THE ASTROPHYSICAL JOURNAL, 325:628–634, 1988 February 15

OJ 287: BINARY PAIR OF SUPERMASSIVE BLACK HOLES

A. SILLANPÄÄ, S. HAARALA, AND M. J. VALTONEN
Turku University Observatory, Finland

B. SUNDELIUS
Chalmers University of Technology and University of Gothenburg, Sweden

AND

G. G. BYRD
University of Alabama
Received 1987 March 5; accepted 1987 July 30

ABSTRACT

A light curve of the BL Lacertae object OJ 287 is constructed in the optical V band using observations between the year 1890 and the present. The light curve shows repeated outbursts at ~ 11.65 yr intervals. Also there is a hint of repeated minima at the interval of 11.0 yr. The structure of the light curve during an outburst resembles the pattern of inflow of gas from an accretion disk to a supermassive black hole in a tidal perturbation. For this reason we propose that OJ 287 is a binary pair of supermassive black holes with an orbital period of 9 yr in the rest frame of OJ 287 and that the light variations are related to tidally induced mass flows from accretion disks into black holes. Numerical experiments using N-body code by Miller have been carried out to study mass flows.

These simulations show that the inflow into the center of a black hole disk during repeated periastron passages of the companion will produce an outburst pattern similar to that observed for OJ 287 with 9 yr period. Indirect observational evidence indicates masses for two black holes of $5 \times 10^9\ M_\odot$ and $2 \times 10^7\ M_\odot$ with a binary semimajor axis of ~ 0.1 pc. The future binary lifetime via gravitational radiation is $\sim 10^5$ yr. Tidal interaction and thus luminosity of the binary model would be greatest in these last stages which is consistent with OJ 287 being one of the brightest quasars.

Subject headings: black holes — BL Lacertae objects

I. INTRODUCTION

The BL Lacertae object OJ 287 has attracted attention for many reasons. It is one of the fastest varying extragalactic radio sources (Valtaoja 1986, and references therein) showing prominent optical as well as radio outbursts (Fig. 1*a*). There is even evidence that the optical outburst has roughly month-long brightness oscillations during the typical 4 month decline after an outburst (Fig. 1*b*). These oscillations appear to repeat themselves from the 1972 outburst to the 1983 outburst (Sillanpää *et al.* 1985). This has encouraged us to collect old observations from the literature to see whether there are other regularities in the behavior of this object.

In light of this observational study, we also conduct a theoretical study of the basic mechanism of the outbursts. Previously Byrd *et al.* (1986), and Byrd, Sundelius, and Valtonen (1987) have done computer studies of the disk inflow in spiral galaxies caused by companion tidal action. The qualitative similarity of OJ 287's outburst time structure and our computer model inflow prompted us to see if our model could be scaled down to simulate similar events in accretion disks around supermassive objects in the nucleus of a giant galaxy.

II. THE OPTICAL LIGHT CURVE

The optical data (in V band) are available from the following sources: Kurochkin (1971*a*, *b*), Tsessevich (1972), Craine and Warner (1973), Visvanathan and Elliot (1973), Kinman *et al.* (1974), McGimsey *et al.* (1975), Miller *et al.* (1976), Usher (1979), Pollock *et al.* (1979), Hagen-Thorn (1980), Takalo (1982), Gaida and Röser (1982), Smith, Leacock, and Price (1982), Corso *et al.* (1984). Lloyd (1984), Sillanpää *et al.* (1985), Sillanpää, Haarala, and Korhonen (1987) and unpublished data from Turku University Observatory. The data have been averaged semimonthly, and the whole data set is presented in Figure 1*a* in millijansky units, using the conversion formulae in Kinman *et al.* (1974).

In spite of large gaps in the data, especially early in the century, it is immediately obvious that the source has had many outstanding outbursts at rather regular intervals. These are listed in Table 1. We also list the expected maxima by using the 1913 and 1983 outbursts as reference points and by dividing the interval in six equal periods of 11.65 yr. We note that the expected maxima occur during the northern late spring in 1936 and in 1971, but the maximum was not observed until the following autumn. Due to lack of observations in the summer period (R.A. = $08^{\rm h}51^{\rm m}$ for OJ 287) this is not unexpected even if the outbursts were exactly in time. For the same reason we do not know whether the 1959 outburst came as scheduled even though the data are consistent with it. The 1947 outburst came too early by 9 months, but this could be partly due to a gap in observations from 1947.3 to 1948.0.

