A helical jet model for OJ287

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ABSTRACT

\textbf{Context.} OJ287 is a quasar with a quasi-periodic optical light curve, with the periodicity observed for over 120 years. This has led to a binary black hole model as a common explanation of the quasar. The radio jet of OJ287 has been observed for a shorter time of about 30 years. It has a complicated structure that varies dramatically in a few years time scale.

\textbf{Aims.} Here we propose that this structure arises from a helical jet being observed from a small and varying viewing angle. The viewing angle variation is taken to be in tune with the binary orbital motion.

\textbf{Methods.} We calculate the effect of the secondary black hole on the inner edge of the accretion disk of the primary using particle simulations. We presume that the axis of the helix is perpendicular to the disk. We then follow the jet motion on its helical path and project the jet to the sky plane. This projection is compared with observations both at mm waves and cm waves.

\textbf{Results.} We find that this model reproduces the observations well if the changes in the axis of the conical helix propagate outwards with a relativistic speed of about 0.85c. In particular, this model explains at the same time the long-term optical brightness variations as varying Doppler beaming in a component close to the core, i.e. at parsec scale in real linear distance, while the mm and cm radio jet observations are explained as being due to jet wobble at much larger (100 parsec scale) distances from the core.

\textbf{Key words.} BL Lacertae objects: individual (OJ287) – quasars: individual (OJ287)

1. Introduction

Optical brightness measurements of the quasar OJ287 have shown cyclical behavior with two well-defined cycles: a 60 year cycle and a 12 year cycle (Valtonen et al. 2006). In 1995 a model was constructed with gave a good account of the 12 year cycle, occurring in two major bursts separated by 1–2 years (Lehto & Valtonen 1996; Sundelius et al. 1997). The model predicted the optical brightness level for every two-week interval from 1996 until 2030, and also explained the brightness of OJ287 at similar steps from 1900 up to 1996. Even though the number of historical data points has increased by an order of magnitude since 1995, the calculated two-week average points still give a fair explanation of the past behavior (Hudec et al. 2013). As to the future predictions, the two-week points have been correct from 1996 to 2010, with surprisingly small errors. Other suggested models, producing a quasi-periodic 12 yr cycle, can be excluded at 5 sigma significance level at present (Valtonen et al. 2011). When time goes on, and if OJ287 continues to produce the expected optical magnitudes at each two-week step, then this confidence level will go up.

A new challenge has arisen with the complex behavior of the resolved radio jet. There it is possible to identify the same 12 yr cycle in the position angle of the radio jet in the sky at the cm wave radio maps (Tateyama & Kingham 2004). Moreover, the 12 year cycle is clearly modulated by a longer time scale variation (Valtonen & Wiik 2012), even though it is too soon to claim that the 60 year cycle is also detected since the radio jet observations cover only about 30 years, in contrast to the 120 year optical light curve. A new twist in the story is the radio jet measurements at mm waves: they show variations of much larger amplitude (Agudo et al. 2012, Tateyama 2013). The first radio maps at these frequencies go back only less than twenty years, and thus it would not be useful to model these data alone. However, a combination of optical variability data together with the jet variations at these two frequency ranges provides enough challenging data to attempt a model.

Valtonen & Wiik (2012) looked at the variations of the rotation axis of the inner accretion disk in the well-defined binary model which gives detailed account of the optical variations (Valtonen et al. 2008). They found that indeed the disk shows a wobble in 12 year time scale that could be associated with the jet variations at cm wavelengths. They also found that a small timing delay of about 16 years is necessary between the disk wobble and the jet changes, in order to give the best account of the data. The model produces two cycles, a short one of about 11 year period, and a long cycle of about 120 years. The latter is understood as the Kozai cycle in the inner accretion disk, inside the pericenter of the binary orbit (Innanen et al. 1997). Subsequently, Valtonen et al. (2012b) investigated the possibility of including the mm wave observations in the same model. They found that the jet cannot be straight in order that the different orientation angles can arise at the same time.

This leads us to a jet model which has been found useful in S5 0836+710 and in other jet sources (Perucho et al. 2012, 2013): a helical jet. This is a way, even if not a unique way, of producing different viewing angles at different distances from the origin of the jet. When we add to this the disk wobble which...
arises from the model based exclusively on optical data, we get a new attempt to model the complex situation in OJ287.

