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OJ287 taken to pieces: the origin of a precessing and rotating jet

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Abstract. OJ287 is the best candidate active galactic nucleus for hosting a supermassive binary black hole at very close separation, corresponding to the orbital period of the order of $\sim$9 yr. We studied the pc-scale jet dynamics in 118 Very Long Baseline Array (VLBA) observations at 15 GHz covering the time between Apr. 1995 and Jan. 2017. To our knowledge, this is the first time, that the kinematics of the Blandford-Znajek jet (originating in the ergosphere of a rotating black hole) and jet sheath (originating from the accretion disk) are seen and traced in observations. We also find that the OJ287 radio jet is rotating and precessing. The jet dynamics as well as the flux-density light curves can be understood in terms of geometrical effects. A binary black hole model can explain the time scale of the precessing motion. Lense-Thirring precession of an accretion disc surrounding a single black hole is consistent with the time scale as well.

1. Introduction

Despite many high-resolution radio interferometric studies of the jets of active supermassive black holes in active galactic nuclei (AGN), still many questions remain to be answered. We do not know yet, whether the central black hole in an AGN is single or binary. We would like to know whether the jets are launched from the ergosphere of the black hole at the expense of its angular momentum (Blandford & Znajek 1977) or at the expense of orbital motion of the gas in the magnetised accretion disk (Blandford & Payne 1982), or a combination of both scenarios.

Many questions relate to the kinematics of the brightness enhancements which are typically seen in these jets on pc-scales and which separate with apparent superluminal speeds away from the central core. Some jets however, do solely, or in addition, show brightness enhancements which remain at similar core separations and only move with apparent subluminal speeds along the jet. The physical nature of those stationary components is still debated, e.g. as recollimation shocks (Daly & Marscher 1988).

OJ287 (z=0.306 (Stickel et al. 1989), a low-synchrotron peaked (LSP) BL Lac Object) is a prototypical AGN which allows us to answer some of these questions. In the following, we present an extract of our results which are described and discussed in full detail in Britzen et al. (2017).

1.1. OJ287 in a very brief summary

OJ287 has been claimed to be the most promising AGN for hosting a supermassive binary black hole at the center. The basis for this claim is a light-curve observed in the optical V band which since 1890 shows repeated outbursts at $\sim$11.65 yr intervals (Sillanpää et al. 1988). Since the light curve during an outburst resembles the pattern of inflow of gas from an accretion disk to a supermassive black hole in a tidal perturbation, Sillanpää et al. (1988) proposed that OJ287 is a binary pair of supermassive black holes with an orbital period of 9 yr in the rest frame of OJ287. They also claimed that the light variations are related to tidally induced mass flows from accretion disks into black holes. Lehto & Valtonen (1996) explained well-defined sharp flares in the light-curve with a model in which a smaller black hole crosses the accretion disk of a larger black hole during the binary orbit of the black holes about each other. Further work by e.g., Lehto & Valtonen (1996), Valtonen & Wiik (2012b), Valtonen et al. (2016) have explored the binary BH nature of this AGN.

While the model by Valtonen et al. (2016) nicely explains the optical data, many still open questions remain. It has proved difficult to relate the flaring variability observed in the optical wavelength regime for OJ287 with the flaring variability observed in the radio on the one hand, and the morphological changes of the pc-radio radio jet on the other hand. In particular, an important question relates to the nature of the radio jet emission and the jet direction - does this really change erratically as the results by Agudo et al. (2012) suggest? Is the origin (or launching of the jet) affected by the plunging scenario (Valtonen et al. 2016)? Can the radio jet direction and its changes tell us more about the origin of the jet? We here summarize our results concerning the physical processes driving the OJ287-jet.

Throughout the paper we adopt the following parameters: a luminosity distance D_L=1.592 Gpc, at the source redshift of z=0.306, with cosmological parameters corresponding to a ΛCDM of the Universe with Ω_m=0.3, Ω=0.7, and H_0=70 km s^{-1} Mpc^{-1}. A proper motion of 1mas yr^{-1} corresponds to an apparent superluminal speed of 14.7c. 1 mas = 4.521 pc.

2. The Observations

OJ287 was studied as part of the MOJAVE[1] (Monitoring Of jets in Active galactic nuclei with VLBA Experiments) survey (e.g., Hovatta et al. 2014, Lister et al. 2009, Lister et al. 2013). The presented study is based on a re-modeling and re-analysis of 118 VLBA data sets obtained at 15 GHz within the MOJAVE program (for details see Britzen et al. 2017). The data cover a time range between Apr 1995 and Jan 2017. In addition, we studied single-dish radio flux-density data at three frequencies (4.8, 8.0, 14.5 GHz) obtained within the University of Michigan (UMRAO) monitoring program. To analyze the optical data, we combined historical light-curve information with data taken by the Abastumani Observatory.

