 \text{ mJy}$ , which is  $\sim 55\%$  of the total source flux density. 4C 34.47 is a fairly low luminosity radio source, having  $P_{178} = 2.5 \times 10^{26}h^{-2} \text{ W Hz}^{-1}$ , which is, however, well above the Fanaroff and Riley (1974) division. The quasar is moderately variable, both in the optical (McGimsey and Miller 1977) and in the radio (Conway, Burn, and Vallée 1977; Jägers *et al.* 1982). The optical spectrum (Grandi and Phillips 1979) shows an unusually narrow H $\beta$  emission-line profile, with FWHM =  $1800 \text{ km s}^{-1}$  (Miley and Miller 1979).

## III. VLBI OBSERVATIONS AND RESULTS

We have observed the core of 4C 34.47 with global VLBI networks at 5 GHz (epochs 1982.27, 1983.27, and 1986.44), and at 10.7 GHz (epoch 1986.40). Parameters pertaining to the various observations are listed in Table 1.

For the 5 GHz observations the 2 MHz bandwidth Mk II recording system was used, whereas for the 10.7 GHz observations we used the more sensitive Mk III system at 28 MHz

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TABLE 1  
PARAMETERS OF THE VLBI OBSERVATIONS

Epoch	Frequency (MHz)	Observing Time (hr)	Antennas <sup>a</sup>
1982.27.....	4992	9	B, S, G, O
1983.27.....	4992	12	B, G, Y27, O
1986.44.....	4992	11	B, W, S, L, K, G, Y27, O
1986.40.....	10,650	11	B, L, K, G, O

<sup>a</sup> B: MPIfR, Effelsberg, West Germany (100 m). G: NRAO, Green Bank, WV (43 m). K: NEROC Haystack Observatory, Westford, MA (37 m). L: Istituto di Radioastronomia, Medicina, Italy (32 m). O: Caltech OVRO, Big Pine, CA (40 m). S: Onsala Space Observatory, Onsala, Sweden (25 m). W: NFRA, Westerbork, Netherlands (fourteen 25 m antennas). Y27: NRAO VLA, near Socorro, NM (twenty-seven 25 m antennas).

bandwidth. Left circular polarization was recorded. After correlation at the MPIfR (Bonn, FRG) and CIT/JPL (Pasadena, California) facilities, the data were calibrated in the usual manner (Cohen *et al.* 1975), and hybrid maps were produced using standard self-calibration techniques (e.g., Pearson and Readhead 1984). The noise level obtained in the maps is typically a few mJy per beam. Systematic uncertainties in the

quoted flux densities are mainly due to uncertainties in the flux densities assumed for the calibration sources, and are estimated to be a few percent. The quantity and quality of the 5 GHz data differed considerably between the three epochs. Particularly the 1982.27 data were of short duration and suffered from weather and technical problems during observation. Figure 1 shows the resulting 5 GHz maps from epochs 1983.27 and 1986.44, and Figure 2 shows the 10.7 GHz map.

The core of 4C 34.47 appears to contain a multicomponent linear structure, which is closely aligned with the overall source axis. We measure a position angle  $167^{\circ} \pm 2^{\circ}$  for the main components of the milliarcsecond scale structure, compared to  $162^{\circ} \pm 1^{\circ}$  for the large-scale jet. The dominant emission in the 4C 34.47 core has a linear triple morphology, the components of which we have labeled A, B, and C. Additional faint, extended emission can be seen, south of component C. This southern extension has been labeled D. The component strengths, separations, and position angles were determined from the four data sets in various ways. First, we measured these parameters directly from the maps. Second, we performed model fitting with a set of Gaussian components using the measured amplitude and closure phases. Third, we performed model fitting using the closure phases only, so as to be independent of amplitude calibration errors. The results are

