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NEW SUPERLUMINAL QUASAR 1633+382 AND THE BLAZAR–GAMMA-RAY CONNECTION

P. D. BARTHEL[1]
Kapteyn Astronomical Institute, P.O. Box 800, 9700AV Groningen, The Netherlands
J. E. CONWAY[1,2]
National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801
AND
S. T. MYERS, T. J. PEARSON, AND A. C. S. READHEAD
Owens Valley Radio Observatory, California Institute of Technology, 105-24, Pasadena, CA 91125

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ABSTRACT

We report detection of superluminal motion in the core of 4C 38.41, associated with the $z = 1.814$ quasar 1633+382. The dominant nucleus in the ~ 30 kpc triple morphology of the radio source displays a core-jet structure on the milliarcsecond scale, and a jet component is found moving outward at 6.1 $h^{-1}c$ ($H_0 = 100\ h$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$). Quasar 1633+382 is a highly variable object, in both the radio and the optical wavebands, and in addition an extremely luminous gamma-ray emitter. It is the ninth gamma-ray blazar displaying superluminal motion. We point out that all gamma-ray active galactic nuclei (AGNs) which have been observed with VLBI sufficiently well have been found to show superluminal expansion. This provides strong support for the commonly accepted hypothesis that AGN gamma-ray emission is produced in a beamed relativistic jet.

Subject headings: galaxies: jets — gamma rays: theory — quasars: individual (1633+382) — radio continuum: galaxies

1. INTRODUCTION

As part of our project to survey the milliarcsecond-scale structure and structural evolution of a complete sample of strong radio sources (Pearson & Readhead 1981, 1988) we here report the discovery of the ninth superluminal source in the sample: 4C 38.41, associated with the $z = 1.814$ quasar 1633+382. This quasar has recently gained attention because of its extremely high gamma-ray luminosity (Kanbach et al. 1992).

2. PREVIOUS OBSERVATIONS OF 1633+382

The radio source 1633+382 was identified with a QSO (Pauliny-Toth et al. 1973) of redshift 1.814 (Strittmatter et al. 1974). The radio source has a triple morphology of $\sim 7''$ angular size, oriented north-south, with a dominant radio core (core fraction 99% at 1.6 GHz; Murphy, Browne, & Perley 1993). Adopting $H_0 = 100\ h$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$,[3] the projected linear extent of 1633+382 is $\sim 30\ h^{-1}$ kpc. The radio spectrum is flat ($\alpha \sim 0$) up to millimeter wavelengths with a spectral turnover at ~ 1 mm (Bloom et al. 1994). Strong variability at both long and short radio wavelengths has been reported (De Bruyn 1994; Spangler & Cotton 1981; Aller, Aller, & Hughes 1992; Seielstad, Pearson, & Readhead 1985; Kühr et al. 1981). Optical photometric monitoring of 1633+382 was reported by Barbieri et al. (1977), and the optical blue magnitude (redshifted UV light) was found to have a variability amplitude of more than 3 mag. Optical violently variable (OVV) core-dominated QSRs are commonly grouped as members of the blazar class.

Quasar 1633+382 was among the first extragalactic objects to be detected by the Energetic Gamma Ray Experiment Telescope (EGRET) on the *Compton Gamma Ray Observatory* (Kanbach et al. 1992; Fichtel et al. 1993). The large redshift of the quasar implies an extremely large gamma-ray luminosity: on the assumption of isotropy the average luminosity of 1633+382 in the 0.1–100 GeV band (emitted) would be $\sim 5 \times 10^{48}\ h^{-2}$ ergs s^{-1} (Mattox et al. 1993).

3. VLBI OBSERVATIONS OF 1633+382

We have made three VLBI maps of 1633+382 at 5 GHz, using antennas of the US and European VLBI Networks, in 1979.25, 1984.40, and 1986.89; see Table 1. The 2 MHz bandwidth Mk II system data were cross-correlated using the JPL/Caltech VLBI processor at the California Institute of Technology in Pasadena and subsequently calibrated in the usual manner (Cohen et al. 1975). Radio maps were produced using standard self-calibration procedures (Pearson 1991; Shepherd, Pearson, & Taylor 1994). The resulting radio maps have comparable restoring beams and reach comparable dynamic range levels, with typical noise levels of 2–3 mJy beam^{-1}.