The significance of the periodicity may be estimated as follows. The outbursts occur within ~ 1 yr of expected times. Five outbursts are expected between 1913 and 1983, i.e., in the 70 yr period there are altogether 2×5 "target" years. The probability that the four observed outbursts hit the "targets" by chance is

$$\tfrac{10}{70} \times \tfrac{8}{70} \times \tfrac{6}{70} \times \tfrac{4}{70} \approx 8 \times 10^{-5} .$$

A closer inspection of the light curve reveals that occasionally OJ 287 goes to a rather low level of brightness. The most

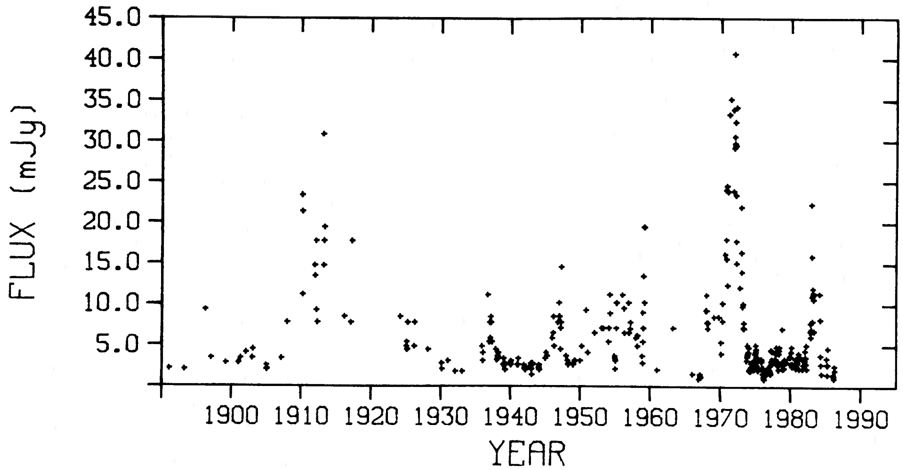

FIG. 1*a*

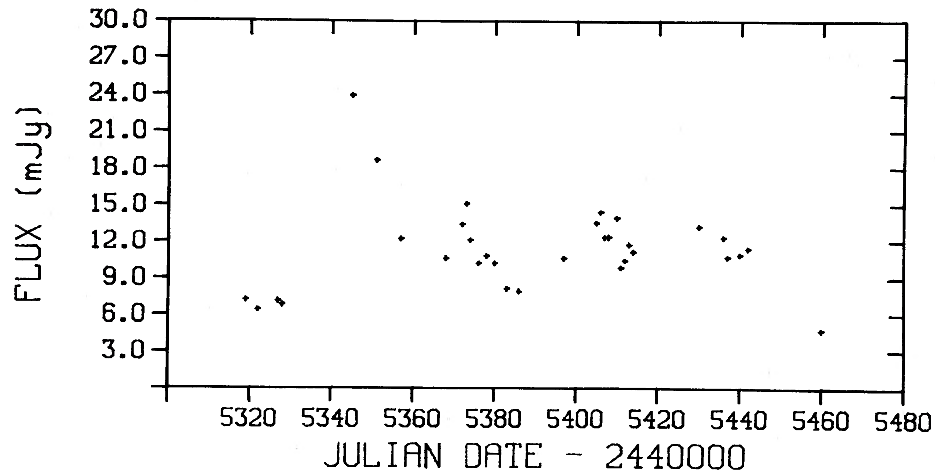

FIG. 1*b*

FIG. 1.—(*a*) Entire data set of optical observations in millijansky (*V* band) which is used in the analysis. Each cross represents the average over one-half month. (*b*) Variation of the light output of OJ 287 during the single 1983 outburst from the observations of Sillanpää *et al.* (1985). For the transformation between the millijansky scale and the *V* magnitudes see Kinman *et al.* (1974).

prominent of these brightness minima occurred at 1943.1, 1955.0, and 1976.2, when the optical flux fell at 50% or below the average flux level of the quiescent period (typically ~7 yr in length). During the three well-observed quite periods, this type of flux decrease happened only once in each period.

To search for a possible periodicity in the distribution of the minima, we have used the periodogram technique of Warner and Robinson (1972). We left out all data points except the ones with low flux levels (the limiting flux density was 2 mJy)

TABLE 1

MAXIMA IN LIGHT CURVE OF OJ 287

Observed Epoch	Flux (mJy)	Expected Epoch
1913.1.........	30.9	1913.1
1936.8.........	11.2	1936.4 (0.4 yr late)
1947.3.........	14.6	1948.05 (0.75 yr early)
1959.3.........	19.5	1959.7 (0.4 yr early)
1971.9.........	40.7	1971.35 (0.65 yr late)
1983.0.........	22.3	1983.0
...	...	1994.65

and searched for time-dependent structure of the data spacing. The data were inspected using periods from 5.0 yr up to 15.0 yr. The difference between individual periods was 0.1 yr.

This analysis suggests an 11 yr periodicity with a double minimum structure. The time interval between the double is ~1 yr. Figure 2 shows the light curves during the three well-observed quiescent periods. The data have been overlaid with an assumed 11.05 yr period of minima; this period seems to agree best with the double minimum structure found above.

In particular, the question of the periodicity of the deep minima is still open. In a previous paper (Sillanpää, Haarala, and Valtonen 1986) it was mentioned that the next two minima should occur between 1987 March and 1988 June, and the next outburst is predicted to take place in 1994. A decline in the flux level of OJ 287 was indeed observed in 1987 January (Sillanpää 1987), but the minimum was not as deep as the 1976 minimum (see Table 2 for the latest observations). Since OJ 287 has been exceptionally faint ever since its last outburst, one cannot put much weight to the dimming in 1987 January. We should wait for 1988 February–March and the expected flux minimum in OJ 287 in order to judge the reality of the repeated flux minima.

