The Astrophysical Journal, 646:36–48, 2006 July 20


# PREDICTING THE NEXT OUTBURSTS OF OJ 287 IN 2006–2010

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*Received 2005 May 19; accepted 2006 April 4*

## ABSTRACT

In its nearly regular cycle of outbursts the quasar OJ 287 is due for another outburst season in 2006–2010. The prediction for the exact timing depends on the adopted model. In the precessing binary model of Lehto and Valtonen the timing depends on the time delay between the impact on the primary disk and the time when the impacted gas becomes optically thin. The time delay in turn depends on the properties of the accretion disk, the accretion rate, and the viscosity parameter $\alpha$, which are not exactly known. We study the flexibility in timing provided by the uncertainties. In order to fix the model, two methods are used: the wobble of the jet, induced by the secondary, and the timing of the 1956 outburst, which has not been previously used. As a result, rather definite dates for the outbursts are obtained, which are different from a straightforward extrapolation of the past light curve. A new optical light curve with many new historical as well as recent points of observation have been put together and has been analyzed in order to reach these conclusions. Also, the high-frequency radio observations are found to agree with the jet wobble picture.

*Subject headings:* quasars: general — quasars: individual (OJ 287)

## 1. INTRODUCTION

In 1980 Tuorla Observatory of the University of Turku started a monitoring program of quasars. The idea was to follow brightness variations of several dozen quasars both at optical and radio wavelengths using the optical telescopes of Tuorla Observatory and the 14 m radiotelescope of the Metsähovi radio research station. The latter is operated by the Helsinki University of Technology. In terms of intensity of observations and wavelength coverage the program is unique. It rapidly produced interesting results that alerted the wider community to take up similar research (Valtaoja et al. 1985). At present a whole network of observatories all over the world carries out quasar monitoring. One of the latest additions to the network is the SATU (St. Augustine-Tuorla) Observatory in Trinidad.

In this paper we describe theoretical interpretations of one of the quasars in our sample, OJ 287. It is interesting in many respects, but the distinguishing feature is the series of outbursts, which have been recorded at about 12 yr intervals through the 20th century. On this basis a binary model has been proposed for OJ 287 with an intrinsic period of about 9 yr, which becomes 12 yr when multiplied by the redshift factor of 1.3 (Sillanpää et al. 1988). From the luminosity of the source we may deduce that the mass of the primary is at least $10^9$ solar masses. Since there are no known stable compact bodies of this mass except supermassive black holes, we may deduce that OJ 287 consists of two such bodies.

Alternative models include quasi-periodic oscillations of an accretion disk surrounding a single black hole. The 12 yr oscillation frequency would then imply a central single black hole of $(3{-}6)\times10^9$ solar mass (Igumenschev & Abramowicz 1999). Quasi-periodic outbursts could also be the property of a jet arising from a single black hole (Hughes et al. 1998). On the basis of the 12 yr periodicity alone one cannot decide between the single black hole and binary black hole models. We have to look at the periodic outbursts in greater detail in order to decide between different models. The successful model has to be able to predict future outbursts and other behavior as closely as possible. This is the main aim of the present paper.

The emission of OJ 287 is associated with a disk of gas, which is slowly accreted into the black hole, and to magnetohydrodynamic jets, which flow out along the axis of rotation of the accretion disk (Turner et al. 1999). The rapid variability of OJ 287 suggests that we are looking at the jet almost directly head-on, which results in a great magnification of the variation of the radiative flux (Teräsranta & Valtaoja 1994). This preferential viewing angle also means that the brightness of OJ 287 is very sensitive to the exact orientation angle $\theta$ between the line of sight and the jet axis. If the jet axis wobbles due to the influence of the companion, the wobble is directly manifested in the observed light curve (Katz 1997).

Another source of brightness variations is due to the impact of the secondary black hole on the accretion disk of the primary. The secondary pierces a channel through the disk and heats the gas in the channel. The heated gas flows out on both sides of the disk and radiates strongly for a period of a few weeks (Lehto & Valtonen 1996; Ivanov et al. 1998). The timing of the impacts allows one to determine uniquely the orbital parameters of the secondary black hole as well as the mass of the primary black hole. The latter has the value of 15 billion solar masses, which is

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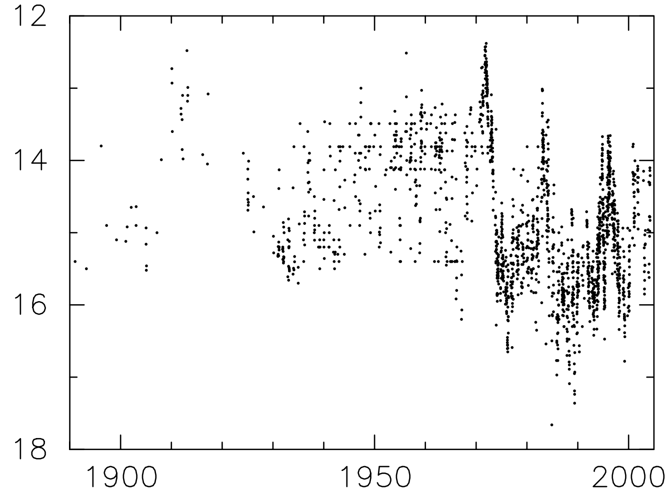


FIG. 1.—*V* light curve of OJ 287. The points are 3 day averages. No upper limits are included.

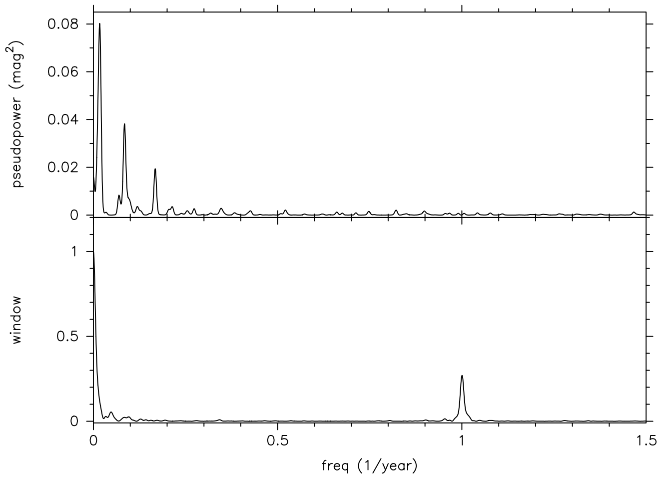


FIG. 2.—Pseudopower of the CLEANed periodogram and the window function of the 3 day average light curve of OJ 287. The abscissa is log of frequency in 1 yr. The coordinates on are on a linear scale and have units of mag$^2$ (periodogram) and unitless (window function).

close to the upper end of the masses determined for other quasars using different techniques (Netzer 2003).

The third source of brightness variations is the variable mass flow rate in the jet, which may derive from variations of accretion rate. The latter may result from the tidal influence of the secondary on the accretion disk of the primary (Sillanpää et al. 1988; Sundelius et al. 1997). The variable mass flow rate causes internal shocks in the jet, which accelerate relativistic electrons. They radiate efficiently by synchrotron radiation (Valtaoja et al. 1992).

The variations of overall light curve are therefore expected to be a combination of at least these three processes. In the following we consider these processes in turns in the binary black hole model.

## 2. ANALYSIS OF VARIABILITY

### 2.1. *The Light Curve*

We have compiled a more extended light curve for OJ 287 than in previous studies (Fig. 1). The historical data points before the OJ-94 collaboration referenced in Takalo (1994) together with densely covered *V*-band data points from the OJ-94 collaboration[2] are adopted to our analysis. New data points were included from Sonneberg Observatory. The magnitude of OJ 287 was estimated visually by experienced observers using a plate microscope and a modified Argelander method. Data were also adopted from Kinman & Conklin (1971), Qian & Tao (2003), and Massaro et al. (2003). In addition, we have obtained archival data from Pulkovo Observatory and more recent CCD measurements from 1.03 m telescope at Tuorla Observatory and the 60 cm KVA Telescope at La Palma.

The data covers the years from 1891 until 2004 and consist of 14,626 individual data points; 14,296 of these are positive detections. Some are remeasurements of the same points. Daily averages provide positive detections on 2968 days. Three-day averages give 1808 data points.[3] We welcome further points to this data set.

The temporal coverage of the observations is uneven. First, there is a gap every year in July–August at the time when OJ 287 is near conjunction with the Sun. On shorter timescales, regular gaps occur on a timescale of a month, one corresponding to the sidereal month and the other to the synodic month. All these three types of gaps are prominent in the data set.

The light curve has an uneven density even on a timescale of years. There are significant increases in observing densities in the 1930s and then again in 1970s after the identification of OJ 287 and again in early 1990s due to onset of the OJ-94 collaboration.

In recent decades, an increase in the sensitivity of detectors has caused the number of positive detections to increase with diminishing numbers of observations reported as upper limits. Many of the gaps in historic data have large numbers of upper limits covering them. If only positive detections are considered, then problems caused by poor phase coverage can be significant (Kidger 2000).

To reduce the weight of the high number of points in recent years, we have analyzed the data set using different lengths of binning (1 day, 3 days, 7 days, 1 month). This reduces out the effects of fast variability in OJ 287, but the subdiurnal variations are not critical in this investigation. We should note that despite these rather strong binnings the median point in each of these light curves is located in recent times.

Visual inspection of the optical light curve of OJ 287 suggests that there might be a regular spacing between giant flares. Stothers & Sillanpää (1997) claim that the null hypothesis of randomly distributed times of outbursts could be rejected at a 2% significance level.

