A 5 GHz SOUTHERN HEMISPHERE VLBI SURVEY OF COMPACT RADIO SOURCES. II.

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ABSTRACT

We report the results of a 5 GHz Southern Hemisphere snapshot VLBI observation of a sample of blazars. The observations were performed with the Southern Hemisphere VLBI Network plus the Shanghai station in 1993 May. Twenty-three flat-spectrum, radio-loud sources were imaged. These are the first VLBI images for 15 of the sources. Eight of the sources are EGRET (> 100 MeV) γ-ray sources. The milliarcsecond morphology shows a core-jet structure for 12 sources and a single compact core for the remaining 11. No compact doubles were seen. Compared with other radio images at different epochs and/or different frequencies, three core-jet blazars show evidence of bent jets, and there is some evidence for superluminal motion in the cases of two blazars. Detailed descriptions for individual blazars are given.

Key words: BL Lacertae objects: general — radio continuum — surveys

1. INTRODUCTION

"Blazar" is the collective name for BL Lacertae objects, optically violent variables, and highly polarized quasars, all of which share extreme observational properties that distinguish them from other active galactic nuclei. These properties include strong and rapid variability, high optical polarization, weak emission lines, and compact radio structure (see Impey 1992). About 200 blazars have been identified (see Burbidge & Hewitt 1992). A possible explanation for the blazar phenomenon within a unified scheme for active galactic nuclei is that their emission is beamed by the relativistic motion of the jets traveling in a direction close to the observer's line of sight. This beaming argument is strengthened by the recent Compton Gamma Ray Observatory (CGRO) discovery that most of the detected high-latitude γ-ray sources are blazars (see, e.g., Dondi & Ghisellini 1995). A comprehensive theoretical review of these sources has been made by Urry & Padovani (1995).

Blazars are an important class of active galactic nuclei (AGNs) because they are thought to be sources with relativistic jets seen nearly end-on. Such sources generally have very compact, flat-spectrum radio cores, which are appropriate for VLBI study. Pearson & Readhead (1988) have

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undertaken a survey of a complete sample consisting of 65 strong Northern Hemisphere radio sources. They provided the first well-defined morphological classification scheme, based primarily on the large-scale radio structure and radio spectra of the sources.

Most surveys to date, however, including the recent Caltech–Jodrell Bank VLBI surveys (Polatidis et al. 1995; Thakkar et al. 1995; Xu et al. 1995; Taylor et al. 1994; Henstock et al. 1995), have been restricted to Northern Hemisphere sources. For example, all the confirmed superluminal radio sources, except the well-known equatorial hemisphere sources. For example, all the confirmed superluminal radio sources, except the well-known equatorial sources. In an earlier paper et al. (Shen 1997, Morabito (1986), and the more extensive SHEVE survey (Preston et al. 1989 and references therein).

Since 1992 we have been carrying out a program to address this deficiency, using VLBI at 5 GHz to study southern radio sources. In an earlier paper (Shen et al. 1997, hereafter paper I) we reported the results from the first observing session, in 1992 November, and presented images of 20 strong sources selected on the basis of their correlated fluxes on intercontinental baselines. In 1993 May we observed a second sample of southern sources, which is the subject of this paper.

Section 2 introduces this blazar sample; § 3 briefly describes the observations and data reduction procedures; § 4 presents the results; the summary and conclusions are presented in § 5. Throughout the paper, we define the spectral index, $\alpha$, by the convention $S \propto \nu^{-\alpha}$ and assume $H_0 = 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.5$.

We selected our sample of southern blazars from Table 1 of Burbidge & Hewitt (1992), which was based on the 2.7 GHz Parkes survey of Bolton, Savage, & Wright (1979) and the 5 GHz survey of Kühr et al. (1981). The sample is defined by the following criteria:

1. Declination: $-55^\circ < \delta < -10^\circ$;
2. Total flux density at 5.0 GHz: $S_{5.0 \text{ GHz}} > 1.0 \text{ Jy}$;
3. Radio spectral index between 2.7 and 5.0 GHz: $\alpha_{2.7, 5.0 \text{ GHz}} \geq -0.5$.

Of the 218 sources listed by Burbidge & Hewitt (1992), 24 meet the above criteria. These include PKS 1334–127, 1504–166, and 1519–273, which were observed in the first session (Paper I) and not reobserved here. The remaining 21 sources are listed in Table 1, along with two additional sources that were included in the observing run: 3C 273 (1226+023) and PKS 1127–145, a radio-loud quasar. PKS 0823–223 has the lowest Galactic latitude of this sample, with $b < 9^\circ$; for all other sources, $|b| > 17^\circ$.

Seven blazars (PKS 0332–403, 0426–380, 0521–365, 1023, 1226, 1504, and 1519) were marginally detected in the first observing run: 3C 273, 1226+023, and 1226+125 belong to the 36-source sample described in paper I but were not observed in 1992 November. Also, six sources (PKS 0208–512, 0521–365, 0537–441, 1127–145, 1226+023, and 1424–418) have been detected by EGRET, on board CGRO (Mattox et al. 1997), and two blazars (PKS 0454–234 and PKS 2005–489) were marginally detected (Thompson et al. 1995; Fichtel et al. 1994). Their names, positions, redshifts, optical identifications, and flux densities at 5 GHz are provided in Table 1.