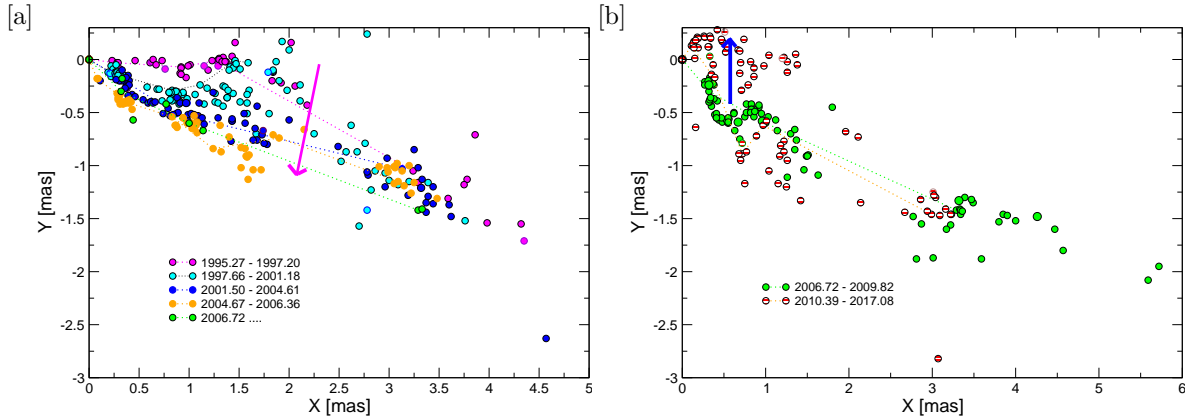[1] www.physics.purdue.edu/astro/MOJAVE/

Figure 1. Jet precession. We plot all the (X, Y) data points of the 118 re-analyzed epochs. The origin (0, 0) is the VLBI core. The counter-jet components have been deliberately taken out. The sequence of the combined effect of rotation and precession starts in time in (a) with the earliest data (magenta). We indicate the motion and evolution in time with different colors. A significant shift in the plane of the sky is indicated with dotted lines. (b) is a continuation of (a). The last epoch in (a) displayed with green circles is the first phase in the plot on the right. From green the data continue with a "jump" to the red-striped circles in (b). In both plots, an arrow indicates the main direction of the projected jet precession motion. In (a) the dominant motion is downward. In (b) the dominant motion is upward.

3. The dynamics of the jet of OJ287

3.1. Precession

We applied (circular) Gaussian components to the data to parametrize the jet emission along the jet. The "ridge line" connects all jet features modeled per epoch. We traced the evolution of these ridge lines in time. The ridge line evolution is shown Fig. 1 (a) and (b). To better indicate how the jet moves in the plane of the sky, we mark the dates by different colors. Fig. 1 (a) shows the earlier data (from 1995.27–2006.72) and (b) the ridge line evolution in later epochs (from 2006.72 –2017.08). The earlier data show how the jet in the plane of the sky moves downward (arrow in magenta indicates the direction of the motion). The later data show an upward trend (indicated by a blue arrow) which starts after epoch 2009.82. The data shown by the stripped circles (red-white) indicate the flip. We assume that the jet motion changed direction and allows a more direct view into the jet (smaller angle to the line of sight). The dominant effect visible in the data is that of a wandering jet in the sky. This is most likely the result of a *precessing* jet. The precessional motion of the jet can also be seen in Fig. 2 (b).

