THE ASTROPHYSICAL JOURNAL, 531:744–755, 2000 March 10

RADIO MONITORING OF OJ 287 AND BINARY BLACK HOLE MODELS FOR PERIODIC OUTBURSTS

E. VALTAOJA
Tuorla Observatory and Department of Physics, University of Turku, FIN-21500 Piikkiö, Finland; esko.valtaoja@utu.fi
H. TERÄSRANTA AND M. TORNIKOSKI
Metsähovi Radio Observatory, Helsinki University of Technology, FIN-02540 Kylmälä, Finland; hte@cc.hut.fi, mtt@cc.hut.fi
A. SILLANPÄÄ
Tuorla Observatory, University of Turku, FIN-21500 Piikkiö, Finland; aimo.sillanpaa@astro.utu.fi
AND
M. F. ALLER, H. D. ALLER, AND P. A. HUGHES
Department of Astronomy, University of Michigan, Ann Arbor, MI 48109; margo@astro.lsa.umich.edu, hugh@astro.lsa.umich.edu, hughes@astro.lsa.umich.edu
Received 1999 June 7; accepted 1999 October 26

ABSTRACT

The BL Lac–type active galaxy OJ 287 exhibits a 12 year periodicity with a double-peaked maxima in its optical flux variations. Several models sought to explain this periodicity, the first one firmly established in any active galactic nucleus (AGN), as a result of the orbital motion of a pair of supermassive black holes. In one class of models the orientation of the jets changes in a regular manner, and the optical flaring is due to a consequent increase in the Doppler boosting factor. In another class of models the optical flaring reflects a true increase in luminosity, either due to an enhanced accretion during the pericenter passage or due to a collision between the secondary black hole and the accretion disk of the primary black hole. However, these models have been based solely on the optical data. Here we consider the full radio flux density monitoring data between 8 and 90 GHz from the Michigan, Metsähovi, and Swedish-ESO Submillimeter Telescope AGN monitoring programs. We find that the radio flux density and polarization data, as well as the optical polarization data, indicate that the first of the two optical peaks is a thermal flare occurring in the vicinity of the black hole and the accretion disk, while the second one is a synchrotron flare originating in a shocked region down the jet. None of the proposed binary black hole models for OJ 287 offers satisfactory explanations for these observations. We suggest a new scenario, in which a secondary black hole penetrates the accretion disk of the primary during the pericenter passage, causing a thermal flare visible only in the optical regime. The pericenter passage enhances accretion into the primary black hole, leading to increased jet flow and formation of shocks down the jet. These become visible as standard radio and optical synchrotron flares roughly a year after the pericenter passage and are identified with the second optical peaks. In addition to explaining the radio and the optical data, our model eliminates the need for a strong precession of the binary and for an ultramassive ($\geq 10^{10}$ $M_{\odot}$) primary black hole. If our interpretation is correct, the next periodic optical flare, a thermal one, should occur around 2006 September 25. Nonthermal, simultaneous optical and radio flares should follow about a year later.

Subject headings: black hole physics — BL Lacertae objects: individual (OJ 287) — radiation mechanisms: nonthermal — radio continuum: galaxies

1. INTRODUCTION

The BL Lac–type active galactic nucleus OJ 287 (0851+202) is one of the most extensively observed sources of its class. With a redshift $z = 0.306$, neither its apparent nor its absolute luminosity is in any way exceptional. However, OJ 287 stands out as the most variable source easily accessible both to optical and to radio telescopes. Consequently, it has been a favorite target of observers since its discovery in 1967 (Dickel et al. 1967). A good source for data on OJ 287 is the review paper by Takalo (1994). Much of the later work is presented in a series of workshop proceedings dedicated to OJ 287 (Kidger & Takalo 1994; Takalo 1996; Tosti & Takalo 1998).

There do not appear to be any significant qualitative differences between OJ 287 and other BL Lac objects. Its host galaxy has an absolute magnitude $M_R \approx -22$, typical for an FR I galaxy (Wurtz, Stocke, & Yee 1996; Wright, McHardy, & Abraham 1998). Its radio-to-optical spectrum resembles those of other BL Lac objects (e.g., Gear et al. 1994). The radio spectrum may be somewhat flatter than for an average BL Lac object (Tornikoski et al. 1993). The last turnover, defined as the frequency above which the quiescent spectrum starts to decrease monotonously, is at a higher frequency than for other sources (Valtaoja et al. 1988); both indicate extreme compactness of the radio core. VLBI observations show only weak parsec-scale features outside the unresolved core (Roberts, Gabuzda, & Wardle 1987; Gabuzda, Wardle, & Roberts 1989; Tateyama et al. 1996; Vicente, Charlot, & Sol 1996). Because of the rapid variability, interpretation of the VLBI maps is difficult, and estimates for the apparent superluminal speeds of the ejected components range from $v/c \approx 4$ (Gabuzda et al. 1989) to ≈ 11 (Marscher & Marchenko 1998). [We use $H_0 = 65$ km $^{-1}$s Mpc^{-1} and $q_0 = 0.1$ throughout the paper. Since the basic parameter in models for OJ 287 is the orbital period of the binary, $P = P_{\rm obs}/(1 + z)$, the assumed values of H_0 and q_0 influence only some secondary parameters of the models, not considered here.] A recent analysis of densely sampled geodetic VLBI data (Tateyama et al. 1999) indicates that the larger values are the correct ones.

Extreme compactness is also indicated by the rapid variations both in the radio and in the optical. Lainela & Valtaoja (1993) have done a structure function analysis of the 22 and 37 GHz radio variations of a large sample of BL Lac objects and other active galactic nuclei (AGNs) monitored at Metsähovi (Teräsranta et al. 1998). While other BL Lac objects have characteristic timescales of a few years, the timescale for OJ 287 is of the order of a few months. Analyzing the same radio monitoring sample of $\approx$100 AGNs, Lähteenmäki, Valtaoja, & Wiik (1999) found that OJ 287 had the shortest variability timescales of all sources included in the sample, with the fastest observed major radio flare having $\tau = dt/d \ln S = 10.7$ days. The corresponding associated variability brightness temperature $T_b = 7 \times 10^{14}$ K was also among the highest in the sample, requiring large amounts of Doppler boosting. Accepting the higher v/c-values for OJ 287, the results of Lähteenmäki & Valtaoja indicate a shocked jet Lorentz factor $\Gamma \approx 15$ and a viewing angle $\theta \approx 2°$. This exceptionally small viewing angle explains many of the observed characteristics of OJ 287. Independent evidence for a small θ is also found from VLBI observations (e.g., Cawthorne & Wardle 1988; Tateyama et al. 1996).

The main claim to fame for OJ 287, however, is the periodic variability in its optical flux. Numerous AGNs, including OJ 287 itself, have been claimed to show periodic variations in either the optical or the radio regime. However, none of the claims has been confirmed by further observations; predicted outbursts or flux maxima have failed to materialize, or the periodicity has become statistically insignificant with the inclusion of further data. OJ 287 remains the only exception. Sillanpää, Haarala, & Valtonen (1988) noticed a regularity in the historical optical light curve of OJ 287, with large flares occurring approximately every 12 years during the last 100 years. The periodicity has persisted even with the inclusion of more data (Kidger, Takalo, & Sillanpää 1992) and was confirmed with the next major optical outburst, which occurred as predicted in late 1994 (Sillanpää et al. 1996a, 1996b). A large international monitoring collaboration, the OJ-94 Project (Takalo 1994), has resulted in a unique optical database which has been used both to confirm the periodicity and to construct detailed models for the regularly occurring flaring events. Figure 1 shows the historical light curve combined with the OJ-94 Project data from Sillanpää et al. (1996a).