### TABLE 1

| Source Name | Other Name | R.A. (B1950) | Decl. (B1950) | $z$ | ID$^a$ | $S_{5 \text{ GHz}}$ (Jy) |
|-------------|------------|--------------|--------------|-----|--------|------------------|
| PKS 0118−272 | OC −230.4 | 01 18 09.5395 | −27 17 07.616 | 0.559 | BLO | 1.18 |
| PKS 0208−512 | OC −210.2 | 02 08 56.9628 | −51 15 07.787 | 1.003 | HPQ | 3.21 |
| PKS 0332−403 | OF −105 | 03 32 25.2390 | −40 18 24.159 | 1.445 | HPQ | 2.60 |
| PKS 0403−132 | OF −116 | 04 03 13.9804 | −13 21 18.164 | 0.571 | OVV | 3.24 |
| PKS 0426−380 | OF −92 | 04 26 54.7094 | −38 02 52.213 | 1.030 | BLO | 1.14 |
| PKS 0438−436 | OF −89 | 04 38 43.1911 | −43 38 53.639 | 2.852 | HPQ | 7.00 |
| PKS 0454−234 | OF −292 | 04 54 57.3064 | −23 29 28.356 | 1.009 | BLO | 2.00 |
| PKS 0521−365 | OF −107 | 05 21 12.8364 | −36 30 16.019 | 0.055 | BLO | 9.23 |
| PKS 0537−441 | OC −220.4 | 05 37 21.0841 | −46 04 44.736 | 0.904 | BLO | 3.80 |
| PKS 0823−223 | OF −110 | 08 23 50.0776 | −20 22 34.772 | 0.910 | BLO | 1.22 |
| PKS 1034−293 | OF −146 | 10 34 55.8356 | −29 18 26.874 | 0.312 | BLO | 1.51 |
| PKS 1127−145 | 3C 273 | 11 27 35.683 | 12 26 33.245 | 0.158 | OVV | 36.70 |
| PKS 1226+023 | 3C 273 | 12 26 33.245 | +02 19 43.458 | 0.158 | OVV | 36.70 |
| PKS 1244−255 | 3C 273 | 12 44 06.7211 | −25 31 26.541 | 0.036 | OVV | 1.55 |
| PKS 1424−418 | 3C 273 | 14 24 42.1366 | −42 52 54.540 | 1.524 | HPQ | 2.12 |
| PKS 1514−241 | AP Lib | 15 14 45.2717 | −24 11 22.582 | 0.049 | BLO | 1.94 |
| PKS 1936−155 | OV −161 | 19 36 36.0246 | −15 32 38.828 | 1.657 | HPQ | 1.64 |
| PKS 1954−388 | 3C 273 | 19 54 39.0430 | −38 53 13.599 | 0.626 | OVV | 2.00 |
| PKS 2005−489 | 3C 273 | 20 05 46.5595 | −48 53 43.464 | 0.071 | BLO | 1.19 |
| PKS 2155−152 | OC −192 | 21 55 23.2428 | −15 01 30.194 | 0.672 | BLO | 1.58 |
| PKS 2240−260 | OV −268 | 22 40 41.8000 | −26 00 12.000 | 0.774 | BLO | 1.00 |
| PKS 2243−123 | OV −172.6 | 22 43 39.7948 | −12 22 40.407 | 0.630 | OVV | 2.38 |
| PKS 2355−534 | OC −180.4 | 23 55 18.1702 | −53 27 56.125 | 1.006 | OVV | 1.66 |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ Optical identification: (BLO) BL Lac object; (HPQ) highly polarized quasar; (WPQ) weakly polarized quasar; (OVV) optically violent variable.

$^b$ Total flux density at 5 GHz, from the literature.

$^c$ No emission lines; absorption-line redshift is listed.
3. OBSERVATIONS

Our VLBI observations were carried out within 48 hours on 1993 May 12–13, using the radio telescopes at Hartebeesthoek (South Africa), Hobart (Australia), Mopra (Australia), Parkes (Australia), Perth (Australia), and Shanghai (China). The observing parameters of these stations are given in Table 2. One element of the Australia Telescope Compact Array (Narrabri, Australia) also observed, but because of a configuration problem during recording, no useful data were obtained.

This second snapshot session followed a similar observing mode and data-processing procedure as the first session (see Paper I), so only a brief outline is given here. All 23 sources in Table 1 were observed in snapshot mode, i.e., three to five 30 minute scans were observed. Data were recorded in Mark II format with 2 MHz bandwidth and left-circular polarization (IEEE convention). The cross-correlation of the data was carried out on the JPL/Caltech Mark II processor in 1994.

Postcorrelation data reduction was done at the Harvard-Smithsonian Center for Astrophysics, using the NRAO AIPS and Caltech VLBI analysis packages. A global fringe-fitting procedure consisting of AIPS tasks was run at a solution interval of 2.5 minutes. The 64 m Parkes telescope was selected as the reference station. Fringes were found for all 23 sources. The visibility data were phase self-calibrated with a 10 s solution interval and a point-source model in AIPS. The data averaging, editing, imaging, deconvolution, and self-calibration were then performed within DIFMAP, a part of the Caltech VLBI package (Shepherd, Pearson, & Taylor 1994). Natural weighting was applied, and only a constant gain factor correction was implemented in the amplitude calibration. Finally, we ran the MODELFIT program in the Caltech VLBI package to fit the closure phases and amplitudes of the calibrated data on each source, in order to obtain a quantitative description of its structure. Up to three Gaussian components were fitted for 22 sources, while six components were used in the case of 3C 273, the strongest source in the sample. In all cases, we feel that these models reasonably characterize the fundamental features observed.

4. RESULTS

The naturally weighted images for the 23 radio sources are presented in Figure 1. In each panel, the size of the restoring beam is shown as a shaded ellipse in the bottom left corner. The lowest contour level in each image is 3 times the rms noise level. The rms noise in the images is a few millijanskys per beam for all the sources except 3C 273, for which the noise level was 18 mJy beam$^{-1}$. The image parameters (peak flux density, restoring beam, and contour levels) are listed in Table 3. The results of the model fitting are given in Table 4, together with the peak brightness temperature for each model component in the rest frame of the source, calculated following the method described in Paper I.

