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An extremely curved relativistic jet in PKS 2136+141

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Abstract. We report the discovery of an extremely curved jet in the high frequency peaking GPS quasar PKS 2136+141. Our multi-frequency VLBA images show a bending jet making a turn-around of 210 degrees on the plane of the sky, which is, to our knowledge, the largest ever observed change in a structural position angle of an extragalactic jet. Images taken at six different frequencies, from 2 to 43 GHz, beautifully reveal a spiral-like trajectory. We discuss possibilities to constrain the 3-D geometry of the source and suggest that it could be used as a testbed for models describing the bending of the relativistic jets.

1. Introduction

A significant fraction of extragalactic jets show some degree of bending – from slightly curved jets up to a complete turn-around of an almost 180°. Very large-angle misalignments have been observed in some core-dominated radio sources, but, generally, misalignment angles larger than 120° are rare (Wilkinson et al. 1986, Tingay et al. 1998, Lister et al. 2001). Up to today, the largest observed ΔP.A. is 177° in the gamma-ray blazar PKS 1510-089, which shows a jet bending almost directly across our line of sight (Homan et al. 2002).

Since core-dominated radio sources have jets oriented close to our line of sight, all intrinsic variations in the jet trajectories are exaggerated in projection – often to a large degree. This implies that rather small intrinsic bends can manifest themselves as large-angle misalignments between the jet axes observed on parsec and kiloparsec scales, or as high as 90° turns in VLBI images.

Variety of explanations have been suggested for the observed bends including ballistic motion of plasmoids ejected from a precessing jet nozzle, ram pressure due to winds in the intracluster medium, the density gradient in the transition to the intergalactic medium and growing magnetohydrodynamic instabilities in the jet propagation. Most likely, different mechanisms work in different sources. It would be valuable to be able to reliably identify the reason for bending in individual sources, since the observed properties of the bend – correctly interpreted – can constrain several physical parameters of the jet and the external medium (see e.g. Hardee 2003).

In this paper, we present VLBA images showing that PKS 2136+141 (OX 161), a quasar type GHz-peaked spectrum source at moderately high redshift of 2.427, has a parsec-scale jet, which appears to bend *over* 180° on the plane of the sky, possibly making it the most curved astrophysical jet ever observed.

In VLA images, PKS 2136+141 is compact, showing no extended emission (Murphy et al. 1993), but has a core-jet morphology in VLBI scales. Both 5 GHz (Fomalont et al. 2000) and 15 GHz (Kellermann et al. 1998) VLBA observations reveal a core-dominated source with a short, slightly bending jet. Kellermann et al. (2004) have measured an apparent superluminal speed of $\beta_{app} = 1.8 \pm 1.4$ for the brightest moving component.

The radio-mm spectrum of the source peaks at 8-10 GHz in the quiescent state and strongly inverted spectrum ($\alpha \geq +0.5$) is seen during outbursts (Tornikoski et al. 2001). This puts PKS 2136+141 into the class of high frequency peakers. The source is variable at radio frequencies showing a factor of ∼ 3 variations in cm-wavelength flux curves with characteristic time scale of ∼ 5 years (M. Aller, private communication). Last strong outburst started around 1998 and the cm-flux was still rising in 2003, indicating that our observations in 2001 caught the source during the rising phase of a major flare.

2. Observations and results

On May 2001 we made multi-frequency polarimetric VLBI observations of four GPS quasars, including PKS 2136+141, using the National Radio Astronomy Observatory's (NRAO) Very Long Baseline Array. Observations were split into a high frequency part (15, 22 and 43 GHz), which was observed on May 12th, and into a low frequency part (2, 5 and 8 GHz) observed on May 14th . Dual polarization was recorded at all frequencies.