A viable model for the optical behavior of OJ 287 must explain at least the three main features apparent even from a cursory inspection of Figure 1: the regularity of the epochs of maximal optical activity, deviations of up to 1 year from strict periodicity, and the double structure of at least the two latest well-observed maxima (Sillanpää et al. 1996b). All the proposed models have assumed that OJ 287 is a binary system of two supermassive black holes, the periodicity (8.9 years in the rest frame) reflecting the orbital motions. The mechanism for producing the optical flaring has been suggested to be enhanced inflow into the larger, "primary" black hole during the periastron passage of the smaller companion (Sillanpää et al. 1988) or the crossing of the primary's accretion disk by the secondary black hole (Lehto & Valtonen 1996). Another class of models seeks to explain the flaring as a geometrical enhancement, an increase in the Doppler boosting caused by a relativistic jet sweeping across, or close to, our line of sight due to the precession of the accretion disk (Katz 1997) or by changes in the orientations of the two jets (one from each black hole) due to the binary's orbital motions (Villata et al. 1998). An alternative, a well-defined quasiperiodic duty cycle of accretion and/or ejection, is in principle also possible (A. Marscher 1999, private communication). The existence of such duty cycles in black hole systems has not yet been investigated in much detail (cf. Ouyed, Pudritz, & Stone 1997; Mirabel et al. 1998). Observationally, the radio outbursts in many AGNs do occur at rather regular intervals (see, e.g., the millimeter flux curves in Teräsranta et al. 1998). However, if the optical flaring, especially the first of the two maxima, is as regular as claimed, one may doubt whether any duty cycle could maintain the required constancy to better than 3 weeks over a period of four cycles and 50 years (cf. Fig. 12). Further studies are clearly needed.

The existence of binary black holes in AGNs and their possible role in the formation and the evolution of powerful radio sources is an important topic. For example, it has been suggested that, in analog to galactic "mini-quasars" (Mirabel & Rodriguez 1994), a supermassive binary greatly enhances the accretion rate and thus the luminosity as compared to a single supermassive black hole (Katz 1997), or

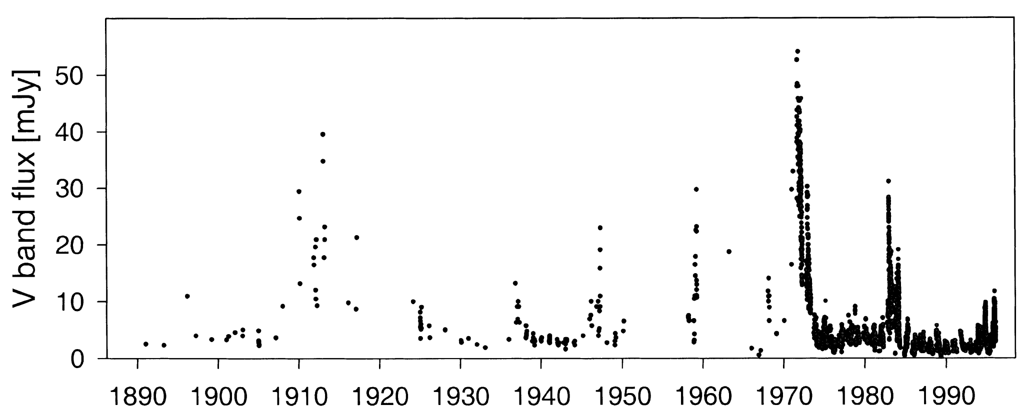

FIG. 1.—Optical V-band flux densities from the OJ-94 Project archive. Note the not quite regularly spaced observed maxima and the double maxima during the latest epochs of activity.

even that a binary is a necessary prerequisite for the formation of a powerful radio jet (Sillanpää 1999). A detailed probing of the physics of AGN cores (Valtonen, Lehto, & Pietilä 1999) and even of the general theory of relativity (Valtonen & Lehto 1997) might also be possible.

Up to now, discussion about the periodicity of OJ 287, its causes and its consequences, has been limited solely to the optical data. In this paper we present the radio monitoring data from the Metsähovi (e.g., Teräsranta et al. 1998) and the Michigan (e.g., Aller et al. 1985) monitoring programs and consider their implications for the proposed models of periodic variations. The radio variations present a very different picture of OJ 287's behavior; our main conclusion is that none of the suggested models for the periodic flaring is satisfactory.

The rest of the paper is organized as follows. In § 2 we present the Metsähovi and the Michigan radio data, augmented by our 90 GHz data from the Swedish-ESO Submillimeter Telescope (SEST; Tornikoski et al. 1996) and from Institut de Radioastronomie Millimetrique (IRAM; Steppe et al. 1993; Reuter et al. 1997), and consider the salient features of the radio flux curves of OJ 287. In § 3 we introduce the proposed models for the optical variability. Section 4 considers some of the problems of each model, in particular those posed by the observed radio behavior. Finally, in § 5 we present an alternative interpretation of the observed optical and radio flux variations.

2. RADIO OBSERVATIONS

The University of Michigan monitoring data on OJ 287 starts in 1971 at 8.0 GHz, with 4.8 and 14.5 GHz added later. The 8 GHz data thus covers the epochs of the three latest periodic optical flares in 1971–1972, 1983–1984, and 1994–1995. Figure 2 shows the Michigan 8 and 14.5 GHz data. It is obvious that no periodic behavior corresponding to the optical cycles is seen. There are no outstanding individual radio flares corresponding to the optical double maxima, nor do the average levels exhibit a 12 year cycle. The highest radio flux levels of the 1980s were reached approximately 12 years after the 1973 maximum, but since then the overall flux levels of OJ 287 have been decreasing, with no sign of renewed major activity around 1997. The 4.8 GHz flux curve (not shown) exhibits similar overall behavior, with decreased characteristic amplitude and rapidity of variations, as usual in AGNs.

The Metsähovi monitoring data, starting in 1980 at 22 and 37 GHz and in 1987 at 90 GHz, cover only the two latest periods (Fig. 2). The spectrum remains very flat at all times; the 90 GHz variations track the 22 and 37 GHz fluxes closely. (For clarity, the 90 GHz data is not shown in the figure.) The millimeter flux levels have also been steadily decreasing since mid-1980s, with the lowest ever observed flux levels reached in 1995. Again, no clear radio counterparts to the optical maxima are apparent, with the possible exception of the last 1996 flare.

Nevertheless, OJ 287 is known to be one of the best candidates for simultaneous, or nearly simultaneous, radio and optical variations (e.g., Valtaoja, Sillanpää, & Valtaoja 1987; Tornikoski et al. 1994; Clements et al. 1995). Formal correlation analyses have given somewhat conflicting results, indicating both nearly synchronous variations with time delays (optical preceeding radio) less than a month and delays up to, and more than, a year (e.g., Hufnagel & Bregman 1992; Clements et al. 1995). This is partly due to

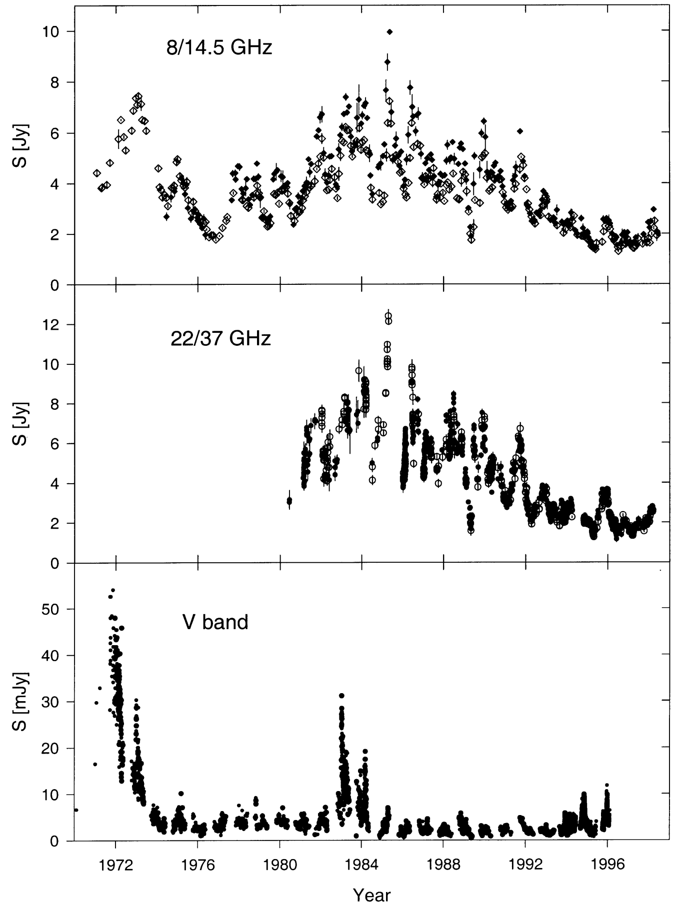

FIG. 2.—Total radio flux density data from the Michigan (8/14.5 GHz) and the Metsähovi (22/37 GHz) monitoring programs: 8.0 GHz (*open diamonds*); 14.5 GHz (*filled diamonds*); 22.2 GHz (*open circles*); 36.8 GHz (*filled circles*). The optical *V*-band data for the same period are also shown.

