High Resolution VSOP Imaging of a Southern Blazar PKS 1921–293 at 1.6 GHz

Z.-Q. Shen,1,3 P. G. Edwards,2 J. E. J. Lovell,2 K. Fujisawa,1 S. Kamenoi,1 and M. Inoue1

1National Astronomical Observatory, 2-21-1 Osawa, Mitaka, Tokyo 181-8588
2Institute of Space and Astronautical Science, 3-1-1 Yoshinodai, Sagamihara, Kanagawa 229-8510
3Academia Sinica Institute of Astronomy and Astrophysics, P.O. Box 1-87, Nankang, Taipei 115

E-mail(ZS): zshen@hotaka.mtk.nao.ac.jp

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Abstract

We present a high resolution 1.6 GHz VSOP image of the southern blazar PKS 1921–293. The image shows a typical core–jet morphology, consistent with ground–based VLBI images. However, the addition of data from the space antenna has greatly improved the angular resolution (especially along the north–south direction for this source), and thus allowed us to clearly identify the core. Model fitting reveals an inner jet component ∼1.5 mas north of the core. This jet feature may be moving on a common curved path connecting the jet within a few parsecs to the 10–parsec–scale jet. The compact core has a brightness temperature of $2.6 \times 10^{12}$ K (in the rest frame of the quasar), an indication of relativistic beaming. We analyzed the source in terms of three models, involving the inverse Compton catastrophe, an inhomogeneous relativistic jet, and the equipartition of energy between the radiating particles and the magnetic field. Our analysis of this γ–ray–quiet blazar shows no preference to any particular one of these models.

Key words: Galaxies: active — Galaxies: nuclei — Quasars: individual (PKS 1921–293)

1. Introduction

The successful launch of the VLBI Space Observatory Programme (VSOP) satellite HALCA marks a great step forward in increasing the resolution over that possible with ground-based radio telescopes at 1.6 and 5.0 GHz (Hirabayashi et al. 1998 and references therein). HALCA’s 8-meter-diameter antenna is in an elliptical orbit with an apogee of 21,400 km, a perigee of 560 km and an orbital period of 6.3 hours. VSOP observations, with a factor of ∼3 improvement in resolution compared to the ground observations at same frequencies, enable a close look at the compact core of active galactic nuclei and as a result, to resolve some individual components within the compact core and jets, and to study the bent jet in the vicinity of the core observed at higher frequencies with ground telescopes. In particular, the addition of HALCA significantly improves the north–south resolution for equatorial and southern radio sources, as illustrated in this paper. VSOP also provides almost an order of magnitude increase to the detectable brightness temperature (from $10^{11}$–$10^{12}$ K to $10^{12}$–$10^{13}$ K for bright sources).

As a highly polarized (cf. Worrall, Wilkes 1990) and optically violently variable quasar (Wills, Wills 1981) with $m_v = 17.5$, PKS 1921–293 (OV–236) is classified as one of the brightest radio–loud blazars known. It shows a dramatic variability from radio to X-ray. Curiously, no γ–ray emission has been detected by EGRET (Fichtel et al. 1994; Mukherjee et al. 1997). At a redshift of 0.352 (Wills, Wills 1981), it has an angular–to–linear scale conversion of $3h^{-1}$ pc mas$^{-1}$ with $H_0 = 100$ h km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$. The existing ground VLBI observations reveal a core–jet structure (cf. Kellermann et al. 1998). Its core is very compact (only a fraction of the beamwidth in diameter), with a brightness temperature ($T_b$) in the rest frame of the source greater than $10^{12}$ K. There is evidence that on a scale of 1–2 $h^{-1}$ pc from the core, the jet moves along a curved trajectory superluminally (Shen et al. 1999) and then appears to end up in a diffuse component about 15 $h^{-1}$ pc from the core (cf. Tingay et al. 1998).