The data were correlated on the VLBA correlator and were postprocessed with the NRAO's Astronomical Image Processing System, AIPS, (Bridle & Greisen 1994) and the Caltech DIFMAP package (Shepherd 1997). Standard methods for VLBI data reduction and imaging were used. To allow estimation of the parameters of the emission regions, the self-calibrated visibilities were model-fitted using the DIFMAP. Circular Gaussian model components were used and we sought to obtain the best possible fit to the visibilities and to the closure phases. Several starting points were tried in order to avoid a local minimum fit.

Figure 1 displays uniformly weighted CLEAN images of PKS 2136+141 at all six frequencies, strikingly revealing a jet which gradually bends 210° with its structural P.A. turn-

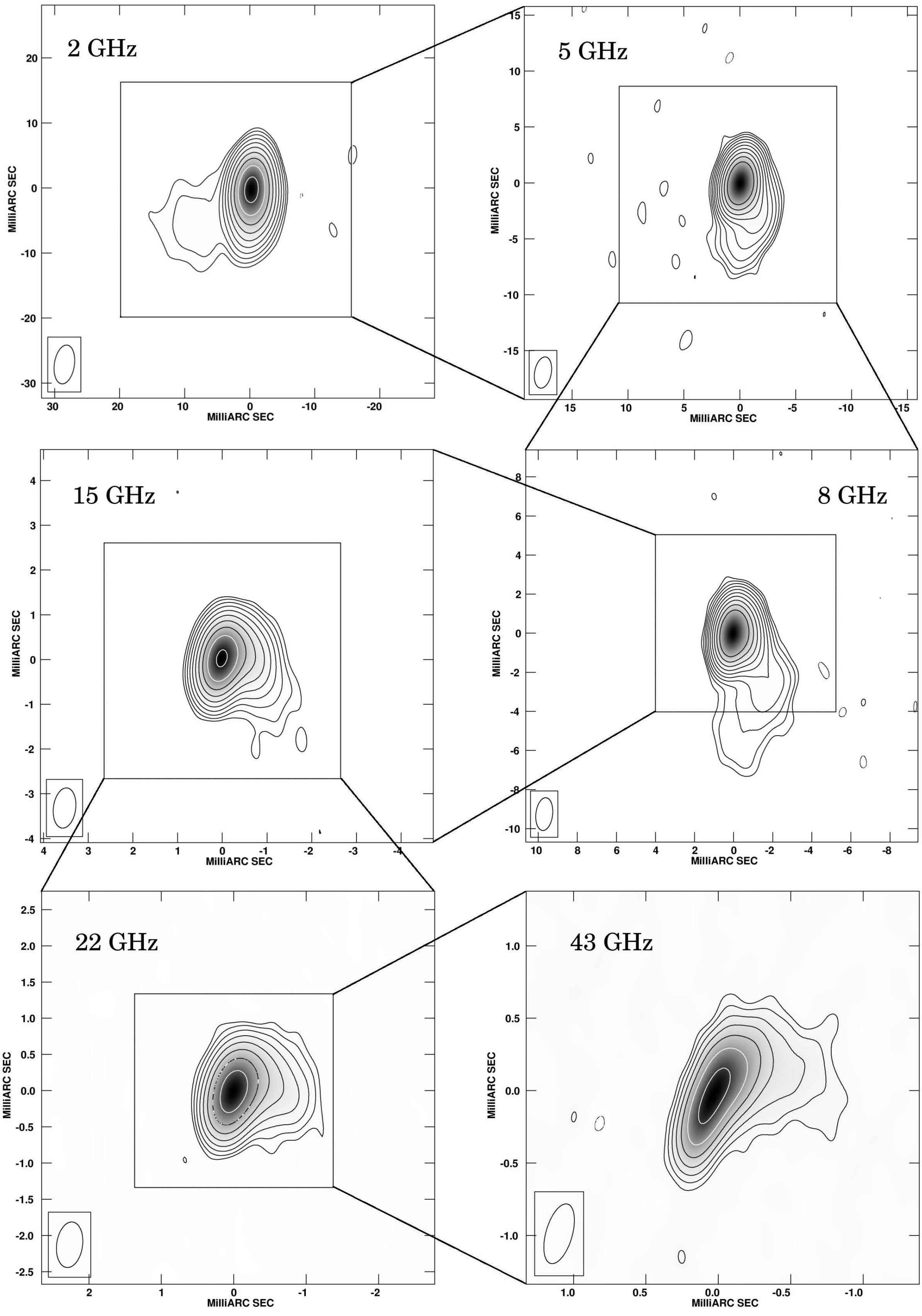

Fig. 1. Compiled figure showing the total intensity images at all six frequencies. Both contours and grey scale represent total intensity. Peak intensities and contour levels are given in Table 1.

ing clockwise from -27° at 43 GHz to +123° at 2 GHz. The source is rather compact at all frequencies with maximum jet extent of approximately 15 mas corresponding to ∼ 120 pc at the source distance[1]. The core is the brightest component in PKS 2136+141 at all frequencies except 43 GHz, at which the brightness peak is located at 0.28 mas from the core. The brightness profiles along the jet at frequencies 2–22 GHz are quite smooth without any pronounced knots. At 43 GHz the core region is either elongated pointing to P.A. of -27° or consists of two distinct components separated by 0.28 mas.

The positions of model-fitted Gaussian components are represented in Figure 2 together with a helical trajectory fitted to the component positions. In order to see if the spiral-like appearance of the jet can be described with a helical trajectory, we tried to fit four simple and purely geometrical models to the data. These included helices on the surface of the cylinder and on the surface of the cone combined with either a constant or linearly growing pitch angle. It turned out that only a helix on the surface of the cone with a linearly increasing pitch angle gives a satisfactory fit to the data ($\chi^2 = 1.7$). The parameters describing the trajectory of the best fit model are: the radius of the cone at the core position, $R = 9.28$ mas, the phase angle at the core position, ψ=177.6°, the half-opening angle of the cone, $\Theta = 37.5°$, the growth rate of the pitch angle, $d\xi/d\phi = 18.7$, and the angle between the axis of the cone and our line of sight, $\Delta = 55.4°$. In Figure 3 we have plotted the Doppler factor, apparent speed, and the angle between the local direction of the jet and our line sight as a function of phase angle of our best fitted helical trajectory. The peak in Doppler factor around phase angle of 10° is almost coincident with apparent brightening of the jet at 0.28 mas from the core in 43 GHz image. Also, the calculated β_{app} is in agreement with the value of 1.8 ± 1.4 measured by Kellermann et al. (2004). Thus, although the model is not based on physical arguments, it fits well to the observed properties of the source. If the bending is, in fact, due to a helical trajectory, the helix should be quickly opening and already asymptotically approaching a straight line in the scale of 15 mas.

3. Discussion

3.1. Reason for bending

There are several possible mechanisms that could be responsible for bending of the jet in PKS 2136+141. Projection effects most likely play a role here and the intrinsic bending angle is much less than the observed one. However, the mere fact that observed ΔP.A. is larger than 180° constrains the possible mechanisms, since it excludes scenarios where the jet is bent by a simple change in the density of the external medium, like e.g. deflection by a massive cloud in the ISM or by a uniform density gradient.

Homan et al. (2002) explained the large misalignment between the pc and kpc scale jets of PKS 1510-089 with a scenario where the jet is bent after it departs the host galaxy, either by the density gradient in the transition region or by ram pressure due to the winds in the intracluster medium. In PKS 2136+141, the bending takes place well within 15 mas from the core, corresponding to a linear distance of 120 pc. If we assume a typical scale size of the elliptical hosts of radio galaxies, ∼ 30 kpc, the angle between the jet and our line of sight would have to be considerably less than 0.2° if the jet bent after departing the galaxy. This would place our line of sight inside the jet opening angle, which is not observed. Thus, the jet in PKS 2136+141 bends before it reaches the outskirts of the host galaxy.