The three maps are shown in Figure 1, with the same absolute contour levels. Errors in the absolute flux density values are estimated to be a few percent. Each map is restored with the same beam, having FWHM 2.00 × 1.00 mas in position angle $-16\overset{\circ}{.}0$, which we consider to be a good representation of the three slightly different beams of the individual epochs.

The three images show a source in which the flux density of the dominant component has systematically increased. 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 dis-

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[1] Formerly at Owens Valley Radio Observatory, California Institute of Technology.

[2] Present address: Onsala Space Observatory, S-43992 Onsala, Sweden.

[3] These values will be used throughout.

TABLE 1

JOURNAL OF OBSERVATIONS

Epoch	Antennas[a]	Frequency (MHz)	Polarization[b]	Time Scheduled (hr)
1979.25[c]......	B, G, F, O, H	4996	Lin90	6.5
1984.40	B, K, G, F, Y1, O, H	4992	LCP	10
1986.89	B, J, W, S, H, K, F, Y27, O	4991	LCP	4

[a] Antennas: B—100 m antenna at Effelsberg, near Bonn (Max-Planck-Institut für Radioastronomie); F—26 m antenna at Fort Davis, Texas (George R. Agassiz Station of the Harvard College Observatory); G—43 m antenna at Green Bank, West Virgina (NRAO); H—26 m antenna near Cassel, California (Hat Creek Observatory, University of California); J—25 m antenna at Jodrell Bank, Cheshire (University of Manchester); K—37 m antenna near Westford, Massachusetts (MIT/NEROC Haystack Observatory); O–40 m antenna near Big Pine, California (Owens Valley Radio Observatory, Caltech); S—25 m antenna at Onsala (Onsala Space Observatory); W—14 25-m antennas of the Westerbork Synthesis Radio Telescope, near Westerbork (Netherlands Foundation for Research in Astronomy); Y1— one 25 m antenna of the Very Large Array, near Socorro, New Mexico (NRAO); Y27—27 25-m antennas of the Very Large Array, near Socorro, New Mexico (NRAO).

[b] Polarization: Lin90—linear, with E-vector in P.A. 90°; LCP—left circular (IEEE convention).

[c] These observations were made in a combined project with R. C. Walker and M. H. Cohen.

cussion. Emerging from the core is a one-sided "jet" which appears to increase in extent with time. Superresolved maximum entropy maps at the first two epochs show that there is a distinct feature in the jet for which positions can be measured (via model-fitting the *uv* data) and which can therefore be used to estimate a jet pattern speed. Because of the increased core flux density and poorer *uv*-coverage of the 1986 data we were not able to obtain a good maximum entropy map at this epoch. An 18 cm VLBI map at 10 mas resolution (Polatidis et al. 1995) shows that at ~20 mas west of the core the jet bends toward the south, through ~90°. Such jet bending is typical in core-dominated QSRs (Readhead et al. 1978). Furthermore, sources which like 1633+382 have almost 90° bends between parsec- and kiloparsec-scale structure seem to be especially common among highly core-dominated sources (Pearson & Readhead 1988; Conway & Murphy 1993; Xu et al. 1994).

4. QUASAR 1633+382 AS A SUPERLUMINAL SOURCE

In order to assess the apparent jet motion in 1633+382 and to quantify its errors we carried out extensive tests fitting Gaussian models to the data sets. Since the 1984 data have long tracks with seven antennas, we began by modeling this data set and then used the resulting model as the starting point for modeling the 1979 and 1986 data. Consistent with our maximum entropy map we could fit the 1984.40 data with a simple two-component model, in which one component is compact and the other elongated roughly east-west. This structure is consistent with that found by Cawthorne et al. (1993) in sparse 5 GHz polarization data observed in 1984.78, although they fitted a model of three circular Gaussians instead of two elliptical Gaussians.

