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THE 2005 NOVEMBER OUTBURST IN OJ 287 AND THE BINARY BLACK HOLE MODEL

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ABSTRACT

We report observations of the largest optical outburst in 20 years in the quasar OJ 287. In some ways it was expected, due to the well-known quasi-periodic 12 yr outburst cycle of OJ 287. In other ways the timing of the outburst was surprising, since calculations based on the periodicity were predicting such an outburst in late 2006. Here we point out that, in the precessing binary black hole model, first proposed by Sillanpää et al., and later refined by Lehto & Valtonen and Sundelius et al., the precession shifts the first outburst of each outburst season progressively to earlier times relative to the mean period. Thus, in this model, the timing of the outburst is quite acceptable, even if it was not predicted. The next test of the model comes in 2007 September when the second brightness peak is due. It may then be possible to detect the shortening of the binary period due to emission of gravitational waves from the system.

Subject headings: BL Lacertae objects: individual (OJ 287) — galaxies: active — gravitation — relativity

1. INTRODUCTION

It has long been suspected that supermassive black holes should appear in binary pairs in a fair number of active galactic nuclei and quasars (Begelman et al. 1980; Roos 1981; Mikkola & Valtonen 1992). It is important to estimate the number of such pairs since they are primary targets of the new generation of gravitational wave detectors. It has been somewhat embarrassing that very few cases of binary black hole systems have been confirmed, in spite of the strong theoretical prejudice in favor of their existence. There are many reported cases of double nuclei (e.g., Owen et al. 1985; Carico et al. 1990; Scoville et al. 1998; Junkkarinen et al. 2001), but none of these are at subparsec separation where the binary black holes pairs can be regarded as independent dynamical units.

As in the case of binary systems in general, the binary black holes are a potential source of high-precision data on quantities such as the black hole mass. For example, the most accurate determinations of stellar masses come from binary systems. The binary nature of the η Carinae system has recently shed light on the very peculiar behavior of this star (Iping et al. 2005). This is especially true for binary black hole systems where it may not be possible to resolve the components observationally. Then the orbit calculations based on celestial mechanics can provide high-precision models that may be checked with observations.

Modern observations of OJ 287 started in 1968, but very fortunately we have in fact observational material of this quasar since 1891. The periodic behavior of OJ 287 was first noticed by Sillanpää et al. (1988; see our Fig. 1). They suggested that the periodic outbursts are due to the binary nature of the system where a secondary black hole perturbs the accretion disk of the primary during pericenter passages, once every 12 yr orbital cycle. The model made predictions about the first outburst of the next cycle in late 1994 that were proven correct (Sillanpää et al. 1996a). This success spurred more theoretical work along the lines of Sillanpää et al. (1988). In the early part of 1995, two studies were carried out: Lehto & Valtonen (1996) showed that the sharp outbursts fit nicely with the idea of an impact of the secondary on the disk of the primary. There are two impacts per pericenter passage, hence the double-peak structure of the light curve. The model based on an "inert" accretion disk provided an exact celestial mechanics solution of the timing of the outbursts.

It was later demonstrated that the celestial mechanics solution is unique and robust: a wide range of astrophysical parameters leads to practically the same orbit solution (Pietilä 1998). In this solution the masses of the two black holes are 16 ± 1.5 and 0.1 ± 0.02 billion solar masses, the observed period of the orbit (larger than the true period by the redshift factor of 1.306) is 12.08 ± 0.02 yr, the eccentricity of the orbit is 0.67 ± 0.01, the semimajor axis of the orbit is 0.052 ± 0.001 pc, and the relativistic precession rate is $33\overset{\circ}{.}3 \pm 2°$ per period.

At about the same time, Sundelius et al. (1996, 1997) produced a model based on the same exact solution, but allowing for a "live" accretion disk. The "live" accretion disk is bent toward the perturbing black hole before the disk impact, which means that the timing is somewhat earlier than in the impact on an "inert" disk. This correction of the timing depends on the distance R of the point of impact from the primary black hole.