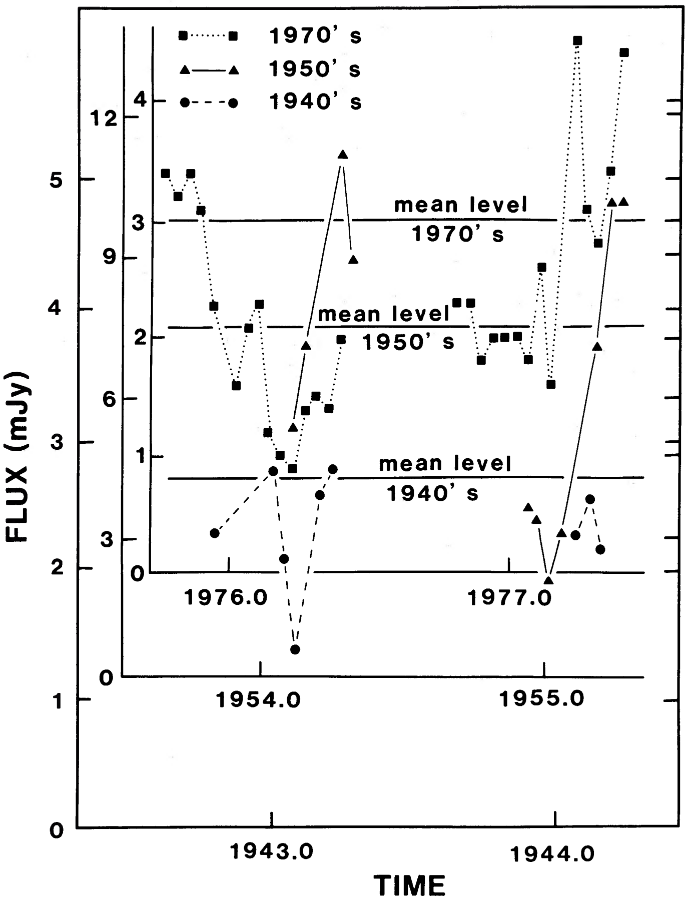

FIG. 2.—Data near the three strong minima overlaid assuming an 11.05 yr period. Data have been scaled to the average flux level during the 7 quiescent years.

TABLE 2

V MAGNITUDES OF OJ 287 IN LATE 1986 AND EARLY 1987

Date	*V*
1986 Nov 13	15.22
Nov 30	15.58
1987 Jan 2	15.79
Jan 4	15.49
Jan 6	16.10
Jan 8	15.59
Jan 9	16.00
Jan 22	15.92
Feb 2	15.36
Feb 3	15.48
Feb 8	15.51
Feb 11	15.69
Feb 22	15.56
Feb 24	15.80
Feb 25	15.72
Feb 27	15.85
Feb 28	15.59
Mar 6	15.72
Mar 30	15.72
Apr 1	15.76
Apr 5	15.63
Apr 14	15.95
Apr 21	15.81
Apr 26	15.79
Apr 28	15.93

III. THE BINARY MODEL

The periodic outbursts suggests that we may be observing a binary system with 11.65 yr orbital period. Considering the large redshift (0.306) of OJ 287, this becomes $\sim$9 yr in the rest frame of the quasar. Begelman, Blandford, and Rees (1980) have considered binary black hole models for active galactic nuclei with orbital periods of the order of 10 yr. They point out that the precession period in a black hole binary system generally exceeds 10^4 yr; thus it is not possible that we could be observing the precession of a relativistic jet on and off the line of sight for OJ 287. Also Whitmore and Matese (1981) and Gaskell (1983) have argued that quasars often have binary nuclei. In the latter reference, the basis for argument is observational. Gaskell proposes that quasar broad emission lines arise from material bound to supermassive objects (SMOs). In contrast, the narrow emission lines arise from more extended nuclear material at rest with respect to the host galaxy (as is observationally verified for nearby quasar-type objects).

In some cases, the two broad lines are displaced $\sim$3000 km s^{-1} on opposite sides of the corresponding narrow lines. This displacement is considered to be caused by the orbital motions of the SMOs. In many other cases where only one displaced broad line is seen, the other member is thought to be present but of insufficient strength to be visible.

Recent observational work has further substantiated this idea. Owen *et al.* (1985) have observed with the VLA that 3C 75 has an apparently double nucleus with two jets originating from each nucleus. These authors conclude that 3C 75 may be a pair of galaxies in the process of merging with the two nuclei $\sim$7 kpc apart. Further spectral support has been found by Peterson, Korita, and Cota (1987) in a Seyfert 1 galaxy. They found two broad-line emitting regions oppositely displaced relative to the corresponding narrow lines $\sim$2700 km s^{-1} relative to one another.