In this letter, we report on the results of a 1.6 GHz VSOP imaging of PKS 1921–293. We describe the observations and data reduction and present a 1.6 GHz VSOP image of PKS 1921–293 in section 2. The evolution of its fine structure and the implication of the high $T_b$ will be discussed in section 3. A brief summary is given in section 4.

Throughout this paper the spectral index, $\alpha$, is defined as $S_\nu \propto \nu^{\alpha}$.
2. VSOP Observations and Data Reduction

The 1.6 GHz VSOP observations of PKS 1921–293 were carried out as part of HALCA’s in-orbit checkout on July 18, 1997 for a total about 1.5 hours. The HALCA data acquisition was successfully done with the satellite tracking stations located in Goldstone (CA, USA), and NRAO Green Bank (WV, USA). The ground radio telescopes consisted of 10 VLBA antennas and the phased VLA of NRAO. The left-circular polarization (LCP) data were recorded in the standard VLBA format with an intermediate frequency (IF) band of 16 MHz. The cross-correlation of the data was carried out on the VLBA correlator at Socorro (NM, USA) with an output preaveraging time of 0.524 and 1.966 seconds for the space-ground and ground-ground baselines, respectively, and 256 spectral channels per IF band.

The post–correlation data reduction was performed in NRAO AIPS and DIFMAP (Shepherd 1997). A priori visibility amplitude calibrations were applied using the antenna gain curves and the system temperatures measured at each antenna including HALCA. In the fringe-fitting run, a solution interval of 1 minute and a point source model were employed. The VLBA antenna at Los Alamos (LA) served as the reference telescope throughout. Strong fringes were consistently detected on space baselines to HALCA as well as all the ground baselines. Following this, the data were averaged over all frequency channels, and then phase self-calibrated with a 10–second solution interval and a point source model for the purpose of further time averaging.

Finally, the visibility data were exported to DIFMAP for imaging. The data were integrated over 30 seconds to reconcile the different preaveraging time from the correlator output as mentioned above. The uncertainties in the averaged visibilities were computed from the scatter of data points within the averaging interval. Some obviously bad data were inspected and removed. Several iterations of cleaning and self-calibration to phases (and amplitudes in the later stages) were performed. To ensure a better angular resolution with HALCA data, uniform weighting of the data was adopted with gridding weights scaled by amplitude errors raised to the power of –1. The resulting image is shown in figure 1. The FWHM beam size is 4.1 mas × 1.1 mas at a position angle of 46°. (For comparison, the synthesized beam of the ground–only observation is 21.7 mas × 5.7 mas along –4°.) The peak flux density and the rms noise level are 4.61 Jy/beam and 7.0 mJy/beam, respectively. Thus, a peak-to-rms dynamic range of 650 is obtained in our short 1.6 GHz VSOP image.

3. Discussion

3.1. Structural Evolution

PKS 1921–293 was unresolved at arcsecond–scale with VLA observations (Perley 1982; de Pater et al. 1985). Ground VLBI images at centimeter wavelengths showed a typical core–jet structure, with a diffuse jet feature located at a position angle ~ 30° with respect to the compact, strong core (cf. Fey et al. 1996; Tingay et al. 1998; Kellermann et al. 1998). At 43 GHz, three–epoch VLBA images provide evidence for a superluminal jet ($\beta_{app} = 2.1 h^{-1}$) within 1–2 $h^{-1}$ pc, which has a sharp bend in the position angle compared to the jet seen on a scale of ten parsecs (Shen et al. 1999).