the fact, apparent in Figure 2, that the strongest optical and radio peaks are not well correlated, and the formally best time delay depends on what period is being considered and whether it includes the major optical flaring episodes. Another factor is the well-known fact that for AGNs, OJ 287 included, the time delays between millimeter and longer wavelength variations, and therefore also between optical and radio variations, increase rapidly with increasing radio wavelength as a result of a combination of shock development and opacity effects (cf. Valtaoja et al. 1987). The radio-optical connection is therefore best seen using millimeter radio data. Tornikoski & Valtaoja (1998) have done a discrete correlation function (DCF) analysis of the optical and the 22–230 GHz radio data sets. They concluded that while no convincing radio versus optical correlation is found either for the entire data set or for the interval 1985–1993 between the major optical outbursts, a number of the smaller outbursts are clearly simultaneous at both frequency bands. Dividing the data streams into randomly chosen 1000 day intervals brings this clearly out in the DCF analysis. An example is shown in Figure 3, where we compare the optical and the 37 GHz variations during the period 1990.5–1994.0 (prior to the latest optical ourbursts). Most of the time the flux variations track each other with no measurable time delays and with similar relative amplitudes. We can conclude that in general the optical- and the radio-emitting regions in OJ 287 must be cospatial.

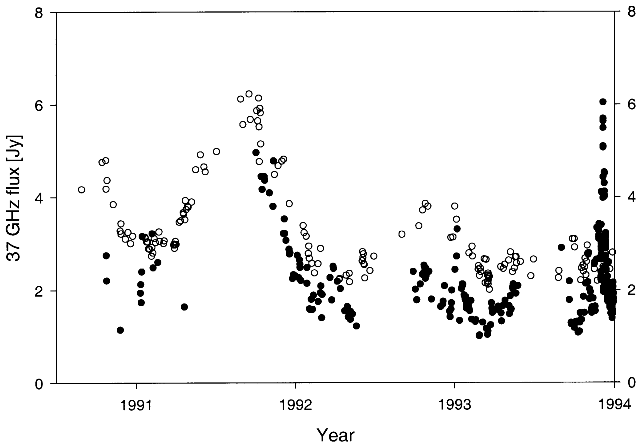

FIG. 3.—Comparison between the 37 GHz radio (*open circles*) and the *V*-band optical (*filled circles*) data during the 3 years before the latest epoch of optical activity.

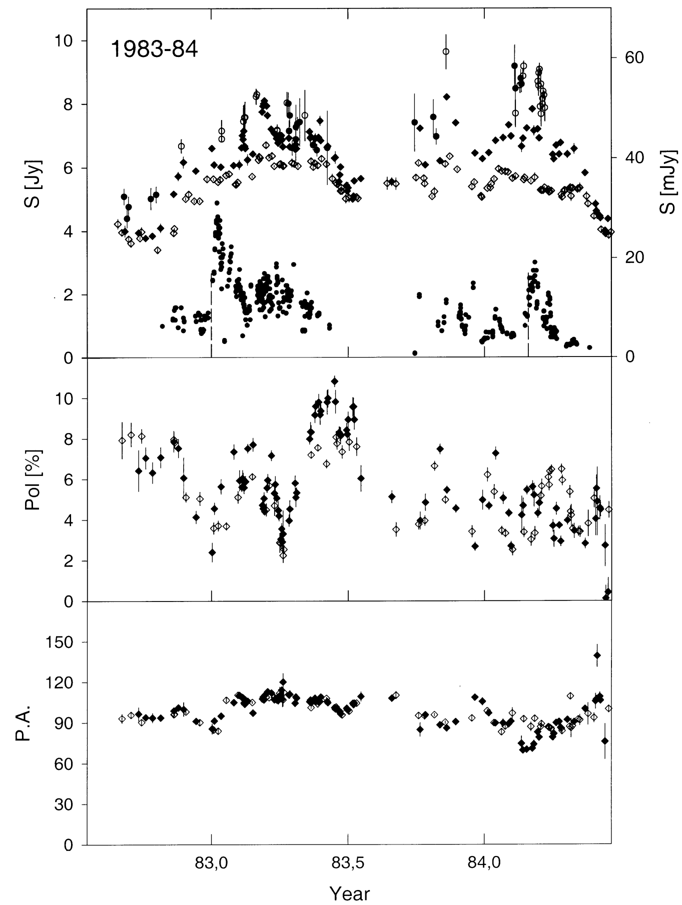

FIG. 5.—Data covering the 1983–1984 epoch of optical flaring: 14.5 GHz (*filled diamonds*); 22 GHz (*open circles*); 37 GHz (*filled circles*); other symbols as in Fig. 4.

Next we compare the details of the optical and the radio variations during the latest three epochs of optical maxima in 1971–1972, in 1983–1984, and in 1994–1996. For each time interval we present all the available optical *V*-band data from the OJ-94 Project archive, together with the radio monitoring data from Michigan and Metsähovi, and for the latest epoch also the 90 GHz data from SEST and IRAM.

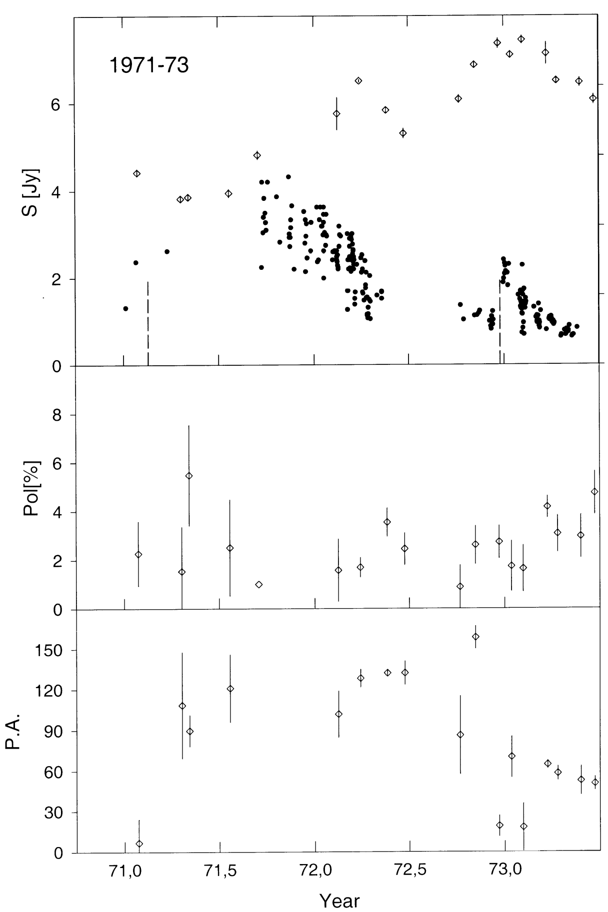

FIG. 4.—Data covering the 1971–1973 epoch of optical flaring: optical *V*-band data (*filled circles*); 8 GHz radio data (*open diamonds*). The uppermost panel shows the total flux densities, the middle one the radio polarization data, and the lowermost one the radio polarization P.A. data. The dashed lines indicate the times of the accretion disk crossings in the Lehto & Valtonen model (see the main text).

For the 1971–1972 period we have only the rather sparse 8 GHz monitoring data from Michigan. In Figure 4 we display a 1000 day interval which includes the whole relevant activity period as well as the times of the disk crossing in the detailed model of Lehto & Valtonen (1996), discussed in more detail in the later sections. The optical flux levels were high already in early 1971, but gaps in the optical data make it impossible to say when the true optical maximum was reached. It is also not possible to state whether the second optical maximum occurred around 1971.6 or first in 1973.0. However, we note that the 8 GHz flux levels seemed to remain rather constant during 1971, peaking first in early 1972, and with a second peak centered around the 1973.0 maximum.