3.2. Apparent superluminal and subluminal jet components

AGN jets reveal brightness enhancements along the jet. Tracing their motion through the epochs of observations allows us to study the dynamics of the jet. We find two types of motion of jet features in OJ287: components moving away from the core with apparent superluminal speeds (the standard *superluminal features* observed in quasar jets) and apparently subluminally moving components (in the direction along the jet) that remain at similar core separations - but - move perpendicular to the jet axis. These latter *"stationary"* components trace the rotation (and precession) of the jet. We show both types of components and their kinematic properties in Fig. 2 (a) and (b). Jet components denoted with **C** + number are those features moving with apparent superluminal speeds away from the core. Components denoted with **pattern** represent
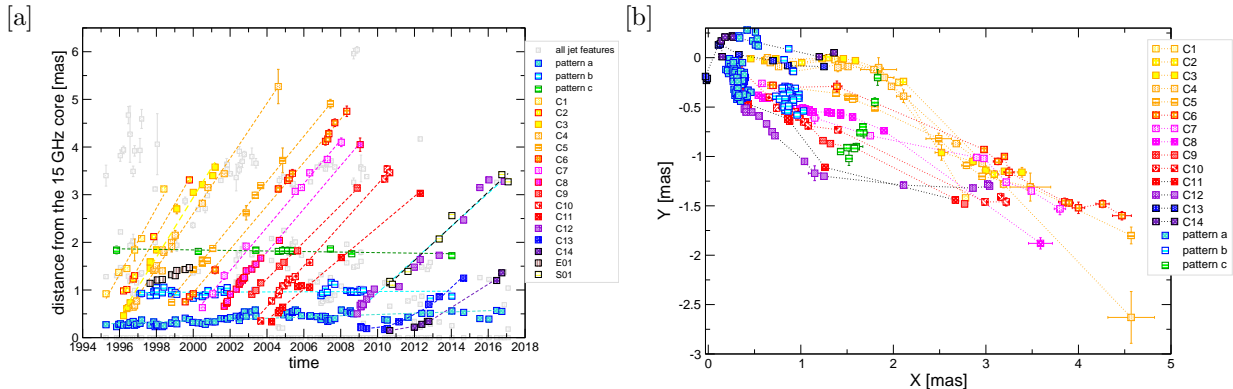
Figure 2. The distance between the 15 GHz core and the jet components plotted as function of time (a). Individual jet components are shown in different colors. For components up to **C12** the linear regression line is superimposed. For components **C13** and **C14** a quadratic fit has been applied (see text for details). (b) shows the components in xy-coordinates. Both figures have been prepared with the counter-jet components deliberately left out.

the stationary features moving with apparent subluminal speeds along the jet. From **C1** to **C11** the apparent speeds of the components are decreasing - almost continuously. Consequently, the viewing angle (assuming Doppler beaming) is increasing between 5.5 and 12.0 deg for the earliest appearing jet feature **C1** to **C11**. This can be interpreted as motion of the emitting source away from the line of sight. Apparent superluminal motion of 4-10c is a common phenomenon in AGN. However, the physical nature of these components is still a matter of debate. We argue that the fast moving components in OJ287 represent the jet originating via the Blandford-Znajek-mechanism. The stationary features observed in the OJ287 jet trace the jet rotation as can be seen in Fig. 4. We propose that they represent the sheath of the jet originating from the accretion disk via the Blandford-Payne mechanism.

3.3. Jet rotation

Evidence for a rotating jet is shown in Fig. 3. Consecutive jet component-paths (those with apparent superluminal motion) appear at systematically different places in the xy-plane. Tracing this movement of these four jet component-paths in Fig. 3 gives the signature of a rotation.
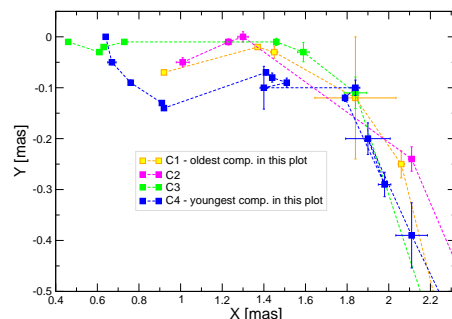

Figure 3. The paths of four consecutive moving jet components are shown, starting with **C1**. **C2** moves on a path displaced upward compared to **C1**, **C3** on a path upward of **C2**. The path of **C4** is clearly below those of the other three jet components. The displacement of the paths indicates rotation.

3.4. Rotation of the stationary jet features

We find that those components that appear to move with apparent subluminal motion in the direction of the jet show significant motion perpendicular to the jet axis. In Fig. 4 we show,

that this motion is compatible with a rotation (perpendicular to the jet axis). This motion is consistent with the motion expected for the sheath of the jet originating in the accretion disk.
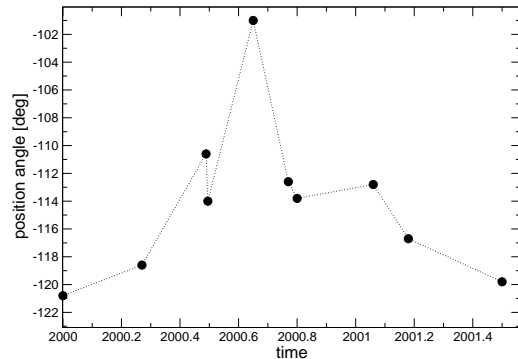

Figure 4. Jet component rotation. The stationary feature **a** reveals evidence for a rotation: the position angle increases up to a maximum value and then decreases again. This motion occurs on a time scale of roughly one year.