PKS 0118–272 (OC – 230.4, Fig. 1a).—This is a BL Lac object with a tentative emission-line redshift of $z = 1.62$ (Adam 1985 and references therein). A lower limit of $z > 0.559$ was suggested from several absorption lines (Falomo 1991; Stickel, Fried, & Kühr 1993). Strong optical variations of 100% within 3 days have been reported (Falomo, Scarpa, & Bersanelli 1994). PKS 0118–272 is also highly optically polarized (Impey & Tapia 1988; Mead et al. 1990).

A 20 cm Very Large Array (VLA) observation revealed a complex structure, while at 6 cm the source exhibited at least three components within 1$^{\prime}$ (Perley 1982). A single-baseline 2.3 GHz VLBI observation yielded a correlated flux density of $0.53 \pm 0.05$, corresponding to a visibility of $0.5 \pm 0.2$ (Preston et al. 1995). Our observations showed a resolved core with diffuse surrounding emission. The data were fitted by a single north-south elongated Gaussian component with a flux density of 0.55 Jy. However, the core accounts for only half the total flux density of the source, which supports the presence of two or three additional weak features in the vicinity. The source has a spectral index of 0.02 at millimeter wavelengths (Steppe et al. 1988), with a total flux density of 0.60 Jy at 230 GHz.

PKS 0208–512 (Fig. 1b).—This flat-spectrum radio source has a redshift of $z = 1.003$ (Peterson et al. 1976). It is classified as a highly polarized quasar or blazar by Impey & Tapia (1988, 1990). It was the second southern AGN (after 3C 279) detected at $\gamma$-ray energies (Bertsch et al. 1993; Blom et al. 1995), with one of the hardest photon spectral indices (von Montigny et al. 1995; Chiang et al. 1995).

No detailed arcsecond-scale structure of the source has been reported in the literature. The SHEVE experiment at 2.3 GHz described it as a Gaussian component with a minimum nuclear flux density of 2.5 Jy (Preston et al. 1989). A 5 GHz VLBI image from 1992 November revealed a core-jet structure along a position angle of 233$^\circ$ (Tingay et al. 1996).

The image from our observation in 1993 May is in excellent agreement with that of Tingay et al. (1996). The source is a single-(Perley 1982).

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### TABLE 2

**ANTENNA CHARACTERISTICS IN 1993 MAY**

| Station (Code) | Diameter (m) | $\eta$ (%) | $T_{\text{sys}}$ (Jy) | Gain (K Jy$^{-1}$) | Polarization | Frequency Standard |
|----------------|--------------|------------|----------------------|------------------|--------------|-------------------|
| Hartebeesthoek (E) | 26.0 | 52 | 970 | 0.100 | LCP | H Maser |
| Hobart (Hb) | 26.0 | 52 | 1700 | 0.100 | LCP | H Maser |
| Mopra (M) | 22.0 | 62 | 500 | 0.086 | LCP | Rubidium |
| Parkes (P) | 64.0 | 43 | 130 | 0.500 | LCP | H Maser |
| Perth (Pr) | 27.5 | 47 | 1400 | 0.100 | LCP | Rubidium |
| Shanghai (Sh) | 25.0 | 56 | 2000 | 0.100 | LCP | H Maser |

**Notes.**—Col. (1): Station name and antenna code in parentheses; col. (2): antenna diameter; col. (3): effective antenna aperture efficiency; col. (4): system temperature; col. (5): system gain factor; col. (6): polarization, IEEE convention; col. (7): type of frequency standard used.
Fig. 1.—VLBI images of the 23 extragalactic radio sources observed in 1993 May. The synthesized beam is shown in the bottom left of each image. See Table 3 for detailed imaging parameters.

has a compact 2.8 Jy core and a 0.3 Jy jet component at an angular separation of 1.7 mas and a position angle of 234° from the central core. A nearly flat spectral index of 0.15 for the core is estimated from the 2.3 and 5.0 GHz results. The derived brightness temperature is $1.9 \times 10^{12}$ K, close to the value of $1.2 \times 10^{12}$ K in Tingay et al. (1996). We note that the $\gamma$-ray emission is also thought to be beamed because of its short variation timescale (of tens of days) and high
observed luminosity (of $10^{48}$ ergs s$^{-1}$ for isotropic emission) (Bertsch et al. 1993). Further study of this source may contribute to a better understanding of the correlation between $\gamma$-ray emission and radio radiation. A lower limit to the Doppler factor is 10.2, using the ROSAT X-ray observation (0.22 kJy at 1 keV) (Dondi & Ghisellini 1995). This implies superluminal motion in the compact core, having an upper limit of 6$^\circ$ to the viewing angle. Comparison of the 1992 and 1993 images taken 6.5 months apart suggests a proper motion of $0.6 \pm 0.7$ mas yr$^{-1}$, corresponding to an apparent speed of $(17 \pm 20)c$. Further high-accuracy VLBI measurements are needed to confirm its superluminal motion.
PKS 0332–403 (Fig. 1c) — This source is a highly polarized quasar (Impey & Tapia 1988, 1990). It has an inverted spectrum that peaks at around 5 GHz (Shimmins et al. 1971) and could be classified as a gigahertz-peaked spectrum (GPS) source (cf. O’Dea, Baum, & Stanghellini 1991). Its redshift of $z = 1.445$ has been widely used in the literature without clear justification. This value is from the Catalogue of Quasi Stellar-Objects (Barbieri, Capaccioli, &
Zambon 1975), in which the reference was incorrect. A new measurement should be made to confirm its redshift.

The arcsecond structure of PKS 0332−403 is dominated by an unresolved core from 6 and 20 cm VLA observations (Perley 1982). Preston et al. (1985) detected a correlated flux of $0.17 \pm 0.03$ Jy, in contrast to a total flux at 2.3 GHz of $4.0 \pm 0.4$ Jy. Single-baseline measurements at 2.3 and 8.4 GHz were also made by Morabito et al. (1986). Our high-
resolution image revealed a strong compact core and a weak unresolved feature to the east (see Table 4). The derived Doppler factor from the ROSAT 0.1–2.4 keV observations (Brinkmann, Siebert, & Boller 1994) is greater than 3.6.