Much more data are available for the 1983–1984 epoch, as shown in Figure 5. The overall radio fluxes were at all-time high levels (cf. Fig. 2), with repeated radio flares superposed on each other. The first optical flare in 1983.0 lacks any radio counterpart, while the second optical flare in 1984.2 was simultaneous with a radio flare seen both at 14.5 GHz in Michigan and at 22 GHz in Metsähovi (Fig. 6). The flare was possibly also seen in the polarized radio flux (Fig. 5), simultaneously with the optical flare at 14.5 GHz and

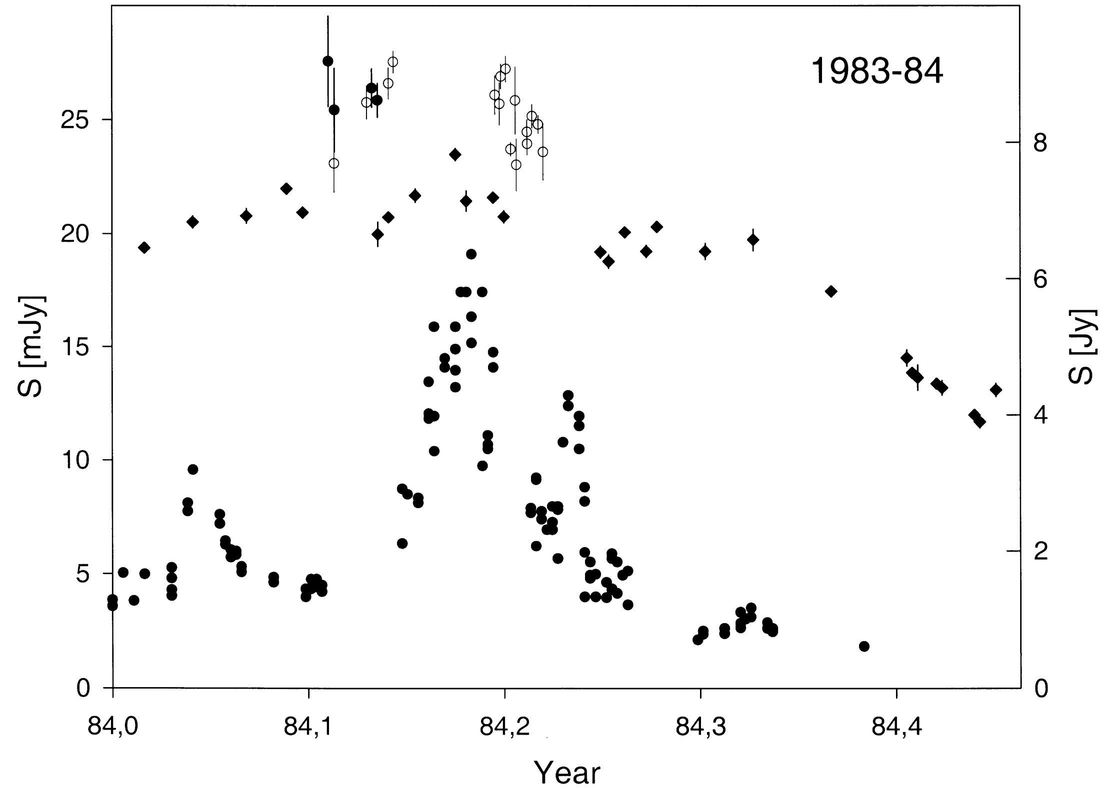

FIG. 6.—Close-up of the optical and the radio variations during the second optical flare in 1983–1984. Symbols as in Fig. 5.

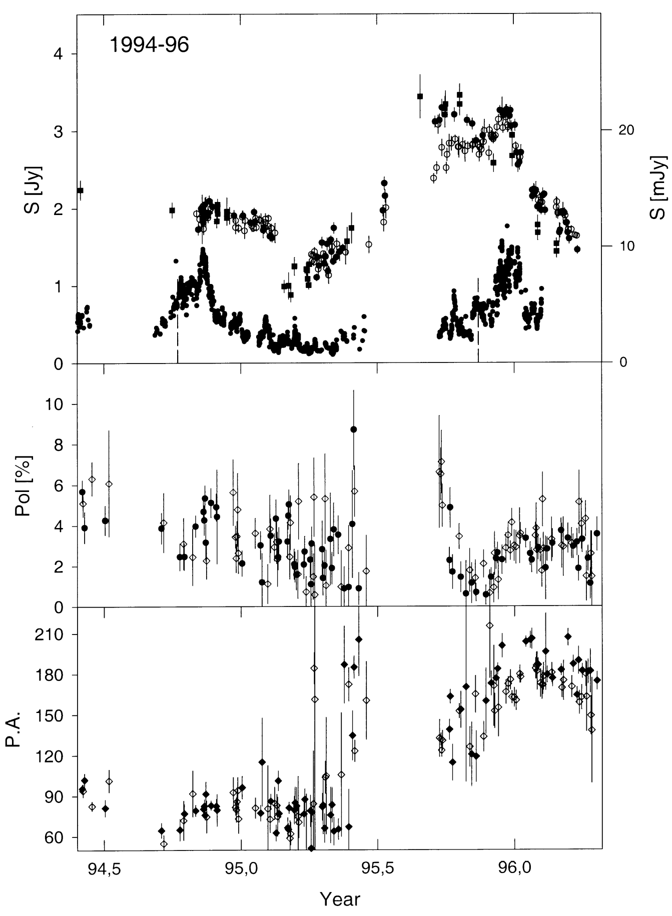

FIG. 7.—Data covering the 1994–1995 epoch of optical flaring. 90 GHz data (*filled squares*); other symbols as in Fig. 5.

delayed by about a month at 8 GHz. (Such a time delay is typical for the radio flux variations in OJ 287, resulting from a combination of flare development and opacity effects; cf. Valtaoja et al. 1987.)

The data for the third epoch 1994–1996 is shown in Figures 7 and 8. Again, the first optical flare (in 1994.8) has no radio counterpart. The radio activity starts to increase $\approx$0.5 years afterward, with a subsequent $\approx 90^\circ$ change in the 8 and 14.5 GHz position angles, and culminating in a broad maximum. The second optical flare (peaking in 1995.9) corresponds to a clear maximum in the 22 and 37 GHz flux curves (and possibly to a polarization flare at 8 and 14.5 GHz). Both the 1984.2 and the 1995.9 optical flares have much substructure. However, a comparison of the radio and the optical flare envelopes shows that the maximum optical-to-radio delay is less than a week. This can be compared with the fastest radio flare timescale of $\approx$11 days, giving an estimate of the light-travel time size of the shocked region and demonstrating that the optical radiation cannot come from any appreciable distance away from the shock. (Note that the Doppler boosting in the jet should affect both equally.)

All radio variations in AGNs (excluding intraday variability and low-frequency interstellar scintillation, not relevant here) can be explained within the shocked jet context (see, e.g., reviews by Robson 1996; Valtaoja 1996; and Ulrich, Maraschi, & Urry 1997). We can therefore conclude that synchronous optical variations also originate in the shocks, not in the vicinity of the black hole and the accretion disk. In general, this seems to be the case for OJ 287, as Figure 3 demonstrates. The same seems to hold for the second of the two optical flares exhibiting simultaneous