2. The inner disk

Our basic model is a binary black hole system where a small companion black hole perturbs periodically the disk of the much larger primary black hole (Valtonen et al. 2010). The parameters are very tightly constrained by the optical data which leaves practically no free parameters in the model. The only exception is the orbital inclination of the secondary orbit relative to the disk which has been unknown until recently. Its determination requires the identification of the spectral lines of the secondary and the measurement of the relative radial velocity. From the recent detection of such a line (T. Pursimo, private communication) we determine the inclination to be close to 50 degrees. Previously the inclination of 90 degrees was used for simplicity; here we calculate both the 50 and 90 degree cases.

We place a ring of particles around the primary, and starting from year 1856, follow the evolution of each disk particle. The calculations are carried out as in Valtonen & Wiik (2012): In the present simulation the number of disc particles is 1500. They are placed in circular orbits between 1.7 and 14 Schwarzschild radii of the primary. For every particle, and for every time step, we calculate the orbital elements of the orbits with respect to the primary. The elements are averaged per calendar year. As there are many integration steps per year, typically each annual mean is based on the average of $10^3$ values. By varying the number of particles it was found that the mean values generated in this way are very robust. Figure 1 shows the time evolution of two of the elements, inclination $i$ and ascending node $\Omega$.

As in Valtonen et al. (2006), the variation of $\Omega$ is negligible in comparison with $i$ (Valtonen and Wiik 2012 had interchanged $i$ and $\Omega$ by mistake; this however had no consequences in that paper apart from wrong labels. Correcting this error, the results agree with the present work.). The evolution of the element $i$ may be well represented by a doubly periodic function

$$i - i_0 = -A_1 \sin \left(2\pi(t-t_1)/P_1\right) - A_2 \sin \left[2\pi(t-t_2)/P_2\right] - C. \quad (1)$$

The amplitudes $A_1$ and $A_2$ depend on the initial inclination $i_0$ as well as on the distance $r$ from the primary black hole. The values of the coefficients are shown in Fig. 2.

We are particularly interested in the inner edge of the disk which presumably connects to the jet which is launched perpendicular to the disk. Therefore we will use the values of $A_1$ and $A_2$ which are appropriate for the inner disk, with $r$ between 1.7 and 3.4 Schwarzschild radii. The smaller value corresponds to the last stable orbit in the accretion disk. We also consider the case of $i_0 = 50$ degrees only, with $A_1 = 3.5$. We notice from Fig. 2 that the amplitudes are somewhat greater for $i_0 = 90$ degrees than for $i_0 = 50$ degrees. The calculation below would lead to small changes in the jet parameters if we used $i_0 = 90$ degrees instead of $i_0 = 50$ degrees. The two periods $P_1 = 116.6$ yr and $P_2 = 11.0$ yr are insensitive to $i_0$.

One of the differences between a gaseous disk and the simulated particle disk is the need to transport information between particles in order to mimic gas behavior. We do this by simply averaging the results over a period longer than one year in order to allow time for dissipative processes. The one year averaging was arbitrarily chosen. Considering that the period rotation of the innermost disk is about 0.5 yr, and that the viscous time scale of the inner disk is about an order of magnitude greater than this, the appropriate averaging time scale is in the range of 5 to 10 years (Krolik et al. 2005). We use 10 yr averaging (as in Valtonen & Wiik 2012) which lowers the coefficient $A_2$ from 2.24 to 0.75. The values for $P_1 = 1903.9$ and $t_2 = 1893.5$ are insensitive to the inclination $i_0$ and to the averaging time scale while the value of $C = 3.13$ is of no importance to what follows.

3. The helix model

We assume that a helical jet emanates from the center of the accretion disk, perpendicular to the disk. This should be true independent of the direction of the spin of the primary black hole (Palenzuela et al. 2010, McKinney et al. 2013). The jet flow is assumed to follow a helical path, due to helical Kelvin-Helmholtz instability (Hardee 2000, 2011; Mignone et al. 2010; Mizuno et al. 2012). The parameters of the helix, the half-opening angle of the helix cone $\theta$ and the wavelength $\lambda$ of the helix are to be determined by fitting into the observational data. Also the viewing angle $\phi$ of the jet at a given time and at a given distance from the origin is a free parameter; however, the evolution of the viewing angle follows from the wobble of the disk.
and contains only one free parameter, the time delay $d$ between the changes in the disk and the corresponding changes at the emitting region (Valtonen et al. 2012b).