The core–jet morphology of our VSOP image is in good agreement with those ground VLBI images made at other centimeter wavelengths. However, the addition of space VLBI antenna greatly improved the resolution (as can be seen from the comparison of the beams with and without HALCA), and thus enables us to clearly identify the compact core. To yield a quantitative description of the source structure, we applied a model consisting of three elliptical Gaussian components to fit both amplitudes and phases in the calibrated visibility data. The results of model parameters and corresponding 1-σ errors are listed in table 1. It reveals that the data are consistent with an inner jet (component 2) at 1.5 mas north of the core (component 1), as well as a large jet feature (com-

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Table 1. Results from Model Fitting to 1.6 GHz VSOP Observation

| Component | S (Jy) | r (mas) | θ (°) | a (mas) | b/a | P.A. (°) |
|-----------|--------|---------|-------|---------|-----|----------|
| 1         | 5.59±0.11 | 0       | 0     | 1.87±0.15 | 0.38±0.03 | 48.9±3.4 |
| 2         | 2.03±0.05 | 1.5±0.2 | 3.4±4.0 | 2.70±0.12 | 0.12±0.01 | 48.0±3.4 |
| 3         | 4.63±0.10 | 5.6±0.1 | 30.4±1.3 | 3.52±0.14 | 0.76±0.08 | 117.8±1.7 |

Notes — S: the flux density of each component; (r, θ): the distance and position angle of each component with respect to the origin defined by component 1 in mas and degrees, respectively; (a, b/a and P.A.): three parameters of Gaussian component, i.e. major axis (FWHM) in mas, ratio of minor to major axes and the orientation angle in degrees of the major axis.

3.2. Brightness Temperature $T_b$

PKS 1921–293 has one of the highest brightness temperatures measured in the rest frame of the source. A 22 GHz VLBI survey (Moellenbrock et al. 1996) gave a lower limit to $T_b > 7.0^{+4.0}_{-2.1} \times 10^{12}$ K for PKS 1921–293. A previous VLBI experiment, using a telescope in Earth orbit, estimated a core $T_b$ of $3.8 \times 10^{12}$ K at 2.3 GHz (Linfield et al. 1989), the highest in the sample for sources with known redshifts. VLBI images made at 5.0 GHz also
found $T_b$ significantly greater than $10^{12}$ K (Shen et al. 1997; Tingay et al. 1998). The derived core $T_b$ from our 1.6 GHz VSOP image is $(2.55 \pm 0.66) \times 10^{12}$ K, which is consistent with those earlier estimates.

It has been shown that there is a limit to $T_b$ for incoherent synchrotron radiation, and a brightness temperature in excess of this limit is ascribed to the effect of Doppler boosting in a relativistic jet beamed toward the observer with a Doppler factor $\delta = \sqrt{\gamma (1 - \beta \cos \theta)}^{-1}$ (cf. Readhead 1994). Here $\gamma = (1 - \beta^2)^{-1/2}$ is the Lorentz factor, $\beta$ is the jet velocity in units of the speed of light and, $\theta$ is the angle between the line of sight and the radio jet axis.

A commonly accepted explanation is that the observed upper limit to $T_b$ ($\sim 10^{12}$ K) is caused by the “inverse Compton catastrophe” (Kellermann, Pauliny-Toth 1969). Using formulae (1a) and (1b) rederived by Readhead (1994), we can calculate this inverse Compton scattering limit as $T_{b,ic} = 1.2 \times 10^{11}$ K for PKS 1921–293. Here we have applied a peak frequency of 8.0 GHz and assumed a high frequency cutoff of 100 GHz. The synchrotron self-absorption turn–over frequency of 8.0 GHz was claimed by Brown et al. (1989) and is confirmed by single–dish measurements from the University of Michigan Radio Astronomy Observatory (UMRAO) made around our VSOP observational epoch, from which we also obtained an optically thin spectral index of $-0.15$ as well as a total flux density of 17.9 Jy at 8.0 GHz. In order to reconcile with $T_b = (1.71 \pm 0.44) \times 10^{12}$ K from our 1.6 GHz VSOP results (here, we have multiplied a factor of 0.67 to convert a brightness temperature derived assuming a Gaussian component to an optically thin uniformly filled sphere), a Doppler boosting factor $D_{ic} = 14.3 \pm 3.7$ is required to avoid the inverse Compton catastrophe. This agrees very well with a lower limit to Doppler factor ($\delta_{ssc}$) of 14 derived from the argument that the observed X-ray emission is produced primarily by the inverse Compton scattering of synchrotron radiation (Guíjosa, Daly 1996 and references therein).