**PKS 0403–132 (OFF –105; Fig. 1d).—**This quasar has strong emission lines and a redshift of $z = 0.571$ (Lynds 1967). It is an optically violent variable source (Bolton et al. 1966) and has a variable, modest linear polarization (Moore & Stockman 1981; Impey & Tapia 1988). There is evidence of variability at X-ray energies (Blumenthal, Keel, & Miller 1982).

The VLA 20 cm image from Wardle, Moore, & Angel (1984) shows a core-jet structure, with an unresolved nucleus extending on opposite sides, and a jet lying at a position angle of $23^\circ$. The nucleus remains unresolved at 6 cm (Morganti, Killeen, & Tadhunter 1993), with a possible weak extension (Wills & Browne 1986). The model from high-resolution VLBI data at 2.3 GHz exhibits two unresolved components, which have a flux density ratio of 5 and a separation of 580 mas along a position angle of $48^\circ$ (Preston et al. 1989).

Our VLBI image at 5 GHz revealed only a compact core, with no other component emission. The weak secondary component in the 2.3 GHz model may be resolved, or have a steep spectrum, or have decayed since 1982. The core component can be fitted by a single 0.5 mas x 0.3 mas Gaussian component with a 0.85 Jy flux density and a brightness temperature of $5.0 \times 10^{11}$ K. This high brightness is consistent with the moderate variation of the source at radio (Romero, Benaglia, & Combi 1995), optical (Bolton et al. 1966), and X-ray (Blumenthal et al. 1982) wavelengths.

**PKS 0426–380 (Fig. 1e).—**This is a BL Lac object with no detected emission lines and an absorption redshift of $z_{abs} = 1.030$ (Stickel et al. 1993). PKS 0426–380 has an optical polarization of less than 3% (Impey & Tapia 1990). VLA observations at 20 cm show a $2^\circ$ extension from the compact core to the position angle of $-24^\circ$ (Perley 1982). Single-baseline VLBI observations yielded correlated flux densities of 0.70 and 0.90 Jy at frequencies of 2.3 and 8.4 GHz, respectively (Morabito et al. 1986).

The data on PKS 0426–380 were modeled by a Gaussian component extended along a position angle of $111^\circ$. Using the absorption redshift and the upper limit to the 1 keV X-ray flux density from ROSAT observations (Brinkmann et al. 1994), the estimated lower limit to the Doppler boosting factor is 3.1. Our model yields a brightness temperature of $7 \times 10^{11}$ K for the core.

**PKS 0438–436 (Figs. 1f, 1').—**This extremely luminous radio quasar has an emission-line redshift of $z = 2.852$ with some absorption lines superposed (Morton, Savage, & Bolton 1978). Optically, PKS 0438–436 is faint with variable polarization (see, e.g., Rusk 1990; Fugmann & Meisenheimer 1988; Impey & Tapia 1988, 1990). It has a complex radio spectrum, flat at low frequencies but very steep above 5 GHz. The flux density at 1.4 GHz is known to vary by 10% over a period of 4 months. The polarization also varies in degree and position angle (Luna et al. 1993). It has been detected by the IRAS satellite (Neugebauer et al. 1986) and also has significant soft X-ray absorption (Wilkes et al. 1992). Both these properties are unusual for a quasar with such a high redshift. No $\gamma$-ray detection was reported from the EGRET all-sky survey (Perley 1982) identified a secondary component $2^\circ$ away from the core at a position
of 7.8 mas at a position angle of $15^\circ$. VLBI observations at 2.3 GHz showed a core-jet structure: two 1.9 Jy circular components separated by 35 mas at a position angle of $-43^\circ$ (Preston et al. 1989).

Our 5 GHz VLBI observation confirms the two-component structure described above, with the same separation and orientation of the two components, to within the errors. To facilitate a comparison, we convolved the 5.0 GHz data with the 2.3 GHz SHEVE beam (13.9 mas $\times$ 7.5 mas at a position angle of 58°) to obtain the image shown in Figure 1f, which has a peak flux density of 1.6 Jy beam$^{-1}$. The lowest contour level is 23 mJy beam$^{-1}$, with a factor of 2 between adjacent contours. It is clear that the northwest component is stronger and more compact than the one to the southeast. We identify the northwest component as the core, which has a brightness temperature of $7.8 \times 10^{11}$ K, 100 times higher than that of the other component. Actually, as can be seen in Figure 1f, the southeast component has been heavily resolved at 5 GHz. The core size agrees well with the analysis of early VLBI measurement at 2.3 GHz, which showed a variable component smaller than 1 mas in diameter (Gubbay et al. 1977). There is about a $120^\circ$ difference in position angle between the arcsecond- and milliarcsecond-scale structures.

*PKS 0454 = 234 (OF = 292; Fig. 1g).*—This is listed as a BL Lac object (Ledden & O’Dell 1985) because of its featureless optical spectrum (Wilkes et al. 1983). An initial redshift determination of 1.009 (Wright, Ables, & Allen 1983) was later refined to $z = 1.003$ (Stickel, Fried, & Kühr 1989). It is a highly polarized quasar, with optical polarization up to 27% et al. PKS 0454 was detected in the 2.3 GHz Tracking