### 2.2. *Global Analysis of Periodicity*

We calculated a (Deeming 1975) periodogram for the light curve of OJ 287 and then performed a CLEAN procedure to remove the effects of sampling (Fig. 2). The CLEAN algorithm developed originally for radio interferometry (Högbom 1974; Schwartz 1978; Clark 1980) and further applied to time series analysis (Roberts et al. 1987) is used to remove from the periodogram artifacts caused by the sampling. We have further modified the algorithm in the sense that we let the gain vary. This provides a better mathematical convergence.

The window function, representing the Fourier transform of the sampling, shows strong peaks at a timescale of a year and its higher harmonics, and also at a timescale of the monthly gaps (both sideral and synodic).

We present the results of our analysis in Table 1. We note two strong frequencies. The stronger peak is around 60 yr (Ω), and

[2] See http://www.astro.utu.fi/oj94.

[3] The raw data is available at http://altamira.asu.cas.cz/iblwg/data/oj287.

TABLE 1

Frequency and Pseudopower of the Peaks Detected by the Variable-Gain CLEAN Analysis of the Light Curve of OJ 287

| Period | 1 day Bins | 3 day Bins | 7 day Bins | 1 month Bins |
|---|---|---|---|---|
| $\Omega$ | 1.6655E-2/9.429E-2 | 1.7017E-5/8.024E-2 | 1.7364E-2/8.059E-2 | 1.8185E-2/7.083E-2 |
| $2\Omega$ | ... | ... | ... | 3.5273E-2/5.077E-3 |
| $\omega-\Omega$ | 6.9421E-2/7.502E-3 | 6.9483E-2/8.324E-3 | 6.9457E-2/7.439E-3 | 6.9235E-2/1.299E-2 |
| $\omega$ | 8.4398E-2/3.968E-2 | 8.4463E-2/3.832E-2 | 8.4831E-2/3.519E-2 | 8.4790E-2/3.341E-2 |
| $\omega+\Omega$ | 9.8525E-2/5.793E-3 | ... | ... | ... |
| $\omega+2\Omega$ | 1.1996E-1/3.087E-3 | 1.1993E-1/3.608E-3 | 1.1836E-1/4.791E-3 | 1.1988E-1/6.812E-3 |
| $2\omega$ | 1.6745E-1/2.288E-2 | 1.6774E-1/1.944E-2 | 1.6855E-1/1.683E-2 | 1.6744E-1/1.071E-2 |
| $2\omega+2\Omega$ | 2.0434E-1/3.147E-3 | 2.1374E-1/3.540E-3 | 2.1475E-1/4.130E-3 | 2.1422E-1/5.411E-3 |
| $3\omega+\Omega$ | ... | ... | 2.7325E-1/4.121E-3 | 2.7302E-1/3.947E-3 |
| $4\omega$ | ... | ... | ... | 3.4514E-1/4.769E-3 |
| $5\omega$ | ... | ... | ... | 4.2810E-1/3.435E-3 |
| 1 $\mathrm{yr}^{-1}-(3/2)\omega$ | ... | ... | ... | 8.9914E-1/5.001E-3 |
| 1 $\mathrm{yr}^{-1}-(1/2)\omega$ | ... | ... | ... | 9.5355E-1/3.483E-3 |
| 2 $\mathrm{yr}^{-1}-\omega$ | ... | ... | ... | 1.8646E-1/3.080E-3 |

Note.—$\Omega$ corresponds to the 60 year period and $\omega$ to the 12 yr period.

the second one ($\omega$) is close to 11.8 yr. Additional peaks occur also. Some of the frequencies observed represent the harmonics of the 12 yr peak. This is due to the apparent nonsinusoidal shape of this variation. The periodogram of the 1 month binned data shows frequencies caused by a beat between the window function's 1 yr peak and the 12 yr peak. All the remaining peaks appear to be various low integer beats of the 12 and the 60 yr peaks. No other consistent strong periodic variations at a level of 0.062 mag on timescales longer than $\sim$20 days are seen in the data.

At this point it should be emphasized that an underlying assumption in this and several other analysis methods is that the variability is characterized by a constant recurring type of variability. If the periodic variability is not constant but has a modulated amplitude, then this shows up in the presence of frequency peaks, with frequencies separated from the main peak by the frequency of amplitude modulation (see, e.g., Norton et al. 1992). A modulation frequency is apparent in our spectra. The modulation frequency is so close to the 60 yr cycle that we consider these two frequencies equal.

### 2.3. *Local Analysis of Periodicity*

We applied a wavelet analysis method to the data (Fig. 3). We adopted a Morlet wavelet, which has the form

$$g^*(f,\tau)=\exp\left\{-icf(t-\tau)-\frac{1}{2}[f(t-\tau)]^2\right\}, \qquad (1)$$

where $f$ is a frequency, characterizing the width of the wavelet package or the variability timescale. This is localized around a center of time indicated by the parameter $\tau$. The constant $c$ equals to $2\pi$.

The wavelet methods are superior to the global methods in detecting local variations. The frequency resolution is not as high as, for example, in the Fourier-transform–based methods, but it is localized in time.

When applied to the light curve of OJ 287, the wavelet analysis reveals that a $\sim$60 yr period is present throughout the data. It also shows that the 12 yr period has a varying amplitude with lower amplitudes in the 1950s and higher ones in the 1920s and 1980s. Faster transient variations can also be seen in the wavelet analysis, but most of these are related to the fast variations within the giant flares and other relatively rapid variations.

## 3. DETERMINATION OF THE BINARY ORBIT

The giant flares associated with disk impacts start very suddenly. The brightness rises by a factor of 4 or so in just a few days; the decay of brightness takes place in the timescale of six weeks (Sillanpää et al. 1996a, 1996b). In the well-observed 1973, 1983, and 1984 flares the flux increased by about 15 mJy in 8 days and then decayed in an exponential manner with the timescale of about 16 days. The fourth flare of the same pattern occurred in 1947, even though only the rising part was seen. Therefore the timing of the beginning of a giant flare is important; the time of maximum brightness is less significant since it depends on the superposed normal flaring activity of the jet and the rise or fall of the long-term jet brightness during the giant flare. See Valtaoja et al. (2000) for a good collection of light curves. Figure 4 gives the light curve of the well-observed 1983 flare as an example. The line represents the standard giant flare light curve adopted in this paper, superposed on the theoretically expected jet flux at the time. Note that the total timescale of doubly peaked giant flare is only about 7.5 weeks.

In principle, all three processes mentioned above could explain the giant flares. However, the timescale of the rise of brightness is several months both in the jet wobble model (Villata et al. 1998) and in the tidal model (Sundelius et al. 1997), much too slow to explain the fast rise of flux in giant flares. The fundamental reason is that the primary has to be rather massive in order to produce enough brightness over the long term, which means that the associated timescales are measured in months. The secondary can be much lighter since its energy production is important only during the brief impacts on the accretion disk of the primary. Here the timescales can easily be in days. Thus the most likely origin of giant flares are the disk impacts. Note that for a right combination of parameters rapid changes can also occur due to a precession of a relativistic jet, as in the models of Katz (1997) and Abraham (2000).

The giant flares of 1947.30 (marking the time of the beginning of the flare), 1972.98, 1983.00, 1984.15, and 1994.75 have been used to construct a unique orbit solution (Lehto & Valtonen 1996). One of the outstanding features of this solution is the requirement that the binary orbit precesses by 33° per period (Fig. 5). This is an exceedingly high rate of precession, but can be explained by relativistic precession. The solution is robust and cannot be modified by much even though there are unknown parameters related to the properties of the accretion disk (Pietilä 1998). Because of the high precession rate, OJ 287 is a unique laboratory

