

0850 + 581: ANOTHER SUPERLUMINAL RADIO SOURCE

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ABSTRACT

We present three 5 GHz VLBI maps of the bright core in the triple radio source 4C 58.17 associated with the quasar 0850 + 581, which indicate an apparent core expansion speed of $(5.3 \pm 0.8)h^{-1}c$ ($H_0 = 100h$ km s $^{-1}$ Mpc $^{-1}$ and $q_0 = 0.05$). We draw attention to the fact that superluminal motion is being found in an increasing number of radio sources with extended morphologies and discuss the difficulties that this poses for simple beaming models.

Subject headings: interferometry — quasars — radio sources: extended

I. INTRODUCTION

We have detected superluminal motion in the core of the triple radio source associated with the quasar 0850 + 581. We are studying this radio source as part of our project to survey the milliarcsecond structure and evolution of a complete sample of radio sources (Pearson and Readhead 1981, 1984*a*, 1986). One of the aims of this survey is to discover more superluminal sources and to determine the relative numbers of such objects. Including 0850 + 581 six members of the sample now appear to be superluminal, and we expect more as our observations proceed. The relative occurrence of superluminal motion in a complete sample of radio sources is an important test for the various models explaining the phenomenon and will be dealt with in a later paper. Here we draw attention to the fact that superluminal motion is being found in an increasing number of radio sources with *extended* morphologies, and we investigate some implications of these findings.

II. PREVIOUS OBSERVATIONS OF 0850 + 581

The radio source 0850 + 581 (4C 58.17) has appeared in several sky surveys (e.g., Kühr *et al.* 1981). It was identified with a quasar (Kühr 1977) of redshift 1.322 (Walsh and Carswell 1982). The radio source has a triple morphology with a dominant core. From a 1.4 GHz VLA map (Hintzen, Ulvestad, and Owen 1983) we deduce a core flux density fraction of 80% at 1.4 GHz, whereas VLA observations by D. L. Shone and I. Browne (unpublished) indicate 95% at 5 GHz. A 5 GHz VLA map of 0850 + 581, reproduced from Shone (1985), is shown in Figure 1. The source has a well-aligned triple morphology of overall extent 15''2, or 85/ h kpc projected linear size ($H_0 = 100h$ km s $^{-1}$ Mpc $^{-1}$ and $q_0 = 0.05$ —these values will be used throughout). A curved knotty structure (jet) leads from the core to the SE hotspot, and diffuse lobe emission is found $\sim 6''$ NW of the core.

The radio spectrum of 0850 + 581 is complex (Kühr *et al.* 1981), and the radio core is slightly variable. Quasi-simultaneous flux density measurements at three frequencies (Rudnick and Jones 1982, 1983) indicate a fairly steep spectrum for the source from 15 to 5 GHz ($\alpha_{15}^5 = -0.5$, $S_\nu \propto \nu^\alpha$), and subse-

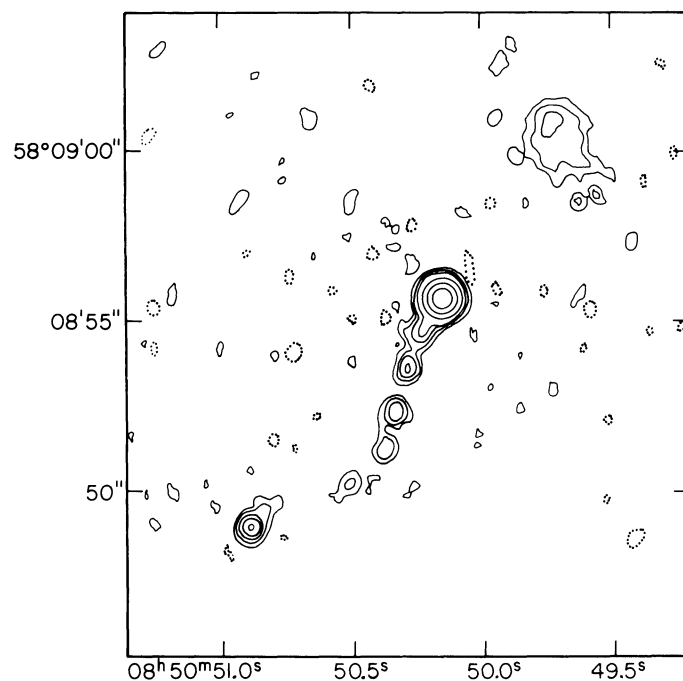


FIG. 1.—VLA map of 0850 + 581 at 4.9 GHz, reproduced from Shone (1985). The contour levels are at $-0.5, 0.5, 1.0, 2.0, 4.0, 8.0, 64.0$, and 256.0 mJy per beam, and the restoring beam is a Gaussian with FWHM $0''.5$.

quent turnover to 1.4 GHz ($\alpha_{1.4}^5 = 0.2$), as well as $\sim 10\%$ variability in total source flux density at 1.4 and 5 GHz. The 10.8 GHz flux density of 0850 + 581 has been monitored with the Owens Valley Radio Observatory 40 m telescope (Seielstad, Pearson, and Readhead 1983). No strong variations were found over a period of 3.9 yr, in agreement with the measurements of Rudnick and Jones.

