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The OJ287 Binary Model and the November 1995 Outburst

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Abstract. A binary black hole model was proposed for OJ287 on the basis of its historical light curve in 1988 by Sillanpää et al.. The model predicted the next outburst in September 1994 on the basis of the idea that tidal transfer of matter in the accretion disk of the primary is responsible for the increased output of the relativistic jet. Even though the outburst did occur, it was late by about 6 weeks. Similar and even greater discrepancies between the binary model and the timing of the outbursts are obvious in the historical light curve. Therefore the binary model was generalized by Lehto and Valtonen to a companion orbit which is highly inclined to the disk of the primary, instead of the zero inclination orbit of the original model. As a result of the inclined orbit the secondary crosses through the disk of the primary twice per period. A bright thermal flash, seen primarily in ultraviolet and optical, is expected at each disk crossing from the shock heated disk gas. It has been possible to identify many of the disk crossing events in the historical light curve in this way. A very satisfactory explanation of the main features of the light curve, including the apparently early or late arrivals of the outbursts can be given. In fact a unique orbit determination is possible when 5 crossings have been exactly timed. The necessary number of the crossings, "superflares", was known after the 1994 event, and the orbit was solved. The solution predicts the timing of the future plane crossings. The next prediction was a superflare which should begin between November 1 and November 15, 1995. The uncertainty in the prediction was due to uncertainty in the accretion disk model: the exact timing will be important for determining the disk parameters. Once the disk model is well known, the next set of outbursts in 2006 and 2007 can be predicted very accurately, to the extend that one can test the General Theory of Relativity in the strong field limit for the first time.

1. Introduction

OJ287 is one of the very few quasars for which we have a fairly continuous light curve over the period of one hundred years. This is due to the fortuitous situation of OJ287 being near the ecliptic and of its relatively high brightness. This is why it has been accidentally photographed during minor planet searches and other solar system work since late last century. The magnitude measurements from literature were put together by Sillanpää et al. (1988) who found that the object brightens up spectacularly at mean intervals of 11.65 yr. Since the last major flare was observed at 1983.0, the following one was expected at 1994.65. The flare was well observed by the OJ-94 campaign (Sillanpää et al. 1996) as well as others. Its timing was a little late, about 1994.76, but otherwise it lived up to expectations.

Sillanpää et al. (1988) proposed that the basic reason for the rather regularly spaced outbursts is a black hole binary system with a period of 9 yr which translates to the observed outburst interval at the observed redshift of 1.3. The problem with this explanation is the irregularity of the exact times of the major flares: they appear to be sometimes early, sometimes late by as much as one year relative to the mean period. In terms of the binary model this would mean that the outbursts are induced at different phase angles relative to the pericenter, and these phase angles vary as much as ±90° on either side of the pericenter. It is difficult to produce such an irregularity in the tidal triggering model of Sillanpää et al. (1988).

In addition, a careful inspection of the light curve during the best observed active phases in 1971 – 1973 and in 1983 – 1985 shows that there are in fact two or even three major peaks in the light curve per active phase. This is also problematic in the tidal triggering model.

Because of these problems Lehto and Valtonen (1996) proposed a new model where the activity is triggered not only by the tides but also by the crossing of the secondary black hole through the accretion disk of the primary. Then two of the major flares per active phase are associated with the impact on the disk and the energy released in the impact while the slower and longer lasting increase in the brightness level is associated with tidal effects.

The attractive feature of this model is the unique solution of the binary black hole orbit and the subsequent possibility of predicting the future light curve of OJ287. The next prediction was the occurrence of another major flare, similar to the 1994 flare, in November 1995. This is associated with the second crossing of the secondary through the disk of the primary. Later also new calculations of the tidal triggering process were carried out and they resulted in the prediction of the third brightening of OJ287 in the early part of 1996 (Sundelius et al. 1996, reported in this conference). Here we concentrate on the former prediction, how well it was fulfilled and what is its significance to the binary black hole model.

2. The binary model

The basic ingredients in the binary black hole model of Lehto and Valtonen (1996) are:
1. the relative timing of five superflares, i.e. outbursts which last 6–8 weeks and reach up to 10 mJy above the base level in the V-band;
2. a model for the time delay between the impact on the disk and the radiation burst in the optical V-band, and
3. a model for the loss of orbital energy.

