Dual-frequency VSOP Imaging of a High-redshift Radio Quasar PKS 1402+044

Jun Yang, Leonid Gurvits, Andrei Lobanov, Sándor Frey and Xiao-Yu Hong

Based on the VLBI Space Observatory Programme (VSOP) observations at 1.6 and 5 GHz, we find that the luminous high-redshift (z = 3.215) quasar PKS 1402+044 (J1405+0415) has a pronounced 'core–jet' structure. The jet shows a steeper spectral index and lower brightness temperature with the increase of the distance from the core. The variation of brightness temperature is basically consistent with the shock-in-jet model. Assuming that the jet is collimated by the ambient magnetic field, we estimate the mass of the central object as $10^9 M_\odot$. The upper limit of the jet proper motion of PKS 1402+044 is 0.03 mas yr$^{-1}$ ($3c$) in the east-west direction.

Acknowledgements: This research was partly supported by the Natural Science Foundation of China (NSFC10473018 and NSFC10333020). Jun Yang and Xiao Yu Hong are grateful to the KNAW–CAS grant. Sándor Frey acknowledges the OTKA T046097 grant. We gratefully acknowledge the VSOP Project, which is led by the Institute of Space and Astronautical Science (Japan) in cooperation with many agencies, institutes and observatories around the world. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has made use of NASA’s Astrophysics Data System, NASA/IPAC Extragalactic Database (NED) and the United States Naval Observatory (USNO) Radio Reference Frame Image Database (RRFID).
1. Introduction

High-redshift radio quasars can facilitate a comparison of structural properties across the redshift space and provide important inputs into tests of cosmological models, such as the "apparent angular size–redshift" and "apparent proper motion–redshift" relations. PKS 1402+044 (J1405+0415) is a flat-spectrum radio source from the Parkes 2.7-GHz survey (0.58 Jy). Optically it is a 19.6-magnitude stellar object with the redshift $z = 3.215$. The MERLIN observations at 1.6 GHz indicated that there is a secondary component at a separation of 0.80'' to the south-west at the position angle of 123° and a faint extended emission at 3.30'' at the position angle of 106°.

VLBI observations [5] at 5 GHz found that the main component consists of a compact core and a resolved jet extending to 18 mas to the west. Here we present some results of VSOP observations at 1.6 and 5 GHz. Throughout the paper, the cosmological model with $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$ is adopted.

2. Observations and data reduction

Using the space antenna HALCA and the Very Long Baseline Array (VLBA), we observed the radio quasar PKS 1402+044 in left circular polarization for 8 hours at 1.6 GHz on 2001 Jan 21 and for 7 hours at 5 GHz on 2001 Jan 20. A priori calibrations were done with the AIPS in a standard way. Fringes were detected on all space–ground baselines. The useful bandwidth after flaging the side channels spans for 22.8 MHz. The imaging, self-calibration and model fitting were done in DIFMAP.

3. Results and discussion

Figure 1 displays a clear core–jet morphology of the quasar PKS 1402+044. The naturally weighted VLBA image detects the weak emission extending up to 150 mas (1 kpc projected distance). The jet shows a wide section between 20 and 70 mas (140 – 500 pc) indicating an expanding jet propagating in a dense ambient medium. Here we identify the compact core (component A) and five emission regions (components B – F). The naturally weighted 5-GHz VSOP image shows that the inner jet is resolved into brighter emission regions. With uniform weighting, the jet is basically resolved out. There is a synchrotron self-absorbed weak component (A1) appearing at the beginning of the jet near the brightest component (A2).
Based on the spectral index image between the two frequencies, we found that the spectral index $\alpha$ ($S_{\nu} \propto \nu^{\alpha}$) varies from $+0.1$ in the inner nuclear region to $-1$ in the outer jet regions. To further confirm the variation, we calculated the spectral index of each component using five-frequency images. The 2.3/8.4-GHz data are from the RRFID\(^1\). The 15-GHz data are from the VSOP support survey by Gurvits et al. (in preparation). The core component has a flat spectrum $\alpha = 0.19$, but the jet components have steeper spectrum: $\alpha_{B+C} = 0.55$, $\alpha_{D} = 0.74$. The spectral difference between the core and jet leads to a decreasing jet to core flux density ratio with increasing frequency. Furthermore, the difference demonstrates the explanation of a decreasing jet to core flux density ratio at a certain observation frequency with increasing redshift for a large radio quasar sample [3].

If the jet is collimated by the ambient magnetic field $B_{ext}$ ($10^{-5}$ G) of the host galaxy, the mass of the central object $M_{BH}$ can be related to the width of the jet $r_{jet}$ [1]:

$$M_{BH} = \frac{r_{jet} (B_{ext} B_{gr})^{1/2}}{10^{13} M_\odot}$$

where $B_{gr}$ is the magnetic field at the Schwarzschild radius. Based on the theoretical assumption [4], one can expect to have $B_{gr} = 10^{4}$ G. Using the measured size 0.3 mas of the component A2, the mass of the central object is $10^{9} M_\odot$.

For the radio core, the brightness temperature $T_{B} = 4 \times 10^{12}$ K is close to but somewhat larger than the inverse Compton limit. Comparing with the limiting brightness temperature $3 \times 10^{11} \delta^{5-6}$ K in the equipartition jet model of Blandford and Königl [2], a lower limit to the Doppler factor $\delta \approx 22$ can be determined. Following the shock-in-jet model of Marscher [7], we assume that the radio emission is dominated by adiabatic energy losses. The jet plasma has a power-law energy distribution, $N(E)dE \propto E^{-s}dE$. The magnetic field varies as $B \propto \rho^{a}$. The Doppler factor is assumed to vary weakly throughout the jet. There is a simple relation: $T_{B,jet} = T_{B,core} (d_{jet}/d_{core})^{\varepsilon}$, where $d_{jet}$ represents the measured size of core and jet features and $\varepsilon = \sqrt{2(s+1) + 3a(s+1)} = 6$. We take $s = 2.5$ and $a = 1$ corresponding to the transverse orientation of the magnetic field in the jet [3]. The estimated brightness temperature values are basically consistent with the observed values.

With another early VLBI observation at 5 GHz in 1986 by Gurvits et al. [5], we estimated an upper limit of 0.03 mas yr\(^{-1}\) ($3c$) of the proper motion in the EW direction.

References

[1] V.S. Beskin 1997, Physi.-Uspekhi, 40(7), 659
[2] R.E. Blandford and A. Königl 1979, ApJ, 232, 34
[3] S. Frey, L.I. Gurvits, K.L. Kellermann et al. 1997, A&A, 325, 511
[4] G.B. Field and A.D. Rogers 1993, ApJ, 403, 94
[5] L.I. Gurvits, N.S. Kardashev, M.V. Popov et al. 1992, A&A, 260, 82
[6] A.P. Lobanov, L.I. Gurvits, S. Frey et al. 2001, ApJ, 547, 714
[7] A.P. Marscher 1990, in Parsec-Scale Radio Jets, ed. J. A. Zensus and T. J. Pearson (Cambridge: Cambridge Univ. Press), 236

---

\(^1\)USNO Radio Reference Frame Image Database, http://rorf.usno.navy.mil/RRFID