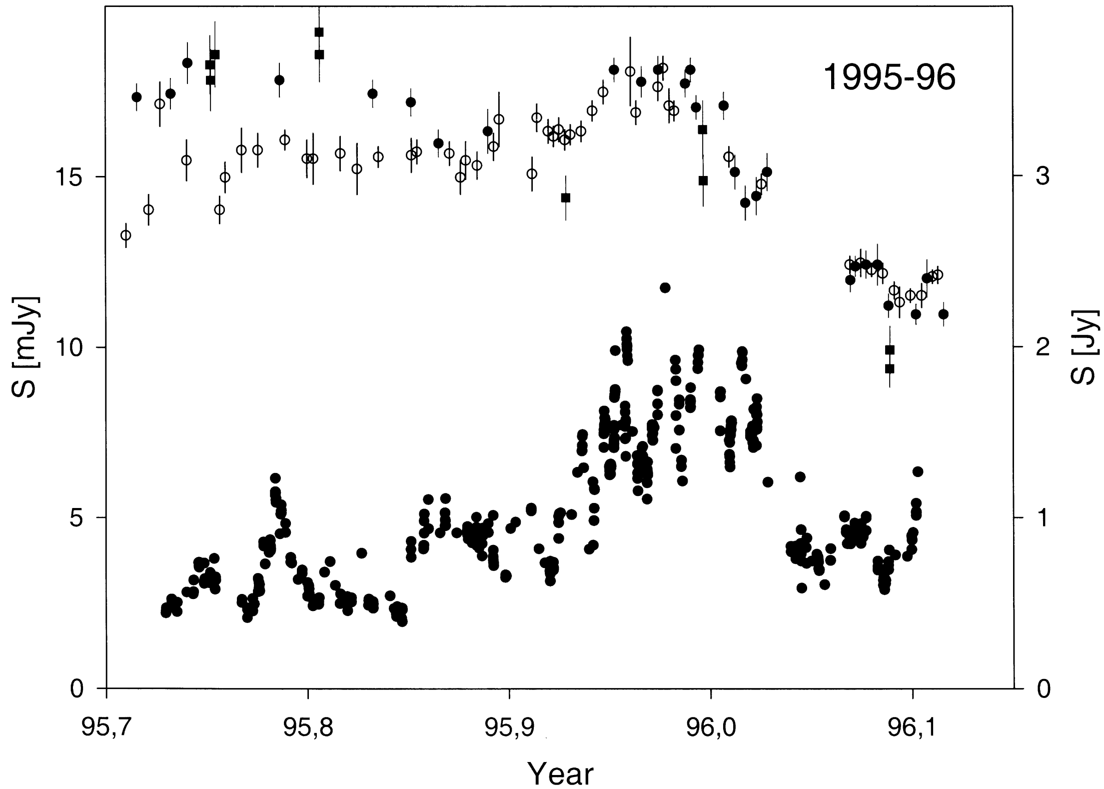

FIG. 8.—Close-up of the optical and the radio variations during the second optical flare in 1995–1996. Symbols as in Fig. 7.

radio and optical variations. However, the first optical flare, lacking a radio counterpart, must have a different nature. Either the first optical flare is not produced by the synchrotron process or the self-absorption turnover is so high that the low-frequency part remains totally self-absorbed.

3. BINARY BLACK HOLE MODELS FOR OJ 287

All the proposed models for the periodic optical outbursts in OJ 287 invoke a binary system of two supermassive black holes. The proposed mechanisms for the outbursts can be divided into two categories. An increase in the observed flux can be caused by changing the orientation of the relativistically moving emission regions, resulting in an increase in the Doppler boosting factor $D = [\Gamma(1 - \beta \cos \theta)]^{-1}$ if the viewing angle θ diminishes. Such "lighthouse" models (cf. Camenzind & Krockenberger 1992) have been proposed by Katz (1997) and Villata et al. (1998).

The model of Katz (1997) suggests an analogy to the galactic binary X-ray sources such as Her X-1 and SS 433. The companion exerts a torque on the primary black hole's accretion disk. As a result, the precessing relativistic jet from the primary sweeps across our line of sight at regular intervals, and the apparent flux from the jet components is enhanced by a factor $\approx D^3$. The second maximum about a year afterward is due to the nodding motion of the precessing disk.

In the model of Villata et al. (1998), both black holes are assumed to have relativistic jets. The two rather similar jets are bent, and during the binary's orbital period, first one and then the other bent portion of the jet is directed toward us, resulting in a regular double-peak structure. A long-term precession causes the observed modulation in the intensity of the optical flares.

In the second class of models the observed flux increase reflects a real increase in the intrinsic luminosity, either through enhanced accretion rate during the pericenter passage or through some emission mechanism operating only during a certain phase of the orbit. These "accretion" models have been considered by Sillanpää et al. (1988), Lehto & Valtonen (1996), Valtonen & Lehto (1997), Sundelius et al. (1997), Valtonen et al. (1999), and Pietilä (1998).

In their original periodicity discovery paper, Sillanpää et al. (1988) suggested that the light variations could be due to tidally induced mass flows from the accretion disk into the black hole. The long-term variations in the outburst amplitudes were explained by precession due to a very massive (20% of the black hole mass) accretion disk around the primary black hole. The double structure of the maxima was not apparent at that time and was not considered by Sillanpää et al.

Lehto & Valtonen (1996) introduced an additional process for producing optical activity during the pericenter passage. Inspecting the optical flux curves during the activity maxima, they identified a rapid flare toward the end of the 1971–1973 outburst, two similar flares during the 1983–1984 outburst (one in the beginning and another one at the end of the active phase), and a fifth one at the beginning of the then ongoing 1994–1996 outburst. They termed these events "superflares" occurring on top of the general outburst and identified them with the times when the secondary black hole crosses the accretion disk of the primary. The interaction between the secondary and the accretion disk is primarily a thermal process, in which the hypersonic black hole punches a hole in the disk, and the shocked gas cools, possibly mainly via bremsstrahlung radiation. More complicated mechanisms transforming the kinetic energy of the secondary into observed radiation can also be envisaged. However, observationally the main point is that the two disk crossings produce the observed double structure.

In the Lehto and Valtonen model there are several possible mechanisms for enhancing the optical flux: the collisions between the black hole and the accretion disk, the enhanced accretion related to these disk crossings, and the general enhancement of the accretion rate caused by the pericenter passage. The flux maxima may be due to any of these processes, and in consequence the observed maxima during the pericenter passages need not be equally spaced, as indeed is the case. In addition, Lehto and Valtonen also invoke a strong precession, which changes the orientation of the secondary's orbit relative to the accretion disk, and consequently the times of the disk crossings from passage to passage. The precession is a general relativistic effect caused by an extremely massive primary.

If the times of the disk-crossing superflares can be identified, it is possible to calculate the parameters of the binary black hole system. Lehto & Valtonen found a best solution for the historical optical flux curve by assuming an orbital period of 12.07 years, an eccentricity of $e = 0.678$, a precession of the major axis of the orbit of $33\overset{\circ}{.}3$ per period, a semimajor axis $a = 0.0558$ pc, and a primary black hole mass of 1.7×10^{11} $M_{\odot}$. The model was further studied by numerical simulations (Sundelius et al. 1997) and refined to include new data and relativistic effects (Valtonen & Lehto 1997; Valtonen et al. 1999; Pietilä 1998). We have identified with dashed lines the times of the superflares and the pericenter passages, as given in Lehto & Valtonen (1996), in Figures 4, 5, and 7.

Both the lighthouse and the accretion models have been claimed to be able to reproduce the observed optical periodicity. Considering the uncertainties in the timing of the outbursts, the gaps in the historical data, and the number of adjustable parameters in the models, such as the eccentricity and the orientation of the binary orbit and the geometry of the relativistic jets, it does not seem to be possible to choose between the models solely on the basis of the optical outburst timing arguments. The by far most developed model variant of Lehto & Valtonen (1996), Sundelius et al. (1997), and Valtonen et al. (1999) attempts a very detailed reproduction of the optical data, but there is still a considerable range of free parameters available for the fitting procedure (cf. Pietilä 1998). In addition, as Figures 4, 5, and 7 show, one may argue about how well the model fits the data and whether the superflares crucial for the model fit really can be identified correctly in the data. To take only one example, there was an optical flare around 1995.87, as predicted by Lehto & Valtonen (1996), but this was only one, and not the largest, of the flares during the autumn of 1995, as Figures 7 and 8 show.

4. RADIO DATA VERSUS THE MODELS

The radio data presented here open a new window in the processes occurring in OJ 287. The radio data shows no 12 year periodicity in the Scargle periodogram analysis (Aller, Aller, & Hughes 1994), and there are no clearly dominant single peaks or periods of major activity occurring at similar intervals. Thus, radio data cannot be used to establish or to confirm the presence of a binary system in OJ 287. This is not surprising, since in the standard models for radio-bright AGNs the radio flux comes from the synchrotron jet and shocks at a distance from the black hole and the accretion disk; typical estimates for this distance are of the order of a parsec (e.g., Marscher & Gear 1985; Courvoisier 1998). The chain of processes starting with an event close to the primary black hole (e.g., the pericenter passage with optical flaring) and ending with the formation of a radio-emitting shock down the jet may be quite complex and nonlinear and the time delays long and not constant. Turning the argument around, there also does not seem to be any reason to question the binary nature of OJ 287 on the basis of radio data.

The main challenge to proposed models comes from comparisons between the radio and the optical variations during the periodic double flares. As was shown in § 2, the first optical flare lacks a radio counterpart, while the second one is simultaneous with a radio flare, thus establishing its emission site as a shocked region in the jet.