III. VLBI OBSERVATIONS OF 0850 + 581

We have made VLBI maps of 0850 + 581 at three epochs using VLBI networks at 5 GHz, using the 2 MHz bandwidth

TABLE 1
PARAMETERS OF THE VLBI OBSERVATIONS

Epoch	Frequency (MHz)	Observing Time (hr)	Antennas ^a
1980.53	5011	5.5	B, K, F, O
1984.39	4992	8.5	K, G, F, Y, O, H
1985.77	4992	3.5	B, L, K, F, Y, O, H

^aB—MPIfR, Effelsberg, W. Germany (100 m); F—Harvard GRAS, Fort Davis, TX (26 m); G—NRAO, Green Bank, WV (43 m); H—UC Berkeley, Hat Creek, CA (26 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); Y—NRAO VLA, near Socorro, NM (one 25 m antenna).

Mark IIC system and recording left-circular polarization. Table 1 summarizes the observations.

The data were cross-correlated with the CIT/JPL processor at the California Institute of Technology and calibrated in the usual manner (Cohen *et al.* 1975). Radio maps were produced using standard self-calibration procedures (e.g., Pearson and Readhead 1984*b*). The data quality and quantity varied considerably at the three epochs. For the first epoch (1980.53) we obtained data from only four stations, whereas the second epoch (1984.39) lacked transatlantic baselines. Finally, the third epoch (1985.77) observations were obtained during four nonconsecutive hours observing, and the data were distributed nonuniformly across the u - v plane. The three maps are shown in Figure 2. Owing to limited u - v coverage and sensitivity, the noise level is typically a few mJy per beam, and owing to uncertainty in the absolute flux densities of our calibration sources, the errors in the quoted flux densities are estimated to be a few percent.

The first epoch map, at 1.5 mas resolution, shows an unequal double source in which a weak (20 mJy) component is seen at 5.4 mas separation in p.a. 153° , with respect to a dominant (825 mJy) component. The second epoch map has a lower noise level, but lower resolution (2.5 mas). In addition to the double structure (separation 5.8 mas), resolved components of low surface brightness are found at 13 mas separation from the main component in p.a. $\approx 150^\circ$. The third epoch map has 1.5 mas resolution: the double structure is seen again, with the weaker component being slightly resolved and a separation of 6.0 mas. Between the second and the third epochs the flux density of the stronger component increased from 825 mJy to 975 mJy. The strength, variability, and compact structure of this component suggest that it should be identified with the quasar core, and we assume that this is the case for the remainder of the discussion. At 1.5 mas resolution (first and third epoch) we detect 20 mJy in the secondary component, whereas this figure is 50 mJy at 2.5 mas (second epoch). It appears that this component is partially resolved.

IV. 0850+581 AS A SUPERLUMINAL SOURCE

The measurements from the maps indicate increasing component separation with time. We have tested the reality of this increase by making maps at the different epochs with the same starting model, by fitting models with Gaussian components using both amplitudes and phases, and by model fitting using only the measured closure phases, so as to be independent of calibration errors. The results are summarized in Table 2. Noise in VLBI data is certainly not Gaussian; hence we have estimated confidence levels from the various mapping and modelling procedures. We have also studied the behavior of the agreement between data and model while forcing offsets from their best-fitting values for the separation and

