Mon. Not. R. Astron. Soc. **293,** L13–L16 (1998)

A beaming model for the OJ 287 periodic optical outbursts

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Accepted 1997 October 1. Received 1997 January 24; in original form 1996 October 3

ABSTRACT

An analytical model for the description of the quasi-periodic optical outbursts observed in the blazar OJ 287 is presented. The astrophysical scenario that can account for the observed double-peaked structure of the cyclic outbursts consists of a pair of supermassive black holes (BHs) in a binary system, both of them creating a jet. The two jets are bent by the interaction of their magnetized plasma with the ambient medium. The combination of this bending with a long-term precession of the jet axes gives rise to a time-dependent orientation of the emitting outflows. The quasi-periodic optical outbursts that we observe arise from the relativistic beaming effect when part of the bent jets is directed toward us. The theoretical result is a light curve that, for a given choice of the model parameters, describes very well the observational data taken over more than a century, and predicts the future behaviour. This successful agreement between model and observations may be further evidence for the presence of binary BH systems in the cores of active galactic nuclei (AGNs).

Key words: galaxies: active – BL Lacertae objects: general – BL Lacertae objects: individual: OJ 287 – galaxies: jets – galaxies: nuclei.

1 INTRODUCTION

The blazar OJ 287 is one of the best-monitored extragalactic sources, its V-band light curve covering more than a century with a total of more than 5000 data points (see Fig. 1). This long time coverage and the good sampling obtained in recent decades provide exceptional information for the study of its optical variability characteristics. Several papers have been dedicated to this interesting subject, from both the observational and the theoretical points of view (e.g. Sillanpää et al. 1988; Sillanpää 1991; Kidger, Takalo & Sillanpää 1992; Sillanpää et al. 1996a,b; Lehto & Valtonen 1996).

The most interesting feature of the OJ 287 optical light curve found in the above studies is an apparent 12-yr outburst cycle, recently confirmed by observations performed as part of an international monitoring campaign, the OJ-94 Project, organized with the aim of monitoring the predicted 1994 outburst (Sillanpää et al. 1996a,b). Another feature of the observed light curve is the double-peaked structure of the outbursts, with changing intensity, shape and separation of the double peaks. This behaviour is more evident in the best-sampled part of the curve, from 1971 onward (Fig. 2). Finally, small-amplitude brightness variations (flickering) are superimposed on the main trend of the light curve.

Sillanpää et al. (1988) modelled the periodic outbursts by means of a supermassive black hole (BH) binary system. In their scenario the brightness variations would be a result of tidally induced mass flows from the accretion disc into the primary BH. A more recent version of this model that can also explain the double-peaked structure of the outbursts has been presented by Lehto & Valtonen (1996). Other possible interpretations of the OJ 287 optical behaviour are described by Sillanpää et al. (1996b) and include a precessing disc model (Katz 1997), a microlensing effect, and the 'lighthouse' model by Camenzind & Krockenberger (1992).

The presence of binary BH systems in the cores of active galactic nuclei (AGNs) (and precession of the axes of the related jets) was first proposed by Begelman, Blandford & Rees (1980), and has since been claimed to explain various pieces of observational evidence about extragalactic sources, such as curved or misaligned jets (e.g. Roos 1988; Conway & Wrobel 1995), double-stranded helical jets (Villata & Ferrari 1995), and double-peaked emission lines (e.g. Eracleous et al. 1995).

In this paper we present an analytical model for the description of the OJ 287 optical light curve, deriving it from a scenario which consists of a pair of jets originating from two BHs in a binary system and interacting with the surrounding ambient medium. The fundamental difference with respect to the previously proposed model (Sillanpää et al. 1988; Lehto & Valtonen 1996) is the quasi-steadiness of the intrinsic flux coming from the source, the periodic outbursts being due solely to the changing direction of the jets, part of the emission of which is periodically beamed in our direction. As in the lighthouse model by Camenzind & Krockenberger (1992), the basic idea is that the variability is due to a beaming factor change of geometrical origin (see also Schramm et al. 1993; Wagner et al. 1995; Steffen et al. 1995). The present model can describe in detail the features of the observed light curve, the double-peaked structure

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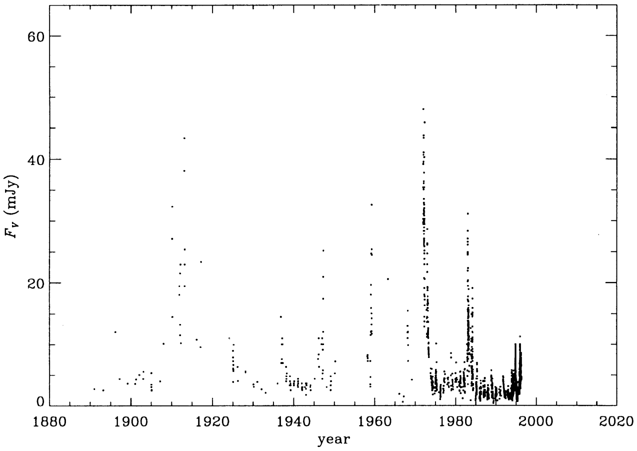

Figure 1. Observed *V*-band light curve of OJ 287.

