PROCEEDINGS OF SCIENCE

Simulated Transverse Distribution of Polarization Properties for Parsec-Scale Jets in Active Galactic Nuclei

Marina S. Butuzova[a,b,*] **and Alexander B. Pushkarev**[a,b]

[a] *Crimean Astrophysical Observatory, Nauchny 298409, Russia*

[b] *Astro Space Center of Lebedev Physical Institute, Profsoyuznaya 84/32, Moscow 117997, Russia*

E-mail: mbutuzova@craocrimea.ru

We present numerical simulations of relativistic jet profiles in total and linear polarization intensity, degree of linear polarization, and direction of the jet's electric vector position angles (EVPAs) transverse to the local jet axis. We consider the motion of jet segments along a helical path and, as a special case, motion in the radial direction. For these simulations we used various magnetic field configurations: (i) helical, with different twist angles, and (ii) toroidal in the central jet spine and poloidal at the jet sheath. The latter case was calculated for various values of the sheath thickness. We established the parameter sets that generally reproduce the transverse distributions of polarization properties observed with VLBI for the jets of the quasars 0836+710 (4C +71.07) and 1611+343.

**** FIXME: European VLBI Network Mini-Symposium and Users' Meeting 2021, ****
**** FIXME: 12 – 14 July 2021 ****
**** FIXME: University College Cork, Cork, Ireland ****

[*] Speaker

PoS(EVN2021)005

1. Introduction

The magnetic field plays an important role in launching, collimation, and accelerating the jets of active galactic nuclei. Configuration of the magnetic field associated with the jet and its regularity are still active areas of research. On the smallest scales (from sub-parsec to a few parsecs), relativistic jets can be probed by very long baseline interferometry (VLBI) observations. The largest full Stokes VLBI observation database has been collected by the MOJAVE (Monitoring Of Jets in Active galactic nuclei with VLBA Experiments) program[1] at 15 GHz. The results of the first epoch polarization analysis are presented in [1]. Recently, several studies [2, 3] have shown that, statistically, the linear polarization degree increases towards the edges of each jet. A determination of the magnetic field configuration in parsec-scale jets is the aim of this study. To reach this goal, we simulated transverse distributions of linear polarization properties for different B-field configurations (Section 2) and found parameter sets, for which we obtained good qualitative correspondence with the observed transverse distribution of polarization properties in jets of the quasars 0836+710 and 1611+343 (Section 3), which both exhibit stable rotation measure across the jet [4].

2. Simulations of transverse distributions of polarization properties

Jet investigations within the framework of the MOJAVE project have revealed changes in the inner jet position angles [5] and motion of jet features which commonly exhibit acceleration/deceleration along curved trajectories [6]. These findings indicate the presence of Doppler factor variations along the jet, which can significantly influence the jet's polarization properties [7]. Therefore, to properly simulate jet polarization, it is necessary to use a more complex jet model which accounts for these variations in speed and trajectory (Fig. 1). To facilitate an analytical expression for the viewing angle of the jet feature exhibiting a curved trajectory, we have used a helical jet model, in which the jet axis forms a helix on the surface of a fiducial cone [8]. Figure 2 illustrates the model parameters: θ_0, ξ, φ, p, ρ, and β. We consider a limited jet part, within which the curvature of a local jet axis is insignificant.

We considered two different types of magnetic field configuration in the helical jet. The first one is of a helical magnetic field characterized by the angle ψ' between the field and the local jet axis. For the calculations we used $\psi' = 0°$, $10°$, $25°$, $45°$, $55°$, $65°$, $75°$, and $90°$. The second configuration is of a poloidal magnetic field in the sheath, which surrounds the central jet spine containing a toroidal field. The transition from the toroidal to the poloidal field occurs at a distance R_j from the jet axis. We took $R_j = 0.25$, 0.33, 0.5, 0.7, and 0.9 of the jet radius at a given cross-section, which we have assumed to be equal $R_j = 1$. We emphasize that all considered magnetic field configurations are strictly ordered. For all parameter sets we used $\xi = 1°$ and $\beta = 0.995$ (the corresponding Lorentz factor is about 10) and constructed the transverse distribution of polarization properties for φ from $1°$ to $351°$ with increments of $10°$. Due to changes in φ, the Doppler factor varies in some range. For different sets of parameters of θ_0 and p, the range is distinct. We divided points of the obtained transverse distributions into three groups according to the corresponding Doppler factor, under which they were obtained. Blue, green, and red points indicate low, medium,