The binary orbit is fully described by 4 parameters (neglecting the orientation in space) and therefore 4 time intervals, i.e. 5 impact times are necessary for a unique solution of the orbit. In the first approximation, one may assume that time delays are constant irrespective of the radial distance of the point of

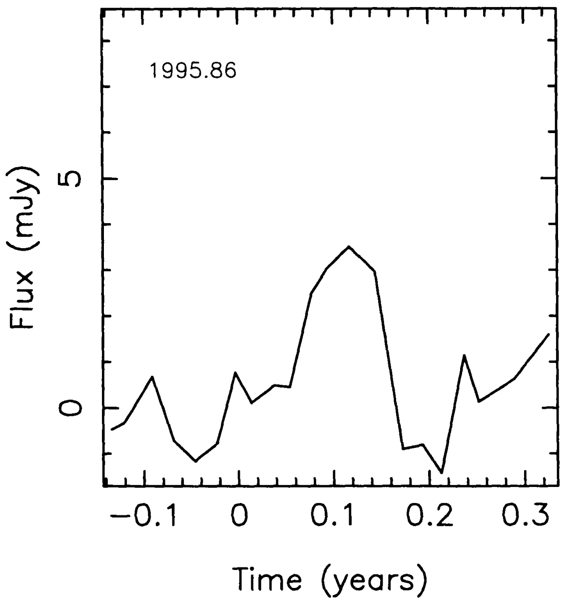

Figure 1. The time averaged light curve of OJ287 around November 1995. The averaging interval is 0.02 yr. The data is courtesy of the OJ-94 campaign (L. Takalo and A. Sillanpää, private communication). The steadily rising brightness has been subtracted.

impact. Also one may neglect the loss of orbital energy. Then one obtains the first model of Lehto and Valtonen (1996), and a prediction that the 1994 and 1995 outbursts should be separated by 1.06 yr.

In the second case of Lehto and Valtonen (1996) a geometrically thin but optically thick α_g-disk model was used (number density $n = 10^{14}\mathrm{cm}^{-3}$, scale height $h = 4 \cdot 10^{14}$cm at the typical impact distance). The collision of a secondary black hole of mass $10^8 M_\odot$ with a speed between 45 000 km s^{-1} (at the pericenter) and 9000 km s^{-1} (at the apocenter) releases typically 10^{55} erg/collision. The energy is transferred by the bow shock of the secondary black hole to the gas of the disk. The shocked, radiation pressure dominated gas is accelerated in the direction of the secondary's orbit. Part of the energy produced in the interaction heats up the unshocked gas of the disk.

The bulk velocity acquired by the shocked gas causes it to exit from the plane of the disk. The gas remaining in the disk will start to close the hole at the local sound speed. Once the shocked gas is outside the disk, it starts to expand. Selfgravity is not very important. The gravity of the secondary is non-negligible when interactions near apocenter are considered.

The gas bubble is initially optically thick. After sufficient adiabatic expansion has taken place, the bubble becomes optically thin. From that moment onwards radiative cooling dominates over adiabatic cooling. This is when an outburst is observed. The model predicts the timelags of the outbursts as compared with the disk-plane crossings. The time delays are small at pericenter and up to two years at apocenter.

The expected amplitudes in a disk interaction model involving a secondary of 100 million solar masses yields amplitudes between about 2 to 8 mJy depend-

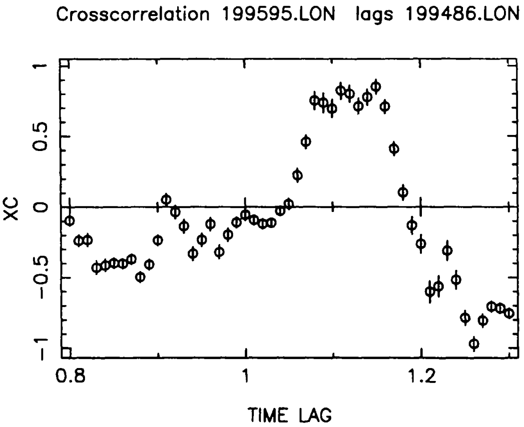

Figure 2. The cross-correlation of the light curves of the 1994 and 1995 superflares.

ing on the orbital radius vector of the secondary on impact. These agree with the observed values.

The prediction of the second model of Lehto and Valtonen (1996) was that the 1994–1995 outburst interval should be 1.10 yr. Orbital energy losses were also neglected in this model.

The 1995 outburst came much as predicted. A time averaged light curve of the outburst event is shown in Fig. 1. Figure 2 shows the cross-correlation of the V-band flux values in the 1994 and 1995 outbursts. It is obvious from Fig. 2 that the outburst interval was greater than 1.06 yr (the prediction of model 1), but that the 1.10 yr interval (model 2) gives an excellent fit to the data. Note that the models were calculated and the paper (Lehto and Valtonen, 1996) was accepted for publication well before there was any indication that a second outburst should occur at all, not to mention the narrow two-week time interval defined by the two models.

In the following we will discuss the details of the model and what one can say about the orbital energy loss due to gravitational radiation.

