THE ASTROPHYSICAL JOURNAL > 464 :170 176, 1996 June 10

VLBI OBSERVATIONS OF SOUTHERN EGRET IDENTIFICATIONS. 1. PKS 0208- 51?, PKS OS?1 365, AND PKS 053'/- 441

S. J. TINGAY
Mount Stromlo and Siding Spring Observatories, ACT 2611, Australia; tingay@mso.anu.edu.au
P. G. EDWARDS
Institute of Space and Astronautical Science, Sagamihara, Kanagawa 2?9, Japan
M. E. COSTA, J. E. J. LOVELL, AND P. M. MCCULLOCH
University of Tasmania, Hobart, 7001, Australia
D. L. JAUNCEY, J. E. REYNOLDS, A. K. TZIOUMIS, V. MIGENES, R. GOUGH, AND E. A. KING
Australia Telescope National Facility, CSIRO, Epping, 2121, Australia
D. L. JONES, R. A. PRESTON, D. W. MURPHY, D. L. MEIER, T. D. VAN OMMEN, M. ST. JOHN, AND D. W. HOARD
Jet Propulsion Laboratory, Pasadena, CA 91109
G. D. NICOLSON
Hartebeesthoek Radio Astronomy Observatory, Krugersdorp, 1740, South Africa
AND
T.-S. WAN AND Z.-Q. SHEN
Shanghai Astronomical Observatory, Shanghai, ?00030, People's Republic of China

Received 1995 November 6; accepted 1995 December 28

ABSTRACT

We present high-resolution very long baseline interferometry images of three southern radio sources that the Energetic Gamma-Ray Experiment Telescope (EGRET), on board the *Compton Gamma Ray Observatory*, has identified as greater than 100" MeV gamma-ray sources. These are the first results in a continuing program of VLBI observations of southern EGRET identifications. For two of these sources, PKS 0208- 51? (at 4.851 GHz) and PKS 0537- 441 (at 4.851 and 8.418 GHz), the images represent first-epoch observations. For the remaining lower redshift object, PKS 05?1 365, we present images from three epochs at 4.851 GHz and an image from one further epoch at 8.418 GHz, spanning approximately 1 yr. We discuss the need for further extensive VLBI observations of EGRET- identified radio sources.

Subject headings: galaxies: active — galaxies: jets — gamma rays: observations — techniques: interferometric

1. INTRODUCTION

The first two dedicated gamma-ray astronomical satellites, SAS ? and *COS B*, yielded between them one identified extragalactic source of greater than 100" MeV gamma rays, the radio source 3C ?-/3 (Bignami & Hermsen 1983). The *Compton Gamma Ray Observatory* (CGRO) was launched in 1991 April. Of the four detectors on board the *CGRO*, the Energetic Gamma-Ray Experiment Telescope (EGRET) is sensitive to the highest energy gamma rays, those in the ?() MeV to 30 GeV range. To date, *CGRO* has discovered over 120 discrete sources of greater than 100 MeV gamma-ray emission.

Of these discrete sources the second EGRET Source Catalog, compiled from observations during phases I and II of the *CGRO* mission (from 1991 April to 1993 July), lists with high confidence 40 identifications of extragalactic radio sources and a further 11 marginal identifications (Thompson et al. 1995). Identifications were classified as marginal if the candidate radio counterpart lies close to but outside the 95% uncertainty contour for the gamma-ray source position. Previously, the high confidence and marginal classifications were based solely on photon statistics (e.g., von Montigny et al. 1995). To avoid confusion, we will use the following terminology: strong and weak describe the statistical significance of detection, and high-confidence and marginal describe the identifications. The rapid optical variability and strong optical polarization of most of these counterpart sources have resulted in their being classified as "blazars."

The absolute gamma-ray luminosities for some EGRET sources are exceedingly high ($\sim 10^{48}$ ergs s^{-1}, approximately the Eddington limit for a 10^{10} $M_{\odot}$ black hole) if isotropic emission is assumed. However, there are reasons for concluding that the emission is not isotropic. A number of the radio counterparts have already been observed with very long baseline interferometry (VLBI). These sources have generally exhibited apparent superluminal motions, suggesting beamed emission from relativistic matter traveling close to our line of sight. If the gamma-ray flux originates in the jet and is also beamed along our line of sight, then the luminosities derived by assuming isotropic emission will be overestimates.