However, it still remains to be explained how the orbital period and the outburst pattern could be related to each other in OJ 287. In light of all the above theoretical and observational results, we propose that OJ 287 has a binary SMO in its nucleus and that the recurrent outbursts are the results of tidal interaction during each 9 yr orbital period. One SMO and possibly both are assumed to have accretion disks. We can go beyond this assertion by using a simple computer model similar to those we have used previously for tidally perturbed disks of spiral galaxies (Byrd, Saarinen, and Valtonen 1986; Byrd *et al.* 1986). In these earlier studies, it was found that tidal perturbations of sufficient strength create global disturbances in the disk and cause a flow of matter into the center of the disk. Assuming that all the matter which flows through a given radius is absorbed at the disk center, e.g., by a black hole, we can obtain a typical pattern of time rate of inflow of matter and thus luminosity during a single pertubing encounter.

Examining Figures 1 or 2 of Byrd *et al.* (1986), we see a resemblance between the rate of inflow during a tidal encounter and the brightness variation pattern in an outburst of OJ 287 shown in Figure 1b.

In order to obtain a starting model for appropriate numerical experiments, we estimate the orbital parameters in OJ 287 binary as follows. In the previous simulations by Byrd *et al.* (1986), the main accretion event in disk simulations lasts $\sim$0.4 orbital periods of the outer edge of the disk, and superposed on it are variations in a time scale of $\sim$0.1 orbital periods. The time scale of a typical outburst in OJ 287 is $\sim$0.4 yr with "oscillations" at ~ 0.1 yr intervals (Sillanpää *et al.* 1985). Consequently we deduce the period of rotation of the outer edge of the main disk to be ~ 1 yr as observed at Earth, or ~ 9.2 months in the frame of OJ 287.

Let us call the radius of the main disk (= primary) r_1 and the semimajor axis of the binary orbit a. Then

$$(a/r_1)^{3/2} \approx 11.65(1 + m) ,$$

if m is the ratio of the secondary mass to the primary mass. If we assume that the secondary is much smaller than the primary, then $a \approx 5r_1$. In order that a small secondary would cause sufficient disturbance in the disk of the primary, the pericenter of the binary orbit q should not be much greater than r_1 based on experience with our previous similations. Putting

$$a(1 - e) \approx 1.5r_1 ,$$

we obtain the eccentricity $e \approx 0.7$.

The model which we will consider is the following: two mass points (black holes) are initially in an elliptic orbit of eccentricity 0.7 around each other. The larger mass point (mass m_1) is surrounded by a self-gravitating disk of matter which is tidally perturbed by the smaller mass point (mass m_2). The disk (mass m_d) lies in the orbital plane of the binary, and it rotates in the same sense as the binary.

The calculations are carried out using the two-dimensional N-body code by Miller (1976, 1978), formulated in a polar coordinate grid. The code uses $\sim 60{,}000$ particles in a smoothed potential. The grid extends from an inner radius (by definition this inner radius is one unit) to an outer radius of 60 units. The softening parameter of the potential was chosen to be 1 unit (see Byrd *et al.* 1986 for details).

The main difference from the previous work (Byrd, Saarinen, and Valtonen 1986; Byrd, Sundelius, and Valtonen 1987), which was applicable to spiral galaxies, is that now we include a point mass at the center of the coordinate grid. This point mass represents a black hole, and particles which fall inside the one unit radius from it are considered as matter falling into the black hole.

Here we report four model runs with two values of the $m_2/(m_1 + m_d)$ ratio and two values of the size of the disk (see Table 3). In all experiments the inner edge of the disk is at one unit, and the central black hole is 5 times more massive than the disk. In runs 1 and 3 the disk is small enough that the secondary stays within the grid area throughout the calculation, i.e., through four orbital revolutions. In runs 2 and 4 the secondary enters the grid area at the beginning of the calculations. After a single approach to the disk it recedes out of the grid, and thereafter its gravitational influence is not counted any more, However, the evolution of the disk is followed through two revolutions of its outer edge.

TABLE 3

PARAMETERS OF THE MODELS

Run	$m_2/(m_1 + m_d)$	Disk Size
1.........	0.04	5.0
2.........	0.04	19.4
3.........	0.187	5.0
4.........	0.187	19.4

Figure 3 shows the rate of infall of particles to the central hole of the disk in run 1. In units of the initial period of revolution of the disk edge, the original orbital period of the secondary was 11.2 units (one time unit corresponds to 9 months in OJ 287). However, the time intervals between the maximal mass inflows were 13.2, 12.5, and 11.9 units. Figure 4 shows that the elliptic orbit shrinks $\sim 3\%$ per revolution and at the same time it precesses by $\sim 15°$ per revolution. The precession is due to the potential of the disk.

In run 1 the radius of the central hole was 20% of the disk radius. In run 2 the hole was reduced in size to 5% of the disk radius. Now no infall at all was observed through the innermost (one unit) radius of the disk. Increasing the disturber mass in run 4 produces inflow, the pattern of which is shown in Figure 5. We notice that the inflow has many submaxima, separated typically by 0.1 time units. The maximal inflow occurs after ~ 0.75 time units, just before the closest passage between the secondary and the disk. As mentioned earlier, these submaxima resemble those seen immediately after an outburst of OJ 287 (Fig. 1*b*).