### TABLE 4

**Source Model Descriptions**

| Source (1) | Component (2) | S (Jy) (3) | r (mas) (4) | $\phi$ (deg) (5) | Major (mas) (6) | Minor (mas) (7) | P.A. (deg) (8) | $T_b$ (10$^6$ K) (9) |
|------------|---------------|------------|-------------|-----------------|----------------|----------------|---------------|-----------------|
| PKS 0118 - 272 | 1 | 0.55 | 0.00 | 0 | 3.8 | 1.5 | 1 | 0.007 |
| PKS 0208 - 512 | 1 | 2.77 | 0.00 | 0.6 | 0.2 | 73 | 1.90 |
| PKS 0332 - 403 | 1 | 1.28 | 0.00 | 1.0 | 0.2 | 106 | 0.64 |
| PKS 0403 - 132 | 1 | 0.85 | 0.00 | 0.5 | 0.3 | 151 | 0.50 |
| PKS 0426 - 380 | 1 | 0.84 | 0.00 | 0.6 | 0.2 | 111 | 0.69 |
| PKS 0438 - 436 | 1 | 1.42 | 0.00 | 0.7 | 0.5 | 119 | 0.78 |
| PKS 0454 - 234 | 1 | 2.04 | 0.00 | 0.8 | 0.4 | 163 | 0.61 |
| PKS 0521 - 365 | 1 | 1.82 | 0.00 | 0.9 | 0.6 | 152 | 0.17 |
| PKS 0537 - 441 | 1 | 3.37 | 0.00 | 0.9 | 0.4 | 75 | 0.86 |
| PKS 0823 - 223 | 1 | 0.40 | 0.00 | 1.2 | 0.3 | 124 | 0.12 |
| PKS 1034 - 293 | 1 | 1.54 | 0.00 | 0.8 | 0.5 | 102 | 0.26 |
| PKS 1127 - 145 | 1 | 1.91 | 0.00 | 1.6 | 1.0 | 81 | 0.13 |
| PKS 1226 + 023 | 1 | 2.12 | 3.23 | 265 | 1.8 | 0.5 | 87 | 0.13 |
| PKS 1244 - 255 | 1 | 2.91 | 1.87 | 215 | 0.8 | 0.5 | 162 | 0.38 |
| PKS 1424 - 418 | 1 | 1.36 | 0.00 | 0.9 | 0.7 | 67 | 0.25 |
| PKS 1514 - 241 | 1 | 1.53 | 0.00 | 1.2 | 0.6 | 177 | 0.11 |
| PKS 1936 - 155 | 1 | 0.97 | 0.00 | 0.6 | 0.5 | 176 | 0.47 |
| PKS 1954 - 388 | 1 | 1.94 | 0.00 | 0.4 | 0.3 | 82 | 1.20 |
| PKS 2005 - 489 | 1 | 0.92 | 0.00 | 1.0 | 0.2 | 71 | 0.26 |
| PKS 2155 - 152 | 1 | 2.10 | 0.00 | 1.8 | 0.1 | 34 | 0.67 |
| PKS 2240 - 260 | 1 | 0.23 | 4.21 | 15 | 1.1 | 0.3 | 26 | 0.05 |
| PKS 2243 - 123 | 1 | 0.23 | 4.21 | 15 | 1.1 | 0.3 | 26 | 0.05 |
| PKS 2355 - 534 | 1 | 1.54 | 0.00 | 1.1 | 0.4 | 31 | 0.35 |
| PKS 0454 - 234 | 2 | 0.20 | 4.88 | 235 | 1.1 | 0.6 | 66 | 0.03 |

**NOTES.**—Col. (1): source name; col. (2): numerical label—component 1 is assumed to be the core; col. (3): flux density of each component; col. (4): distance of each component from the origin defined by component 1; col. (5): position angle of each component with respect to the origin; cols. (6)–(8): parameters of Gaussian model—major and minor axes of each component (FWHM) and the position angle of the major axis, respectively; col. (9): peak brightness temperature.
and Data Relay Satellite System (TDRSS) experiment on a baseline of 1.8 Earth diameters (Linfield et al. 1989), and in a 22 GHz ground survey on a baseline of 10,000 km (Moellenbrock et al. 1996). Our 5 GHz VLBI image shows an asymmetric morphology with a strong core and a compact jetlike component to the northwest at a position angle of $-62^\circ$. The brightness temperature of the core as derived from our model is about $6 \times 10^{11}$ K. A Doppler beaming factor of 5.3 is estimated using the X-ray flux density at 1 keV and core structural parameters. For comparison, a value of 3.6 was derived from the variability timescale (Dondi & Ghisellini 1995).

**PKS 0521−365 (Fig. 1h).**—This radio source has been identified with an N galaxy (Bolton, Clarke, & Ekers 1965). A redshift of $z = 0.055$ has been measured from both absorption features and emission lines (Danziger et al. 1979). It is one of five radio sources (see Crane et al. 1993) that have prominent optical counterparts to their radio jets (Danziger et al. 1979; Folomoto 1994 and references therein). The *Hubble Space Telescope* has resolved the optical jet structure (Macchetto et al. 1991). High optical polarization has been measured in the jet and the nucleus as well (Sparks, Miley, & Macchetto 1990 and references therein). This suggests a synchrotron origin for the optical radiation. It has strong X-ray emission (Pian et al. 1996) and has been marginally detected above 100 MeV by EGRET (Fichtel et al. 1994; Lin et al. 1995).

Its arcsecond-scale radio structure is dominated by an extended lobe to the southeast, rather than by the compact core itself (Wardle et al. 1984; Keel 1986; Sleee et al. 1994). A radio jet follows closely, in direction and extent, the optical jet to the northwest (Ekers et al. 1989). The magnetic fields inferred from the polarization measurements at the optical and radio wavelengths are parallel to the jet direction in the jet, and perpendicular to the jet in the core. From 2.3 GHz VLBI observations, the core was modeled as a circular source 1.4 mas in diameter, with a flux density of 1 Jy (Preston et al. 1989).

VLBI observations at 5.0 and 8.4 GHz revealed a 0.5 Jy jet component at a position angle of $310^\circ$ (Tingay et al. 1996). No apparent motion could be determined from four-epoch measurements over a period of 1 yr.