The inhomogeneous relativistic jet model (Blandford, Königl 1979; Königl 1981) also sets an upper limit to the measured brightness temperature. This limit is independent of frequency and depends very weakly on the observables with an approximate expression as $T_{b,j} \sim 3.0 \times 10^{11} D_j^{5/6}$ K, here $D_j$ is the Doppler factor associated with this jet model. This results in a $D_j = 12.7 \pm 4.0$, which is very similar to $D_{ic}$ from the inverse Compton catastrophe. Combining with the detected superluminal jet motion $\beta_{app} = 3.0$ (Shen et al. 1999; choosing $h = 0.7$ here), we can derive its bulk Lorentz factor ($\gamma$) and the jet angle with the line of sight ($\theta$) as follows: $\gamma_{ic} = 7.5$ and $\theta_{ic} = 136$ from $D_{ic} = 14.3$, and $\gamma_j = 6.7$ and $\theta_j = 230$ from $D_j = 12.7$, respectively. Both models require about the same relativistic beaming factor to explain the high $T_b$ for PKS 1921–293, and we cannot distinguish between them.

Readhead (1994) introduced the “equipartition brightness temperature” cutoff ($\sim 10^{11}$ K) from a statistical analysis. In the case of PKS 1921–293, it gives a limit of $T_{b,eq} = 9.8 \times 10^{10} \delta^{0.78} h^{-2/17}$ K. The 1.6 GHz VSOP core significantly exceeds this limit, and therefore an equipartition Doppler factor as large as $(39.1 \pm 12.9) h^{0.15}$ is needed. This is about 3 times the values of $D_{ic}$ and $D_j$ and suggests that PKS 1921–293 may not be in equipartition. If PKS 1921–293 is not in equipartition, we can use ratio $D_{eq} / \delta = T_b / T_{b,eq}$ with the assumption that $\delta$ is 13 (a value close to $D_{ic}$, $D_j$ and $\delta_{ssc}$) to derive an equipartition Doppler factor $D_{eq} = (30.6 \pm 7.9) h^{2/17}$, and then $\gamma_{eq} = 14.8$ and $\theta_{eq} = 0.94$.

4. Conclusions

We have carried out a VSOP observation of the southern blazar PKS 1921–293. The overall source morphology is consistent with previous ground VLBI results. As is clear from figure 2, the space VLBI observations are critical for isolating the core of the source and permit images to be made with much finer spatial resolution than is possible with the ground VLBI at the same frequency. In the
case of PKS 1921–293, the high resolution provided by VSOP data, especially along the north-south direction, plays an irreplaceable role in our resolving an inner jet component at about 1.5 mas north of the compact core. When compared with the ground VLBI images, this feature is believed to relate to the emission on its curved trajectory from the bent jet within 1–2 $h^{-1}$ pc to the 10 pc–scale elongated jets.

By model fitting VSOP calibrated data, we obtain a core brightness temperature of $2.6 \times 10^{12}$ K in the source rest frame under the assumption that the source has a Gaussian brightness distribution. This is in excess of $10^{12}$ K, and implies a relativistic beaming in the core. We analyzed the source in terms of three models, involving the inverse Compton catastrophe, an inhomogeneous relativistic jet, and the equipartition of energy between the radiating particles and the magnetic field. We found no significant difference in Doppler factors for first two models, though inhomogeneous jet model is more realistic compared to the homogeneous sphere model in compact radio sources. Both models, however, will eventually lead to a particle dominated departure from equipartition state according to the equipartition argument. Otherwise, a relatively large Doppler factor is needed in order to maintain equipartition of energy in the source. Thus, our analysis of high $T_b$ in this $\gamma$–ray–quiet blazar PKS 1921–293 is not in favor of any particular models. More VSOP imaging study of these strong blazars with high brightness temperatures will be necessary to improve our understanding of the physical process within.

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amplitude vs. u-v distance

uv coverage