We will first consider the region of optical emission in the jet. After experimenting with different parameter values, we find that the overall brightness evolution is well modeled if $\theta = 4$ degrees, and the minimum viewing angle of the cone axis is $\phi_{\min} = 1.8$ degrees. As the first step to obtain these values, the best sinusoidal long-period fit to the optical magnitude data was determined. This fit is shown in Figure 3. Then the angular parameters of the helical model were varied at intervals of 0.1 degrees, and for each model a light curve was produced, and for each theoretical light curve a similar sinusoidal fit was performed. The best match with the observations was obtained with the above mentioned values. Their uncertainty may be estimated as $\pm 0.1$ degrees.

The time delay $d = 1.4$ yr. It could also be $58.3 \pm 1.4$ yr, i.e. with a shift of one half of the cycle period. However, the distance of the optically emitting region is more likely to be around $1.4 \times \Gamma$ lyr than $60 \times \Gamma$ lyr from the center (Agudo et al. 2012, Kushwaha et al. 2013). Moreover, the rather abrupt jump of the optical polarization by $\sim 90$ degrees around 1995 occurs only in the model with the shorter time delay (Fig. 4). The theoretical values in Figure 4 were calculated assuming that the electric vector of the radiating electrons is always perpendicular to the jet and the assumed prevailing parallel magnetic field. The jump in calculated values is noticeably larger than observed. However, as discussed in Valtonen & Wiik (2012), there is a possibility that the electric vector is not strictly perpendicular to the jet direction, but at a small angle to it. This is expected as the optical emission is likely to originate from a compression in the jet, which in turn strenghtens the perpendicular component of the magnetic field, and causes the magnetic field direction to bend at the compression. In the case of OJ287, the magnetic field along the jet has been observed to be vary all the way from parallel to perpendicular (Gabuzda & Gómez 2001). If we do assume an angle offset of about 15 degrees, the calculated values match the observations.

In this model the magnetic field of the optical emission region lies more or less parallel to the jet, as was concluded also in previous work (Valtonen & Wiik 2012). The required Lorentz factor $\Gamma = 14$, in agreement with other determinations (Jorstad et al. 2005, $\Gamma = 16.5 \pm 4$; Hovatta et al. 2009, $\Gamma = 15.4$; Savolainen et al. 2010, $\Gamma = 9.3$; Agudo et al. 2012, $\Gamma = 14 \pm 5$). Also the viewing angles reported from observations fall within the range of the model (Jorstad et al. 2005, $\phi = 3.2 \pm 0.9$ degrees; Hovatta et al. 2009, $\phi \sim 3.3$ degrees; Savolainen et al. 2010, $\phi \sim 1.9$ degrees; Agudo et al. 2012, $\phi = 2 \pm 1.3$ degrees). The spectral index is $-0.8$, which takes into consideration of the internal extinction in OJ287 host galaxy (Valtonen et al. 2012b).

Since the properties of the helix cone are now fully determined by the optical data, we may apply the model to radio data. Figure 5 plots the rotation of jet direction in the sky.

The x-axis represents $\phi$ while the y-axis represents $i$. The position angle of the jet is calculated as $\arctan(y/x)$. These position angles are plotted in Fig. 6 to show the fit to the mm wave data points (Agudo et al. 2012a).

The time delay is 50 yr with respect to optical. It could also be 50 $\pm$ 11.6 yr, but we choose the smallest possible value. For the cm wave data (Valtonen & Wiik 2012), the fit is shown in Fig. 7.
The two curves in the figure present a 3 yr difference in the timing. Since the resolution of the observations has improved during the 30 year period, it is expected that the early part and the latter part of the observations would fit a slightly different model. Overall, the time delay with respect to optical data is ~ 218 yr. This is a much greater value than was considered by Valtonen & Wiik (2012). The value could be even greater, 218 + 116.6 yr, but we choose again the smallest possible delay.

In Figure 5, the jet direction is taken at the point in the helix which corresponds to x = 0.5. This scale is subsequently associated with the mm wave jet. It then leads to a definite physical scale (see the discussion below). In Figure 5, we trace a point in the jet in the sky plane as a function of time. Ten different (closely spaced) values of time delay are used. No forward motion of this point is included, but if you imagine such a motion towards the right in the figure, then one may guess that the outward moving structure would look like multiple streams. In Figure 5, the outward motion is included, and the positions projected in the sky are averaged in the form of a contour map of the density of points.

This is also the observed pattern at high resolution (Tateyama 2013).

The only unsolved helix parameter remaining is the helix wavelength. The cm and mm emitting regions are 218 - 50 yr = 168 yr apart in the model, which is 168/116.6 ≈ 1.4 cycles. We later use this value to find the wavelength, after the positions of the mm and cm regions are estimated in the following.