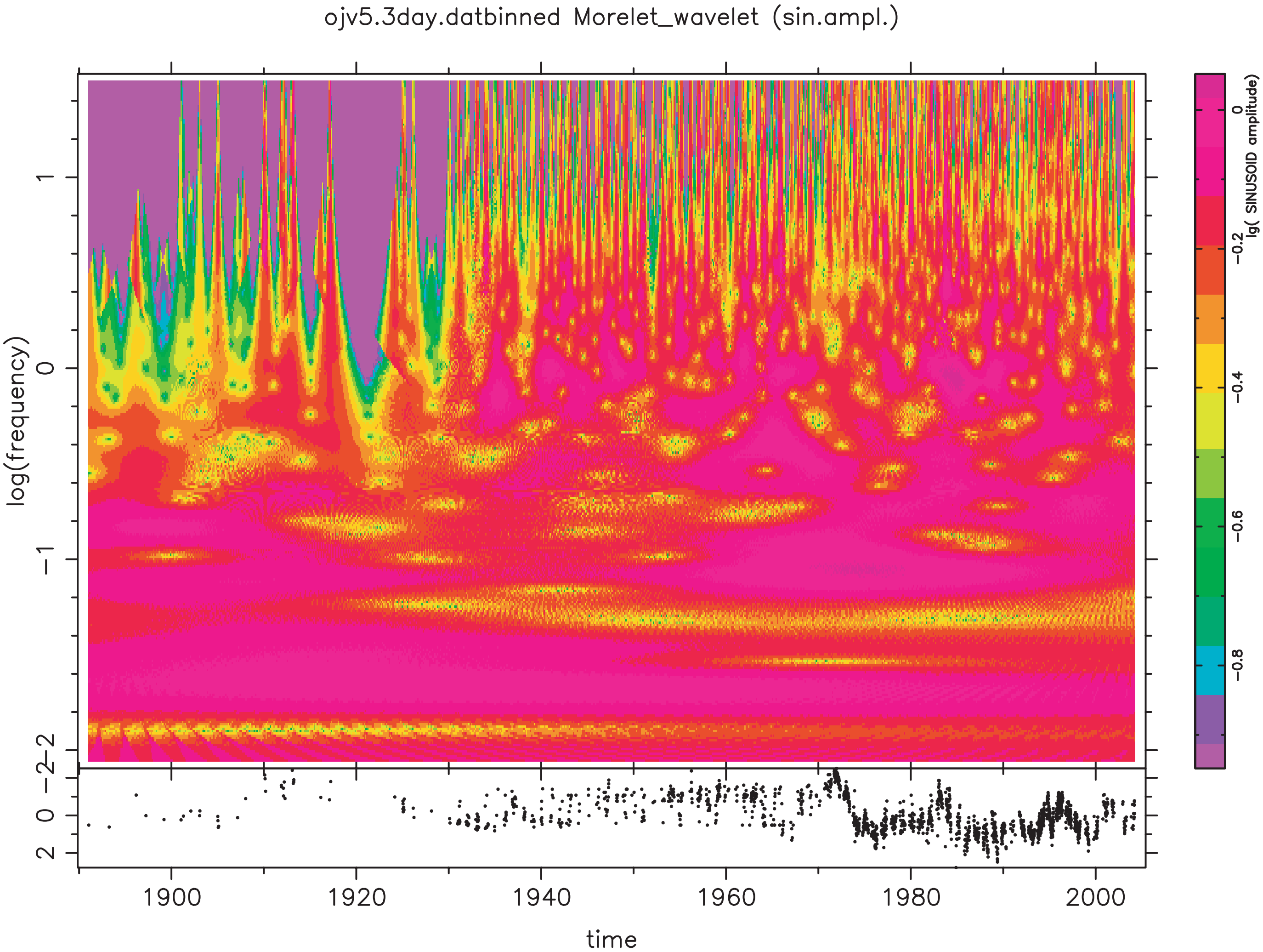


FIG. 3.—Sinusoidal amplitudes of the wavelet transform of the of the 3 day average light curve of OJ 287. The abscissa is time in years. The respective part of the light curve is shown in the lower panel. The coordinates of the wavelet transform is the frequency of variability. The color denotes the amplitude of the sinusoidal-like Morlet wavelet fit at combination of a given timescale and frequency.

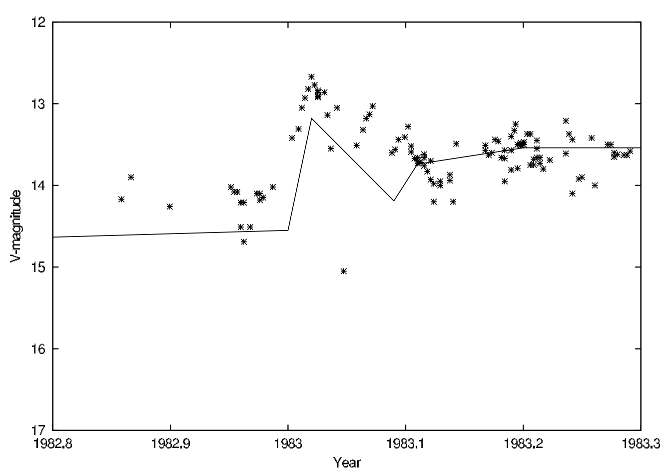


FIG. 4.—Theoretical light curve (*solid line*) and observations around the giant flare of 1983. The points are 3 day averages. Model parameters: $\alpha = 0.85$, mass flow rate $= 0.003$.

for the study of extremely strong gravitational fields, including the loss of orbital energy to gravitational radiation (Valtonen & Lehto 1997).

Another interesting feature of this solution is the fact that there is a dip in the optical light curve every time the secondary traverses a fixed line in the orbital plane (Takalo et al. 1990; Takalo 1994; Pietilä et al. 1999). This line is about 4° from the jet axis (Lehto & Valtonen 1996). If the dip signifies an eclipse of the jet by the secondary, we obtain the orientation of the system relative to the line of sight, i.e., the line of sight is about 4° from the jet line (Valtonen et al. 1999). We call this angle $\phi$ in the following.

An alternative binary model has also been advanced which has no precession of the major axis (Valtaoja et al. 2000). This model predicts the next giant flare in 2006 September. In the precessing binary model the timing of the next flare is a difficult problem since the major axis of the orbit of the secondary currently lies at about 45° angle relative to the plane of the accretion disk; only a small change in the orbital parameters leads to a large change in the time of the disk impact. Moreover, since the burst of radiation does not occur immediately after the impact on the disk, but with a time delay of up to several weeks (Lehto & Valtonen 1996), the time delay formula has to be known very well. But the previous events of timing have been obtained when

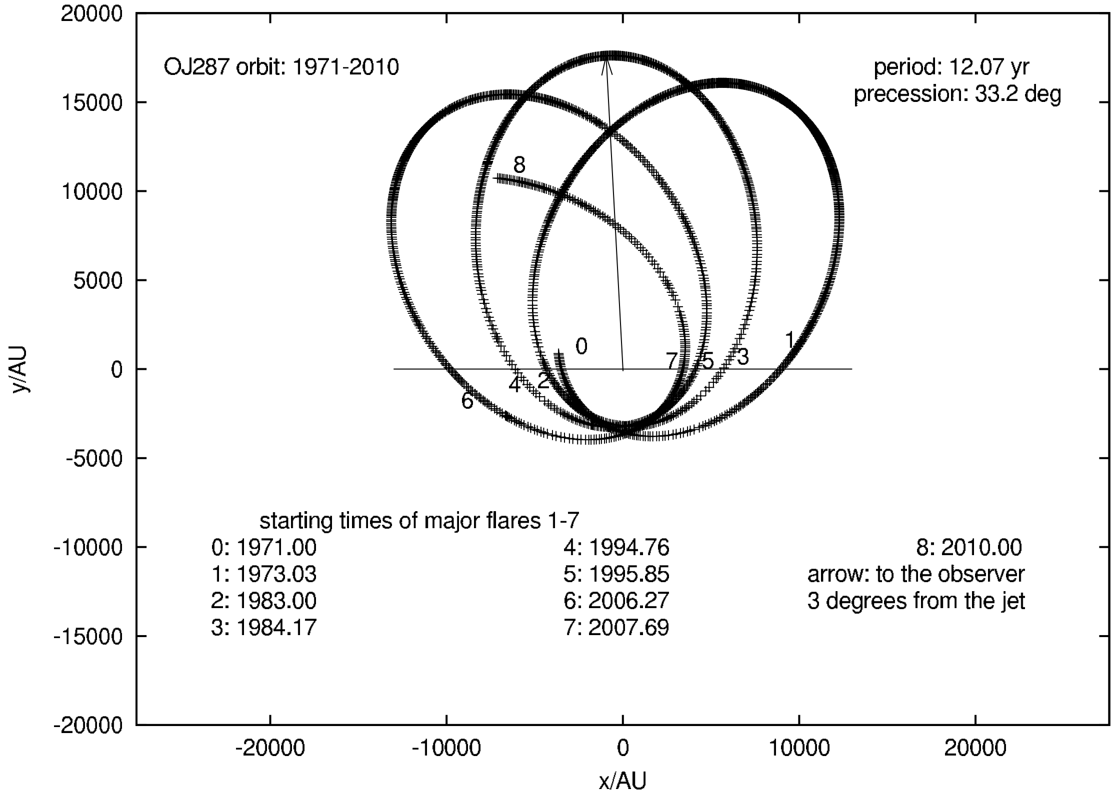


Fig. 5.—Orbit of OJ 287 binary system between 1971 and 2010 in the precessing binary model. Giant flares occur subsequent to the disk crossings. Orbital positions of the secondary are shown at the times of giant flares (numbers 1–7). This model assumes that the line of sight (*arrow*) is projected to the orbital plane at angle $\phi$, which is 3° from the jet line (normal to the disk). The disk is seen edge-on and is represented by a horizontal line.

the point of impact is relatively close to the primary black hole; thus the time delay in 2005/2006 cannot be extrapolated from previous similar events. Previous work has put the timing of the outburst somewhere in the range 2006 March–May (Lehto & Valtonen 1996; Valtonen & Lehto 1997; Pietilä 1998), while taking account of the disk bending (Sundelius et al. 1997) moves the outburst to November 2005. The outburst has now been observed (Valtonen et al. 2006).

## 4. JET WOBBLE

When the secondary black hole approaches the accretion disk of the primary, it pulls the latter toward itself. Assuming that the orbit of the secondary and the accretion disk are (nearly) perpendicular to each other, the disk gas that is pulled "up" rotates away from the impact point with newly acquired inclination. After the first impact the secondary moves quickly to the other side of the primary, impacts the disk for the second time, and then pulls the disk "up" again on the way out. If the major axis of the orbit is perpendicular to the disk plane, the two pulls of the disk more or less cancel each other and the inclination of the accretion disk remains unchanged. However, in the case of the precessing binary, the orientation of the major axis changes from orbit to orbit, and therefore the two pulls are typically unequal: the inclination of the disk evolves. The evolution of the inclination follows the same period as the precession: the full cycle takes 130 yr, but because of the symmetry relative to the two sides of the disk, the system starts repeat itself (almost) after about 60 yr, i.e., after five orbital periods.