Run 3 repeats the same encounter with a smaller disk. Figure 6 shows the inflow pattern, and Figure 7 gives the behavior of the orbit of the secondary. The time differences between the maximal inflows are 10.6, 7.2, 5.8, 5.5, and 5.1 units. Because of rapid shrinking of the secondary orbit, the system is short-lived, and at the end of the calculation the disk is totally disrupted.

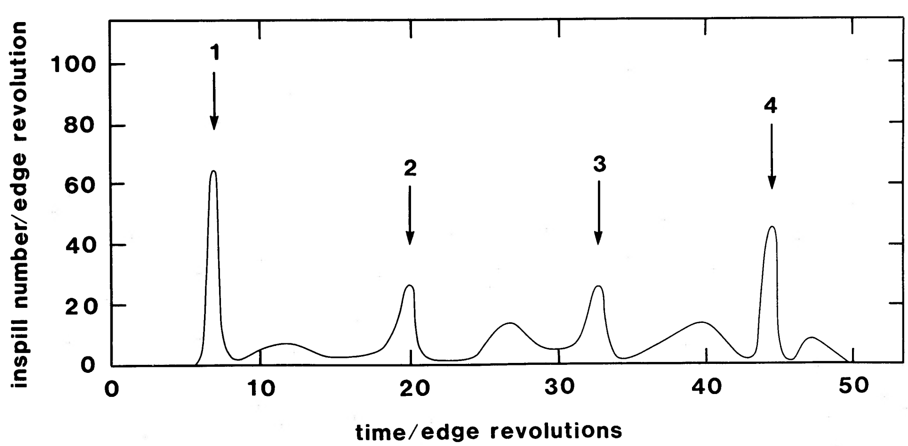

FIG. 3.—Time rate of mass inflow to the disk center in run 1. Arrows indicate the four close encounters of the two black holes.

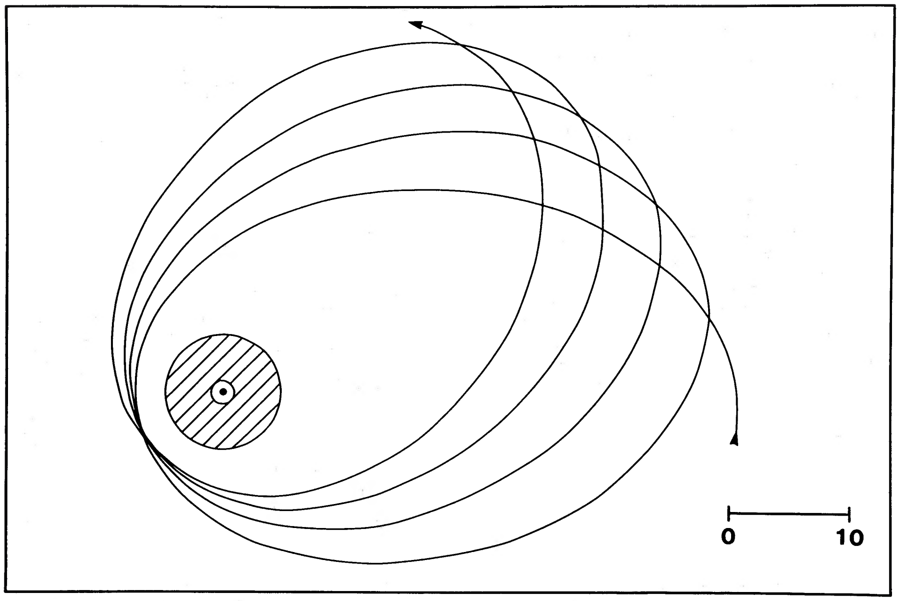

FIG. 4.—Evolution of the orbit of the secondary black hole around the primary in run 1. The primary disk is drawn to scale.

IV. DISCUSSION

a) *Orbit and Disk Parameters*

It is not clear exactly how the gas flow toward the black hole is transformed into radiant energy. However, as mentioned earlier, it is reasonable to assume that the greater the mass inflow, the greater is the radiated power. Comparing the pattern of mass inflow in our various computer simulations with the pattern of light variations in OJ 287, we see that run 1 gives a fairly good match to the outburst pattern (Fig. 1*a* vs. Fig. 3) over the time when observations are available. Apparently the interaction between the disk and the secondary is too strong in the model since the orbit shrinks noticeably, and no such feature is seen in the observations. This interaction may be reduced by assuming a smaller mass for the disk. For a smaller disk mass the outburst pattern remains similar to Figure 3 but with the inflow rates reduced accordingly.

b) *Possible Eclipses*

A lighter disk would also reduce the amount of precession per revolution. Precession may be required by observations if the light minima turn out to be periodic and occur at intervals of 11.0 yr, shorter than the 11.65 yr period of outbursts. Then the minima may be interpreted as eclipses which take place at the apocenter part of the elliptic orbit in such a way that the disk surrounding the smaller black hole eclipses part of the larger disk. If the double minimum structure is confirmed, then the primary may have two bright regions (e.g., two jets) which are eclipsed in succession. The difference in the two periods indicates a precession of $\sim 5°$ per revolution. This magnitude of precession may arise from general relativistic effects. If the inner edge of the disk in the model of run 1 is identified with the last stable orbit about the black hole (three Schwarzschild radii), the system becomes fully determined: the mass of the primary is 5×10^9 $M_\odot$, and the major axis of the binary is