We reach slightly different local minima in reduced χ^2 whose overall agreement factors are indistinguishable (all within 0.05 of unity), depending on our starting model and the route taken in fitting the 1984 data (i.e., the order in which component shape and position are varied to fit the data). The range of separations corresponding to these minima is 1.95 ± 0.15 mas, where the error represents the estimated 99% confidence level. Starting from our best-fitting 1984 model we find that the 1979 data then dictate a reduced separation to 1.25 ± 0.15 mas. These results imply a jet component proper motion of 0.14 ± 0.06 mas yr^{-1} between 1979.25 and 1984.40.

It proved impossible to fit the 1986 data set simply by varying the flux density and shape of the core component in the 1984 model. Fitting the 1986 data requres a change in the position and shape of the secondary component. In addition, a third component close to the core is probably required. Because of this increased complexity of the source, the poorer hour angle coverage of the data, and the increased flux density of the primary core component, we find that a number of slightly different models are able to fit the 1986 data with similar agreement factors. The best-fitting model whose structure is closest to the image shown in Figure 1 (*right*) has three components with a weak outermost component having a separation of 2.55 ± 0.20 mas and a third component of ~0.5 Jy at separation 0.3–0.4 mas in P.A. ~ −42° with respect to

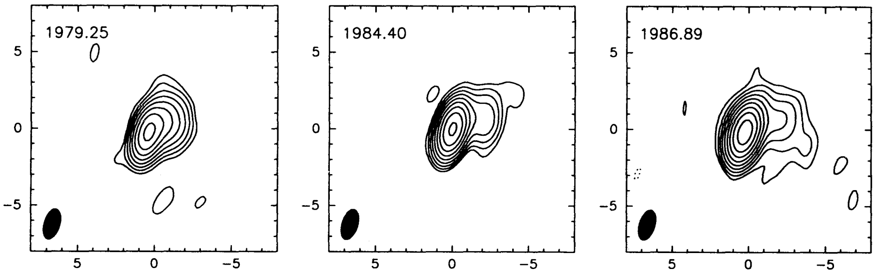

FIG. 1.—5 GHz VLBI maps of 1633+382, restored with a beam having FWHM 2.00 × 1.00 mas, in P.A. $-16\overset{\circ}{.}0$. Relative right ascension and declination are plotted, with tickmark spacings of 1 mas. *Left*, Epoch 1979.25: peak brightness 1.210 Jy beam^{-1}, contours at −0.62, 0.62, 1.23, 2.46, 4.92, 9.84, 19.68, 39.36, and 78.73 percent; *middle*, epoch 1984.40: peak brightness 2.196 Jy beam^{-1}, contours at 0.34, 0.68, 1.36, 2.71, 5.42, 10.84, 21.68, 43.37, and 86.73 percent; *right*, epoch 1986.89: peak brightness 2.976 Jy beam^{-1}, contours at −0.25, 0.25, 0.5, 1.0, 2.0, 4.0, 8.0, 16.0, 32.0, and 64.0 percent.

the primary core component. Identifying the weak outermost component with that seen at radius 1.95 ± 0.15 mas in 1984 implies a proper motion value of 0.24 ± 0.14 mas yr^{-1} between 1984.40 and 1986.89. This value is consistent with the estimate found from comparing the 1979 and 1984 data. Our model-fitting results are summarized in Table 2.