Although extragalactic EGRET sources are consistently identified with bright, flat-spectrum radio sources, not all bright, flat-spectrum radio sources are detectable gamma-ray sources. The assumption that the gamma-ray emission is beamed has been used to infer that the width of the gamma-ray beam is smaller than that of the radio beam, under the "unified scheme" assumption that all bright, flat-spectrum radio sources are gamma-ray sources. Adopting a beam size for the radio emission of ~ 14 , Salamon & Stecker (1994) derive a beam size for the gamma-ray em -

sion of ~4°. However, Dondi & Ghisellini (1995) argue that the radio and gamma-ray beams must be collimated to the same extent, and they suggest that the EGRET sources are detected because they are currently in a high state of gamma-ray emission, thus leaving those sources currently in a low state undetected.

Indicators of relativistic beaming are therefore relevant for models of the gamma-ray emission. For example, the models proposed by Salamon & Stecker (1994) and Dondi & Ghisellini (1995) have quite different implications for the distribution of line of sight angles of the relativistic jet in EGRET sources. Salamon & Stecker predict that all gamma-ray sources have their jets aligned within 4° to the line of sight, whereas Dondi & Ghisellini imply a broader distribution of angles to the line of sight.

Such predictions of the beaming characteristics of EGRET sources may be tested by comparing the VLBI properties of radio sources, such as superluminal motions and radio core brightness temperatures, over the full range of gamma-ray activity (nondetections, weak detections, and strong detections) and examining any similarities or differences between these populations.

In this paper we describe the first high-resolution VLBI observations of three southern EGRET radio sources, PKS 0208−512, PKS 0521−365, and PKS 0537−441, all high-confidence identifications in the second EGRET catalog. In § 2, our observations, reductions, and analysis methods are outlined. The results for the individual sources are presented in § 3, where we derive estimates of the radio core brightness temperatures. We conclude with a discussion of the existing VLBI observations of EGRET sources in § 4.

2. OBSERVATIONS AND DATA REDUCTION

Our VLBI observations, summarized in Table 1, were all made using the Mark-II recording system (Clark 1973) and the SHEVE (Southern Hemisphere VLBI Experiment) array of telescopes. The array, its properties, and operational modes have been described elsewhere (Preston et al. 1989; Jauncey et al. 1994).

All data were recorded with left circular polarization (IEEE convention) and upper sideband with a bandwidth of 1.8 MHz, and subsequently they were correlated at the Block II Caltech/JPL processor in Pasadena, California. The data were fringe-fitted in NRAO's Astronomical Image Processing System (AIPS) before being passed to the Caltech reduction software package for coherent averaging in time. An initial calibration, available from measured system temperatures and antenna sensitivities, was applied to calibrator sources of known total flux density observed in the same experiment. A single time-independent scaling factor was determined for each antenna by amplitude self-calibration on the calibrator sources and applied to the amplitudes of the program sources to improve the initial calibration. The error in the flux density scales was then estimated by imaging the program source data and noting the telescope-based corrections made during the self-calibration stages. In all cases, these corrections were less than 10% and often less than 5%. The data were imaged using DIFMAP (Shepherd, Pearson, & Taylor 1994), part of the Caltech package (Pearson 1991) with 512 × 512 maps and pixel sizes ranging between 0.1 and 0.5 mas. Brightness temperatures were found for components which were deconvolved from the synthesized beam using the JMFIT task in AIPS. JMFIT returns only an upper limit on the size of completely unresolved components but returns an estimated size, with upper and lower limits, for components that are resolved. In the case of unresolved core components, we were able to derive lower limits to the brightness temperature from the limit on the size and the total flux of the component. For the cores that were resolved, we could derive an estimate of the brightness temperature from the estimated size and the total flux.

For PKS 0521−365, high-resolution multiepoch and multifrequency data are available, and so, in addition to the above procedures, the following analyses were performed. Limits on the jet-to-counterjet surface brightness ratios were made directly from the images. We estimated spectral indices using the total flux in each component measured from the images. The multiepoch data were used to estimate the apparent speed in the jet of PKS 0521−365. To this end, we used the Caltech task MODELFIT to fit simple Gaussian components to the amplitudes and closure phases, either two or three components at each epoch, keeping the core component as our arbitrary phase center.