For the outbursts used in the calculation of the exact model of Lehto & Valtonen (1996), the correction is negligible, but when we want to calculate the timing of the outburst arising from the 2005 disk crossing, we need to include the disk bending. The Sundelius et al. model gives the time of the first impact of the current outburst season as 2005 March 14, and the radiation peak from this impact was expected later, at a time that was not calculated precisely by Sundelius et al. Simply trying to line up previous outbursts in an optimal manner, with or without regard to any underlying theory, leads one to expect that the first outburst event should not take place earlier than 2006 September (Kidger 2000; Valtaoja et al. 2000).

There are numerous other models that also attempt to explain the quasi periodicity of OJ 287 (e.g., Katz 1997). It is our understanding that these other models do not have the possibility of the double-outburst peaks shifting relative to the mean

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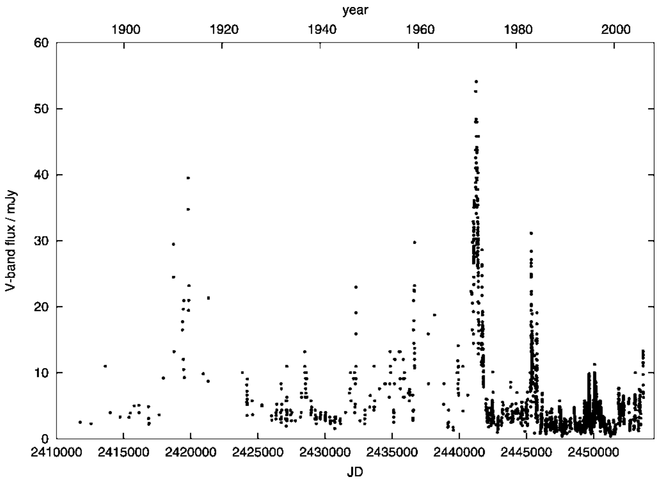

FIG. 1.—Historical light curve of OJ 287. This BL Lacertae object has outbursts at 12 yr intervals, and each outburst is composed of two sharp peaks. The 2005 peak at the right edge of the figure is presumably the first of the two peaks of the new cycle of activity. The data are plotted in linear scale.

period. In fact, most other models do not even attempt to explain the fact that only a small fraction of the outburst energy comes from the double peaks (lasting only a couple weeks) and that the primary burst of energy comes from the long-lasting (typically 3 yr) increase of the base emission level that occasionally (e.g., in 1972) even rises above the double-peak level. It is because of this difference between the general outbursts and the shifting double peaks that OJ 287 can be called, at best, quasi-periodic, not periodic on a 12 yr timescale (Kidger 2000).

In this Letter we report recent observations of the optical flux of OJ 287 and then show that the observations of the 2005 November outburst agree with the expected timing.

2. OBSERVATIONS

Since OJ 287 is a bright object, around 15 in V magnitude at the base level, it is not difficult to observe. The problem arises mostly with having observers ready to monitor its behavior from night to night. For scheduling reasons, large telescopes cannot be used for monitoring of this kind. Fortunately, even very modest telescopes are enough for this work. The main problem is the weather; it requires observers on many continents to ensure that at least one observing site has good observing conditions every night. The authors of this Letter operate telescopes in North and South America, Africa (Canary Islands), Europe, and Australia.

The observations were acquired using the small (0.3–1.0 m) telescopes listed in Table 1. CCD images were obtained in the V and R bands using the exposure times listed in Table 1. Instrumental magnitudes of OJ 287 and calibrated comparison stars in the field (Fiorucci & Tosti 1996) were measured using standard aperture photometry. The magnitude of OJ 287 was then obtained by comparing its brightness to several comparison stars in the field. Color effects and the fact that the University of Alabama observations were calibrated using a different comparison sequence (Smith et al. 1985) lead to small (maximum 0.05 mag) offsets between different data sets. However, given the large amplitude of brightness variations in OJ 287, these offsets are insignificant. Finally, the R magnitudes were transformed to V magnitudes using a transformation $V - R = 0.3$, and the V magnitudes were transformed to a linear scale. The assumption of constant color is justified by Sillanpää et al. (1996b), who show that the color of OJ 287 remains constant over a large range of brightness levels (see their Fig. 3). The results of the observations are shown in Figure 2 where they are compared with theory. Note that in 2005 November, OJ 287 was as bright, or brighter than it was at any other time since the early 1980s.