4. Jet properties

Using the typical viewing angle φ = 2 degrees, the deprojection factor is ~ 30. The projected linear scale of the jet in the sky is ~ 4.6 parsec per milliarcsec. The mm wave jet is observed with resolution which is ~ 0.2 milliarcsec, while the cm wave jet has the resolution of ~ 1 milliarcsec. Thus the apparent speed at which the changes at the foot of the jet proceed outwards is ~ 28 pc/50 yr = 1.7c. The value calculated for the cm wave jet, ~ 130 pc/218 yr = 2c is similar. Thus the kink also moves relativistically.

We may estimate the kink speed as follows. The time it takes the VLBI knots to move through the mm wave jet is ∆t_knot ~ 1 yr. This may be compared with the kink travel time ∆t_kink ~ 50 yr for the same distance. These quantities are functions of the relative velocities β_knot and β_kink, respectively, and of the viewing angle φ. The two time intervals are related by

\[ \frac{\Delta t_{\text{kink}}}{\Delta t_{\text{knot}}} = \frac{\beta_{\text{knot}}(1 - \beta_{\text{kink}} \cos \phi)}{\beta_{\text{kink}}(1 - \beta_{\text{knot}} \cos \phi)}. \]  

Putting φ = 2 degrees, β_knot = 0.9974 (corresponding to Γ = 14), and

\[ \frac{\Delta t_{\text{kink}}}{\Delta t_{\text{knot}}} \sim 50, \]  

we get

\[ \beta_{\text{kink}} = 0.85 \]  

corresponding to Γ ~ 3.5. Thus the true time delay is ~ 175 yr between optical and mm waves. The corresponding true delay between mm and cm waves is ~ 630 yr. Since the two emitting regions are 1.4 cycles apart in the model, the true wavelength of the helical wave is about 70 pc. Considering the projection factors, this corresponds to about 0.5 milliarcsec separation in the sky. Sinusoidal features with this wavelength may be recognized in the maps of Tateyama (2013).
5. Discussion

Peruco et al. (2012) discuss fitting a helical jet model to S5 0836+710 which has wiggly jet. Even though in their case the source of the wiggles is not known, they discuss parameters that could lead to the observed pattern. These parameters are not very different from the parameters that we found for OJ287. The big advantage in the case of OJ287 is the well specified origin of the jet wobble which is completely determined by the optical variability data. In this paper we use the optical data to determine the basic properties of the helical jet, its opening angle as well as the direction at a given time. Then there is only the wavelength of the helix and the flow speed to be determined. These are found by fitting the model to the mm wave and the cm wave jet orientation data.

Note that in this model there are two flow speeds, the jet flow with \( \Gamma = 3 \), and a slower flow with \( \Gamma \sim 3.5 \) that carries the information about the jet wobble from the base of the jet outward. This requires a spine–sheath structure for the jet (Hardee et al. 2007; Hardee et al. 2007), with the sheath bulk flow moving with \( \Gamma \sim 3.5 \). However, we cannot rule out the possibility that the information of the jet wobble is carried by e.g. an oscillating disturbance in the sheath. In this case the wave motion may propagate with \( \Gamma \sim 3.5 \) with actual bulk flow of the sheath being much slower. The latter picture is qualitatively supported by considering 3D-animations of the entire jet given by the model. These demonstrate the visibly oscillatory character of the resulting 3D-jet. The fast jet is narrow; its value is not specified in the model, but observationally its half opening angle should be \( \theta_{\text{fast}} = 0.8 \pm 0.4 \) degrees (Jorstad et al. 2005). The slow jet is wide, with the half-opening angle of \( \theta_{\text{slow}} = 4 \) degrees. These opening angles follow the mean relation between \( \theta \) and \( \Gamma \) found by Pushkarev et al. (2009).

It is interesting that this simple model explains the apparently complex dual jet seen in observations by Tateyama (2013).

6. Summary

The complex behavior of the radio jet has been shown to result from a model with three main assumptions. (1) OJ287 is a binary black hole system whose orbit is described by the celestial mechanical solution of parameters. This solution is complemented by the missing parameter, the inclination of the binary with respect to the disk of the primary, determined from recent spectroscopy. (2) The jet propagates along the rotation axis of the inner disk. (3) The jet has spine–sheath structure, and the spine follows a helical path.