Adopting the Gaussian models from Table 2 we used the estimated 99% confidence levels to obtain a weighted least-squares fit to the three-epoch apparent proper motion of the secondary jet component: $\mu = 0.16 \pm 0.03$ mas yr^{-1}. We recall that the uncertainty in this value is due to the limited resolution of the observations, noise in the data, and the fact that the weak secondary component is resolved. The measured proper motion yields an apparent velocity $\beta_{\text{app}} = (6.1 \pm 1.1)$ h^{-1}. This is a typical velocity for core-dominated superluminal quasars (e.g., Hough & Readhead 1987). In the standard model for superluminal motion (e.g., Pearson & Zensus 1987), the jet must be oriented at an angle $\theta < 18\overset{\circ}{.}6$ from the line of sight in order to produce an apparent expansion speed this large, and the Lorentz factor of the flow must be at least $\gamma = 6.2$ (for $h = 1$).

In summary, the nuclear radio emission in quasar 1633+382 has brightened from 1.7 Jy (1979.25) to 2.5 Jy (1984.40) to 3.6 Jy (1986.89). A component in a curved milliarcsecond scale jet is found to be moving away with velocity 6.1 $h^{-1}c$, while fading from 0.5 to 0.3 to 0.1 Jy. The 1986 data suggest that close to the core, a new component of ~0.5 Jy has appeared and is moving away in the northwestern direction at yet undetermined velocity.

Our (1979–1986) proper motion of 0.16 mas yr^{-1} is similar to the value 0.2 mas yr^{-1} measured by the MIT VLBI group in 1974.5–1977.6 (Cotton et al. 1977; Cotton 1994). Examining the centimeter-wavelength flux history (Aller et al. 1985, 1992) we see that the appearance of both moving components was preceded by a radio outburst. This behavior is also seen in the Seielstad et al. (1985) data. Such relationships between core brightening and the appearance of jet components have been observed previously in other blazars (e.g., Mutel et al. 1990; Zensus et al. 1990) and may therefore be causal.

5. DISCUSSION

Biermann et al. (1987) calculated the expected synchrotron self-Compton X-ray flux for 1633+382 from a crude VLBI measurement of its radio core size and compared this value with the *Einstein Observatory* IPC detection (Ku, Helfand, & Lucy 1980; see Mattox et al. 1993 regarding the signal-to-noise ratio of this detection). On the simplest assumptions, the inferred X-ray deficit dictates bulk relativistic motion with Doppler factor $\delta = [\gamma(1 - \beta \cos \theta)]^{-1} > 3.5$. Therefore, except for its low optical polarization (1.1% ± 2%; Impey, Lawrence, & Tapia 1991), 1633+382 displays all the properties of a luminous blazar: highly dominant radio core with synchroton self-Compton deficit, variable emission at radio and optical wavelengths, and superluminal motion. It is interesting to note that although the measured polarization is low, Impey et al. (1991) measure a good alignment for the optical polarization and the VLBI jet position angle (−64° vs. ~ −65°; see Fig. 1 and Table 2). This being another typical blazar characteristic (Impey et al. 1991), the identification of 1633+382 as such is without doubt.

Quasar 1633+382 being identified as a superluminal blazar, the question arises as to the origin of its strong gamma-ray emission. From inspection of the current gamma-ray active galactic nucleus (AGN) list (Fichtel et al. 1994) it is clear that EGRET detects exclusively luminous, core-dominated, flat-spectrum radio sources. Blazar characteristics such as strong optical polarization and variability are commonly found. As pointed out, for instance, by Fichtel (1994) these facts suggest that strong gamma-ray emission and blazar properties are physically related. Additional support is provided by gamma-ray variability. In order to avoid photon-photon opacity effects in regions with a high photon density (e.g., Jelley 1966) the gamma-ray–emitting volumes must be considerably larger than inferred from the variability timescales, unless the high-energy radiation is beamed. This argument has been used by Maraschi, Ghisellini, & Celotti (1992 and Henri, Pelletier, & Roland (1993) for 3C 279, and by Mattox et al. (1993) for 1633+382. The latter authors calculate a minimum gamma-ray Doppler factor of 6.5 for 1633+382.