To make matters more concrete, we have calculated the evolution of a disk of particles (about 1000 in all), which are in circular orbits and in a common plane around the primary. The particles are placed in rings of equal separation from the inner edge at 10 Schwarzschild radii of the primary to the outer edge at 20 Schwarzschild radii. Each ring has 33 particles at equal angular intervals. The particles are noninteracting: therefore a relativistic three-body code has been used (Mikkola & Aarseth 2002). Initially the inclinations of the disk particles are 90° (or nearly 90°). During the binary orbit of the secondary around the primary, the average inclination of all particles that remain in the disk is calculated. It is assumed that since we are really trying to model elements of gas, these elements will settle through mutual collisions in a plane defined by the mean inclination. This assumption is not trivial. It amounts to saying that the sound crossing time through the disk is of the order of the orbital time of the secondary. This condition was applied by Romero et al. (2000, 2003) to the binary black hole models for 3C 273 and AO 0235+16. Following these authors, the rigid disk condition can be translated to a condition for the minimum thickness of the accretion disk. In our case it requires a disk flaring angle greater than 10°, larger than is normally assumed in the standard disk models (Sakimoto & Coroniti 1981). However, it is in agreement with the particle disk simulations by Sundelius et al. (1997). In case of OJ 287, the frequent impacts on the disk by the secondary increase the sound speed and the thickness of the disk. In the present work, we aim at calculating the orientation of the jet, which is connected to the disk at its base. Magnetohydrodynamic simulations by Turner et al. (1999) show that the jet reacts to changes in the disk in about one orbital time of the disk at its inner edge. The relevant speed in this case is the Alfvén speed in the magnetized material above the disk which is much greater than the sound speed in the disk. Our model is far from complete. It should be complemented by magnetohydrodynamic calculations of the perturbed disk-jet connection. However, they are beyond the scope of the present paper.

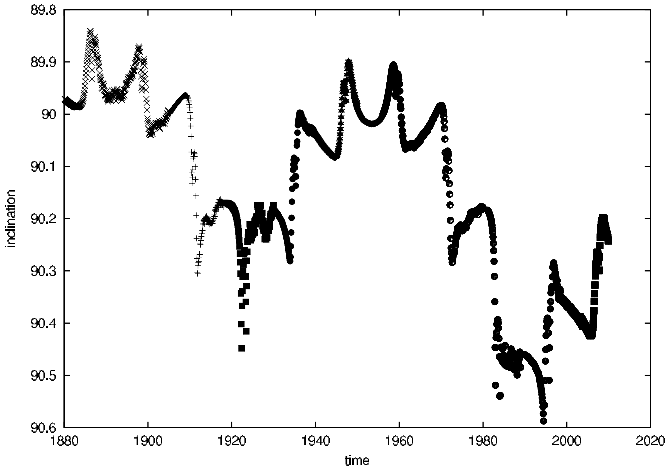


FIG. 6.—Median inclination of the disk particles as a function of time in the precessing binary model. The disk extends from 10 to 20 Schwarzschild radii from the primary black hole. The calculation is restarted half way between two outburst seasons (pericenter passages) by collecting all particles to the median inclination plane and circularizing the orbits.

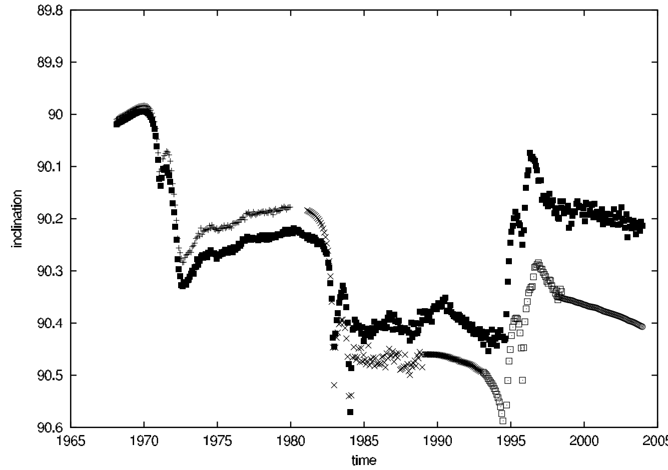


FIG. 7.—Two calculations of the median inclination of the disk particles. The first one is carried out as explained in the caption of the previous figure (*varying symbols*). The second calculation is a single run without restarts (*squares*). The two calculations agree qualitatively but disagree in detail.

In our simulations we use the orbital parameters determined by Lehto & Valtonen (1996). At the beginning of the simulation, the secondary is far from the disk; at the end the mean disk is calculated when the secondary is again far from the disk. For the next encounter of the secondary with the disk, the particles are again placed in a plane with a common inclination (the previous mean inclination) and the process is repeated. In this way the history of the mean inclination as a function of time is evaluated, starting from 1880 and going to 2010 in future. Experimenting with different inner and outer radii within the previous range has shown that the result is not very sensitive to this choice. The evolution of the disk inclination is shown in Figure 6. The evolution consists of rather sudden jumps between different inclination values. The exact values of the jumps depend on the radial range of the particles in the rings, but qualitatively Figure 6 gives a good description of the behavior of the mean disk.

Figure 7 shows a shorter segment of the same curve as in Figure 6, but calculated by two different methods. The first method is as described above, while in the second method the evolution of the disk is followed through several binary periods without adjusting the inclinations to the common mean value in between. The two results are qualitatively similar.

As we can see from the historical record of Figure 1, the expected 60 yr cycle is apparent in brightness variation (Sillanpää et al. 1988). The variation in the mean brightness is about 1 mag. On the other hand, the calculated maximum variation of the disk inclination during the 60 yr cycle is half a degree. Let us suppose that the disk inclination determines the orientation of the jet. Then we expect a half-a-degree wobble in the jet direction during the same period. The wobble takes place in a direction perpendicular to the orbital plane of the binary.

Let us look at the relativistic jet from a viewing angle $\theta$ which is greater or equal to $1/\Gamma$, where $\Gamma$ is the Lorentz factor. Then the magnitude difference between the viewing angle $\theta$ and a smaller viewing angle $\theta_0$ is approximately

$$\Delta m = -2.5 \log\left(\frac{S}{S_0}\right) = 12.5 \log\left(\frac{\theta}{\theta_0}\right), \qquad (2)$$

where $m$ is the magnitude, $S$ and $S_0$ the observed fluxes from the jet of spectral index $-0.5$. The jet is assumed to be highly relativistic and the viewing angles small enough that $1 - \cos(\theta)$ is approximately $1/2(\theta)^2$. Let us assume that the change of $\theta$ (the wobble) $\Delta\theta \ll \theta_0$, i.e.,

$$\log\left(\frac{\theta}{\theta_0}\right) = \frac{1.0}{2.3} \ln\left(1 + \frac{\Delta\theta}{\theta_0}\right) = \frac{1.0}{2.3}\frac{\Delta\theta}{\theta_0}, \qquad (3)$$

and therefore

$$\Delta m = 5.43 \frac{\Delta\theta}{\theta_0}. \qquad (4)$$

We see that the observed $\Delta m = 1.0$ and the theoretical wobble $\Delta\theta = 0\overset{\circ}{.}5$ leads to $\theta_0 = 2\overset{\circ}{.}7$. The condition for the Lorentz factor becomes $\Gamma > 20$. These values are not unreasonable based on other evidence (Teräsranta & Valtaoja 1994; Lähteenmäki et al. 1999; Tateyama & Kingham 2004).

Therefore it becomes possible to change the inclination scale in Figure 6 to a magnitude scale by a simple linear transformation. This transformation has been carried out in Figure 8. The solid line is the theoretical prediction from the jet wobble, while

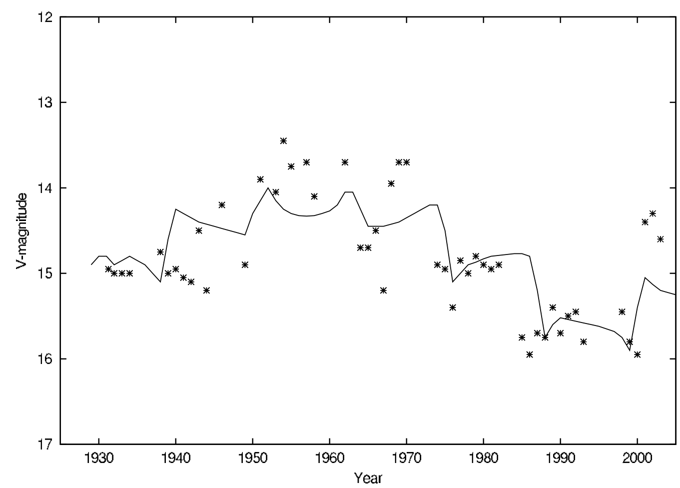


FIG. 8.—Magnitude variations resulting from the jet wobble as a result of inclination variations shown in Fig. 6 (*solid line*). The inclination variations $\Delta\theta$ are connected to the magnitude range $\Delta m$ as explained in the text, with an optimum choice of zero point. The stars represent observed seasonal $V$ magnitudes, excluding times of major outbursts. Note that there is a shift of the curve relative to the points in forward direction by 4 yr, perhaps indicating that this is the response time of the jet to the changing disk inclination.

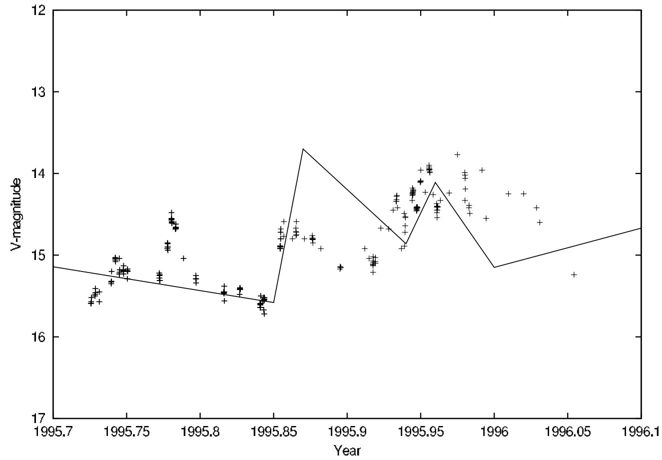


FIG. 9.—Theoretical light curve (*solid line*) around the 1995 giant flare as compared with observations. This flare represents the only case in the historical light curve where the start of the outburst is shadowed by the accretion disk of the secondary. A similar phenomenon should occur during the 2007 giant flare. Model parameters: $\alpha = 0.85$, mass flow rate $= 0.003$.

the star symbols represent the median quiet level of OJ 287. The quiet level points are obtained by taking seasonal median values whenever at least five observations have been reported for the season. The points representing outburst seasons have been left out (Hudec et al. 2001; Pursimo et al. 2000). The process is by no means unique. However, the resulting curve may be taken as representative of the kind of behavior of OJ 287, which should be compared with the wobble model.