4.1. *The Lighthouse Models*

The radio data pose a grave problem for the lighthouse models. If the optical outbursts are due to enhanced Doppler boosting in the jet, why is the radio emission, coming from the same source, not similarly boosted? There clearly are no radio enhancements by a factor of 10 or so over the average radio levels during the optical outbursts. In the precessing disk model of Katz (1997), the whole jet changes direction, and therefore the boosting of radio emission is inevitable. In the two-jet model of Villata et al. (1998), only a small part of each jet becomes oriented toward us. One might argue that these parts of the jet for some reason do not radiate in the radio regime, and so we do not observe comparable radio enhancements, but such an ad hoc explanation seems rather contrived. The lighthouse models also offer no explanation why the first of the two optical flares does not have a radio counterpart, while the second one does.

Independent of the radio data, there is also another strong argument against increased Doppler boosting as an explanation of the optical flux enhancement. A change in D not only enhances the observed flux density by a factor of D^3, it also compresses the observed timescales by a factor of D. A conservative estimate of the required change in the Doppler boosting factor can be obtained from the data shown in Figure 1. Assuming that $S_{\rm obs}$(quiescent) ≤ 3 mJy and $S_{\rm obs}$(flare) ≥ 30 mJy, the change in the Doppler boosting factor resulting from a change in the viewing angle must be D(flare)/D(quiescent) $\gtrsim 10^{1/3}$, if the whole jet is involved. If only a fraction $s < 1$ of the jet receives the extra boost, the ratio becomes larger by a factor of s^{-3}. In the particular model solution presented in Villata et al. (1998), $s = 6 \times 10^{-4}$ and D(flare)/D(quiescent) must be $\gtrsim 25$.

However, there is no evidence that the optical variability timescales during outbursts are larger than during the quiescent epochs between them. The *amplitude* of variations is naturally larger, but the variability timescales, defined as $\tau = dt/d \ln S$, are similar. Figure 9 shows two 150 day slices of the total data set of Figure 1, plotted using $\ln S$ instead of S. The variability timescales, both for the night-to-night variations and for the longer term, are similar both during the minimum flux epoch in early 1986 and during the maximum flux epoch in late 1994.

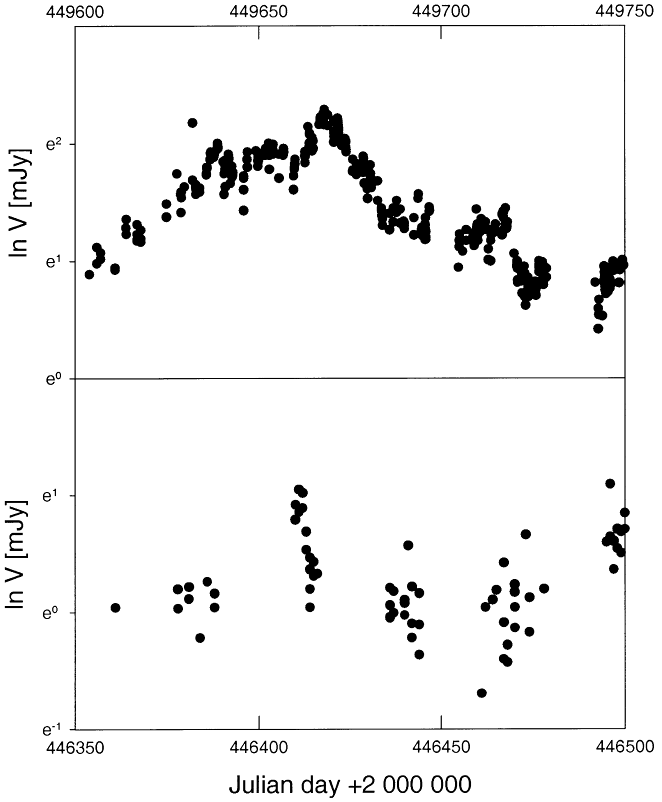

FIG. 9.—Variability at high and low optical flux levels. *Upper panel*: a 150 day period during the optical maximum in late 1994. *Lower panel*: a 150 day period during the quiescent flux levels in early 1986. Note that the data are plotted as ln S vs. time, so the slopes of the flux density curves are directly proportional to the variability timescales.

4.2. *The Accretion Models*

The original model of Sillanpää et al. (1988) has only one mechanism for producing outbursts, tidal interaction between the secondary and the primary's accretion disk during the pericenter passage, and it cannot explain the double structure of the optical maxima. Also, there is no obvious way to produce both "standard" synchrotron flares simultaneously visible both in the optical and in the radio domain, and optical flares lacking radio counterparts.

The scenario of Lehto & Valtonen (1996) at first appears to provide a simple explanation for the double structure, the secondary crossing the accretion disk both before and after the pericenter and producing the two superflares. Tidal interactions during the pericenter passage, as well as the perturbation of the accretion disk during the crossings, may in addition enhance accretion, plausibly resulting in additional optical activity. The enhanced accretion rate can also lead to an increase in the outflow, which later on becomes visible as new synchrotron-emitting shocks down the jet. The numerical simulations of Sundelius et al. (1997) indeed reproduce the general characteristics of the optical flux variations, assuming that the optical flux is directly related to the accretion rate.

The penetration of the accretion disk by the secondary black hole is primarily a thermal process, and so one does not a priori expect synchrotron radiation from the collision. This indeed seems to be what happens during the first "superflare." But what about the second superflare, which does have a radio counterpart? As we have argued above, this indicates that the optical radiation must originate from a shocked region down the jet. If this is the case, it cannot be identified with the second accretion disk crossing as in the Lehto & Valtonen model.

There remains the possibility that the radio synchrotron flare is somehow created directly as a result of the accretion disk crossing, which would explain its simultaneity with the optical flare. As the processes involved in hypersonic collisions between a black hole and an accretion disk have not been investigated in any detail, one cannot exclude this possibility on theoretical grounds. However, all the radio total flux density and polarization data indicate that the radio flares in question have characteristics typical to the ordinary shock-induced flares down the jet. Would a collision produce so similar radio flares?

Even if we assume that the second disk crossing somehow produces also a synchrotron radio flare, the lack of such a flare in the first crossing must still be explained. Recent analytical work and simulations by Ivanov, Igumenshchev, & Novikov (1998) indicate that the collision results in a rather symmetrical two-sided outflow of hot gas from the disk. Both disk crossings should therefore produce similar effects, even if the disk is seen face-on and the secondary in the first crossing emerges from the disk and in the second crossing disappears behind it.

Another argument, unrelated to the radio data, against the accretion models in their present form comes from the parameters required in the model fits. Attempts to fit the observed irregularly spaced optical maxima require one to assume that the orbit of the secondary black hole precesses very rapidly. In Sillanpää et al. (1988) the cause of the precession was assumed to be a massive accretion disk around the primary black hole. A mass of $\sim 20\%$ of the primary black hole mass was required in the model fit. Such ultramassive accretion disks are unlikely to exist. In the detailed model of Lehto & Valtonen (1996), the precession was assumed to be caused by a very massive primary. The precession rate required for good model fits to the optical data is large, over 30° per orbit. With the relativistic precession given by $\Delta\theta = 6\pi GM/c^2 a(1 - e^2)$, the primary must have a mass in excess of $10^{10}\ M_\odot$. (In a recent analysis of the Lehto & Valtonen model, Pietilä [1998] found acceptable fits for primary masses between 1.47×10^{10} and $1.67 \times 10^{10}\ M_\odot$.) One problem with such a huge mass is that the lifetime of the system is only about $\sim 10^4$ years due to gravitational radiation losses. While such a system would make a wonderful laboratory for general relativity, as Valtonen & Lehto (1997) have suggested, the extremely short timescales give rise to questions about the likelihood of observing such a rare system in, cosmologically speaking, close vicinity.

The required mass in itself is also problematic. The estimated differential mass density of active black holes peaks at much lower values (e.g., for $z = 0.5$ at $\log M = 7.5$ in Haehnelt & Rees 1993) and decreases exponentially for larger masses. The mass estimates of individual black holes are, with a couple of exceptions, well below $10^{10}\ M_\odot$, and seem to depend on the bulge luminosity of the host galaxy (e.g., Richstone et al. 1998). With $M_R \approx -22$, typical for a FR I galaxy (Wurtz et al. 1996; Wright et al. 1998), the expected black hole mass in OJ 287 is of the order of 10^9 $M_\odot$ or less. While such estimates do not disprove the existence of an exceptionally massive black hole in OJ 287—after all, OJ 287 *is* exceptional—they at the very least encourage one to search for alternative explanations not requiring the strong precession required in the Lehto & Valtonen model.