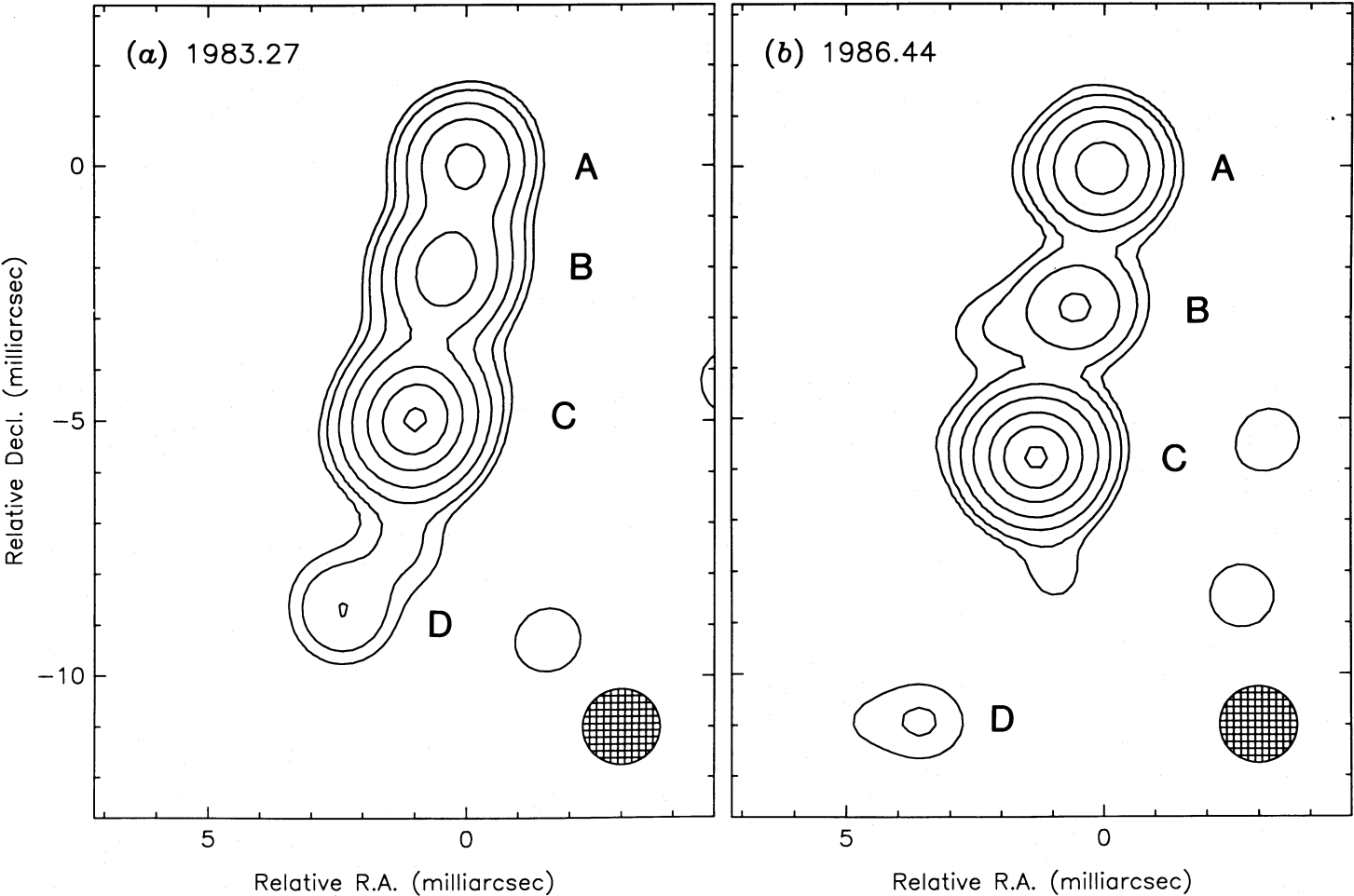


FIG. 1.—VLBI maps of the 4C 34.47 core at 5 GHz, restored with a 1.5 mas circular beam. (a) Epoch 1983.27: peak brightness 125 mJy beam<sup>−1</sup>, contours at −3, 3, 5, 10, 20, 40, 65, and 95%; (b) Epoch 1986.44: peak brightness 150 mJy beam<sup>−1</sup>, contours at −3, 3, 5, 10, 20, 40, 65, and 95%.