Figure 8 shows stepwise evolution: there is a rather well defined mean level of brightness between the outbursts, but the level is different from one binary orbit to the next. A comparison of the timing of the flux level changes between theory and observations seems to show that the observations lag behind the theory by about 4 yr, which is the typical orbital period in the inner disk. The theoretical times have been moved forward by this amount in Figure 8. It may be that this is the response time of the jet to the disk wobble. A more detailed comparison is difficult because the extra flux from disk impacts and from tidally induced increase in accretion occur close to the time of the expected flux level steps.

Note that in a nonprecessing model the inclination will also change in steps. However, due to the constancy of the position angle of the major axis of the binary orbit, the steps are always of the same size and lead to one direction only. Therefore the jet wobble leads to at most one maximum of brightness, corresponding to the time when the jet axis passes closest to the line of sight.

We could imagine that the jet line is in the orbital plane of the binary (if the disk inclination is exactly 90° plus or minus the wobble) while the line of sight is about 2° off the orbital plane. Then once during each orbit the secondary passes in front of the line of sight to the inner jet. The radius of the system of gas clouds surrounding the secondary black hole is estimated to be about 6° as seen from the primary (Lehto & Valtonen 1996), which means that it blocks light from the inner jet once during each passage; thus it is reasonable to interpret the dips in the light curve as eclipses. The eclipse should be centered on zero phase angle $\phi$ of the orbit.

An interesting consequence of the possibility of eclipses is that the light from the 1995 outburst would have been blocked by the same gas clouds during the first 10 days of the event. This may explain why the optical flux did not rise to the maximum brightness immediately. Other outbursts in our historical record should not have been affected in this way. However, the eclipse

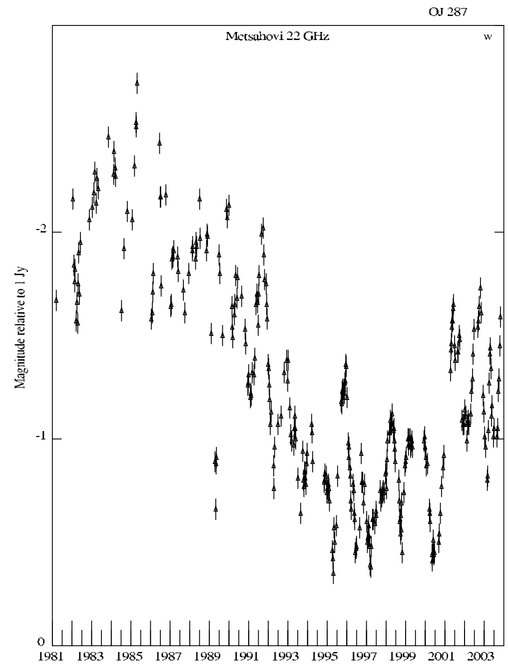


FIG. 10.—Plot of 22 GHz observations of OJ 287 at Metsähovi. The scale is in magnitudes, with the reference point (zero) at 1 Jy. The points are weekly averages.

phenomenon should repeat itself again in the first 10 days of the 2007 giant flare. Figure 9 shows the comparison of observations at late 1995 with the theoretical light curve, excluding extinction. It is seen that about a 1 mag extinction would suffice to bring the 1995 outburst in line with the standard light curve.

The jet wobble should show itself also in radio flux. The Michigan group has covered the radio flux variations very well since 1971 (Hughes et al. 1998). If we leave aside the repeated outbursts, some of which may relate to the tidal influence of the secondary, and only look at the base level of activity at 8 GHz,

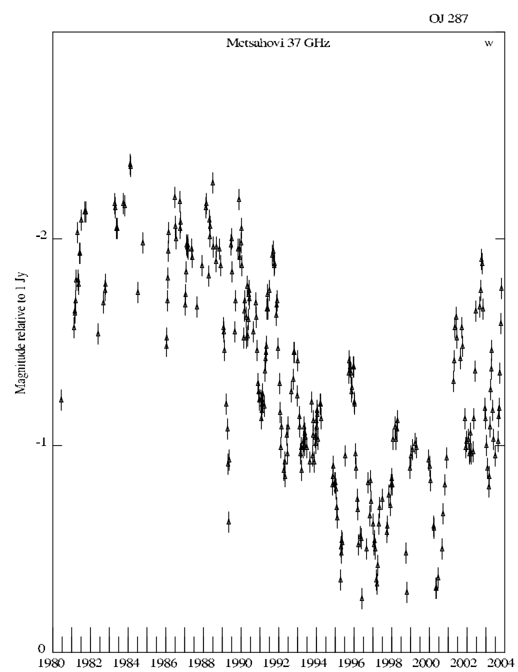


FIG. 11.—Plot of 37 GHz observations of OJ 287 at Metsähovi. The scale is in magnitudes, with the reference point (zero) at 1 Jy. The points are weekly averages.

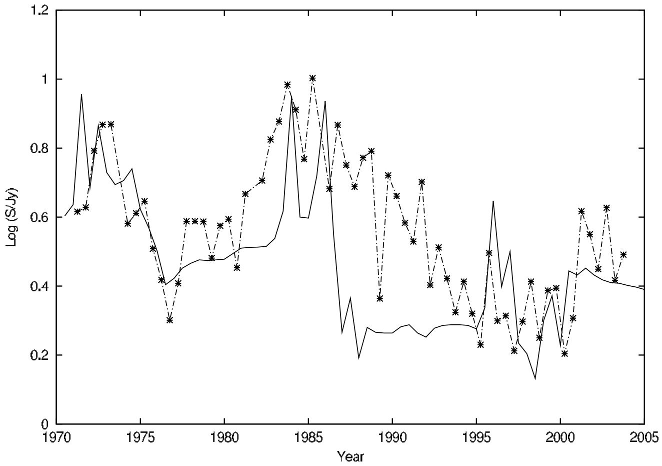


FIG. 12.—Radio flux variations at 22 GHz resulting from the jet wobble and from the tidal perturbations of the disk. The crosses connected by the dashed line are the semiannual, median flux values from Metsähovi (1981–2003) and from Michigan (1971–1980: observations at 8 GHz multiplied by a factor of 1.08). The beaming effect of the theoretical curve has been delayed by 4 yr; the profiles and the timing of the tidal features are as given by Sundelius et al. (1997).

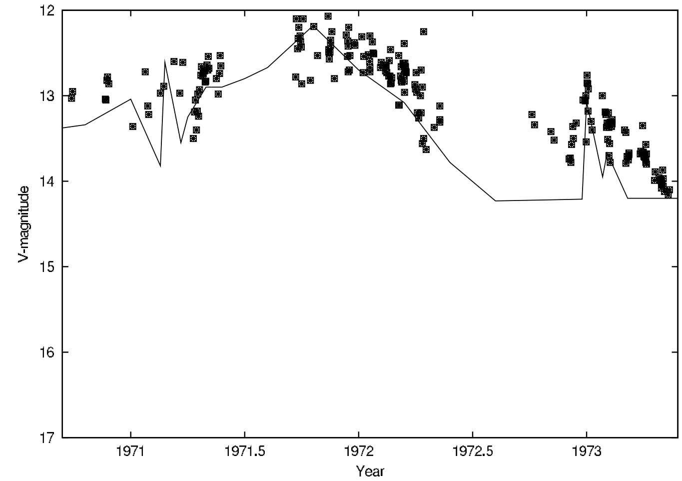


FIG. 13.—Theoretical light curve (*solid line*) and observations around the 1972 tidal outburst. The observations are 3 day averages. The giant flares are the narrow double peaks at 1971.14 and 1972.98, and the tidal outburst is the wide feature starting at about 1971.50. Model parameters: $\alpha = 0.85$, mass flow rate $= 0.003$.

we find a steady drop of this level from 1971 (at about 4 Jy) until late 1990s (at about 1 Jy). This is also the general expectation of the jet wobble model. If the model is correct, the base level should have started a recovery around year 2000, and it should reach the mid 1980s base level of about 2.5 Jy at latest in 2014. The most recent observations seem to indicate that the recovery has indeed started. This is contrary to the expectation from the nonprecessing model, where the source should continue to decline in brightness until the jet is so badly aligned ($\sim 5°$) with the line of sight that the source is not seen any more.

Figures 10 and 11 show the 22 GHz and 37 GHz light curves from Metsähovi observations, respectively. The points are weekly averages. The fluxes are presented in a logarithmic scale since it provides the most direct test with the wobble theory. Figure 12 compares the theoretical flux level at 22 GHz with observations. For the theoretical calculation, the jet misalignment angle of $\theta_0 = 2\overset{\circ}{.}7$ was used. The measurements are shown in the figure as semiannual mean values since 1981. The data points from the period 1971–1980 are from the Michigan group, measured at 8 GHz (Aller et al. 1985), and corrected by the typical spectral factor of 1.08 to make them comparable to the 22 GHz points. The theoretical curve combines both the tidal transfer events (Sundelius et al. 1997; see the next section) and the beaming effect. The beaming effect has been delayed by 4 years, as in the case of the optical comparison. The theoretical tidal transfer outbursts have been normalized to the height of the observed 1980's outbursts. This normalization makes the 1996 theoretical outburst somewhat too big. The reason for the discrepancy could be a somewhat nonlinear relation between the rate of the mass transfer to the jet and the jet brightness, as suggested by Heinz & Sunyaev (2003).