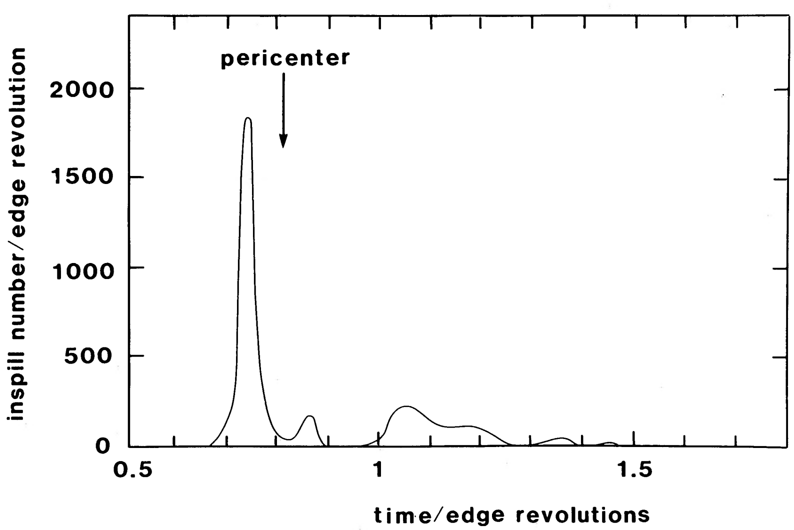

FIG. 5.—Details of mass inflow rate in run 4 during and after a single encounter between the two black holes

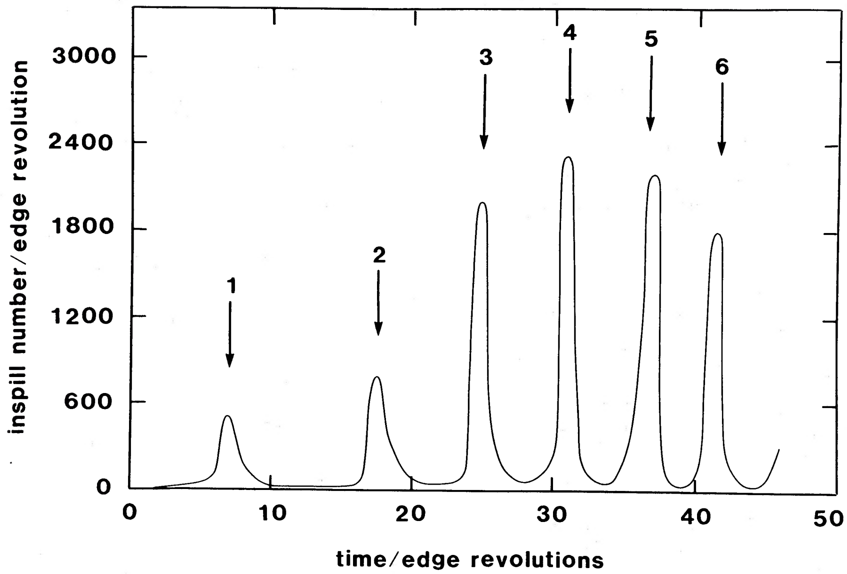

FIG. 6.—Time rate of mass inflow to the disk center in run 3. Arrows indicate the six close encounters of the two black holes.

$\sim$0.1 pc. This corresponds to $\sim 10^{-5}$ arcsec at the distance of OJ 287 and is consequently unresolvable with present instrumentation.

c) Light Variations and the Mass of the Black Holes

Correlation studies of 22 and 37 GHz radio data and optical data give about 0.1–0.2 yr time delay between optical and radio events (Valtaoja, Sillanpää, and Valtaoja 1987). If this delay is interpreted in terms of light travel time from the site of optical emission to the site of radio emission, the extent of the source would be expected to be similar to the binary orbit dimension mentioned above. Exact details depend on the model; see Valtaoja, Sillanpää, and Valtaoja (1987) for discussion.

It is expected that periodic light variations may occasionally occur in accretion disk–black hole systems due to orbital motion of radiating regions around the black hole. The expected period is $\sim 50 M_6$ s, if M_6 is the mass of the black hole in millions of solar masses. Variations in the time scale of $\sim$15–40 minutes have been reported in OJ 287 (Visvanathan and Elliot 1973; Frohlich Goldsmith, and Weistrop 1974; Kulshrestha, Joshi and Deshpande 1984; Valtaoja *et al.* 1985; Dreher, Roberts, and Lehàr 1986), which in the local frame of reference reduces to 12–30 minutes. This would suggest a black hole mass of $\sim 2 \times 10^7 M_\odot$. The Eddington luminosity $L_E = 1.3 \times 10^{44} M_6$ ergs s^{-1} corresponding to this mass is less than the total luminosity of OJ 287 ($\sim 10^{47}$ ergs s^{-1} at maximum brightness), but is greater than the proposed periodic part of the flux ($\sim 10^{44}$ erg s^{-1}). Thus we may associate the periodic part of the flux and the mass of $\sim 2 \times 10^7 M_\odot$ with the smaller black hole in the binary system.