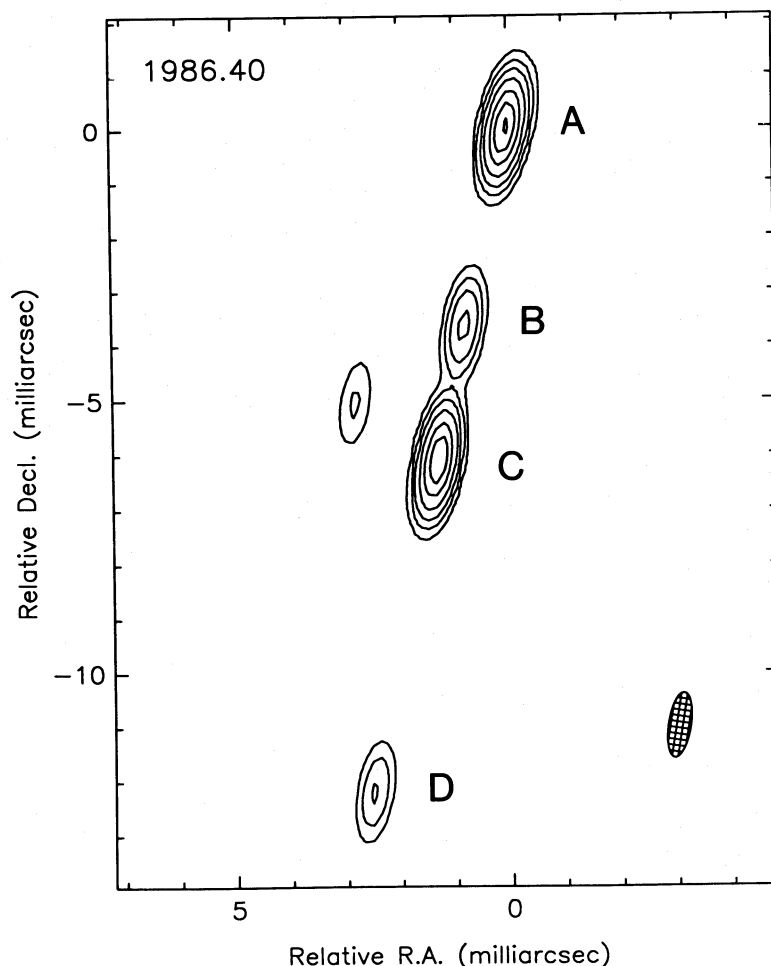


FIG. 2.—VLBI map of 4C 34.47 core at 10.7 GHz (epoch 1986.40), restored with a  $1.2 \times 0.4$  mas beam, in P.A.  $-9^\circ$ . Peak brightness is  $108 \text{ mJy beam}^{-1}$ , contours are  $-2, 2, 5, 10, 20, 40, 65$ , and  $95\%$ .

summarized in Table 2. As stated above, the 1983.27 and 1986.44 data sets are of higher quality than the 1982.27 data set. This is reflected in the estimated  $1 \sigma$  errors, listed in the Table.

TABLE 2  
KINEMATIC PROPERTIES OF 4C 34.47

Epoch	Component	Flux Density (mJy)	Separation (mas)	P.A.
1982.27.....	A	$90 \pm 10$	0	$0^\circ$
	B	$110 \pm 10$	$2.15 \pm 0.15$	$168 \pm 1$
	C	$100 \pm 10$	$4.65 \pm 0.10$	$170 \pm 1$
1983.27.....	A	$90 \pm 5$	0	0
	B	$100 \pm 5$	$2.25 \pm 0.10$	$169 \pm 1$
	C	$145 \pm 5$	$5.05 \pm 0.05$	$169 \pm 1$
	D	$\sim 15$	$\sim 9.1$	$\sim 164$
1986.44.....	A	$110 \pm 5$	0	0
	B	$35 \pm 5$	$2.75 \pm 0.10$	$169 \pm 1$
	C	$160 \pm 5$	$5.95 \pm 0.05$	$169 \pm 1$
	D	$\sim 10$	$\sim 11.5$	$\sim 161$
1986.40.....	A	$109 \pm 5$	0	0
	B	$23 \pm 5$	$3.50 \pm 0.10$	$168 \pm 1$
	C	$110 \pm 5$	$6.25 \pm 0.05$	$169 \pm 1$
	D	$\sim 9$	$\sim 12.6$	$\sim 167$

#### IV. 4C 34.47 AS A SUPERLUMINAL QUASAR

Our 1986 data indicate that component A should be identified as the radio nucleus in 4C 34.47, since it is found to have a flat radio spectrum ( $\alpha_5^{10.7} = 0.0$ ,  $S_\nu \propto \nu^\alpha$ ). Components B and C have steep spectra, on the other hand ( $\alpha_5^{10.7} = -0.6, -0.5$ , respectively). Identifying component A with the nucleus, the milliarcsecond scale structure in the core of 4C 34.47 appears asymmetric in the same sense as the large-scale radio jet, analogous to that observed in other extended quasars (e.g., Bridle and Perley 1984). We initially claimed (Barthel *et al.* 1985), that 4C 34.47 had two-sided jet emission on the milliarcsec scale. This claim was based on the assumption of the brightest core component being identified with the actual nucleus, which assumption now appears to be incorrect. Our new data furthermore show that components B and C, and probably also component D, are moving away from the nucleus. The location of component D, however, is poorly constrained by the data, and we therefore discard this component from further discussion. Weighted least-squares fits result in apparent proper motion  $\mu_B = 0.15 \pm 0.04 \text{ mas yr}^{-1}$  ( $1 \sigma$ ) and  $\mu_C = 0.29 \pm 0.02 \text{ mas yr}^{-1}$ . Using the adopted cosmology, these proper motions convert to transverse velocities  $v_{\text{app},B} = (1.3 \pm 0.3)c$ , and  $v_{\text{app},C} = (2.5 \pm 0.2)c$ . The 10.7 GHz separations were found to be greater than the 5 GHz separations (at almost the same