[1]http://www.physics.purdue.edu/astro/MOJAVE/index.html

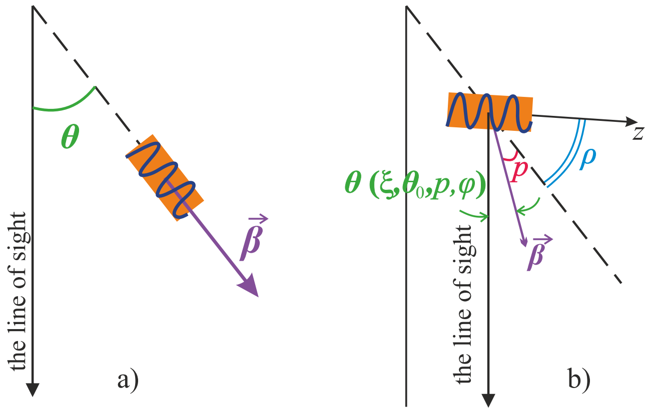

Figure 1: a) Common jet model geometry. The velocity vector of the straight jet coincides with the jet axis: the viewing angle θ is constant. b) The jet geometry used in this work. The figure shows one segment of the helical jet, the axis of which is z. The dashed line shows the radial direction. The line of sight, axis, and velocity vector of the segment do not lie in the same plane. In both figures, the spiral schematically shows the spatial orientation of the magnetic field in the jet element.

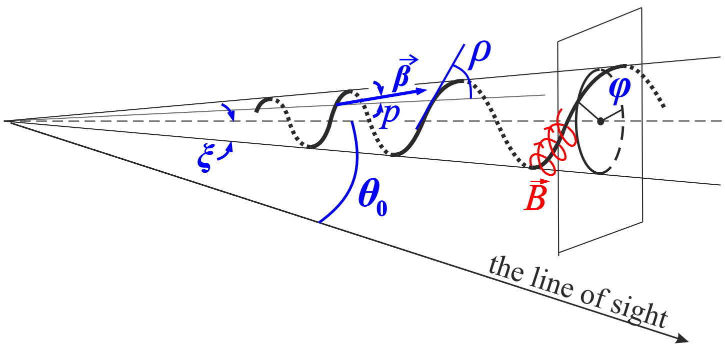

Figure 2: Scheme of the helical jet. ξ is the half opening angle of the jet, θ_0 is the angle between the cone axis and the line of sight, p is the motion direction angle to the cone generatrix, β is the jet segment speed, ρ is the angle of a tangent to the jet segment axis to the cone generating line, φ is the azimuth angle characterizing a segment location on the cone surface relative to the observer. The red curve schematically represents the helical magnetic field in the jet.

and high Doppler factors for a given parameter set. Each theoretical distribution shown in Fig. 3 and 4 indicates these ranges of Doppler-factor subdivisions.

3. Comparison with observations

For comparison with the observational data, we selected the quasars 0836+710 ($z = 2.218$) and 1611+343 ($z = 1.4$) (see Fig. 3 and 4, respectively), which both exhibit rich polarization structure on parsec-scales and show no gradient in the Faraday rotation measure transverse to the jet axis [4]. As φ value is unknown for a given jet feature at a given epoch, we use the stacked linear polarization data having components with different φ to make a proper comparison with the simulations. Stacking allows us to cover all features at all trajectories over time and delineate