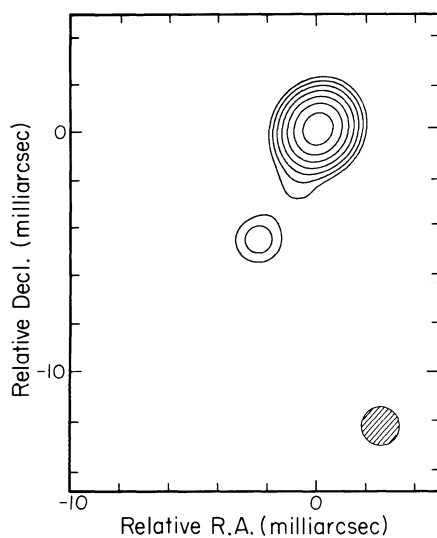


FIG. 2a

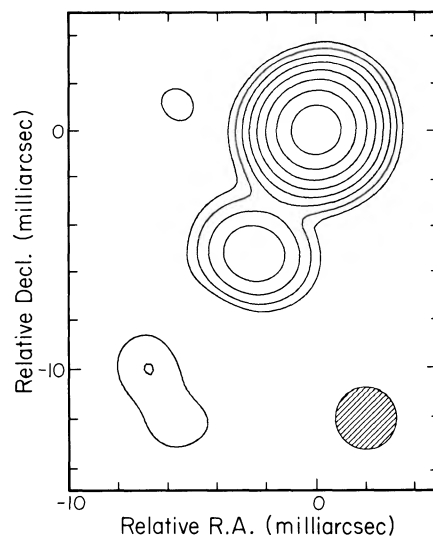


FIG. 2b

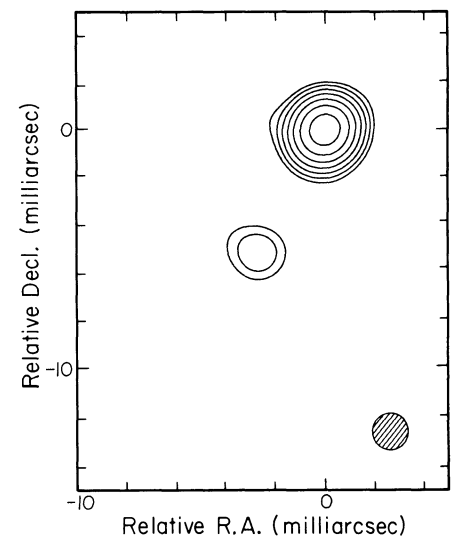


FIG. 2c

FIG. 2.—VLBI maps of 0850+581 at 5 GHz. (a) Epoch 1980.53: peak brightness 730 mJy per beam (1.5 mas FWHM); contours at $-1.0, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0$, and 64.0% . (b) Epoch 1984.39: peak brightness 738 mJy per beam (2.5 mas FWHM); contours at $-0.5, 0.5, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0$, and 64.0% . (c) Epoch 1985.77: peak brightness 862 mJy per beam (1.5 mas FWHM); contours at $-1.0, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0$, and 64.0% .

TABLE 2
KINEMATIC PROPERTIES OF 0850 + 581

Epoch	Component Separation (mas)	Component Position Angle
1980.53	5.36 ± 0.20	$153^\circ \pm 3^\circ$
1984.39	5.72 ± 0.36	$154^\circ \pm 4^\circ$
1985.77	6.00 ± 0.20	$152^\circ \pm 3^\circ$

NOTE.—The quoted errors are 99% confidence limits, estimated from the various procedures described in § IV of the text.

position angle of the two main components. Maximum 99% confidence levels, estimated from these combined procedures, appear in Table 2. A weighted least-squares fit to these data indicates an apparent proper motion $\mu = 0.12 \pm 0.019$ mas per year (1 σ error), or an apparent transverse velocity of $(5.3 \pm 0.8)h^{-1}c$. The uncertainty in this velocity is due to the limited resolution of the observations, noise in the data, and to the fact that the secondary component is resolved. Resolution effects also limit the accuracy in determining the displacement position angle, but the values obtained (see Table 2) are in good agreement with the p.a. of the first component of the kpc scale jet, which is 151° .

We conclude that 0850 + 581 is almost certainly a superluminal radio source. This brings the total number of superluminal radio sources to 10: 3C 120, 3C 179, 3C 273, 3C 279, 3C 345, NRAO 140, and BL Lac (see, e.g., Cohen and Unwin 1984), 1928 + 738 (Eckart *et al.* 1985), 1642 + 690 (Pearson *et al.* 1986), and 0850 + 581 (this *Letter*). The most popular model explaining superluminal motion is that of bulk relativistic outflow along a direction near the line of sight (e.g., Cohen and Unwin 1984). Bulk relativistic motion of the emitting plasma with Lorentz factor $\gamma = (1 - \beta^2)^{-1/2}$ at an angle θ to the line of sight may manifest itself as transverse motion with apparent velocity $\beta_{\text{app}} = (\beta \sin \theta)/(1 - \beta \cos \theta)$ exceeding one. For 0850 + 581 the actual bulk velocity β is minimized for $\gamma_{\text{min}} = 5.4/h$, at $\theta = 10.7h^\circ$. We note two peculiarities for this new superluminal source: first, the radio source is not highly variable, compared to most of the other known superluminals (e.g., Cohen and Unwin 1984), and second, its projected linear size of $85/h$ kpc is large; if the

entire source makes an angle $\theta = 10.7h^\circ$ to the line of sight, the deprojected linear size is $460/h$ kpc.

V. SUPERLUMINAL MOTION IN EXTENDED QUASARS

As stressed above, 0850 + 581 is an extended triple radio source with fairly well-aligned large scale components. The five superluminal quasars having such morphologies are listed in Table 3.

