OJ 287: optical – VLBI connection under a single supermassive black hole

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Purpose. OJ 287 exhibits 12-year optical flares, originated due to helical jet. We determine geometrical and kinematic parameters of the helical jet, which allow describing optical and VLBI properties simultaneously.

Helical jet model. We assume that the helical jet axis lies on the surface of a notional cone (Fig. 1). The coincidence of the supermassive black hole location and the cone apex is not necessary. To describe the jet kinematics, we divided the jet into components in such a way that the jet axis is a straight line within each one. Note that we do not associate the jet components directly with the observed VLBI jet features, as their physical nature may be different, but these features reflect the position of the jet flow on the sky plane.

Note, the optical emission region locates at a fixed distance from the cone apex, and it is closer to the true jet origin than the observed VLBI jet core.

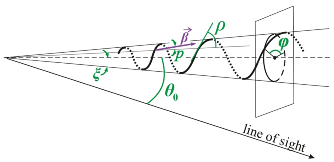

Fig. 1. Scheme of the helical jet:
ξ is the half opening angle of the jet,
***θ*₀** is the angle between the cone axis and the line of sight,
p is the motion direction angle to the cone generatrix,
β is the jet component speed,
ρ is the angle of a tangent to the jet component axis to the cone generatrix,
φ is the azimuth angle characterizing a component location on the cone surface relatively to the observer.

VLBI data. We made use of a set of 145 epochs of VLBA observations of OJ 287 carried out at 15 GHz since 1994 through 2019 (MOJAVE program and archival experiments). We calculated the innermost jet position angle (PA_{in}) in three ways (Fig. 2):

1) as the position of the ridgeline point closest to the 15 GHz core feature;
2) and 3) as the position of the major axis of an elliptical Gaussian component fitted the core together with one or two circular Gaussian components for other jet, respectively.

Using equation (see [1])

$$PA_{in}(\varphi) \approx -\arctan\left(\frac{\sin\varphi}{\theta_0/\xi+\cos\varphi}\right)+PA_0,$$

where PA_0 is the PA of the cone axis, we fitted obtained data, accounting that $\varphi=2\pi t/T+\varphi_0$, where φ_0 is the initial phase, T is the period of PA_{in} change. Obtained parameters are listed in Table 1.
We estimated β from the maximum apparent speed of the jet features [2].

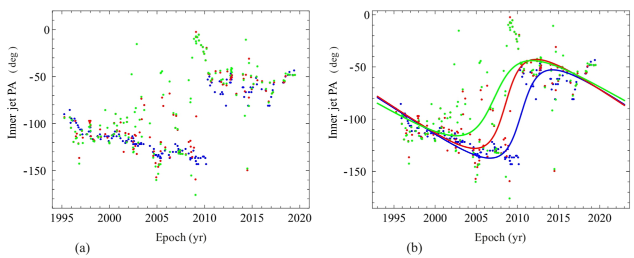

Fig. 2. Evolution of PA_{in} of the innermost OJ 287 jet direction (a) and its approximation under the helical jet model (b).

Table 1. Obtained helical jet parameters.

Parameters	ξ	θ_0	T_{PA}	β	p	ρ
Value	1°	1.5°	28.3 yrs	0.9979	2.5°	10°

Optical-VLBI connection. The flux variability period produced by a change in Doppler factor δ depends on a rate of a change in φ of components crossing through the emission region (Fig. 1). In their outward motion, the components of the helical jet pass consecutively first through the optical emission region. After passing through this region, the magnetic field strength, electron density, and possibly energy spectrum of emitting particles become such that it is impossible to generate a significant flux density of synchrotron optical radiation. Moving further down the jet, the physical parameters in the components change, and at a certain fixed distance from the true jet base, the component becomes less opacity for 15 GHz radiation, forming the 15 GHz VLBI core, and the component becomes optically thin for the 15 GHz radiation further downstream.

As shown in [3], the variability periods of values, originated at a different distance from the true jet origin, can be different if $p\neq0°$. The period of δ change, which is expressed as

$$T=\frac{2\pi r\sin\xi\cos\rho}{\beta c\sin(\rho-p)},$$

Where r is a distance from the cone apex to a cross-sectional plane passing through the region, in which the observed radiation at a given frequency is generated. Using this equation we found ρ for p obtained from assumptions:

1) $\delta(p,\varphi)$ reaches a high value at the maximum;
2) the ratio of maximum and minimum values of δ is close to the maximum of possible ones.