Our high-resolution data disclosed a second jet component near the compact core. The parameters of these components are listed in Table 4. The two jet components are aligned with the VLA jet (302" ± 2"; Keel 1986) and optical jet (311" ± 2"; Cayette & Sol 1987). No beaming effect is needed for the core brightness temperature of $1.7 \times 10^{11}$ K. This is consistent with the nondetection of superluminal motion. The $\gamma$-ray luminosity between 100 MeV and 5 GeV is about $3.2 \times 10^{44}$ ergs s$^{-1}$ (Lin et al. 1995), the second lowest in the sample of $\gamma$-ray–loud AGNs. All of these observations suggest a large angle in PKS 0521−365 between the ejection direction and the line of sight. Pian et al. (1996) derived a viewing angle of $30^\circ$ with bulk Lorentz factor of 1.2. This leads to a predicted jet-counterjet ratio of 64, assuming a jet spectral index of $-1.0$. However, none of the existing VLBI images reveal any feature on the opposite side of the core. Further high dynamic range VLBI images will help constrain the modeling of this source.

**PKS 0537−441 (Fig. 1j).**—This is a $z = 0.894$ (Peterson et al. 1976) transition object between classical BL Lac objects and quasars (Cristiani 1985; Maraschi et al. 1985; Giommi, Ansari, & Micol 1995). It has displayed substantial variability at X-ray energies (Treves et al. 1993 and references therein) and has shown similar variation timescales and amplitudes at wavelengths ranging from infrared to X-ray (Tanzi et al. 1986), suggesting that these emissions may originate from the same spatial region. The source is also a strong variable EGRET $\gamma$-ray source (Thompson et al. 1993b).

On the arcsecond scale, the source is core dominated with a bright secondary component separated by $7.2^\circ$ at a position angle of $305^\circ$ (Perley 1982). The SHEVE 2.3 GHz observation showed a 4.2 Jy core with a diameter of 1.1 mas (Preston et al. 1989). Recent VLBI observations at 4.9 and 8.4 GHz (Tingay et al. 1996) show a jetlike component to the north of the compact core.

Our 5 GHz VLBI image confirmed the asymmetric core–jet structure, in good agreement with the results from Tingay et al. (1996). However, the VLBI jet component differs by $70^\circ$ in position angle from the VLA secondary component (Perley 1982). The VLBI core has a brightness temperature of $8.6 \times 10^{11}$ K. Unfortunately, the existing VLBI data were insufficient to determine the proper motion of the jet in this EGRET-identified radio source.

**PKS 0823−223 (Fig. 1j).**—This is a BL Lac object (Wright et al. 1979; Wilkes et al. 1983) with an absorption redshift of $z_{abs} = 0.910$ (Falomo 1990 and references therein). It shows high optical polarization (Impey & Tapia 1990). No $\gamma$-ray emission was detected by EGRET (Fichtel et al. 1994).

VLA observations show a diffuse structure on arcsecond scales at 20 cm (Perley 1982). Our 6 cm VLBI image can be modeled by a 1.2 mas × 0.3 mas Gaussian component with a flux density of 0.4 Jy. The earlier total flux density measurement of 1.8 Jy (Impey & Tapia 1990) and VLA structure imply that PKS 0823−223 has some extended structure that is resolved and therefore undetected by our VLBI observations.

**PKS 1034−293 (OL −259; Fig. 1k).**—This is a BL Lac object with a redshift of $z = 0.312$ (Stickel et al. 1989 and references therein) and that displays high optical polarization, of up to 14% (Wills et al. 1992). PKS 1034−293 is a strong millimeter-wavelength source with a variable flux density between 1.0 and 3.0 Jy (Steppe et al. 1988, 1992, 1993).

Previous VLBI observations described PKS 1034−293 as a core-dominated, strong compact radio source (Robertson et al. 1993; Morabito et al. 1986). The TDRSS experiment at 2.3 GHz fitted it as a 0.58 Jy, 0.44 mas circular Gaussian component (Linfield et al. 1989).

Our VLBI data were fitted with an elliptical Gaussian component 0.8 mas × 0.5 mas, with a flux density of 1.5 Jy. The derived brightness temperature is $2.5 \times 10^{11}$ K, consistent, within the errors, with the measurement of $4.6 \times 10^{11}$ K from the 22 GHz ground survey (Moellenbrock et al. 1996) and $9.2 \times 10^{11}$ K from the 2.3 GHz TDRSS experiment (Linfield et al. 1989).

**PKS 1127−145 (OM −146; Fig. 1l).**—This is a high-redshift quasar with broad emission lines at $z = 1.184$ (Wilkes et al. 1983; Wilkes 1986) and absorption lines at $z_{abs} = 0.313$ (Bergeron & Boissé 1991). It has low optical polarization (Impey & Tapia 1990; Wills et al. 1992;
Tornikoski et al. (1993) and is not an optically violently variable source (Pica et al. 1988; Bozyan, Hemenway, & Argue 1990). It has been identified in the Second EGRET Catalog at energies above 100 MeV (Thompson et al. 1995).

PKS 1127–145 was unresolved in VLA observations (Perley 1982). It is strong and compact, and was detected at both 2.3 and 15 GHz on TDRSS baselines larger than 14,000 km (Linfield et al. 1989, 1990). Two-epoch VLBI observations at 1.7 GHz (Padrielli et al. 1986; Romney et al. 1984) found that PKS 1127–145 was slightly extended to the north. No structural variation between the two epochs (1.7 yr) was seen. A proper motion of 0 ± 0.02 mas yr⁻¹ in the source was reported by Vermeulen & Cohen (1994). The 5 GHz image of Wehrle et al. (1992) resolved the source into two compact components plus a weak extension to the northeast.

Our VLBI observation revealed two Gaussian components. The brighter component, with a flux density of 1.9 Jy, is larger than the weaker (1.1 Jy) component (see Table 4). These two components have similar brightness temperatures of ~1.3 × 10¹¹ K. They are probably related to two components of nearly equal strength resolved by Wehrle et al. (1992) and, possibly, to the east-west structure observed at 1.7 GHz (Padrielli et al. 1986; Romney et al. 1984). We find no evidence of a northeast extension, seen by Wehrle et al. (1992). We note that early VLBI experiments at 18, 13, and 6 cm indicated at least three distinct components in the source, implying source evolution (Kellermann et al. 1971; Weiler & de Pater 1983).