## 5. TRANSFER OF MATTER TO THE JET

Sillanpää et al. (1988) and Sundelius et al. (1997) considered tidally induced accretion as the reason for the outbursts in OJ 287 during each pericenter passage. Such events should take place shortly after the pericenter, and they should last typically for 3 yr. A good example of a tidally induced event is the great 1972 outburst. Such events are quite different from the giant flares, which are much sharper features of the light curve. Put together, the two giant flares and the single tidal event form an outburst season at 12 yr intervals. The latest season started with the 1994, and 1995 giant flares and continued with the 1996 broad (and energetically the most important) outburst. The regular 12 yr periodicity is seen only in the broad tidal events. Due to precession, the giant flares shift in a regular and predictable manner relative to the tidal (main) outburst. Figure 13 shows the comparison of observations with the theory during the 1972 outburst season. The theory includes tidally induced accretion, magnified by beaming effects, as well as the two giant flares of this period.

The detailed mechanism of transfer of matter from the disk to the jet is unknown. In some theories the magnetic field lines connect the disk from about 10 Schwarzschild radii to the disk axis where the field lines are tightly twisted in a jet (e.g., Turner et al., 1999). Particles, which are lifted from the disk, follow the field

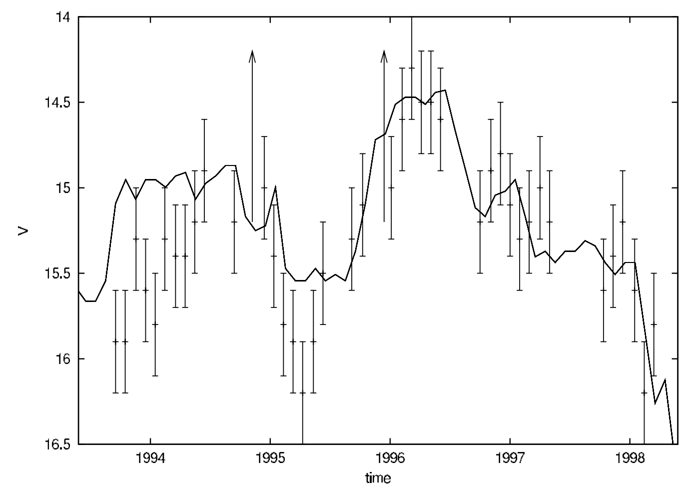


FIG. 14.—Logarithm of the rate of escape of particles from the disk, the disk being defined as those particles which lie within 2° of the mean plane, during the 1996 outburst season (*solid line*). The line has been shifted 0.25 yr forward in time in order to improve the fit with observations. The average value is shown by a short horizontal line. The vertical bars indicate the typical range of flaring activity. The two giant flares have been removed from the positions shown by arrows. The range of observed magnitude variations is about 1.4 times greater than the range of the particle escape rate. This supports a relation of the type jet flux $\sim$ mass flux$^{1.4}$ (Heinz & Sunyaev 2003). The shift between theory and observations is presumably related to the time it takes particles to travel from the disk to the jet.

TABLE 2

Giant Flares, Fades, and Tidal Outbursts in OJ 287 in the Precessing Binary Model

| Flares | Status | Fades | Status | Tidal (optical) | Size[a] | Status | Tidal (radio) | Size[a] | Status |
|---|---|---|---|---|---|---|---|---|---|
| 1894.18...................... | No data | ... | ... | ... | ... | ... | ... | ... | ... |
| 1898.70...................... | No data | ... | ... | ... | ... | ... | ... | ... | ... |
| 1901.64...................... | Summer | ... | ... | ... | ... | ... | ... | ... | ... |
| 1910.63...................... | Summer | ... | ... | 1911.30 | I | No data | ... | ... | ... |
| | ... | ... | ... | 1913.10 | II | Seen | ... | ... | ... |
| 1912.08...................... | Seen | ... | ... | 1916.20 | III | ? | ... | ... | ... |
| 1922.50...................... | Summer | ... | ... | ... | ... | ... | ... | ... | ... |
| 1923.59...................... | Summer | ... | ... | 1924.00 | II | Seen | ... | ... | ... |
| 1934.19...................... | No data | ... | ... | 1936.00 | I | Seen | ... | ... | ... |
| 1935.40...................... | Summer | ... | ... | 1937.20 | II | Seen | ... | ... | ... |
| 1945.48...................... | Summer | ... | ... | ... | ... | ... | ... | ... | ... |
| 1947.30...................... | Seen | ... | ... | 1947.90 | I | Seen | ... | ... | ... |
| 1956.24...................... | Seen | ... | ... | 1959.50 | I | No data | ... | ... | ... |
| 1959.22...................... | Seen | ... | ... | 1960.20 | II | Seen | ... | ... | ... |
| 1963.58...................... | Summer | 1970.11 | No data | ... | I | ... | ... | ... | ... |
| 1971.14...................... | Seen | ... | ... | 1971.70 | I | Seen | 1971.50 | I | ? |
| 1972.98...................... | Seen | ... | ... | ... | ... | ... | 1972.60 | II | Seen |
| | ... | 1980.68 | Seen | ... | ... | ... | 1974.60 | II | Seen |
| 1983.00...................... | Seen | ... | ... | 1984.00 | II | Seen | 1983.80 | I | Seen |
| 1984.15...................... | Seen | 1989.38 | Seen | 1985.20 | II | Seen | 1985.70 | I | Seen |
| 1994.75...................... | Seen | ... | ... | 1995.60 | II | Seen | 1995.80 | II | Seen |
| | ... | ... | ... | 1996.60 | I | Seen | 1996.80 | III | Seen |
| 1995.85...................... | Seen | 1998.11 | Seen | 1997.20 | II | Seen | ... | ... | ... |
| 2005.81...................... | Seen | ... | ... | ... | ... | ... | ... | ... | ... |
| 2007.68...................... | Sep 7 | 2008.67 | Sep 4 | 2008.20 | II | Jan–May | 2007.40 | IV | May–Jun |
| | ... | ... | ... | ... | ... | ... | 2010.90 | III | Nov–Dec |

[a] I = strongest feature, IV = weakest feature.

lines and end up in the jet at some later time. We now consider this process in the light of our disk simulations.

Figure 14 shows the number of particles lifted out of the disk per unit time during the 1996 outburst season. The scale is logarithmic (with an arbitrary zero point) in order that a comparison with the magnitude scale can be made directly. The assumption is that the brightness scales as the mass flow rate out of the disk. In reality the relation may not be quite linear but follow, e.g., brightness proportional to (mass flow rate)$^{1.4}$ (Heinz & Sunyaev 2003). For comparison, the available data points from this period are also shown (Sillanpää et al. 1996a, 1996b; Pietilä et al. 1999). The definition for a particle being lifted from the disk is that its inclination becomes greater than 2°; however, the results are not sensitive to the exact value of the inclination. We see that the theory explains the main outbursts quite satisfactorily. The two giant flares have been removed from the positions indicated by the arrows.

Based on the same model as Figure 14, we find that the main (tidal) outburst of the 2008 outburst season should begin in 2007 September, more or less coinciding with the second giant flare, and it should reach a broad maximum in 2008 February–March. Rather similar light curves have been obtained by Sundelius et al. (1997) by counting particles that cross into the 10 Schwarzschild radius circle for the first time. Table 2 lists the expected maxima of tidal outbursts according to these calculations. The tidal features are broad, lasting typically for 1 yr, and their strength varies. We have categorized the expected strength by classes I–IV, I being the strongest and IV the weakest. There can be several tidal outbursts per season. Note that the flux rise in tidal outbursts occurs over several months rather than in days, contrary to giant flares.

## 6. GIANT FLARES

An analytical theory of giant flares was derived by Lehto & Valtonen (1996), while Ivanov et al. (1998) carried out numerical simulations of some special cases (perpendicular impacts). We have also studied the behavior of the disk of particles at the immediate neighborhood of the impact site. For the parameters of the binary model, the region of interest was deemed to be within the radius of 200 AU from the impact, which is about 3 times the Bondi accretion radius. Figure 15 shows the particles of the 1994 impact region from a rectangle of diameter of 400 AU, excluding particles inside a circle of 100 AU from the impact site, after the

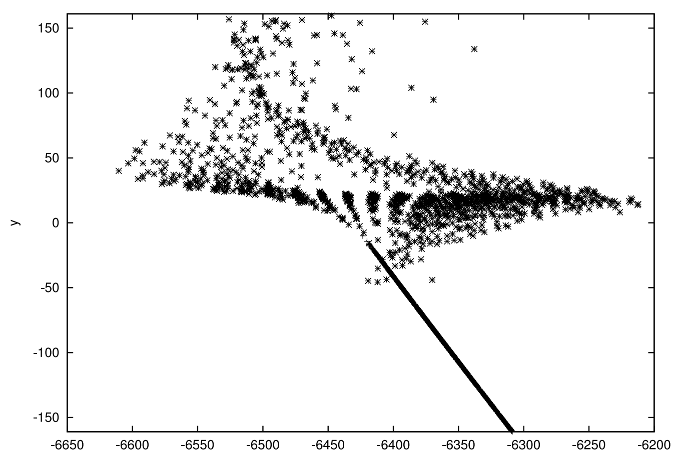


Fig. 15.—Positions of particles in the disk after the impact by the secondary in 1994. The orbit of the secondary is shown by the solid line pointing to the lower right, which is the direction of the recession of the secondary after the impact. The particles were initially in a rectangle of 400 AU in diameter centered on the point of impact, excluding particles within 100 AU of the impact site. The particles are projected onto the orbital plane of the secondary. The original disk was a horizontal line at $y = 0$ in this projection. The $x$-coordinate measures the distance from the primary black hole in AU.