Column (2) in this table lists the projected angular size of the large-scale triple morphology; column (3), the redshift of the associated quasar; column (4), the projected linear size (kpc); column (5), the measured proper motion (mas per yr); column (6), the apparent transverse velocity in units of c ; column (7), the angle to the line of sight which would minimize the actual Lorentz factor of the bulk flow in the standard beaming model, $\theta_{\text{min}} = \text{arccot}(\beta_{\text{app}})$; column (8), the deprojected linear size (kpc), calculated using θ_{min} ; and column (9), relevant references. The deprojected linear sizes in column (8) are comparable to the projected linear size of the largest known quasar, 4C 34.47 ($600/h$ kpc; Jägers *et al.* 1982 and Barthel and van Breugel 1986). It is not clear why a considerable fraction of superluminal radio sources should be at the top end of the linear size distribution (see, e.g., Miley 1980).

In order to compute the deprojected linear sizes, we have assumed that θ_{min} applies to the extended structure as well as to the compact structure. One way of reducing the overall sizes is to decouple the values of θ for the compact and the extended morphologies. Based on the sample of superluminals known in 1982, this decoupling was proposed previously by Schilizzi and De Bruyn (1983). However, from Table 3 only NRAO 140 and 3C 179 were known in 1982, and it appears now that the linear size problem and the need for decoupling has increased. The possibility of long time scale wobbling or precession of the ejection axis was proposed by Readhead *et al.* (1978) and Schilizzi and De Bruyn (1983). Intrinsic bending of the kiloparsec scale jets away from the line of sight is an attractive possibility, since the maps of the large-scale morphologies of 0850 + 581, 1642 + 690, and 1928 + 738 do show (one-sided) jet curvature on the order of a few degrees per arcsecond. To explain the superluminal motion, the beaming model requires the core morphology of 1928 + 738 to

TABLE 3
EXTENDED TRIPLE SOURCES SHOWING SUPERLUMINAL MOTION

Source (1)	Angular Size (2)	z (3)	Linear Size (kpc) ^a (4)	μ (mas yr ⁻¹) (5)	β_{app} (6)	θ_{min} (7)	Deprojected Linear Size (kpc) ^a (8)	References (9)
NRAO 140.....	11''	1.258	62/ h	0.13	5.4/ h	10°5 h	340/ h	1, 2
3C 179	16	0.846	80/ h	0.14	4.2/ h	13.4 h	350/ h	3, 4
0850 + 581	15	1.322	85/ h	0.12	5.3/ h	10.7 h	460/ h	5
1642 + 690	11	0.75	53/ h	0.34	9.3/ h	6.1 h	500/ h	6
1928 + 738	45	0.302	132/ h	0.6	7.5/ h	7.6 h	1000/ h	7, 8, 9

^a Calculated assuming $H_0 = 100h$ km s⁻¹ Mpc⁻¹ and $q_0 = 0.05$.

REFERENCES.—(1) Marscher and Broderick 1982. (2) Schilizzi and De Bruyn 1983. (3) Porcas 1981. (4) Porcas 1984. (5) This *Letter*. (6) Pearson *et al.* 1986. (7) Eckart *et al.* 1985. (8) Lawrence *et al.* 1985. (9) Simon 1986.

be within a 15° cone (for $h = 1$). In order to have an average deprojected linear size of, say, $300/h$ kpc, the θ -value of the large-scale morphology should be $\sim 25^\circ$. We therefore conclude that an overall jet bending between 10° and 25° would suffice to explain the most stringent of these three cases. We note that this is a modest constraint, met by several large-scale jets (e.g., Bridle and Perley 1984), and we also note that small misalignments between kiloparsec and parsec scale structure in large triple sources, with values up to 12° , have been reported (Linfield 1981; Barthel *et al.* 1985).

Another possibility does not decouple θ for the small-scale and large-scale morphologies, but rather the bulk flow from the pattern speed. Blandford (1984), Phinney (1985), and Lind and Blandford (1985) pointed out that the observed compact structure of a radio source is highly sensitive to the bulk velocity field: the velocity of the radio emitting material (e.g., in a shock front) does not have to be in the overall flow direction. On this model the beaming in sources like 0850 + 581 could be explained as being due to oblique shocks, thereby decoupling the beaming and the measured superluminal motion from the general flow. In addition, nonbeaming theories (e.g., Cavaliere, Morrison, and Sartori 1971; Lynden-Bell 1977; Norman and Miley 1984) also decouple the pattern speed from the bulk plasma flow. A combination of the above-mentioned models can be envisaged.

VI. CONCLUSIONS

The quasar 0850 + 581 is the tenth radio source to show superluminal motion in its core. Based on the increasing number of superluminal radio sources having extended large-scale morphologies, we conclude that either misalignments between the small-scale and the large-scale structure are common, or the relativistic beaming model in its simplest form is inadequate to explain the observations.

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