PKS 1226+023 (3C 273; Fig. 1m).—This well-known radio source has been identified with a 12th magnitude object at a redshift of z = 0.158 (Hazard, Mackey, & Shimmins 1963; Schmidt 1963). It shows optical variation, which was first analyzed by Smith & Hoffleit (1963), but does not have high optical polarization (Appenzeller 1968). It is very bright across the wave bands from radio to γ-rays. It was the only γ-ray source known before the CGRO observations (Swanenburg et al. 1978; Bignami et al. 1981), and one of the first two extragalactic sources detected by EGRET (Mattox et al. 1997 and references therein).

The large-scale structure from the VLA and MERLIN shows a compact, flat-spectrum core and a single jet extending about 23″ from the core at a position angle of 222° (Conway et al. 1993). This source has received considerable attention since the VLBI technique became available, due mainly to its intensity and variability. Multifrequency VLBI observations show a bright core and a number of jet components extending toward the southwest (see, e.g., Davis, Unwin, & Muxlow 1991; Zensus et al. 1988).

Our VLBI observation of this equatorial quasar has a good north-south resolution with a beam of 1.6 mas × 0.88 mas at a position angle of 33°. We fitted six components, labeled 1 through 6, to the data. The strong component 1 at the eastern end is identified as the core. No counterjet is visible. Components 2–6 are jet components, or knots in the continuous jet, which have a similar position angle of ~230° and increasing distance to the core (from 1.9 mas for component 2 to 15.2 mas for component 6). Along this position angle, there is a distinct emission gap between components 5 and 6. Such morphology is consistent with other published results (e.g., Zensus et al. 1988). Comparison with earlier observations enables us to identify the components in our image with those seen previously: our components 2, 3, and 4 are respectively C₁₀, C₉, and C₈ (Abraham et al. 1994). Our component 5 is C₇₄ (Cohen et al. 1987). The more extended component 6 in our image is more difficult to identify and may be C₉ (Unwin et al. 1985; Zensus 1987; Charlot, Lestrade, & Boucher 1988) or possibly a mixture of C₆ and other components (such as C₅, C₄, or even C₃) (see Cohen et al. 1987; Unwin et al. 1985). Such identification is in good agreement with the observational picture of the evolution of the different components in 3C 273 (see Abraham et al. 1996).

PKS 1244–255 (Fig. 1n).—This source is a blazar (Bersanelli et al. 1992), having violent optical variation (Bozyan et al. 1990 and references therein) and high optical polarization (Impey & Tapia 1988, 1990). It has strong emission lines corresponding to a redshift of z = 0.638 (Falomo, Scarpa, & Bersanelli 1994).

VLBI observations yielded correlated flux densities of 0.48 Jy at 2.3 GHz, 1.01 Jy at 8.4 GHz (Morabito et al. 1986), and 0.91 Jy at 22 GHz (Moellenbrock et al. 1996). Our VLBI image shows a simple compact core elongated at a position angle of 116°, with a brightness temperature of 5.6 × 10¹¹ K. This is consistent with the measurement of a lower limit of 4.0 × 10¹¹ K from the 22 GHz survey.

PKS 1424–418 (Fig. 1o).—This is a highly optically polarized quasar (Impey & Tapia 1988, 1990). An accurate redshift measurement of z = 1.524 was made by Stickel et al. (1989). Data on PKS 1424–418 from the 2.3 GHz SHEVE observations were modeled by two circular components separated by 23 mas (Preston et al. 1989). Our VLBI image shows two components separated by ~3 mas. Assuming the stronger component is the core, the position angle of the weaker component is 260°, significantly different from the reported value for the two 2.3 GHz components of 236°/284° (Preston et al. 1989). There is a difference in alignment of 90° between the VLBI and VLA structures. Using the model results, we obtain a very flat spectral index of −0.04 for the central core. For comparison, we calculated a spectral index of 0.20 from the correlated flux density measured at 2.3 and 8.4 GHz (Robertson et al. 1993). An asymmetry was also inferred from these data.

PKS 1514–241 (AP Lib; Fig. 1p).—This source is a classical BL Lac object (Strittmatter et al. 1972). The redshift is z = 0.0486, based upon both absorption lines and emission lines (Rodgers & Peterson 1977 and references therein). It has been characterized as an optically violent variable (Carini et al. 1991; Bozyan et al. 1990; Webb et al. 1988) and a highly polarized quasar (Wills et al. 1992).

This source shows a core-jet morphology on arcsecond scales in 6 and 20 cm VLA images (Morganti et al. 1993; Antonucci & Ulvestad 1985; Ulvestad, Johnston, & Weiler 1983). A component 0″2 from the core at a position angle of 120° was reported by Perley (1982).

Our VLBI image of this BL Lac object shows only a single component, 1.2 mas × 0.6 mas in size, with elongation in the north-south direction, and a flux density of 1.53 Jy. The brightness temperature is 1.1 × 10¹¹ K, which is consistent with the value of ~1.5 × 10¹¹ K from the 22 GHz survey (Moellenbrock et al. 1996).

PKS 1936–155 (OV – 161; Fig. 1q).—This is a blazar with high optical polarization (Fugmann & Meisenheimer...
identify the core with the stronger component, although both components have similar brightness temperatures.

PKS 2243 - 123 (OY 172.6; Fig. 1w)—This is an optically violent variable and a highly polarized quasar (Impey & Tapia 1988, 1990; Wills et al. 1992), with a redshift of $z = 0.630$ (Browne et al. 1975). This radio source has also been classified as a GPS source, because its spectrum shows a turnover at $\sim 2.3$ GHz (Cersosimo et al. 1994).