5. AN ALTERNATIVE INTERPRETATION OF THE FLUX VARIATIONS

A possible explanation is to assume that the two optical flares are caused by different processes. The nonthermal nature of the second flare seems to be well established on the basis of the simultaneous radio flare, and there seem to be no reasons to assume that it does not originate in a synchrotron-emitting shocked jet at a distance from the black hole and the accretion disk. On the other hand, if the first flare is a thermal one as indicated by the lack of radio variations, the only plausible emission site is the accretion disk or its close vicinity.

Optical polarization data support the assumption of two different emission processes. A thermal flare is unpolarized. The integrated degree of polarization should therefore decrease as the flare rises and the fraction of thermal radiation increases, while the angle of polarization, determined by the nonthermal optical radiation, should not change. This seems to be the case for the first optical flare in 1983, as Figure 10 shows. As the flux increased, the optical polarization decreased from 10%–15% to almost zero, with no systematic change in the position angle (P.A.). For the corresponding first flare in 1994 the optical polarization data have not yet been published, but similar behavior has been reported by Efimov & Shakhovskoy (1996): the degree of polarization is anticorrelated with the optical flux, while the P.A. remained around 150°.

In contrast, a synchrotron flare is polarized. The integrated degree of polarization should increase as the flare rises, and the P.A. should change, the exact behavior depending on the quiescent and the flare magnetic field geometry. This is what clearly happened in 1984 during the second of the two optical flares (Fig. 11.) The degree of polarization increased from a few percent to over 30% as the flare grew in strength, and there was a marked change in P.A. from about 90° to 160°. Only a few polarization measurements were obtained during the second optical flare in 1995/96, but the average degree of polarization was higher than during the first flare in 1994, and it increased with increasing flux (Efimov & Shakhovskoy 1998).

On the other hand, both analytical calculations (Lehto & Valtonen 1996) and numerical simulations (Sundelius et al. 1997) show that the penetration of an accretion disk by a black hole can generate the required amounts of thermal radiation. We also note that if we assume a constant period of 11.86 years and fix the epoch with the first optical flare of 1994, the sharp flares in 1947, 1959, and 1983 agree with this period to better than 3 weeks. (The same fact was indepen-

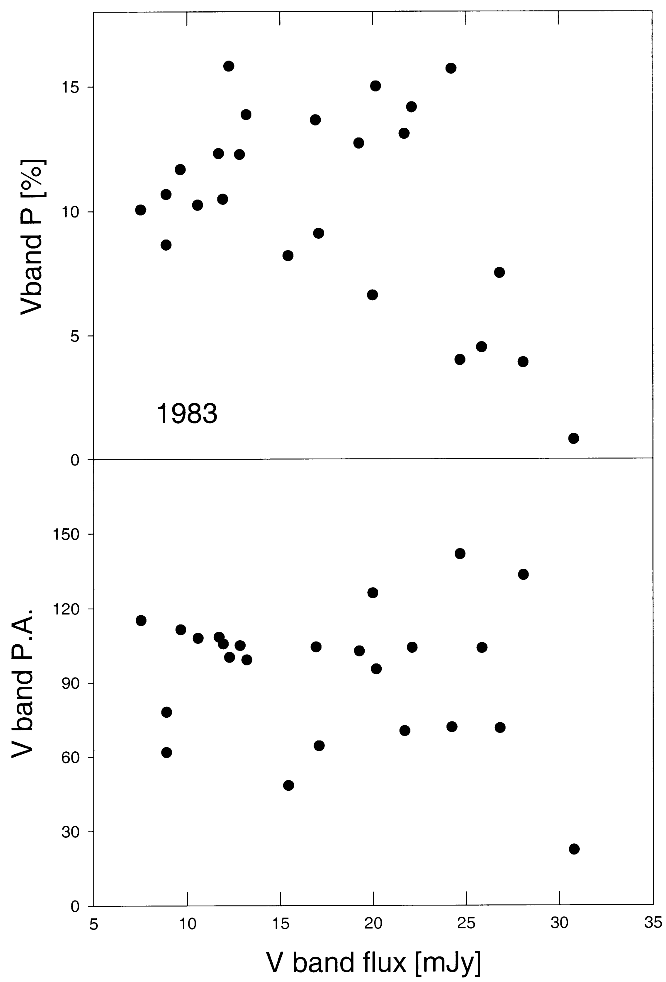

FIG. 10.—Degree of optical polarization and the optical P.A. vs. the optical flux density during the first flare in 1983. The polarization decreases as the flux increases, while the average P.A. does not change, as expected for a thermal flare. For references to data, see Takalo (1994).

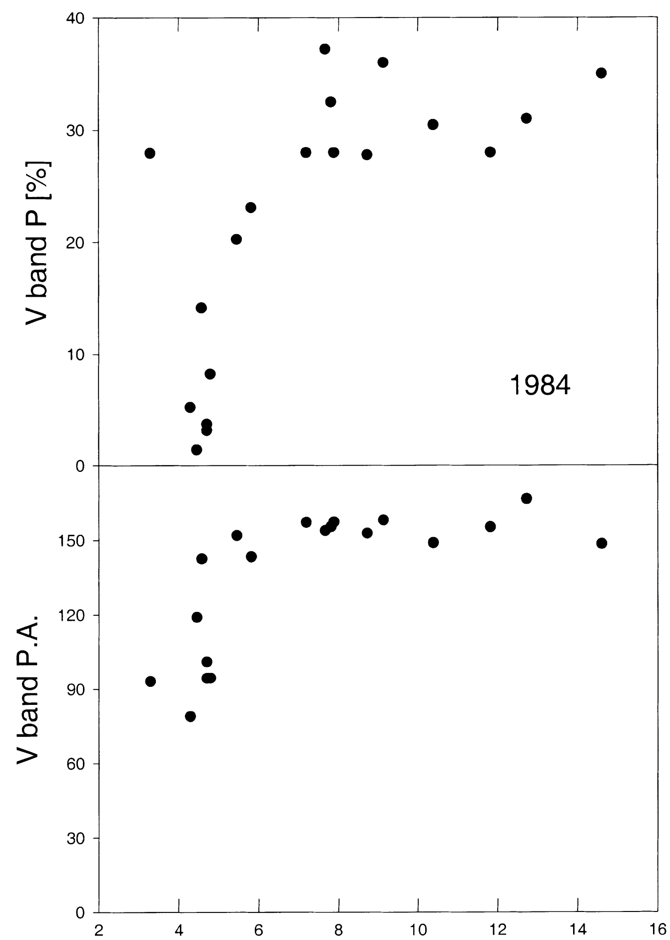

FIG. 11.—Same as Fig. 10, but for the second optical flare in 1984. The polarization increases as the flux increases, and the P.A. changes drastically, as expected for a synchrotron flare.