The model allows us to determine the jet parameters. There is prior information on some, but not all of the parameters. Thus the model increases our knowledge of the jet in this case. The value for the spine \( \Gamma = 14 \) agrees with previous determinations, as does the typical sheath viewing angle 2 degrees. The sheath opening angle of 4 degrees was not previously known, neither the Lorentz \( \Gamma = 3.5 \) for the sheath. The helical wavelength of ~ 70 pc is also determined for the first time, even though it could also be determined from the high resolution maps of Tateyama (2013). It is also interesting that the period of the helical motion agrees in order of magnitude with the Kozai cycle of inner accretion disk. Moreover, the fact that the variation of optical polarization follows the model allows us to state definitely that the magnetic field is parallel to the jet in the optical emission region, a conclusion which was only tentative in earlier work (Valtonen & Wiik, 2012).

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References

Aguado, I., Jorstad, S. G., Marscher, A. P., et al. 2012a, in Journal of Physics Conference Series, Vol. 535, 012032
Aguado, I., Marscher, A. P., Jorstad, S. G., et al. 2012b, ApJ, 747, 63
Gabuzda, D. C. & Gómez, J. L. 2001, MNRAS, 320, L49
Hardee, P., Mizuno, Y., & Nishikawa, K.-I. 2007, Astrophys. Space. Sci., 311, 281
Hardee, P. E. 2000, ApJ, 533, 176
Hardee, P. E. 2007, ApJ, 664, 26
Hardee, P. E. 2011, in IAU Symposium, Vol. 275, IAU Symposium, ed. G. E. Romero, R. A. Sunyaev, & T. Belloni, 41–49
Hovatta, T., Valtaoja, E., Tornikoski, M., & Lähteenmäki, A. 2009, A&A, 494, 527
Hudec, R., Bašta, M., Pihajoki, P., & Valtonen, M. 2013, A&A, in press
Innanen, K. A., Zheng, J. Q., Mikkola, S., & Valtonen, M. J. 1997, AJ, 113, 1915
Jorstad, S. G., Marscher, A. P., Lister, M. L., et al. 2005, AJ, 130, 1418
Krolik, J. H., Hawley, J. F., & Hirose, S. 2005, ApJ, 626, 1008
Kushwaha, P., Sahayanathan, S., & Singh, K. P. 2013, ArXiv e-prints, 1305.0506
Lehto, H. J. & Valtonen, M. J. 1996, ApJ, 460, 207
McKinney, J. C., Tchekhovskoy, A., & Blandford, R. D. 2013, Science, 339, 49
Mignone, A., Rossi, P., Bodo, G., Ferrari, A., & Massaglia, S. 2010, MNRAS, 402, 7
Mizuno, Y., Lyubarsky, Y., Nishikawa, K.-I., & Hardee, P. E. 2012, ApJ, 757, 16
Palenzuela, C., Garrett, T., Lehner, L., & Liebling, S. L. 2010, Phys. Rev. D, 82, 044045
Peruco, M., Hardee, Y. Y. K. P., Lobanov, A. P., Aguado, I., & Martí-Vidal, I. 2013, ArXiv e-prints, 1301.2049
Peruco, M., Kovalev, Y. Y., Lobanov, A. P., Hardee, P. E., & Aguado, I. 2012, ApJ, 749, 55
Pushkarev, A. B., Kovalev, Y. Y., Lister, M. L., & Savolainen, T. 2009, A&A, 507, L33
Savolainen, T., Homan, D. C., Hovatta, T., et al. 2010, A&A, 512, A24
Sundelius, B., Wahde, M., Lehto, H. J., & Valtonen, M. J. 1997, ApJ, 484, 180
Tateyama, C. E. 2013, ApJS, 205, 15
Tateyama, C. E. & Kingham, K. A. 2004, ApJ, 608, 149
Valtonen, M. J., Ciprini, S., & Lehto, H. J. 2012a, in Journal of Physics Conference Series, Vol. 355, 012032
Valtonen, M. J., Ciprini, S., & Lehto, H. J. 2012b, MNRAS, 427, 77
Valtonen, M. J., Gopakumar, A., Mikkola, S., Wiik, K., & Lehto, H. J. 2012b, in Proc. ICGC Intern. Conf., Goa
Valtonen, M. J., Lehto, H. J., Nilsson, K., et al. 2008, Nature, 452, 851
Valtonen, M. J., Lehto, H. J., Sillanpää, A., et al. 2006, ApJ, 646, 36
Valtonen, M. J., Lehto, H. J., Takalo, L. O., & Sillanpää, A. 2011, ApJ, 729, 33
Valtonen, M. J., Mikkola, S., Merritt, D., et al. 2010, ApJ, 709, 725
Valtonen, M. J. & Wiik, K. 2012, MNRAS, 421, 1861