Another obvious possibility explaining the observed bend is a precessing jet where the components ejected at different times to different directions move ballistically, and form an apparently curved locus. Such models have been used to describe oscillating 'nozzles' observed in some BL Lac sources (e.g. Stirling et al. 2003, Tateyama & Kingham 2004). Jet precession can be due to the Lense-Thirring effect in case of misalignment between the angular momenta of accretion disk and a Kerr black hole, or it can occur in a binary black hole system where secondary black hole tidally induces precession to the accretion disk. In case of PKS 2136+141, we should be able to easily test the precessing jet model with future high frequency VLBI observations. If the jet is ballistic with a precessing inlet, we should observe the orientation of the most compact part of the jet to change with time. Also, the components should not follow a curved trajectory, but rather go along straight lines starting from the core.

Observed bends in astrophysical jets can also be a manifestation of growing magnetohydrodynamic instabilities, which can launch helical distortions of the jet propagating either as a body mode displacing the entire jet or as a surface mode producing helically twisted patterns on the surface of the jet (see e.g. Hardee 1987, 2003). With current data, it is difficult to study whether the observed bend in PKS 2136+141 could be modeled with such instabilities, since no complete 'twist' is observed and thus, the wavelength, wave speed and growth rate of the disturbance cannot be unambiguously determined.

3.2. 3D-trajectory from future observations

With further VLBI observations, we would be able to measure how the flux density S_{obs}, opening angle Ψ_{obs} and apparent speed β_{app} change as a function of both time t and position

Table 1. Parameters of Maps

Frequency (GHz)	rms noise (mJy beam^{-1})	Peak Intensity (mJy beam^{-1})	Contour c_0^a (mJy)
2	0.6	1153	1.7
5	0.4	1811	1.0
8	0.3	1890	0.9
15	0.7	1429	2.5
22	1.9	1153	5.8
43	2.2	512	6.1

[a] Contour levels are represented by geometric series $c_0(1, ..., 2^n)$, where c_0 is the lowest contour level indicated in the table.

[1] Throughout the paper we use following values for cosmological parameters: H_0=71km/s/Mpc, Ω_M=0.27 and Ω_Λ=0.73.