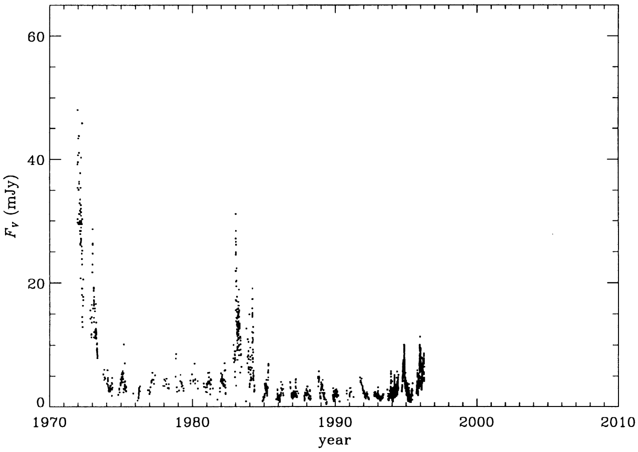

Figure 2. The last and best-sampled part of the light curve shown in Fig. 1.

of the outbursts and their relative intensity and separation included. In Section 2 we present the model, while in Sections 3 and 4 the main results and conclusions, respectively, are briefly outlined.

2 THE MODEL

The aim of our model is to describe the general behaviour of the OJ 287 optical light curve, i.e. the sequence of the double-peaked outbursts separated by lower flux states. Since we are interested in the main trend of the source brightness, we shall not take flickering into account.

Consider two BHs in a binary system, both of them creating a jet. For simplicity we suppose that the BHs rotate along circular orbits around their mass centre and that their mass ratio is close to one. The two jets have similar characteristics and their axes form the same angle ψ with the angular momentum vector of the orbital motion (the axis of the orbital plane), but have different azimuthal orientations. This is required in order to explain the double-peaked structure of the outbursts, each peak being due to one of the jets. As will be clear in the following, it is the time separation between the two peaks of the outbursts that fixes the phase difference ϕ between the jet axes.

The two jet axes precess around the orbital axis with a period $|p|T$, where T is the orbital period of the two BHs. In the following formulae positive (negative) values of p correspond to prograde (retrograde) precessions with respect to the orbital motion. The ambient medium surrounding the binary system is probably not in corotation with the BHs and the apexes of their jets; hence we must imagine some kind of distortion of the outflows caused by the magnetohydrodynamic interaction between the magnetized flows and the ambient medium. We can simply consider that the magnetic field lines along which the plasma is flowing are partially trapped in the non-corotating medium, so that the jets are bent backwards with respect to their orbital motion. This bending of the magnetic field in the jets of a BH binary system could also be at the origin of the double-stranded helical structures observed in some jets like those of M87, 3C 66B and 3C 264 (see e.g. Villata & Ferrari 1995). Indeed, far away from the orbital plane the continuous bending and the magnetic tension of the field lines should lead the two jets to twist around each other in an equilibrium double-helix structure with the appearance of a single jet.

A detailed modelling of this bending would introduce a number of parameters that would make the model not very manageable. Hence, instead of considering a continuous jet bending, we describe the jet as a 'broken' jet, having a straight part following the original jet axis and an outer segment forming an angle ζ with the former. The bent part of the jet is always directed backwards with respect to the orbital motion, so that we are in the presence of a sort of precession of the outer segment around the original axis. It is this change of direction that produces the observed outbursts: they are the result of the relativistic beaming effect when the outer jet points toward us. If the observer's line of sight is parallel to the orbital axis, this happens if the bending angle ζ is similar to the inclination angle of the jet axis ψ and when this axis has the same azimuth of the orbital velocity vector (i.e. it points forward with respect to the BH motion), so that the jet is bent parallel to the orbital axis, namely in the observer's direction. (This would occur once per revolution if the jet axis did not have its own long-term precession.) In this case it is easy to understand that the broken jet description is equivalent to a continuous bending one: the interesting part of the continuously bent jet is just the one that is more affected by beaming, namely the one that we consider in the broken jet, the remaining parts contributing much less to the observed flux.