TABLE 1
THE TELESCOPES USED IN OBTAINING THE DATA IN FIG. 2

Telescope	Mirror Diameter (m)	Band	Exp. Time (minutes)
GCO	0.30	R	1 × 5
KVA	0.35	R	4 × 3
SATU	0.40	V	5 × 1.5
Tuorla Observatory	1.03	R	4 × 3
UA	0.40	R	6 × 4

NOTES.—GCO = Grove Creek Observatory, Australia; KVA = Kungliga Vetenskapsakademien, La Palma, Canary Islands; SATU = St. Augustine–Tuorla, Trinidad; UA = University of Alabama. The last column gives the typical exposure time used to obtain one data point.

3. THE TIMING

One of the properties of the exact orbit solution in the binary black hole model is that the binary orbit precesses. Therefore, the distances R of the points of impact shift in a regular manner from one cycle to the next, and thus also the "live" disk correction varies. By including the "live" disk correction, Sundelius et al. were able to predict the beginning of the 1995 outburst with the accuracy of 3 days. With the delays in publishing, this prediction appeared in print after the fact.

The next challenge of the theory was to predict the outbursts of the next cycle. Sundelius et al. stated that the timing is uncertain because of the relatively large impact distance, and they did not give an exact date. Even though they did not mention it, the limits of the timing were easy to calculate: the time delay calculated by Lehto & Valtonen (1996), 0.49 yr, is the minimum value since it refers to the rigid disk assumption; in a live disk, the value has to increase. Thus, the outburst could not start before 2005 September. On the other hand, one could extrapolate the time delay from Table 3 of Lehto &

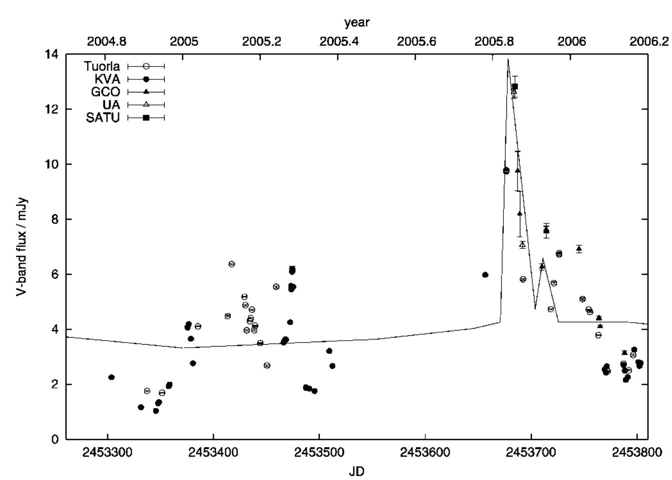

FIG. 2.—Theoretical light curve of OJ 287 in the precessing binary black hole model (*solid line*) together with observational points. The 2004/2005 part of the light curve shows the level of brightness and typical behavior of the source in the last few years. The theoretical line is not a fit to the observations but represents a typical outburst profile, added on top the expected base level of brightness at the calculated time.

Valtonen (1996), using the impact distance $R = 4$ (in units of the pericenter of the orbit) that is given by Sundelius et al. (1996). This leads to a time delay of 0.9 yr and the predicted outburst in 2006 January. Sundelius et al. (1997) quote at this point the value of 1.4 yr for the time delay, which is simply an error due to a poor analytical fitting function to the tabulated values. As we will explain below, this has to be viewed as the latest possible time rather than the optimal prediction.