3. THE INDIVIDUAL SOURCES

3.1. *PKS 0208−512*

PKS 0208−512 was detected with a strong statistical significance (>5σ) by EGRET (von Montigny et al. 1995). The high-confidence identification is with an $m_V = 17.5$ high-polarization quasar at a redshift of 1.003 (Savage 1975; Peterson et al. 1976; Impey & Tapia 1988). PKS 0208−512 has the hardest gamma-ray spectrum of all EGRET sources, with a differential spectral index of 1.689 ± 0.046

TABLE 1

OBSERVATION LOG

Source	Epoch	Frequency (GHz)	Participating Telescopes[a]
PKS 0208−512	1992 Nov 28	4.851 GHz	Pk, Hb, Cg, Mr, Pr27, Ht
PKS 0521−365	1992 Nov 23	4.851 GHz	Pk, Hb, Cg, Mr, Pr27, Ht, Sh
	1993 Feb 15	4.851 GHz	Pk, Hb, Cg, Mr, Pr27
	1993 May 14	4.851 GHz	Pk, Hb, Mr, Pr27
	1993 Oct 21	8.418 GHz	Pk, Hb, Cg, Mr, Pr15
PKS 0537−441	1992 Nov 24	4.851 GHz	Pk, Hb, Cg, Mr, Pr27, Ht, Sh
	1994 Feb 25	8.418 GHz	Ds45, Pk, Hb, Cg, Mr

[a] Ds45 = Tidbinbilla (Deep Space Network, 34 m), Pk = Parkes (Australia Telescope National Facility [ATNF], 64 m), Hb = Hobart (University of Tasmania, 26 m), Cg = Culgoora (ATNF, 22 m), Mr = Mopra (ATNF, 22 m), Pr15 = Perth (European Space Agency, 15 m), Pr27 = Perth (Telstra, 27 m), Ht = Hartebeesthoek Radio Astronomy Observatory (26 m), Sh = Shanghai Astronomical Observatory (25 m)

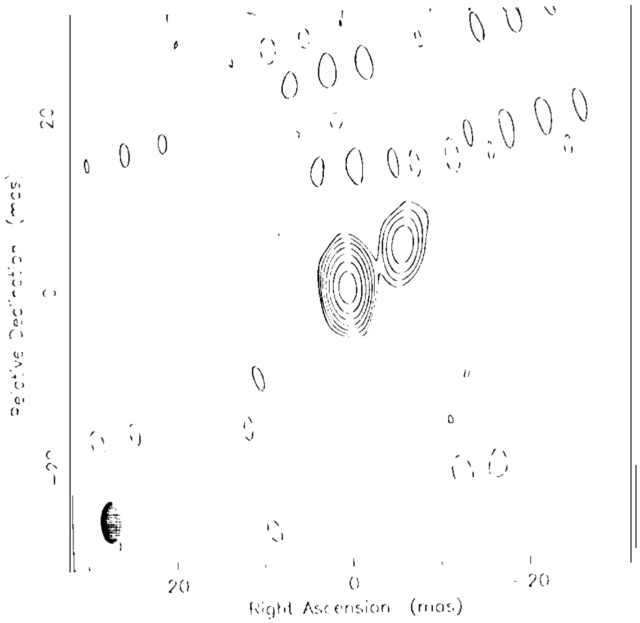

FIG. 2. VLBI image of PKS 0521−365 at 4.851 GHz from 1992 November 23. Map peak is 1.27 Jy beam^{-1} with contours of −1, 1, 2, 4, 8, 16, 32, and 64% of peak and a beam FWHM of 4.68 × 2.32 (mas) at a position angle of 1°.45

FIG. 3. VLBI image of PKS 0521−365 at 4.851 GHz from 1993 February 15. Map peak is 1.77 Jy beam^{-1} with contours of −0.5, 0.5, 1, 2, 4, 8, 16, 32, and 64% of peak and a beam FWHM of 3.74 × 2.27 (mas) at a position angle of 0°.58.