The above scenario with the line of sight parallel to the orbital axis would produce a light curve that is perfectly periodic both in the time interval between the pairs of outbursts and in their shape and intensity. The observational data do not correspond to such a simple model. In order to fit the outbursts with their changing intensity and shape, we must suppose that the orbital axis is not aligned with the line of sight but forms a small angle ι with it.

The theoretical optical flux as a function of time is calculated according to the simple beaming formula $F(t) = \delta^3(t)F'$ (see e.g. Begelman, Blandford & Rees 1984; Ghisellini et al. 1993; Urry & Padovani 1995), where F' is the steady optical flux measured in the source rest frame and δ is the beaming or Doppler factor $\delta = [\gamma(1 - \beta\cos\theta)]^{-1}$, β being the bulk velocity of the emitting plasma in units of the speed of light, $\gamma = (1 - \beta^2)^{-1/2}$ the corresponding Lorentz factor, and θ the angle between the jet direction and the line of sight. Taking γ as a parameter that is independent of time, what we need is then the angle θ as a function of time.

According to our model we have to compute four different functions $\theta(t)$: one for each of the considered parts (bent and unbent) of each jet. All the parameters of the model are considered equal for the two jets and are fixed by the observed light curve. With a given azimuthal orientation of the line of sight and with ω being the angular velocity of the orbital motion, for the unbent part of the jets we have (the subscripts 1 and 2 refer to the two jets)

$$\cos\theta^{\mathrm{u}}_{1,2}(t) = a^{\mathrm{u}}_{1,2}(t)\sin\iota + \cos\psi\cos\iota, \tag{1}$$

with

$$a^{\mathrm{u}}_{1}(t) = \sin\psi\cos\frac{\omega t}{p}, \tag{2}$$

$$a^{\mathrm{u}}_{2}(t) = \sin\psi\cos\left(\frac{\omega t}{p} + \phi\right). \tag{3}$$

On the other hand, the formulae relevant to the bent parts are

$$\cos\theta^{\mathrm{b}}_{1,2}(t) = a^{\mathrm{b}}_{1,2}(t)\sin\iota + b^{\mathrm{b}}_{1,2}(t)\cos\iota, \tag{4}$$

$$\begin{aligned} a^{\mathrm{b}}_{1}(t) = {} & \sin\psi\cos\zeta\cos\frac{\omega t}{p} \\ & - \cos\psi\sin\zeta\cos\frac{\omega t}{p}\cos\left(\frac{p-1}{p}\omega t\right) \\ & + \sin\zeta\sin\frac{\omega t}{p}\sin\left(\frac{p-1}{p}\omega t\right), \end{aligned} \tag{5}$$

$$\begin{aligned} a^{\mathrm{b}}_{2}(t) = {} & \sin\psi\cos\zeta\cos\left(\frac{\omega t}{p} + \phi\right) \\ & + \cos\psi\sin\zeta\cos\left(\frac{\omega t}{p} + \phi\right)\cos\left(\frac{p-1}{p}\omega t - \phi\right) \\ & - \sin\zeta\sin\left(\frac{\omega t}{p} + \phi\right)\sin\left(\frac{p-1}{p}\omega t - \phi\right), \end{aligned} \tag{6}$$

$$b^{\mathrm{b}}_{1}(t) = \cos\psi\cos\zeta + \sin\psi\sin\zeta\cos\left(\frac{p-1}{p}\omega t\right), \tag{7}$$

$$b^{\mathrm{b}}_{2}(t) = \cos\psi\cos\zeta - \sin\psi\sin\zeta\cos\left(\frac{p-1}{p}\omega t - \phi\right). \tag{8}$$

Then, we must assume a value for the ratio f between the optical flux coming from the outer (bent) segment and that produced by the inner (unbent) jet, as measured in the jet rest frame. In practice, the unbent part of the jets provides the low-state flux between the outbursts, these latter occurring when the bent-part fluxes are beamed towards our telescopes.

3 RESULTS AND DISCUSSION

The analytical formulation of the model presented in the previous section involves some parameters, which are fixed by the comparison of the predicted light curve with the observational one. A choice of parameters which allows us to describe the data fairly well is indicated in Figs 3 and 4, where the result of our model is shown. A detailed treatment of the model sensitivity to parameter variations is beyond the scope of this paper: what we want to stress is that a simplified treatment like this is able to reproduce all the main characteristics of the observed light curve. As for the flickering, which we have neglected, it may be due to intrinsic variability of the emission. A more sophisticated jet model would not produce substantially different results: indeed, the quite small ratio between the intrinsic fluxes of the bent and unbent parts of the jets ($f = 6\times10^{-4}$) indicates that the bent segment that we consider can be just interpreted as the small portion of a continuously bent jet, the flux of which is periodically beamed in our direction.