3. The orbital energy loss

The binary model was described in detail in Lehto and Valtonen (1996). In essence, we have a binary black hole with component masses $17.7 \cdot 10^9 M_\odot$ and about $10^8 M_\odot$ which go around each other in a (redshifted) period of 12.07 yr and in an orbit of eccentricity $e = 0.67$. The major axis of the orbit precesses 33° per period, i.e., the system is extremely relativistic and will collapse due to gravitational radiation within the next $4 \cdot 10^4$ yr even though the shortening of the period was neglected in the model. The semi-major axis of the binary is 0.056 pc which corresponds to about 10^{-5} arc sec in the sky at the distance of OJ287 (for the Hubble constant of $H_0 = 60$ km s^{-1} Mpc^{-1}). It is not possible to resolve the binary with current methods, but it may be within reach in the near future with space VLBI if both black holes are strong radio sources.

How serious is the neglect of the orbital energy loss in the models of Lehto and Valtonen (1996)? We have calculated further models where the gravitational

Table 1. The relative timing of the superflares in different models (m_2 is the mass of the secondary in units of $10^8 M_\odot$) compared to observations.

Model I (no rad'n) $m_2 = 0.98$	Model II $m_2 = 0.98$	Model III $m_2 = 0.72$	Model IV $m_2 = 0.60$	Observed times
1947.30	1947.30	1947.29	1947.29	1947.30
1959.21	1959.22	1959.21	1959.21	1959.22
1972.99	1973.00	1972.98	1972.97	1972.98
1983.00	1983.00	1983.00	1983.00	1983.00
1984.16	1984.16	1984.16	1984.16	1984.16
1994.77	1994.75	1994.75	1994.75	1994.77
1995.86	1995.84	1995.85	1995.85	1995.87
2006.35	2006.30	2006.23	2006.21	

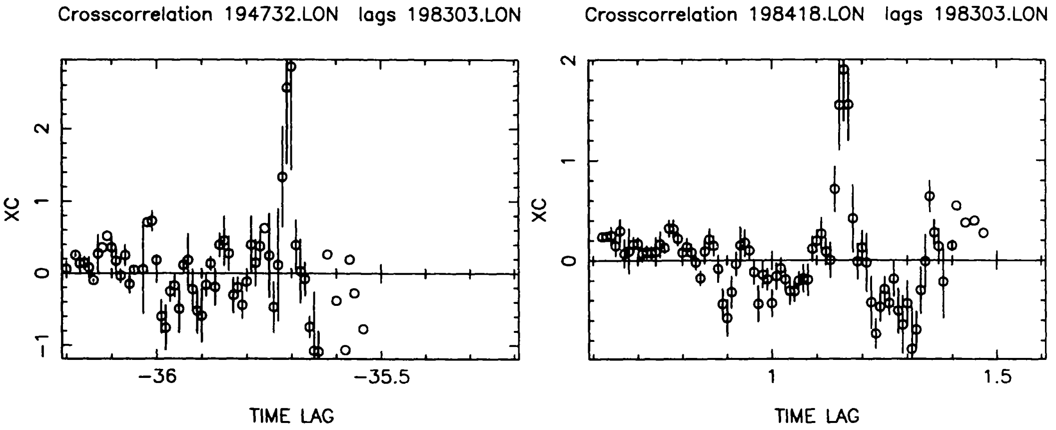

Figure 3. The cross-correlation between the 1983 superflare and some other superflares. Time lag is the time difference between the 1983.00 flare and the 1947.30 flare (left) and 1984.16 flare (right).

radiation terms are included in the equation of motion (see Valtonen et al. 1995 for details). Table 1 shows the timing of the outbursts in a number of the models. Note that the timing is relative to the outburst at the beginning of 1983; it is given the exact time of 1983.0 and it refers to the beginning of the outburst. The brightness maximum for a superflare occurs sometime close to the beginning of the superflare (as in 1983) sometime during the second rise of the superflare about one month later (as in 1994). We do not consider the exact times of the brightness maxima important since they may be related to random processes such as variations in opacity and geometrical configurations of radiating and absorbing gas clouds.

In order to obtain relative timing of the various outbursts, we have carried out cross-correlation studies between the flux values of the 1983 superflare and the other superflares.

Figure 3 shows examples of the correlation diagrams. Using the cross-correlation method as well as the manual superposition of light curves on top of each other we have derived the timings of altogether seven superflares relative to each other. These are also shown in Table 1. As the timing of the superflares is accurate only within ±0.01 yr (i.e., within one week), it is obvious from Table 1 that currently we cannot claim to have detected the orbital energy losses.

The first opportunity to test the expected radiation loss comes in 2006. Then the superflare may start as early as in March if the radiation is important, but is not expected until May if the radiation is negligible. This will also be a test of the General Theory of Relativity.

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