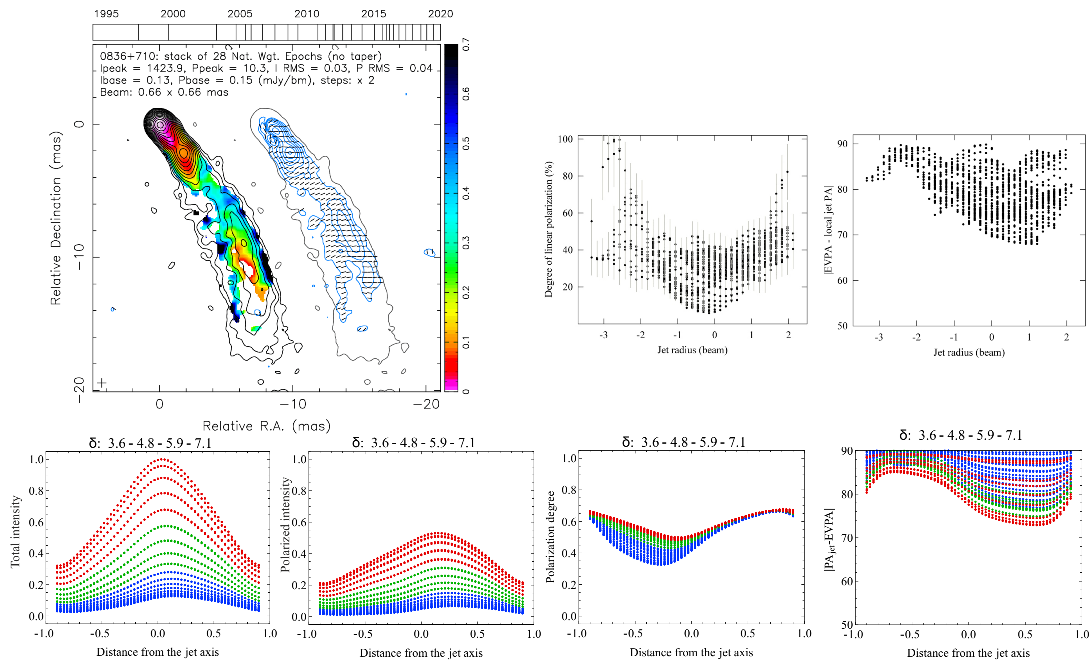

Figure 3: *Upper panel*: VLBI polarization observations of 0836+710 (left). Color scale represents a degree of linear polarization. The polarized intensity is plotted with blue contours, shifted from the total intensity black contours. The sticks indicate the electric wave vectors. The observed transverse distributions of the polarization degree and EVPA were obtained from 4 to 10 mas from the core (right). *Bottom panel*: The theoretical transverse distributions of normalized total and polarized intensity, the fractional polarization, and the deviation of electric vector position angles from the local jet direction. The parameters are $\psi' = 25°$, $p = 2°$, $\rho = 4°$, $\theta_0 = 10°$, $\beta = 0.995$. Red, green, and blue colors are associated with Doppler factors, which values lie within intervals of 5.9–7.1, 4.8–5.9, and 3.6–4.8, respectively.

the stable component of the magnetic field associated with a jet. There is an excellent qualitative correspondence between the simulated and observed data.

4. Conclusions

The results of our simulation analysis are as follows:

1) The spread of the electric vector position angle values from 0° or 90° is due to the non-radial motion of the jet segments.

2) The case of a pure helical magnetic field or a “spine-sheath” configuration can simultaneously explain the transverse profiles of polarized intensity, fractional polarization, and EVPA orientation without introducing turbulent disordering of the jet’s plasma.

3) Different shapes of transverse cuts of the observed polarization properties can be explained by different parameter sets of the helical jet model and various magnetic field configurations.

4) Comparison with observations allows to derive basic jet characteristics (namely, magnetic field configuration, azimuthal component of the jet velocity, twist angle of the jet flow, jet viewing angle), distributed in a narrow range of plausible parameter space.