Our detection of superluminal motion in 1633+382 is not just consistent with the suggested gamma-ray–blazar physical connection, but makes this picture rather unavoidable. Fichtel et al. (1994) lists 25 positive EGRET Active Galaxy detections. Of those 25, nine objects have high-sensitivity, properly sampled, multiepoch VLBI maps, and all nine were found to display superluminal motion. Five of the nine objects (3C 273, 3C 279, 3C 454.3, Mrk 421, and CTA 102) were regularly observed with VLBI because of their high radio flux density and blazar characteristics. The object 0234+285 was monitored as part of a survey of highly variable radio sources (Wehrle et al. 1992). The other three objects appear in complete VLBI surveys: S5 0836+710 and S5 0716+714 in the Witzel et al. (1988) complete sample and (the present) 1633+382 in the Pearson & Readhead (1988) sample. Superluminal motion in 3C 273, 3C 279, 3C 454.3, Mrk 421, 0234+285, and 0836+710 is without doubt (Vermeulen & Cohen 1994), whereas for CTA 102 new observations (Wehrle & Cohen 1989) do not contradict the motion reported by Bååth (1987).

TABLE 2

GAUSSIAN MODELS

		SECONDARY COMPONENT			THIRD COMPONENT		
EPOCH	PRIMARY COMPONENT FLUX DENSITY (Jy)	Flux Density (Jy)	Separation[a] (mas)	P.A.[a]	Flux Density (Jy)	Separation[a] (mas)	P.A.[a]
1979.25.......	1.15 ± 0.1	0.55 ± 0.1	1.25 ± 0.15	−59° ± 3°	...	...	...
1984.40.......	2.25 ± 0.05	0.25 ± 0.05	1.95 ± 0.15	−69 ± 1	...	...	...
1986.89[b]......	2.95 ± 0.05	0.12 ± 0.05	2.55 ± 0.20	−70 ± 1	0.55 ± 0.05	~0.35	~ −42°

[a] Separation and position angle values are specified with respect to the primary component.

[b] There is not a unique best-fitting model for the 1986 data; the present three-component model provides a good fit, resembles the VLBI image (Fig. 1, *right*), and is consistent with the 1979 and 1984 models.

The object 0716+714 is an extreme member of the class of intraday variable BL Lac objects (Quirrenbach et al. 1991) and will be in the superluminal class provided its redshift exceeds the likely value of 0.28 (Stickel, Fried, & Kühr 1993). Our detection of superluminal motion in 1633+382 leads us thus to predict that many strong gamma-ray–emitting AGNs will be found to show superluminal motion, if monitored over a sufficient length of time. We note with interest, however, that the converse is not true: well-known superluminal blazars such as 3C 345 have so far not been detected in gamma rays.

Blazar characteristics and, in particular, superluminal motion are generally attributed to the effects of a relativistic jet being viewed at a small angle (e.g., Blandford & Rees 1978; Blandford & Königl 1979). The resulting Doppler boosting can have extreme consequences for observed luminosities, and calculated gamma-ray luminosities assuming isotropic emission are incorrect. In addition, the Doppler blueshift may explain the high millimeter flux in blazars in general and EGRET blazars in particular. In fact, 10 of the EGRET AGNs have been observed at 3 mm (3C 273, 3C 279, 3C 454.3, 0202+149 [4C 15.05], 0234+285 [4C 28.07], 0235+164, 0420−014, 0827+243, 1101+384 [Mrk 421], and 1633+382 [4C 38.41]), and all 10 were detected (Owen et al. 1978; Owen, Spangler, & Cotton 1980; Owen & Puschell 1982). Bloom et al. (1994) also draw attention to the flat millimeter spectra of the gamma-ray–detected blazars.

In summary, a very strong case can be made that gamma-ray emission in AGNs finds its origin in a relativistic jet closely oriented to the line of sight. Such a mechanism would explain the observed blazar, overall spectrum, and variability properties of the EGRET AGNs. As reviewed by Marscher & Bloom (1994), the synchrotron self-Compton process in a relativistic jet is a leading candidate for the gamma-ray emission in blazars. Monitoring of blazars in all bands from radio to gamma rays and comparison of the flare characteristics is needed to refine this relativistic jet model.

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