The reason why we have to know the time delay is that even though the disk impact is exactly known in the model, the burst of radiation is delayed by the optical thickness of the impacted matter. The event is seen only after the radiating matter has become optically thin, i.e., when the radiation from the whole bubble of hot gas created by the disk impact can reach us. The delay time T is a function of the distance from the center R, but it also depends on the accretion disk model. It requires a fitting of the timing model with observations to determine the delay function. Since the timing of the 1995 outburst was not used in the exact celestial mechanics solution, it can be used to check the delay function. The success of Sundelius et al. in explaining the timing of this outburst suggests that the Lehto & Valtonen (1996) time delay model is basically correct, at least for small impact distances.

We actually can do a little better than the above estimate of time delay and narrow down the expected outburst time from the 5 month interval to about 3 weeks. As we mentioned above, the principal uncertainty comes from the fact that all previous well-observed impact events took place closer to the central black hole than the 2005 impact. We have to extrapolate beyond what is known by previous applications of the model. Here we use the standard accretion disk model and the time delays based on it.

Figure 3 shows the time delays in the Sundelius et al. model as a function of R for well-observed outburst events. The straight line is a regression through the points. It cuts $R = 4$, the impact distance of the 2005 event, at $T = 0.62$ yr. Even though it is not necessarily true that the extrapolation from the past events should be done on a straight line, it is certainly the simplest assumption and gives at least a first-order model.

The second way to estimate the outburst time is to take a closer look at the Lehto & Valtonen (1996) timing model. In this model, the delay time depends on the disk thickness and the local density at the point of impact. In standard accretion disk theories (e.g., Sakimoto & Corotini 1981), these quantities are functions of the mass transfer rate in the disk, and for a given central mass, the latter is proportional to the absolute luminosity of the accretion disk. Lehto & Valtonen (1996) used the luminosity value of 3×10^{47} ergs s^{-1} as quoted by Worrall et al. (1982). Since most of the emission seems to come from the jet, with a high Doppler boosting factor, it is certain that the disk luminosity is well below this value. The value given by Bassani et al. (1983) of 1.3×10^{46} ergs s^{-1} may be more relevant here. Reducing the disk luminosity shortens the delay time. Thus, the Lehto & Valtonen (1996) values at large impact distances have to be viewed as upper limits.

How much should the time delays be shortened? Valtonen et al. (2006) use the recently discovered 1956 outburst peak (not shown in Fig. 1; it is about as high as the 1913 and 1972 peaks; see Hudec et al. 2001 for a preliminary report). It occurred earlier than predicted by Lehto & Valtonen. In order to optimize the model, including the 1956 peak, one has to scale down the delay times by a factor of 0.71 ± 0.02. The relevant model is very close to one of the models calculated by Pietilä (1998; $\alpha = 0.85$, mass flow rate $= 0.003$ relative to the Eddington rate). If we simply apply the same correction to the 2005 delay, the delay length becomes $T = 0.64 \pm 0.02$ yr, i.e., practically identical to the straight line extrapolation.

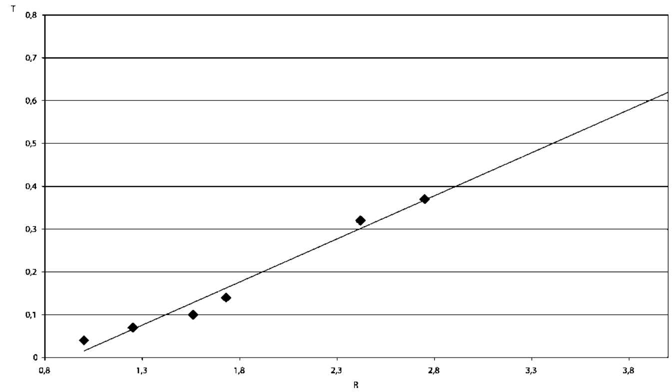

FIG. 3.—Extrapolation of the time delays T (in years) in the Sundelius et al. (1997) model in the impact distance range $R = 1$–4 (one unit of R is 0.0171 pc). The 2005 impact happened at $R = 4$.