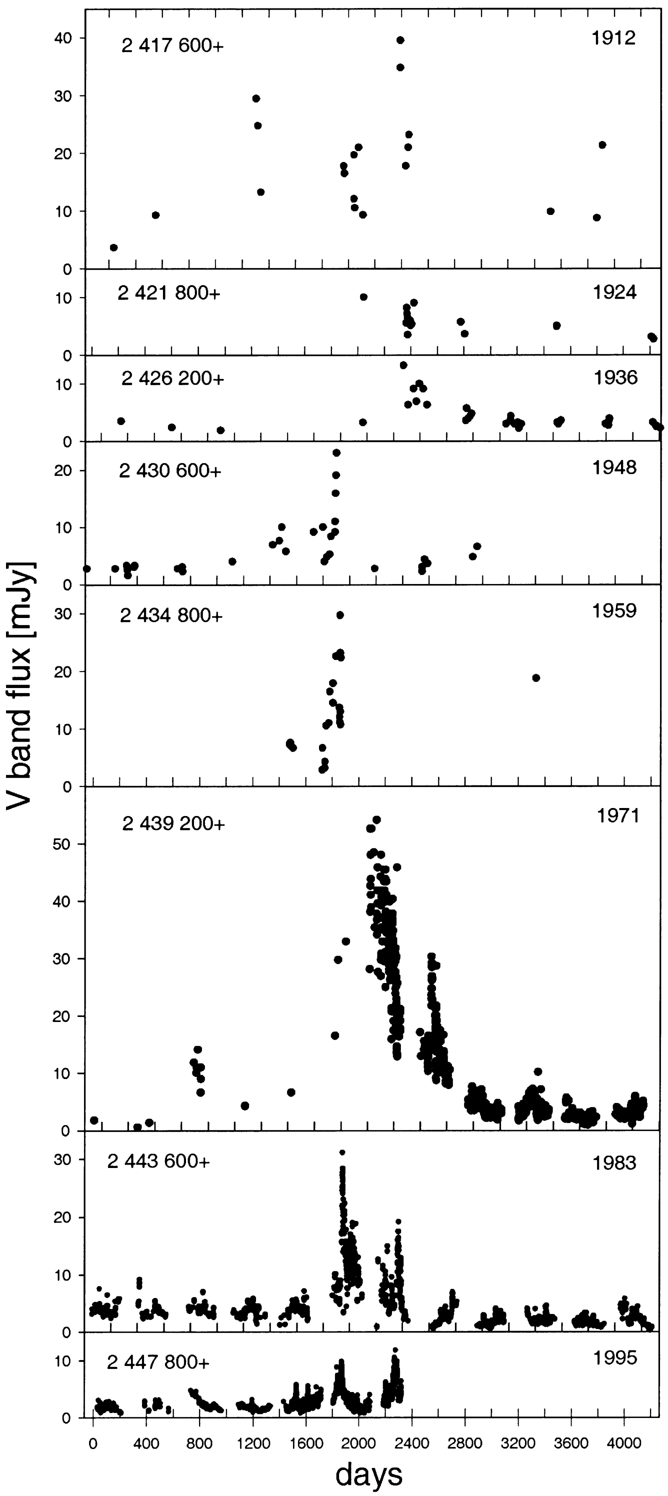

FIG. 12.—Optical flux density curve between 1906 and 1996, folded assuming a period of 4330 days. For each panel, the Julian date of the first 20 day tick mark is given in the upper left corner and the year of the midepoch in the upper right corner.

dently pointed out by Sillanpää 1999.) In Figure 12 we have folded up the optical flux curve using this period. Note that in 1971 no observations were done at the time of the predicted maximum, but the two data points on both sides of it show that the fluxes were high around the calculated epoch. The strict periodicity seen here is a strong indication that we are seeing the primary event, not radiation from later secondary processes (e.g., from shocks formed in the jet).

Thus, it is possible to identify the first of the twin optical flares, the thermal one, as the crossing of the accretion disk by the secondary black hole just as in the Lehto & Valtonen model. A constant period of 4330 ± 10 days can be assumed, with no precession needed. Consequently, there is no need for an extremely massive primary black hole, and the problems pointed out in the previous section are eliminated. (Recall that the need to invoke strong precession came from trying to fit two disk crossings, the Lehto & Valtonen superflares, to the observed two major peaks.)

What about the second optical peaks, the maxima in 1972, 1984, and 1995/96? As at least the two last ones were synchrotron flares, a natural explanation is that the later activity, roughly a year after the disk crossing, is the result of enhanced accretion rate and consequent shock formation down the jet. The time for the disturbance to propagate from the penetration point to the inner edge of the accretion disk and subsequently down the relativistic jet cannot be estimated with our present knowledge (or rather lack of it) of the physics of the accretion disks and relativistic jets and of their size and geometry in the particular case of OJ 287; the best one can say is that a year or so does not appear unreasonable. One does not expect that the time interval is constant, and so the accretion-induced optical (and radio) activity need not come at exactly regular intervals, nor be exactly similar from one pericenter passage to another, as indeed seems to be the case.

Unlike in the Lehto & Valtonen model, the geometry of the system cannot be determined from the data. With the binary period P fixed by the observed maxima, the size of the orbit a depends on the assumed primary and secondary black hole masses M and m: $a = [P^2 G(M + m)/4\pi^2]^{1/3}$. For masses of the order of $10^8\ M_\odot$, the apocenter of the orbit is at a distance of about $2500 r_g$ ($r_g = GM/c^2$), and for $\sim 10^9\ M_\odot$, at $\sim 500 r_g$. If the orbit of the secondary is roughly coplanar with the accretion disk, as one expects the case to be (cf. Ivanov et al. 1998), the second crossing of the accretion disk therefore occurs in the outer regions of the accretion disk. In a gas pressure–dominated disk the surface density drops as $r^{-3/5}$ (Shakura & Sunyaev 1973; Ivanov et al. 1998). The motion is approximately Keplerian, and so $v(\text{crossing}) \propto r^{-1/2}$. One sees that at the more distant crossing the secondary's speed is smaller, typically by an order of magnitude, and the density of the disk is only a fraction of that at the pericenter crossing. The thermal flare is therefore much smaller, lost in the other flux variations, and the smaller accretion-enhanced secondary activity is also unobservable.

6. CONCLUSIONS

We have presented a new interpretation of the observed optical and radio variations of OJ 287. We suggest that the activity observed at 12 year intervals is due to two different, though related, processes in a binary black hole system. At strictly regular intervals of 11.86 years, the secondary black hole crosses the accretion disk of the primary black hole, causing a thermal flare which is unpolarized and visible only in the optical regime. About a year later, the disturbance has propagated down the relativistic jet and results in the growth of new synchrotron-emitting shocks. These become visible both in the optical and in the radio regimes as polarized synchrotron flares and are responsible for the distinct double-peaked nature of the optical periodic outbursts. Most of the jet activity, however, is unrelated to the binary processes (as is the case in ordinary nonbinary AGNs). The postpericenter radio flares do not dominate the radio flux curve, and, not being strictly periodic as the disk-crossing optical flares are, they are not detected in periodicity analysis either.

The main advantages of our scenario, as compared to the Lehto & Valtonen double penetration model, are as follows:

1. An explanation of the different characteristics of the double optical peaks, of which the first one appears to be thermal and strictly periodic, and the second one nonthermal and only approximately periodic.
2. An explanation of the lack of a radio flare during the first optical peak and of a simultaneous radio flare during the second one.
3. No extreme assumptions about the binary black hole masses are needed, since no strong precession is required to explain the historical optical flux variations.

A constant period of 11.86 years also may give a better fit to the historical data. The best Lehto & Valtonen model seems to fail during the 1920s and 1930s (M. J. Valtonen 1999, private communication; Pietilä 1998), whereas by assuming a constant period we can identify the maxima observed in 1925 and 1937 as the secondary optical peaks occurring about a year after the disk-crossing flares, occurring during gaps in the historical data.

Our best fit to the disk crossing maxima in 1947, 1959, 1983, and 1994 gives a period of $P = 4341$ days with $T_0 =$ JD 2,449,676. However, the optical flux was still rising at the time of the last observations in 1947 and 1959, so an alternative is to use only the latest two crossings. This gives $P = 4324$ days and $T_0 =$ JD 2,449,667. Using $P = 4330 \pm 10$ days with $T_0 =$ JD $2{,}449{,}670 \pm 10$ fits all the data quite well. The next disk crossing and a sharp optical flare are therefore predicted to occur within 2 weeks of 2006 September 25 (JD 2,454,004). This thermal flare should be unpolarized and have no radio counterpart, while a period of enhanced nonthermal optical and radio activity is expected toward the end of 2007. The corresponding predictions of the only viable alternative scenario, the double penetration model of Lehto & Valtonen, predicts the first optical event around 2006.23–2006.36 (late March to mid-May; Valtonen & Lehto 1997), thus providing a definite test.

If our interpretation is correct, several questions need to be addressed in the future work. The interaction between the black hole and the accretion disk needs to be investigated in more detail, as well as the chain of events leading from the disk crossing to jet flow enhancement. The generally similar amplitude of the first and the second optical peaks is a curious coincidence, especially considering that in our model the second one is considerably Doppler-enhanced radiation from the relativistic jet. Historical data may still be found in the plate archives of observatories; especially valuable would be data filling the gaps around the times of the predicted disk crossings. The need for optical polarization monitoring for identifying thermal and nonthermal processes is obvious. Finally, a dense VLBI monitoring should reveal the causal connections between optical and radio flaring and the formation of new shocks in the jet. In particular, the first of the optical flares should not coincide with an extrapolated zero VLBI separation epoch, while the second one should.

This work has been supported by several Academy of Finland project grants. H. D. A. and M. F. A. acknowledge support of the UMRAO by the University of Michigan and by a series of grants from the NSF. We would like to thank L. Takalo and M. Valtonen for useful comments.

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