3.5. OJ287 jet appears as a helix
Collecting the data of one phase of the precession reveals a pattern resembling a *helix*. This is shown in Fig. 1 (b) with the circles filled in green. The signature of the helix results from an interplay of several directions of motions, in particular the components moving away from the core (with apparent superluminal speeds) and those components moving with apparent subluminal speeds in the direction along the jet but revealing significant motion perpendicular to the jet axis.

3.6. Time-scales of VLBI kinematics match light-curve variability periodicities
The short timescale of the rotation of the most prominent stationary component **a** coincides with the time-separation of the outbursts visually apparent in the radio light-curve (at 15 GHz) of about one year. The longer timescale (roughly 11-15 years) of half of the jet precession scale compares well with a period of enhanced activity in the single-dish radio flux-density monitoring data (UMRAO). This timescale compares quite nicely with the dominant periodicity quoted for the optical light-curve. It seems likely that the orbital motion of the rotating jet can - via Doppler beaming - explain the observed time-scales in the radio light-curve and in the optical light-curve. This is discussed in more detail in Britzen et al. (2017).

4. Conclusions
Our results for the OJ287 allow us to resolve some of the still outstanding questions related to the origin and dynamics of its jet and the physical nature of the radio variability of OJ287. We also offer an alternative explanation for the origin of the historical optical variability. In Britzen et al. (2017) we propose that the stationary components represent the sheath of the jet while the superluminal components represent the long sought-after Blandford-Znajek jet. To our knowledge, this is the first time both can be discriminated and investigated with regard to their kinematics. The physical origin of the radio variability of AGN has often been attributed to the accretion phenomenon. Matter is being accreted and part of this matter is ejected into the jet and appears as a jet component - this is a short summary of the generally accepted paradigm. We here show that the radio variability in OJ287 originates in the geometry of the system - the rotating jet determines the timescale of the rapid radio variability. The longer time scale variability seems to originate in the precession of the jet. We thus explain the radio variability in OJ287 in terms of deterministic, geometric processes.
Based on observations and application of the well-known black hole mass relations, a value of $4 \times 10^8 M_\odot$ has been derived (Liu & Wu 2002). Refering to this estimate and the mass
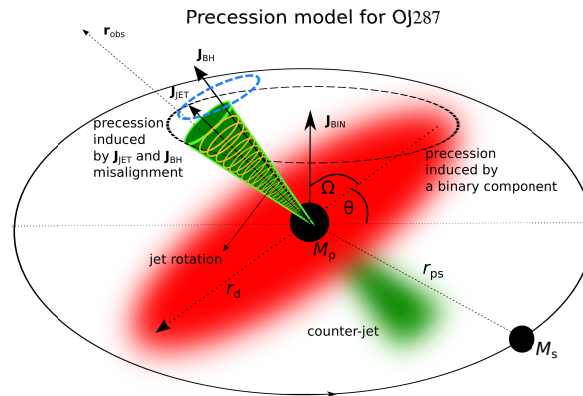
Figure 5. Sketch to illustrate two of the scenarios discussed in more detail in Britzen et al. 2017: 1. The Lense-Thirring precession due to the misalignment of angular momenta of the Kerr black hole and that of the accretion disc. 2. The disc-jet precession due to the torques induced by a secondary black hole.

determined within the Valtonen-model ($10^{10} M_\odot$), we discuss several possible scenarios in Britzen et al. (2017) to explain the observed jet precession (e.g., see Fig. 5). Both the Lense-Thirring precession and the precession due to a binary companion can explain the observed precession time scales. A binary black hole scenario - however - seems more likely. Our findings are consistent with a mass of $10^8 M_\odot$, which can correspond to the mass of a single black hole or the total mass of the binary. A massive black hole of $10^{10} M_\odot$ is not required to explain the observed phenomena and time scales. OJ287 is a prototypical object. It is thus possible and likely that our findings have implications for the jets of BL Lac objects or AGN in general. This can significantly change our understanding of jet component motion, jet launching, radio variability, and the accretion process. Detailed modeling of the jet kinematics is in preparation.

4.1. Acknowledgments

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