If we add the time delay of $T = 0.64 \pm 0.02$ yr to the time of the disk impact (2005.20 $\pm$ 0.02), the predicted time of the 2005 outburst is at the beginning of 2005 November. Figure 2 also shows the predicted light curve of OJ 287. The base level of the light curve comes from the calculations of the brightness level of the source outside the outburst seasons. This calculation is described elsewhere (Valtonen et al. 2006). Added to the base level is a standard outburst light curve that is an average over many earlier well-observed events. The observed outburst is as expected in every respect, in timing as well as with regard to the size of the outburst. Note that the uncertainty in the timing comes mainly from the extrapolation in Figure 3; it is of the order of 3 weeks ($\pm$0.03 yr).

4. DISCUSSION

If we regard the observed outburst at the beginning of 2005 November as a confirmation of the basic binary model, then the period should become shorter by 0.01 yr per period due to gravitational radiation; this has not yet been detected. Due to the uncertainty in the extrapolation of the time delay, the shortening of the period cannot be measured from the 2005 November outburst at this time. If the time delay function becomes better determined in the future, e.g., with new data from the historical records, and if more observations of the 2005 November outburst exist, which outline the early rapid rise of this event, then it may become possible to untangle the shortening of the period from the delay function. In principle, the shortening of the period should show up as an advance in the time of the outburst by several weeks (the advance can be much bigger than the change in period because the optimal solution will have a slightly different orientation of the major axis of the binary that may translate to a big change in the timing far from the pericenter; Valtonen & Lehto 1997) and should thus have been easily observed.

The reduction of the orbital period may become detectable at the next expected outburst around 2007 September 10 (Valtonen & Lehto 1997). It is essential that the first rapid rise of the brightness is caught. This is not an easy task; for the 2005 November outburst, the authors of this Letter missed this crucial part of the light curve due to inclement weather at our primary observing sites. Therefore, it is hoped that the worldwide collaboration would work even better in 2007 September.

The parameters of the model may seem somewhat extreme in comparison with textbook values. The mass of the primary is almost at the upper limit of black hole masses detected by other indirect methods (e.g., Gu et al. 2001). But one has to remember that the detection of supermassive binary black holes is difficult. If one considers various selection effects, the OJ 287–type system is very much what one expects to find from a large pool of binary black holes (Yu 2002). For a detection in variability studies, the period of the binary cannot be much longer than about 10 years. This is an extremely short period for supermassive black hole binaries; in general, one would expect periods of thousands of years. To find a binary with only about a 10 year period, one has to have rather extreme conditions satisfied. The primary black hole has to be massive, so that it can be detected from a large distance. That means that it should be well above the black hole mass—bulge luminosity correlation, as may well be the case for OJ 287 (Yanny et al. 1997; Heidt et al. 1999). On the other hand, the lifetime of such a massive binary is extremely short, and its likelihood of becoming observed is very small, unless the mass ratio is very high. This again seems to be true for OJ 287. Finding a binary quasar is thus possible in this very small corner of the mass ratio versus primary mass plane. The fact that at least one such system has been found gives credibility to the expectation that binary black holes are indeed common and that there should be adequate sources of gravitational waves to motivate the use of the space-based gravitational wave antennas.

OJ 287 has been observed in many other wavelengths besides optical, including extensive radio monitoring over 35 years. It is generally thought that radio emission, as well as many other forms of radiation, arises exclusively in the jet. The connection between disk crossings and radio emission is so far unclear and requires further studies (Valtonen et al. 1999; Valtaoja et al. 2000). It will perhaps be clarified when the current outburst season is over. During the previous cycles, major radio events took place in 1973, 1975, 1984, 1985, and 1995, all related to definite jet feeding events in the precessing binary black hole model. There are reasons to expect similar outbursts in radio in 2007 May–June and again (even bigger) in 2010 November–December (Valtonen et al. 2006). Valtaoja et al. (2000) explain the 1973, 1984, and 1995 events as delayed responses of disk impacts, and they expect a similar event toward the end of 2007.