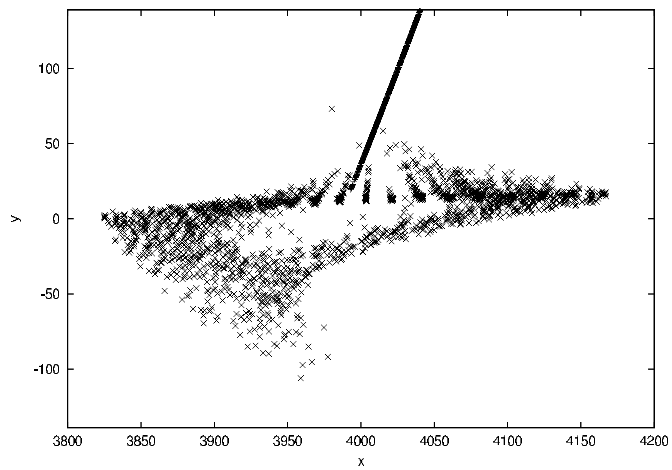


FIG. 16.—Same as Fig. 15, except that the disk particles are shown after the 1995 impact. The secondary now recedes to the upper right.

impact. The line leading to the lower right is the orbit of the secondary after the impact. The disk particles have been projected onto the binary plane. The disk has been pulled "up" by about 15 AU and has been tilted by about $5^{\circ}$. The corresponding illustration of the local patch of the disk after the 1995 impact is shown in Figure 16. Particles that pass closer to the secondary acquire occasionally very high speeds, up to half the speed of light. This agrees with Ivanov et al. (1998) when their model is scaled to the present problem.

The high speeds of the gas elements lead to shock waves, which accelerate particles to relativistic velocities. Since the accretion disk is strongly magnetic, particles will radiate via synchrotron radiation as well as via bremsstrahlung. The model of Lehto & Valtonen (1996) dealt with bremsstrahlung only, but it is easily expanded to include also synchrotron radiation. The latter will increase the optical depth and lead to a somewhat later time of the outburst. The effect is difficult to quantify since the number density of relativistic electrons arising in the collision process is not known. The fact that the degree of optical polarization drops during the outbursts without a corresponding sudden jump in the position angle of polarization suggests that the increased flux is unpolarized and is likely to be bremsstrahlung (Sillanpää 1991; Takalo 1994; Efimov & Shakhovskoy 1996; Pursimo et al. 2000; Wang et al. 2000).

The spectrum of bremsstrahlung in the optical region is close to a power law of spectral index $-0.5$ (Lang 1999). The synchrotron spectrum of OJ 287 also follows more or less a power law but with a steeper spectrum (index about $-1$). Therefore the total spectrum (bremsstrahlung plus synchrotron) should rise more strongly toward the ultraviolet end at the time of giant flares than at other times. Observations confirm this prediction of the bremsstrahlung model: the spectral index is flatter by about 0.2–0.5 units during the giant flares than outside the giant flares (Takalo & Sillanpää 1989; Pursimo et al. 2000). However, Kidger et al. (1995) and Sillanpää et al. (1996b) find little evidence of the spectral flattening in the red end of the spectrum. In the ultraviolet region the bremsstrahlung spectral index becomes about $-1.8$, again in agreement with the measurements during the 1994 giant flare (Pursimo et al. 2000).

The shock waves occur most strongly on the same side of the disk as the secondary after it has crossed the disk (Ivanov et al. 1998). Therefore, if there is radio emission connected with the disk crossing, it should be associated primarily, or entirely, with the "out" type giant flares, such as the 1973, 1984 and 1995 flares. This may indeed be the case (Valtaoja et al. 2000).

Alternatively, the radio flares coincide accidentally with the second optical flare because of the delayed response of the jet emission to the disk crossing (Valtonen et al. 1999). In this model the transfer of disk particles through the 13 Schwarzschild radius circle is counted (rather than 10 Schwarzschild radii in the optical). Very little radio emission is expected from OJ 287 during the 2008 season. The strongest event is expected in 2011, and it should be only half the strength of the 1995 radio outburst. It is the much weaker counterpart of the 1975 and 1985 radio flares (see Table 2). The observed similarity of the position angle behavior of the radio and optical polarization favors the jet origin of the radio emission (Sillanpää 1991; Pursimo et al. 2000).

The expansion of hot gas takes place over a wide angle in the models of Ivanov et al. (1998), but it is due to the artificial vertical density profile of the disk. In real exponential atmospheres of the disk the flow of gas is focussed to a more jetlike stream (Sanders 1976). The jets arising from a disk impact are probably not more than mildly relativistic and therefore we do not expect very much Doppler boosting. Thus the previous calculations of the brightness of the giant flares should be close to correct. Also the $5^{\circ}$ or so tilt in the jet direction relative to the normal of the disk should not have observable consequences.

## 7. BACK TO THE ORBIT

It appears now that the angle $\phi$ between the jet line and the projected (onto the orbital plane) line of sight is even smaller than the $4^{\circ}$ assumed previously. It is possible to decrease the angle $\phi$ by decreasing the delay between the time of impact and the time of maximum brightness. The time delay is a function of the mean density of matter in the accretion disk. The density depends on the mass accretion rate and the viscosity parameter $\alpha$. The mass transfer rate was set rather arbitrarily to 0.1 in units where the critical (Eddington) accretion rate is unity while the parameter $\alpha$ was put equal to 1 (Lehto & Valtonen 1996). The calculation of the relative accretion rate requires knowledge of the unbeamed absolute luminosity of OJ 287, which cannot be calculated very exactly. Lehto & Valtonen (1996) used the luminosity $3 \times 10^{47}$ ergs $s^{-1}$ as quoted by Worrall et al. (1982). Bassani et al. (1983) give $1.3 \times 10^{46}$ ergs $s^{-1}$. Thus the mass transfer rate could be a factor of 23 lower than in Lehto & Valtonen (1996). The $\alpha$ parameter is also unknown. Therefore we are well justified in modifying the disk parameters. The lowering of the mass transfer rate may bring the time delay to a value that is consistent with the wobble interpretation. It is also reasonable from the point of view of accretion disk models (Sakimoto & Coroniti 1981).

Pietilä (1998) carried out an extensive survey of precessing binary models in which he varied the above two parameters. He used the same five giant flares as Lehto & Valtonen (1996) to fix the basic model, allowing an uncertainty of 1 week for the beginning of these outbursts. Then he selected models that gave the timing of the 1995 outburst within a much wider range. He found about 250 acceptable models. He justified the wide range of the timing of the 1995 giant flare by the relatively small rise of the initial 1995.85 event. However, when we take account of the expected dimming of light by the secondary in the beginning of this giant flare, the above timing becomes just about the only possibility. The timing of the drop in the degree of polarization also agrees with this interpretation of the light curve (Pursimo et al. 2000). The number of suitable models that satisfy this additional requirement is only about six in Pietilä 's work.

Another way to study the exact timing of the 1995 giant flare is to perform wavelet analysis of the variability timescales in OJ 287 around the times of giant flares (Lehto 2003). There appears a marked increase in rapid variability just at 1994.75 and 1995.85, which lasts through the 6 week giant flare period. Since the excess radiation in the giant flares comes from regions smaller than the regions of jet emission, it is not surprising that the rapid variability (in days) becomes more prominent.

At the time of writing of Pietilä (1998) the timing of the 1998 fade was not yet known; in fact it was one of the tests of the correctness of the basic model. After the exact time of the 1998 fade was found, only two models remained in the set calculated by Pietilä (1998). They both have a low accretion rate (0.003 in the above units) and relatively high $\alpha$ (0.45 and 0.85, respectively). Considering that the Eddington luminosity of OJ 287 is about $2\times10^{48}$ ergs $s^{-1}$ and that there must be a large Doppler boosting correction (about factor of 5; Xie et al. 2002) in the calculated luminosity, the accretion rate 0.003 relative to the Eddington rate is quite reasonable. It agrees also quite well with observations of other active galactic nuclei (Bian & Zhao 2003).

We can search for the optimum value of the parameters if we find one more well-determined giant flare in the historical light curve. The best additional outburst at present is the 1956.24 event, which is among the three strongest ever recorded in OJ 287 (Hudec et al. 2001). It happened earlier than it was predicted in the original model, but it is highly sensitive to the time delay parameter. By lowering the time delay parameter $t_0$ by a coefficient of 0.71 we get the correct timing for the 1956.24 event while keeping the previously found good results for the 1947, 1959, 1971, 1973, 1983, 1984, 1994, and 1995 events. At the same time, the 1963 event is pushed to the summer of 1963, which explains the lack of this feature in the historical light curve. The 2005 November event is discussed by Valtonen et al. (2006). In this case the time delay model is very close to the one calculated by Pietilä (1998) for the accretion rate 0.003 and $\alpha = 0.85$. The main uncertainty in the light curve of the 1956 event is the lack of observations from the rising part of the giant flare (Fig. 17). Only its decline is well documented. In principle, an earlier date for the beginning of the outburst is also possible, as far back as 1956.15.

Another change to the 1996 model of Lehto and Valtonen is required by the hydrodynamic simulations of disk impact (Ivanov et al. 1998). According to these simulations, the bursting of hot

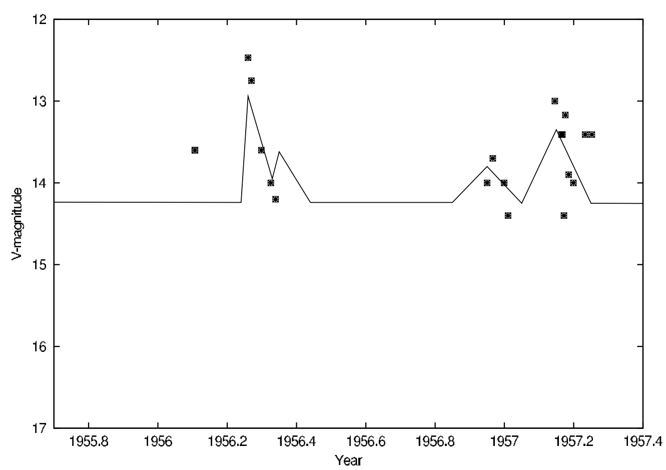


Fig. 17.—Theoretical light curve (*solid line*) and observed points in the historical light curve of OJ 287 around the time of the 1956 great outburst. The beginning of the outburst is at 1956.24 in the theoretical curve. Model parameters: $\alpha = 0.85$, mass flow rate = 0.003.