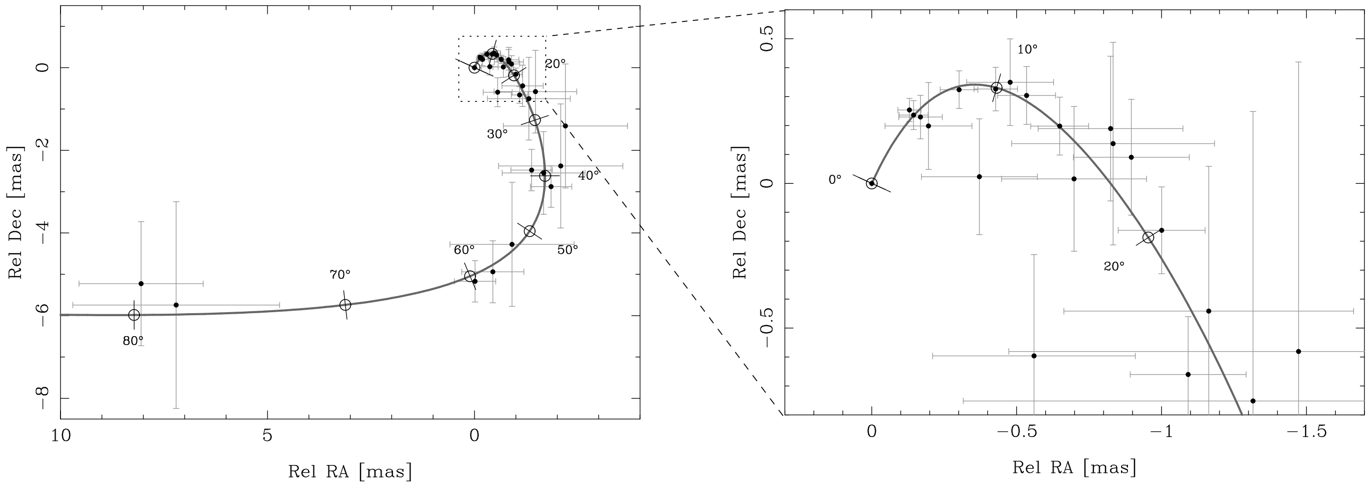

Fig. 2. Positions of model-fit components at all six frequencies. At each frequency the core is placed to the origin, and hence, no frequency shifts of self-absorbed core are taken into account. The left image shows the whole source and the right highlights the inner 2 mas. The errors in component positions are determined by using Difwrap program (Lovell 2000) and they should be considered as very conservative estimates. The solid line represents the best fit of a geometrical model describing a helix on a surface of a cone with linearly growing pitch angle.

z along the jet. S_{obs}, Ψ_{obs} and β_{app} all depend on the angle $\theta(z)$ between the local jet direction and our line of sight:

$$S_{obs}(z,t) = [\Gamma(t)(1-\beta(t)\cos\theta(z))]^{-(2-\alpha)} \cdot S(z,t) \quad (1)$$

$$\sin\Psi_{obs}(z) = \frac{\tan\Psi(z)\cos\theta(z)}{\sin\theta(z)} \quad (2)$$

$$\beta_{app}(z,t) = \frac{\beta(t)\sin\theta(z)}{1-\beta(t)\cos\theta(z)}, \quad (3)$$

where β is the flow speed of the jet, $\Gamma = 1/\sqrt{1-\beta^2}$, α is the measured spectral index ($S \propto \nu^{\alpha}$), $S(z,t)$ is an intrinsic flux density and $\Psi(z)$ is an intrinsic jet opening angle. If we take β and Ψ to be constants and assume some simple form for $S(t,z)$, we can try to fit for $\theta(z)$ and thus, determine the 3-D trajectory of the jet.

The knowledge about 3-D trajectory would place strong constraints on any physical model trying to explain the observed curvature in PKS 2136+141, hopefully making it possible to distinguish between the models. Keeping that in mind, this source may prove to be a good testbed for different bending scenarios in future.

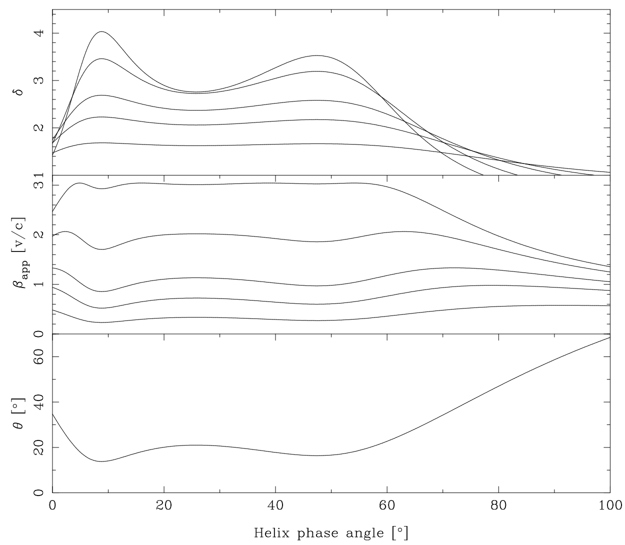

Fig. 3. Doppler factor δ, apparent jet speed β_{app} and angle θ between the jet and our line of sight as a function of phase angle of a helical trajectory depicted in Figure 2. The assumed jet velocities in two upper panels are $\beta = 0.95$, 0.9, 0.8, 0.7 and 0.5 (from top to bottom).

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