As the first well-established close binary black hole system, OJ 287 has wider significance. It forms a laboratory for studies of accretion disks and jets, and, most of all, for the theory of gravitation in very strong gravitational fields. The extreme $33^{\circ}.3$ precession brings home this point most forcefully. It may also be possible to determine the orientation of the jet relative the observer. According to the VLBI experiments as well as the binary model, the jet is very narrow, only about 2° in width, and points only 4° away from us (Tateyama & Kingham 2004). This explains much about the extreme variability of OJ 287 (Teräsranta & Valtaoja 1994). The time delays of the sharp radiation peaks are functions of the accretion disk properties such as the mass inflow rate and the disk thickness (Pietilä 1998); this is one of the very few ways of getting concrete information on these parameters that are central to the modern theories of active galactic nuclei.

REFERENCES

Bassani, L., Dean, A. J., & Sembay, S. 1983, A&A, 125, 52
Begelman, M. C., Blandford, R. D., & Rees, M. J. 1980, Nature, 287, 307
Carico, D. P., Graham, J. R., Matthews, K., Wilson, T. D., Soifer, B. T., Neugebauer, G., & Sanders, D. B. 1990, ApJ, 349, L39
Fiorucci, M., & Tosti, G. 1996, A&AS, 116, 403
Gu, M., Cao, X., & Jiang, D. R. 2001, MNRAS, 327, 1111
Heidt, J., et al. 1999, A&A, 352, L11
Hudec, R., Hudec, L., Sillanpää, A., Takalo, L., & Kroll, P. 2001, in Exploring the Gamma-Ray Universe, Proc. Fourth *INTEGRAL* Workshop, ed. B. Battrick et al. (ESA SP-495; Noordwijk: ESA), 295
Iping, R. C., Sonneborn, G., Gull, T. R., Massa, D. L., & Hillier, D. J. 2005, ApJ, 633, L37
Junkkarinen, V., Shields, G. A., Beaver, E. A., Burbidge, E. M., Cohen, R. D., Hamann, F., & Lyons, R. W. 2001, ApJ, 549, L155
Katz, J. I. 1997, ApJ, 478, 527
Kidger, M. 2000, AJ, 119, 2053
Lehto, H. J., & Valtonen, M. J. 1996, ApJ, 460, 207
Mikkola, S., & Valtonen, M. J. 1992, MNRAS, 259, 115
Owen, F. N., O'Dea, C. P., Inoue, M., & Eilek, J. A. 1985, ApJ, 294, L85
Pietilä, H. 1998, ApJ, 508, 669
Roos, N. 1981, A&A, 104, 218
Sakimoto, P. J., & Corotini, F. V. 1981, ApJ, 247, 19
Scoville, N. Z., et al. 1998, ApJ, 492, L107
Sillanpää, A., Haarala, S., Valtonen, M. J., Sundelius, B., & Byrd, G. G. 1988, ApJ, 325, 628
Sillanpää, A., et al. 1996a, A&A, 305, L17
———. 1996b, A&A, 315, L13
Smith, P. S., Balonek, T. J., Heckert, P. A., Elston, R., & Schmidt, G. D 1985, AJ, 90, 1184
Sundelius, B., Wahde, H., Lehto, H. J., & Valtonen, M. J. 1996, in ASP Conf. Ser. 110, Blazar Continuum Variability, ed. H. R. Miller, J. R. Webb, & J. C. Noble (San Francisco: ASP), 99
———. 1997, ApJ, 484, 180
Tateyama, C. E., & Kingham, K. A. 2004, ApJ, 608, 149
Teräsranta, H., & Valtaoja, E. 1994, A&A, 283, 51
Valtonen, M. J., & Lehto, H. J. 1997, ApJ, 481, L5
Valtonen, M. J., Lehto, H. J., & Pietilä, H. 1999, A&A, 342, L29
Valtaoja, E., Teräsranta, H., Tornikoski, M., Sillanpää, A., Aller, M. F., Aller, H. D., & Hughes, P. A. 2000, ApJ, 531, 744
Valtonen, M. J., et al. 2006, ApJ, in press
Worrall, D. M., et al. 1982, ApJ, 261, 403
Yanny, B., Jannuzi, B. T., & Impey, C. 1997, ApJ, 484, L113
Yu, Q. 2002, MNRAS, 331, 935