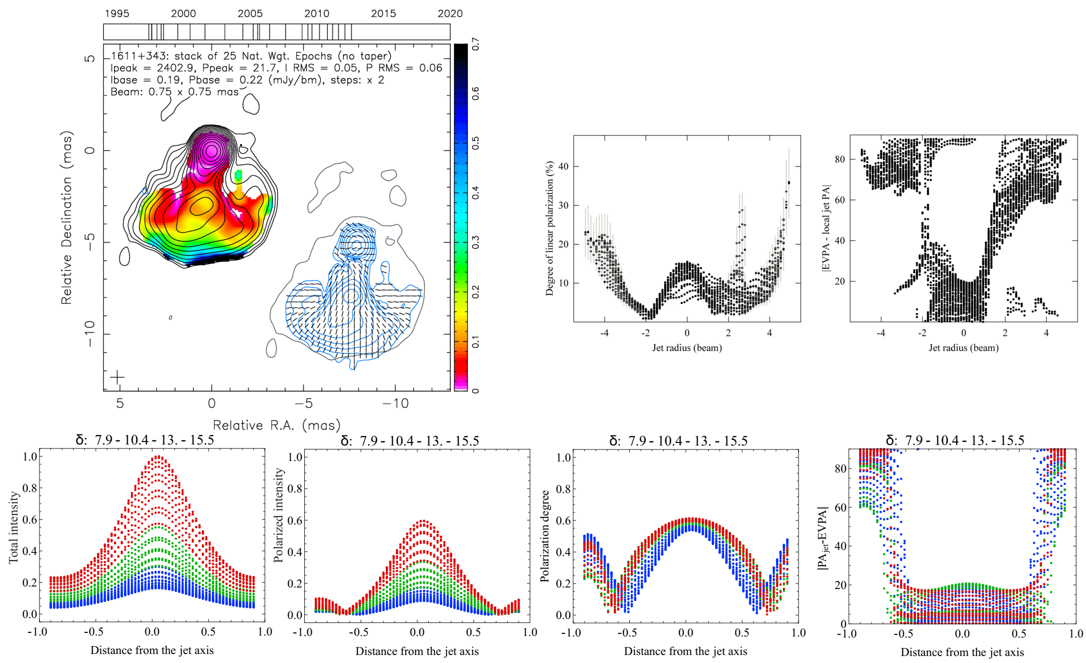

Figure 4: *Upper panel*: VLBI data for 1611+343 (left). Color scale represents a degree of linear polarization. The polarized intensity is plotted by blue contours, shifted from the total intensity black contours. The sticks indicate the electric wave vectors. The observed transverse distributions of the polarization degree and EVPA obtained from 2 to 4 mas from the core (right). *Bottom panel*: The theoretical transverse distributions of total and polarized intensity, the fractional polarization, and the deviation of electric vector position angles from the local jet direction. The parameters are $R_j = 0.9$, $p = 5°$, $\rho = 25°$, $\theta_0 = 2°$, $\beta = 0.995$. Red, green, and blue colors are associated with Doppler factors, which values lie within intervals of 13−15.5, 10.4−13, and 7.9−10.4, respectively.

Acknowledgments

This research was partly supported by the Russian Science Foundation grant 21-12-00241.

References

[1] M.L. Lister and D.C. Homan, *MOJAVE: Monitoring of Jets in Active Galactic Nuclei with VLBA Experiments. I. First-Epoch 15 GHz Linear Polarization Images*, Astron.J. **130** (2005) 1389.

[2] A. Pushkarev, Y. Kovalev, M. Lister, T. Savolainen, M. Aller, H. Aller et al., *Linear Polarization Properties of Parsec-Scale AGN Jets*, Galaxies **5** (2017) 93.

[3] M.L. Lister, M.F. Aller, H.D. Aller, M.A. Hodge, D.C. Homan, Y.Y. Kovalev et al., *MOJAVE. XV. VLBA 15 GHz Total Intensity and Polarization Maps of 437 Parsec-scale AGN Jets from 1996 to 2017*, Astrophys.J.S. **234** (2018) 12.

[4] T. Hovatta, M.L. Lister, M.F. Aller, H.D. Aller, D.C. Homan, Y.Y. Kovalev et al., *MOJAVE: Monitoring of Jets in Active Galactic Nuclei with VLBA Experiments. VIII. Faraday Rotation in Parsec-scale AGN Jets*, *Astron.J.* **144** (2012) 105.

[5] M.L. Lister, M.F. Aller, H.D. Aller, D.C. Homan, K.I. Kellermann, Y.Y. Kovalev et al., *MOJAVE. X. Parsec-scale Jet Orientation Variations and Superluminal Motion in Active Galactic Nuclei*, *Astron.J.* **146** (2013) 120.

[6] D.C. Homan, M.L. Lister, Y.Y. Kovalev, A.B. Pushkarev, T. Savolainen, K.I. Kellermann et al., *MOJAVE. XII. Acceleration and Collimation of Blazar Jets on Parsec Scales*, *Astrophys.J.* **798** (2015) 134.

[7] M. Lyutikov, V.I. Pariev and D.C. Gabuzda, *Polarization and structure of relativistic parsec-scale AGN jets*, *MNRAS* **360** (2005) 869.

[8] M.S. Butuzova, *Geometrical and Kinematic Parameters of the Jet of the Blazar S5 0716+71 in a Helical-Jet Model*, *Astronomy Reports* **62** (2018) 116.