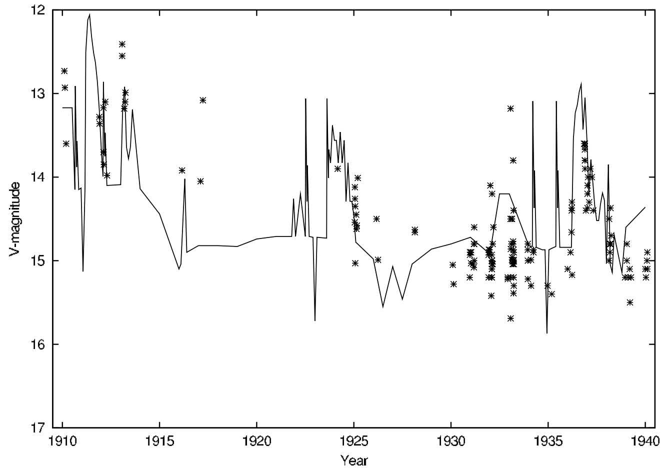


Fig. 18.—Theoretical light curve (*solid line*) in 1910–1940 compared with observations. The observations are 3 day averages. The timescale in this figure is quite different from that in the previous figures. The typical season of activity consists of two relatively narrow peaks (giant flares), a wider feature, i.e., the tidal outburst, possibly a significant fade in the light curve and a precursor activity, which occurs typically before the first giant flare of the activity season.

gas from the disk starts well before the companion has arrived at the original midplane of the disk. The zero reference time would be more properly the time of entering the disk rather than crossing the original midplane. In effect this results in rotating the disk plane in the original model by the half-opening angle of the disk. At the typical distance of the impacts it is about 3°, and it brings $\phi$ this much closer to zero.

The total effect of these minor corrections to the original model is to bring it in agreement with the 60 yr periodic variation cycle of the "quiet" level, as well as explaining one more (1956) giant flare and the lack of observation of another one (1963 flare). Table 2 summarizes the current observational situation of giant flares and fades (eclipses) in the best model. We have also made an effort to identify the 1934 expected giant flare in the historical record, but unfortunately there is a gap in data just at the expected outburst time (1934.19) and the two weeks following it.

## 8. PRECURSORS

It appears that OJ 287 becomes active at a low level already well before the first disk impact of the outburst season. We may

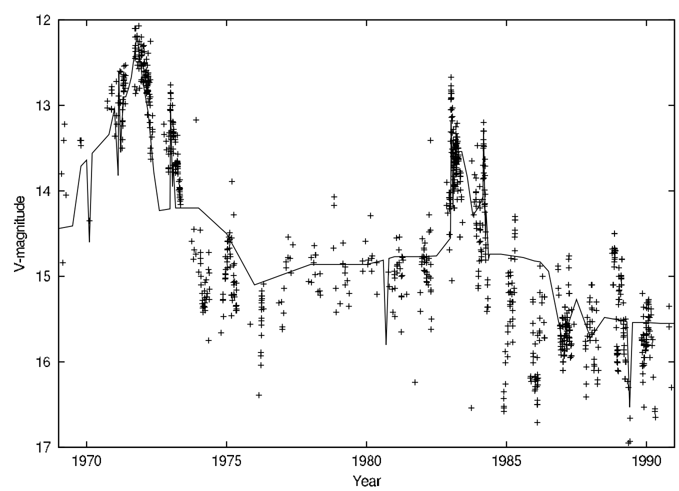


Fig. 19.—Theoretical light curve (*solid line*) in 1970–1990 compared with observation. The observations are 3 day averages. Model parameters: $\alpha = 0.85$, mass flow rate = 0.003.

term these first signs of activity as precursors. There was a prominent precursor at the end of 1993, almost a year before the 1994 giant flare (Kidger et al. 1995). Earlier on in the historical record, the 1910 flare may belong to the same category (Fig. 18). As Figure 14 shows, the precursor activity seems to be associated with the increase of inclinations of the disk elements. These elements presumably end up in the jet, where they cause increased brightness. The tidal transfers are not significant yet at this time and thus precursors do not appear in theoretical light curves, which only include tidal outbursts, beaming, and disk impacts. The light curve of Figure 18, as well as the light curve of Figure 19 from 1970s and 1980s, includes the calculated precursor activity. It is therefore of interest to calculate the precursor activity of the 2005–2010 outburst season. The model shows the beginning of activity already at the end of 2003, and that it should have continued rather steadily until the November 2005 outburst. The reason why we expected precursors over the period of several years before 2005 is that the approach angle of the secondary relative to the disk is very shallow (about 45°) this time, and therefore the influences of the secondary start early. Also, the disk crossing takes place already in 2005 March. The precursor activity was observed, and will be reported elsewhere.

## 9. DISCUSSION

The models that have been suggested as an explanation of the 12 yr periodicity in OJ 287 fall in two broad categories: single black hole models and binary black hole models. If nothing else were known about OJ 287 except for the 12 yr periodicity and the larger 130 yr cycle, the single black hole model should be favored. For a $(3-6)\times10^9$ solar mass black hole, accretion disk oscillations in both cycles are expected (Igumenschev & Abramowicz 1999). But these are only quasi-periodic oscillations. They could explain the periodicity analysis of § 2, but not outbursts occurring at exactly predictable times. If we take the list of outbursts at approximately 1947, 1959, 1971, 1983, and 1995, obviously the next year of outburst in this sequence is 2007. In a single black hole model the outburst in 2005 November appears too early.

Several different binary models have also been suggested. Sillanpää et al. (1988) considered a companion in the plane of the accretion disk. The reason for this choice had more to do with the capabilities of numerical simulation than astrophysical needs. The model calculation showed that an increased mass transfer toward the center of the accretion disk arises somewhat before the pericenter passage of the companion, and that there are secondary oscillations of accretion flow at about 1 yr intervals thereafter. In broad outline this model describes the multiple peak structure of the outburst seasons. Sundelius et al. (1997) confirmed the main results for different inclinations. This model is capable of producing outbursts at regular intervals, and it can be used to predict the next outburst. The prediction is 2006 September.

One of the problems of the pure tidal model is the suddenness of the outbursts that we call giant flares. The rise time of the giant flares is far too rapid for the timescales of an accretion disk and a jet associated with it, for any reasonable size black hole that could be responsible for the great luminosity of OJ 287. Also, there is no explanation for the larger cycle of brightness variation in this model. Geodetic precession is too slow by orders of magnitude, and the jet wobble suggested by Katz (1997) and studied in more detail in this paper leads to a one-way gradual change in the disk inclination, not to a cycle, at least not to a cycle of short period. The 1956 outburst is also problematic in this model.

A solution to many of these problems is offered by the precessing binary model of Lehto & Valtonen (1996). It provides a theory of the giant flares quite naturally and explains their properties, which appear at first sight quite surprising: the decrease of the degree of polarization without a corresponding change of the position angle of polarization, and the change to a flatter spectral index. The rise and decay times of giant flares, as well as their peak fluxes, are much as expected. But more importantly, it is possible to construct a unique mathematical model based on only six giant flares, and to predict the exact times of all past and future giant flares in this model.

An additional bonus of this theory is that it also explains the tidal events, and the radiation associated with them, both in the optical and radio bands. The tidal events vary from one orbit to another because of the changing orientation of the binary orbit relative to the accretion disk. So far the predictions go well with observations. Another bonus is the prediction of the larger cycle of flux variations, arising from jet wobble. If we allow a 4 yr delay between the changing disk orientation and the response of the jet to it, we get a fair correspondence between expected and observed light curves, both in optical and in radio. The amplitude of the larger cycle is a free parameter, but the phase is fixed by the giant flares.

The precessing binary model allows us to determine many details of the system that are not generally known in other quasars: mass flow rates in the accretion disk, the viscosity parameter $\alpha$, and the relation between the mass flow rate and jet brightness, in addition to the exact properties of the binary. The most fun is the complete prediction of the future light curve: the evolution of the basic brightness and the expected outbursts: their times and magnitudes, both in radio and in optical. This is where the big difference between the precessing model and other two models lies: while the two other models make some general predictions about future outbursts (2006 September or sometime in 2007), the precessing model is at a much more quantitative stage. OJ 287 can prove it wrong at any time; on the other hand, the longer OJ 287 continues to follow the theoretical light curve, the more confidence we have in the model.

The current theoretical uncertainties are such that it would be advisable to follow OJ 287 through the whole outburst season 2005–2010. Especially the summer break periods may become crucial, and it is hoped that the break would remain as short as possible. It is impossible to observe OJ 287 for about 3 weeks, but immediately before the break and right after it the object should be observable at low geographical latitudes, close to the equator, where the morning and evening twilight is short.

We wish to thank S. Jorstad and V.A. Hagen-Thorn for providing us data from the archives of Pulkovo Observatory. We thank also L. Takalo, A. Berdyugin, E. Lindfors, and M. Pasanen for providing up the latest data points from the 1.03 m Tuorla Telescope. We acknowledge the support of the grant 49011 Calculation of Orbits by the Academy of Finland. The studies of the magnitudes of the objects near the plate limits used in this study are related to the project A3003206 of the Grant Agency of the Academy of Sciences of the Czech Republic.

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