In longer time scales Kinman *et al.* (1974) observed a correl-

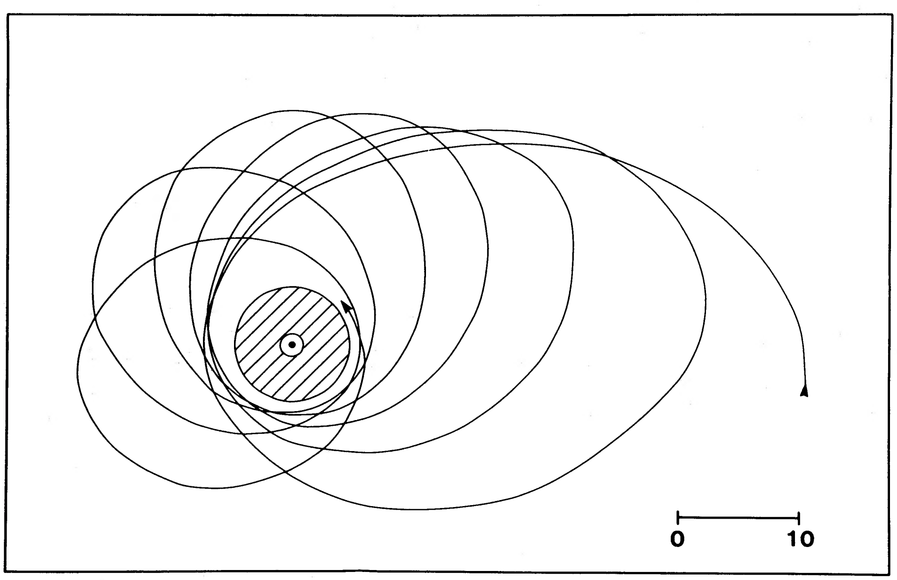

FIG. 7.—Evolution of the orbit of the secondary black hole around the primary in run 3. Primary disk is drawn to scale.

ation time scale of 8 days in the optical flux values of OJ 287. The analysis of 22 and 37 GHz data from Metsähovi observatory (Valtaoja *et al.* 1987) indicates that the time scales of shortest significant (at 1% level) flux variations occur in 2–4 days. If this is associated with the larger black hole, its mass would be of the order of $5 \times 10^9\ M_\odot$. An accretion disk–black hole system of this mass and radiating at 10^{47} ergs s^{-1} would be well below the Eddington limit. About 5 $M_\odot$ yr^{-1} of disk gas would be consumed in order to produce the luminosity. If the disk mass is originally comparable to the black hole mass and is consumed at this rate, then the lifetime of the system could be over hundred million years.

However, gravitational radiation is a more serious limiting factor to the longevity of the system. With the component masses mentioned above and the 9 yr orbital period the system lifetime becomes only a few times 10^5 yr. We would then conclude that OJ 287 is in a short-lived, even though highly luminous, stage of evolution. However, this conclusion is strongly dependent on the interpretation of variability data and should be viewed with caution until more detailed variablility studies of OJ 287 have been carried out.

V. CONCLUSION

We have constructed historical light curves of OJ 287 and found that it exhibits periodic outbursts at intervals of 11.6 yr (observer frame) or 9 yr (frame of OJ 287). The individual outbursts show an initial maximum with decaying submaxima at intervals of $\sim$1 month.

We propose that these characteristics are caused because OJ 287 has SMO binary in its nucleus with the members having an accretion disk around them. The outbursts at 9 yr intervals would be caused by the tidal action of the companion the disk of the larger black hole. We demonstrate via computer simulations that the inflow into the center of such a disk during the repeated periastron passages of a companion will produce an outburst pattern similar to that observed in OJ 287 with the 9 yr period. Similarly the submaxima during one outburst are also produced.

Indirect evidence was used to try to derive the masses of the objects and the physical size of their orbit around one another. The masses are probably $5 \times 10^9\ M_\odot$ and $2 \times 10^7\ M_\odot$ for the two objects. The major axis for this pair with a 9 yr period is $\sim$0.1 pc, well below the VLBI resolution limit. The future lifetime of this binary due to gravitational radiation is a few hundred thousand years. The tidal interaction (in our model) and thus luminosity would be greatest during the last stages of orbital decay of a supermassive binary pair. This is consistent with OJ 287 being one of the brightest quasars. The orbital speed of our proposed binary is $\sim$10 times greater than the orbital speeds proposed in the much lower luminosity Seyfert system examined by Gaskell (1983).

The authors thank R. H. Miller for providing a copy of his program. M. J. V. and G. G. B. thank Onsala Space Observatory for hospitality during part of this project. G. G. B. acknowledges support by a NORDITA grant and an NSF/EPSCOR grant.