epoch 1986.4). This is probably due to edge-brightening or frequency-dependent optical depths, as in the well-known superluminal 3C 345 (Biretta, Moore, and Cohen 1986). We note that the core component A has remained approximately constant in flux density, in contrast to the jet components. Jet component B appears to fade, whereas C is found to brighten, during the motion down the jet. Using only the first and second epoch data, Barthel *et al.* (1985) estimated an upper limit of  $0.15 \text{ mas yr}^{-1}$  for component motion in 4C 34.47. The apparent inconsistency with the present results should be attributed to the fact that the former figure was based on crude, visual comparison of visibility amplitudes, whereas we performed an elaborate analysis of three epoch data to obtain the present, more accurate numbers. With particular attention to component C, we conclude that 4C 34.47 is a superluminal radio source.

As described by Pearson and Zensus (1987), the phenomenon of superluminal motion in extragalactic radio sources has been explained successfully in the framework of the relativistic beaming model, in which bulk relativistic outflow, with Lorentz factor  $\gamma = (1 - \beta^2)^{-1/2}$ , along a direction making a small angle  $\theta$  with the line of sight, is observed as transverse motion with apparent velocity  $\beta_{\text{app}} = \beta \sin \theta / (1 - \beta \cos \theta)$  exceeding one. This model can explain why many superluminal radio sources have blazar properties (e.g., Impey 1987), have core morphologies which are one-sided and curved (e.g., Readhead *et al.* 1978), and generally show relatively narrow permitted emission lines (e.g., Miley and Miller 1979; Wills and Browne 1986). In the context of this beaming model, the superluminal velocity of component C implies that 4C 34.47 lies within  $44^\circ$  of the line of sight, and minimizing the bulk flow velocity would imply  $\theta_{\text{min}} = 22^\circ$ , at  $\gamma_{\text{min}} = 2.7$  (for  $h = 1$ ). The probability for a randomly oriented radio source to lie within a  $44^\circ$  cone is 28%: we would expect, but do not find a few quasars to be larger than this largest known quasar. From the implied orientation, the inferred deprojected size of 4C 34.47 would exceed 800 kpc. As for the other extended superluminal quasars (Barthel *et al.* 1986), this deprojected size would be "uncomfortably" (Barthel 1987) large.

In order to maintain the beaming hypothesis, several modifications to the simple model have been proposed recently. Wobbling or precession of the beam axis, as a way of decoupling the small- and large-scale orientation, has been suggested by Readhead *et al.* (1978) and Schilizzi and De Bruyn (1983).

This seems an attractive solution for superluminal sources with curved outer structure, since small misalignments between pc and kpc-scale structure are not unusual in extended sources in general, and the amount of bending required to explain the observed superluminal motion is fairly modest. Another possible solution is to assume that the jet has a large opening angle at mas-scale and is collimated further out. The observed VLBI structure may actually represent a strongly boosted part of the flow which is significantly misaligned from the overall bulk flow (e.g., Phinney 1985; Barthel *et al.* 1986). Although both mechanisms may help alleviate the above mentioned problems in some lobe-dominated superluminal quasars, in the case of 4C 34.47 neither of them seems to apply. The radio jet is almost perfectly linear and highly collimated over its entire length, from the pc-scale core to the southern lobe  $200h^{-1}$  kpc away. This high degree of linearity and collimation appears to rule out a significant decoupling of the milliarcsec scale and extended structure. An alternative solution would be to decouple the pattern speed and bulk jet flow altogether, as in screen models (Miley 1983; De Waard 1986) or oblique shock models (Phinney 1985; Marscher 1987).

On the other hand, it might be argued that 4C 34.47 can indeed be explained within the simple beaming model. The low superluminal velocity is indicative of a moderately beamed source, and an orientation of the radio source within a  $44^\circ$  cone can indeed explain the apparent jet one-sidedness (provided the bulk relativistic flow persists in the large-scale jet), the observed core strength and variability, and the observed H $\beta$  line profile (Wills and Browne 1986). A severe objection to this picture has been the apparent absence of unbeamed counterparts of 4C 34.47. A companion paper (Barthel 1989) addresses this objection at length and presents evidence that powerful radio galaxies may well be the unbeamed counterparts of the beamed quasi-stellar radio sources.

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