VLA observations exhibited an unresolved core with a $4''$ extended component at a position angle of $40^\circ$ (Perley 1982; Browne & Perley 1986; Morganti et al. 1993). Observations on a single long baseline measured correlated flux densities of 0.78 and 1.23 Jy at 2.3 and 8.4 GHz, respectively (Morabito et al. 1986).

Our VLBI data can be fitted as a compact core with a flux density of 2.28 Jy, and size of 1.1 mas $\times$ 0.4 mas, with a corresponding brightness temperature of $4.0 \times 10^{11}$ K. The core has a north-south elongation. We note that there is a depression at the east-west side of the core, which might indicate the emergence of a new component. A second-epoch VLBI observation in 1995 October showed a resolved structure, with a jetlike component to the south, 1.12 mas from the strong central component (Shen, Hong, & Wan 1998). A proper motion of 0.22 mas yr$^{-1}$ is estimated, which corresponds to an apparent superluminal motion of 4.6c in the jet.

PKS 2355 - 534 (Fig. 1w)—This is an optically violent and highly polarized source (Impey & Tapia 1988, 1990), with a high redshift of $z = 1.006$ (Jauncey et al. 1984). There have been no previous measurements of the radio structure. Our image shows two components with similar size but different flux densities. The stronger component, which may be the core, has a brightness temperature of $3.5 \times 10^{11}$ K. The second component is located at a distance of 4.9 mas at a position angle of $235^\circ$.

5. SUMMARY

In this paper we have defined a sample of Southern Hemisphere core-dominated blazars. Of the 24 blazars in the sample, three were observed earlier with the same array. The other 21 in the sample and two other sources were observed in 1993 May with the Southern VLBI Network plus the Shanghai radio telescope. This is part of the Southern Hemisphere 5 GHz VLBI Survey project, the aim of which is to improve the study of southern extragalactic radio sources (see Paper I). Our study also adds significantly to the number of sources whose structures can be compared on arcsecond (kiloparsec) and milliarcsecond (parsec) scales (Table 5). The misalignment of jetlike structures on these scales is an important unsolved problem for the understanding of compact sources.

The main conclusions presented in this paper can be summarized as follows:

1. We have detected and imaged all 23 radio sources, of which 15 are first-epoch VLBI images. These are PKS 0118 - 272, 0332 - 403, 0426 - 380, 0454 - 234, 0823 - 223, 1034 - 293, 1244 - 255, 1514 - 241, 1936 - 155, 1954 - 388, 2005 - 489, 2155 - 152, 2240 - 260, 2243 - 123, and 2355 - 534.

2. Most of the blazars are resolved and display simple morphology, with 12 having core-jet structures and 11 having single-core structures. Observations with increased
sensitivity will probably reveal many more core-jet structures (e.g., 2243–123). We have compared our VLBI images with other radio images. Only three (PKS 0426–436, 0537–441, and 1226+023) of the 12 core-jet blazars were found to have curved jets. Superluminal motion was inferred from two-epoch observations for two blazars. No. 4, 1998 SOUTHERN BLAZARS 1369

3. Eight of these blazars (PKS 0208–512, 0454–234, 0521–365, 0537–441, 1127–145, 1226+023, 1244–255, and 1255–234) of the 12 core-jet blazars have now been imaged by our survey project. A systematic study of the VLBI properties of these γ-ray-blazars and comparison with other non-γ-ray sources will improve our understanding of the beaming characteristics in blazars and the properties of EGRET sources.

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TABLE 5

SUMMARY OF SOURCE POSITION ANGLES AT ARCSECOND AND MILLIARCSECOND SCALES

| SOURCE NAME  | OPTICAL TYPE | Arcssecond Scale | Milliarcsecond Scale | Difference | EGRET SOURCE |
|--------------|--------------|------------------|----------------------|------------|--------------|
| PKS 0118–272 | B Diffuse     | N/A              | 45                   | 22         | Yes          |
| PKS 0208–512 | Q 225         | 234              | 9                    |            | Yes          |
| PKS 0332–403 | Q Unresolved  | 103              |                      |            | Yes          |
| PKS 0403–132 | Q 23          | 45               | 22                   |            | Yes          |
| PKS 0426–380 | B 336         | N/A              |                      |            | Yes          |
| PKS 0438–436 | Q 15          | 122              | 107                  |            | Yes          |
| PKS 0454–234 | B N/A         | 318              |                      |            | Yes          |
| PKS 0521–365 | Q 302         | 320              | 18                   |            | Yes          |
| PKS 0537–441 | B 305         | 14               | 69                   |            | Yes          |
| PKS 0823–223 | B Diffuse     | N/A              |                      |            | Yes          |
| PKS 1034–293 | B N/A         | N/A              |                      |            | Yes          |
| PKS 1127–145 | Q 41          | 265              | 136                  |            | Yes          |
| PKS 1226+023 | Q 222         | 230              | 8                    |            | Yes          |
| PKS 1244–255 | Q N/A         | N/A              |                      |            | Yes          |
| PKS 1424–418 | Q 250         | 260              | 90                   |            | Yes          |
| PKS 1514–241 | B 120         | N/A              |                      |            | Yes          |
| PKS 1936–155 | Q Unresolved  | N/A              |                      |            | Yes          |
| PKS 1954–388 | Q Diffuse     | N/A              |                      |            | Yes          |
| PKS 2005–489 | B N/A         | N/A              |                      |            | Yes          |
| PKS 2155–152 | Q 0           | 15               | 15                   |            | Yes          |
| PKS 2240–260 | B N/A         | 314              |                      |            | Yes          |
| PKS 2243–123 | Q 40          | 180              | 140                  |            | Yes          |
| PKS 2355–534 | Q N/A         | 235              |                      |            | Yes          |

* (B) BL Lac object; (Q) quasar.