REFERENCES

Begelman, M. C., Blandford, R. D., and Rees, M. J. 1980, *Nature*, **287**, 307.
Byrd, G. G., Saarinen, S., and Valtonen, M. J. 1986*a*, *M.N.R.A.S.*, **220**, 619.
Byrd, G. G., Valtonen, M. J., Sundelius, B., and Valtaoja, L. 1986, *Astr. Ap.*, **166**, 75.
Byrd, G. G., Sundelius, B., and Valtonen, M. 1987, *Astr. Ap.*, **171**, 16.
Corso, G. J., Purcell, B., Ciroux, M., and Schultz, J. 1984, *Pub. A.S.P.*, **96**, 705.
Craine, E. R., and Warner, J. W. 1973, *Ap. J. (Letters)*, **179**, L53.
Dreher, J. W., Roberts, D. H., and Lehár, J. 1986, *Nature*, **320**, 239.
Frohlich, A., Goldsmith, S., and Weistrop, D. 1974, *M.N.R.A.S.*, **168**, 417.
Gaida, G., and Röser, H.-J. 1982, *Astr. Ap.*, **105**, 362.
Gaskell, C. M. 1983, in *24th Liège Ap. Colloquium Quasars and Gravitational Lenses* (Liège: Université de Liège Institut d'Astrophysique), p. 473.
Hagen-Thorn, V. A. 1980, *Ap. Space Sci.*, **73**, 263.
Kinman, T. D., Wardle, J. F. C., Conklin, E. K., Andrew, B. H., Harvey, G. A., Macleod, J. M., and Medd, W. J. 1974, *A.J.*, **79**, 349.
Kulshrestha, A. K., Joshi, U. C., and Deshpande, M. R. 1984, *Nature*, **311**, 733.
Kurochkin, N. E. 1971*a*, *Astr. Tsirk.*, **644**, 1.
———. 1971*b*, *Astr. Tsirk.*, **654**, 7.
Lloyd, C. 1984, *M.N.R.A.S.*, **209**, 697.
McGimsey, B. Q., Smith, A. G., Scott, R. L., Leacock, R. J., Edwards, P. L., Hackney, R. L., and Hackney, K. R. 1975, *A. J.*, **80**, 895.
Miller, H. R., Wingert, D. W., McGimsey, B. Q., Anderson, E. S., Mullikin, T. L., and Folsom, G. H. 1976, *A.J.*, **81**, 298.
Miller, R. H. 1976, *J. Comput. Phys.*, **21**, 400.
———. 1978, *Ap. J.*, **224**, 32.
Owen, F. N., O'Dea, C., Inoue, M., and Eilek, J. A. 1985, *Ap. J. (Letters)*, **294**, L85.
Peterson, B. M., Korista, K. T., and Cota, S. A. 1987, *Ap. J. (Letters)*, **312**, L1.
Pollock, J. T., Pica, A. J., Smith, A. G., Leacock, R. J., Edwards, P. L., and Scott, R. L. 1979, *A.J.*, **84**, 1658.
Sillanpää, A. 1987, *IAU Circ.*, No. 4296.
Sillanpää, A., Haarala, S., and Korhonen, T. 1987, *Astr. Ap. Suppl.*, in press.
Sillanpää, A., Haarala, S., and Valtonen, M. J. 1986, *Turku Univ. Obs. Inf.*, No. 108.
Sillanpää, A., Teerikorpi, P., Haarala, S., Korhonen, T., Efimov, Y., and Shakhovskoy, N. M. 1985, *Astr. Ap.*, **147**, 67.
Smith, A. G., Leacock, R. J., and Pica, A. J. 1982, in *Low Frequency Variability of Extragalactic Radio Sources*, ed. W. D. Cotton and S. R. Spangler (NRAO: Green Bank), p. 55.
Takalo, L. O. 1982, *Astr. Ap.*, **109**, 4.
Tsessevich, V. D. 1972, *Astr. Tsirk.*, **688**, 7.
Usher, P. D. 1979, *A.J.*, **84**, 1253.
Valtaoja, E. 1986, in *Quasars*, ed. G. Swarup and V. K. Kapahi (Dordrecht: Reidel), p. 79.
Valtaoja, E., *et al.* 1987, in preparation.
Valtaoja, E., *et al.* 1987 *Nature*, **314**, 148.
Valtaoja, L., Sillanpää, A., and Valtaoja, E. 1987, *Astr. Ap.*, in press.
Visvanathan, N., and Elliot, J. L. 1973, *Ap. J.*, **179**, 721.
Warner, B., and Robinson, E. L. 1972, *M.N.R.A.S.*, **159**, 101.
Whitmore, D. P., and Matese, J. J. 1981, *Nature*, **293**, 722.

G. G. Byrd: Department of Physics and Astronomy, University of Alabama, Box 1921, University, AL 35486

S. Haarala, A. Sillanpää, and M. J. Valtonen: Turku University Observatory, Tuorla, SF-21500 Piikkiö, Finland

B. Sundelius: Department of Astronomy, Chalmers University of Technology, S-41296 Gothenburg, Sweden