TABLE 2

LIMITS ON JET-TO-COUNTERJET SURFACE BRIGHTNESS RATIO (R) AND CORE-JET SEPARATION (d) FOR EACH OF THE PKS 0521−365 EPOCHS

Epoch	Frequency (GHz)	R	d (mas)
1992.91......	4.8	>9.3	$7.8^{+1.4}_{-1.6}$
1993.12......	4.8	>8.6	$8.6^{+1.4}_{-1.6}$
1993.37......	4.8	>5.0	$9.4^{+1.4}_{-2.0}$
1993.80......	8.4	>2.9	$10.3^{+1.2}_{-1.8}$

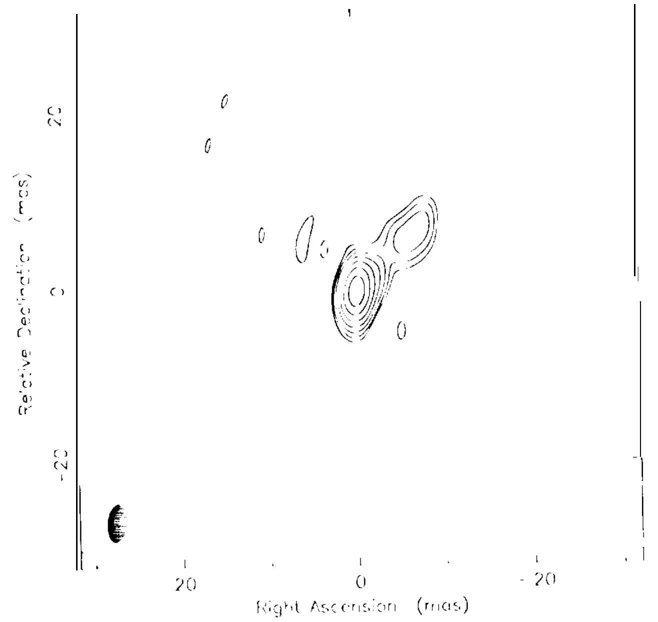

FIG. 4. VLBI image of PKS 0521−365 at 4.851 GHz from 1993 May 14. Map peak is 1.95 Jy beam^{-1} with contours of −1, 1, 2, 4, 8, 16, 32, and 64% of peak and a beam FWHM of 4.26 × 2.13 (mas) at a position angle of −6°.29.

proposed by Falomo et al. (1995) for PKS 0521−365 but also with a model which has a highly relativistic flow closely aligned to our line of sight. However, the brightness temperature, which is well below the nominal inverse Compton limit of 10^{12} K, does not favor PKS 0521−365 as a highly beamed radio source. Observations at later epochs will allow us to constrain further any apparent motion in the jet of PKS 0521−365, giving a more complete indication of the importance of relativistic beaming.

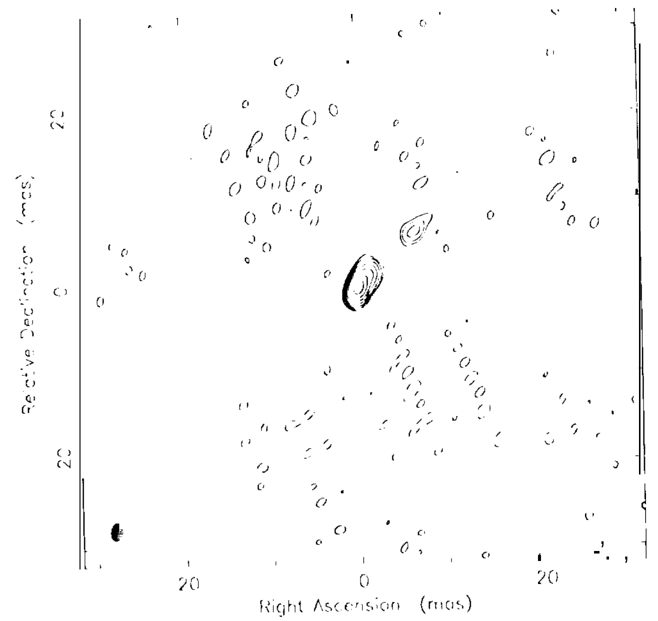

FIG. 5. VLBI image of PKS 0521−365 at 8.418 GHz from 1993 October 21. Map peak is 1.56 Jy beam^{-1} with contours of −1, 1, 2, 4, 8, 16, 32, and 64% of peak and a beam FWHM of 2.04 × 1.34 (mas) at a position angle of −10°.1.

core-jet morphologies. In the case of PKS 0208−512 and PKS 0521−365, the position angle of the milliarcsecond-scale structure seen with VLBI aligns with the position angle of the arcsecond-scale radio structure. The milliarcsecond-scale position angle of PKS 0537−441 is somewhat misaligned from its arcsecond-scale position angle.