The result suggests that $p = 10$ and that the BH orbital period $T = 10.8$ yr. In the absence of the jet axis precession this period would also correspond to the time breaks between outbursts; precession lengthens the outburst period to the observed 12 yr.

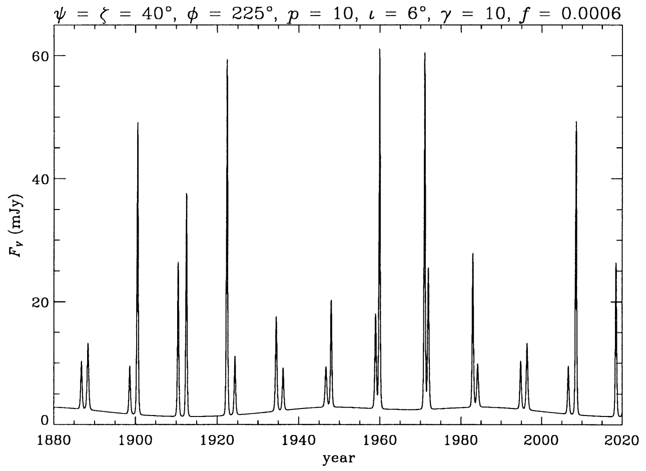

Figure 3. Theoretical light curve of OJ 287 according to the displayed choice of parameter values.

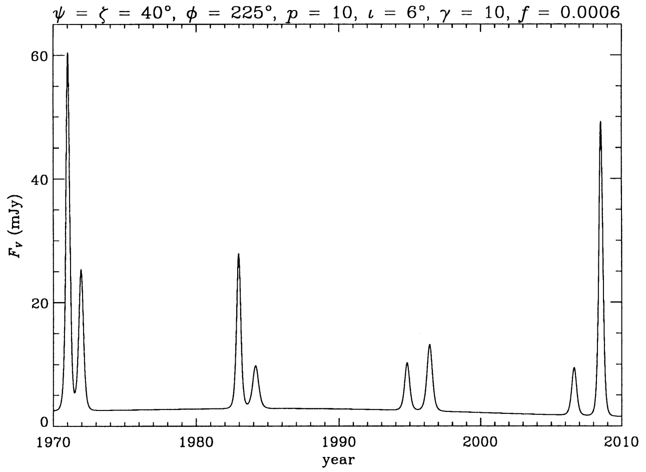

Figure 4. Part of the curve shown in Fig. 3, containing the last three outbursts and the prediction for the next one.

The theoretical light curve also contains the predictions of the model for the next periodic events. In particular, the first of them would be composed of a relatively small outburst (with a peak of about 10 mJy) followed by a bigger one (around 50 mJy). These two outbursts would occur around the middle of 2006 and 2008. As for the later predictions, one must consider that the curve is perfectly periodic over 108 yr, and hence what should happen after 2020 can be seen to be what has happened from 1912 forward. In particular, the next double peaks should be more separated with respect to the last three (about 2 yr compared with about 1–1.5 yr).

Obviously, the choice of well-fitting parameter values is probably not unique, and other values may give an equally good fit to the data but different predictions.

Support for this model seems to come from observations in other bands. Indeed, during the 1994 outburst no brightening in the radio and X-ray bands was detected, while γ-ray detection revealed a simultaneous high state (Sillanpää et al. 1996a). This agrees with the current jet model in which the X-ray emission comes from the apex of the jet while the radio emission comes from the outer regions, namely from zones not affected by the bending we are considering, whereas the γ emission is believed to be cospatial with the optical emission.

4 CONCLUSIONS

We have outlined a scenario which can account for the singular behaviour of the observed optical light curve of OJ 287. Its quasi-periodic double-peaked structure would be due to the relativistic beaming effect on the emission coming from two similar jets originating from two BHs in a binary system. The existence of a long-term precession of the jet axes appropriately oriented with respect to the orbital axis, and the interaction of the magnetized outflows with the ambient medium are the essential ingredients of the model. A particular inclination of the orbits with respect to the line of sight is the geometrical condition needed to obtain a good match between the theoretical and observed light curves.

In order to fit the observed double-peaked outbursts we have made some simple assumptions (similar BH masses and jet characteristics), but they must not be considered as binding: our purpose is to show that a binary system scenario can account for the observed optical behaviour, and not to state which is the exact physical situation. This would require a better sampling of the previous outbursts.

We believe that the successful agreement between our model and observations might be further proof of the existence of binary BH systems in the cores of AGNs, as well as a key method for the investigation of their characteristics, in view of a better physical understanding of these still largely unknown and mysterious objects.

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