Obtained p and ρ are in Table 1.

Using the formulation in [4], described the Kelvin-Helmholtz instability in a jet, we found that it is possible to form the helix obtained by our parameters. From Fig. 3 it is seen that Mach number in the jet flow (M_{in}) and the ratio of the jet and surrounding medium densities (η) have possible values.

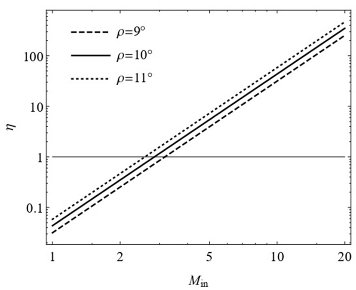

Fig. 3. Dependence of η on M_{in} for parameter of OJ 287 jet. The horizontal line marks $\eta = 1$.

Helical jet precession. Under the helical jet, δ reaches a fixed maximum value for a fixed φ. Therefore, the difference of peak fluxes for 12-year flares can reflect a precession of the helical jet (Fig. 4).

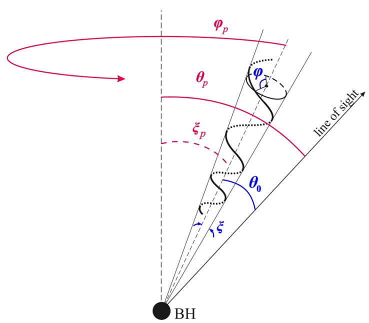

Fig. 4. A sketch of the helical jet precession: the blue color marks geometrical parameters of the helical jet, the red color marks geometrical parameters of the precession of the helix axis.

For each flare, we found the values of θ_0 from the ratio of maximum and minimum fluxes and fitted ones under the assumption about the periodic change of θ_0 (Fig. 5). We obtained θ_p=1.8°, ξ_p=0.7°, and the precession period is 92±8 years in the observer's reference frame, which corresponds to the period of ≈1200 years in the source reference frame.

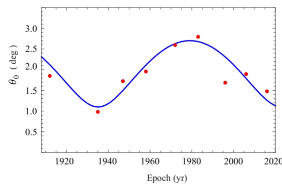

Fig. 5. Changes of the angle between the jet helix axis with the line of sight due to the precession of the OJ 287 jet.

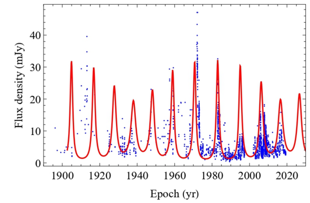

Fig. 6. Observed data points (blue circles) and simulated light curve under the helical jet precession (red line) in V band.

The precession period of 1200 years can originate from the precession of a single supermassive black hole. Figure 7 illustrates values of the black hole's specific angular momentum a and the viscosity parameter a_{vis} for different accretion rates in Eddington units for the case of inner disc precession [5].

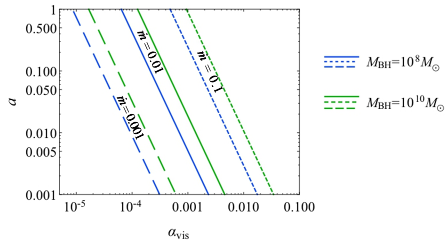

Fig. 7. Relations of parameters a and a_{vis} for various M_{BH} and accretion rate.

If there is the precession of the outer part of the accretion disc [6], then for a=0.1-1 this region locates at distance (30-300)r_g from a black hole with $M_{BH}=(10^8\text{-}10^{10})M_{sun}$.

Conclusions

1) Optical and VLBI data correspond to a helical jet with the non-radial motion of its components.
2) Such jet can form by hydrodynamic instabilities.
3) True jet precession appears in the difference of peak flux values of 12-year flares and can originate in a system of a single supermassive black hole with its accretion disc.

More detail of this investigation see in
Butuzova & Pushkarev, Universe, 6, 11, 2020
arXiv: 2103.13845.

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