The brightness temperatures of the cores suggest that PKS 0208−512 and 0537−441 may be more highly beamed than PKS 0521−365. In particular, PKS 0208−512 has a brightness temperature at the 10^{12} K inverse Compton limit for synchrotron radiation. This difference in brightness temperature correlates with the strong statistical EGRET detection of PKS 0208−512 and 0537−441 ($> 5\sigma$ significance) but with the weak statistical detection of PKS 0521−365 ($4 < \sigma < 5$ significance), even though PKS 0521−365 is much closer to us. It is important to repeat here that we are considering the significance of the EGRET detection based on the photon statistics, given that the identifications can be made, as Thompson et al. (1995) assert, with high confidence.

Unfortunately, on the basis of the brightness temperatures for these three sources we cannot make a strong statement concerning the importance of relativistic beaming for detection by EGRET. Further constraints for these objects will be available as we obtain images from future epochs. Can we, however, examine the existing VLBI data in the literature and find any trends which could link the gamma-ray and VLBI characteristics of the EGRET-identified sources or differentiate the EGRET-identified radio sources from radio sources which have not been identified by EGRET?

First, nine of the 11 identified EGRET sources listed by Thompson et al. (1995) which have been well studied with VLBI are known or possible superluminal radio sources (Vermeulen & Cohen 1994; Barthel et al. 1995; this work). The mean apparent speed in the VLBI jets of these 11 EGRET-identified sources is $5.6h^{-1}c$ with a standard deviation of $7.3h^{-1}c$.[1]

Second, while there is substantial evidence that some strong EGRET-identified radio sources are highly beamed, some others do not appear to be. Some of the strong EGRET sources, for example 1226+023 (e.g., Unwin et al. 1985), are clearly highly superluminal, whereas others such as 1222+216 (Hooimeyer et al. 1992) are perhaps consistent with subluminal speeds. There are also some highly beamed radio sources that have not been identified by EGRET, such as 1641+399 (e. g., Biretta, Moore, & Cohen 1986). The mean apparent speed for the core selected quasars and BL Lac objects which are listed by Vermeulen & Cohen (1994) and have not been identified by EGRET is $3.9h^{-1}c$, with a standard deviation of $3.0h^{-1}c$ (based on 24 objects and using the same criteria as for the EGRET-identified sources).

Unfortunately, these data do not allow us to make a firm conclusion about possible differences or similarities in VLBI properties between the radio sources that EGRET has identified and the many others that EGRET has not identified. The mean values for the apparent VLBI speeds are easily consistent at the 1σ level, but the standard deviations on the distributions are large. We feel that, given the overall reliability of the data and the small samples, any definite conclusion is premature.

Thus, more VLBI observations, over the full range of gamma-ray strength (nondetection, weak detection, and strong detection), will be required before the question posed above can be properly answered. The need for Southern Hemisphere observations of the high-confidence EGRET identifications is especially apparent since 13 of 40 lie south of $\delta < 0^\circ$. Our continuing VLBI observations are aimed at addressing this need.

We express our gratitude to the time-assignment committees of the participating observatories, the management of the Deep Space Network, Telstra (Australia) and the European Space Energy. We also thank the staff of the Caltech/JPL correlator. S. J. T. and J. E. J. L. acknowledge support via Australian Postgraduate Awards and the Australia Telescope National Facility student program. P. G. E. acknowledges receipt of a Monbusho Fellowship. We also acknowledge support from the Perth Astronomy Research Group and the Australian Research Council. The Australia Telescope is operated as a national facility by CSIRO. Part of this research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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[1] This estimate includes the highest reliability VLBI observations listed by Vermuelen & Cohen (1994) for nine sources, the observations of Barthel et al. (1995) for 1633+382, and the data for PKS 0521−365 appearing in Table 2. Where multiple observations of similar reliability were available for a single source from Vermuelen & Cohen (1994), they were used to form an average value for the source.

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