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OUTBURSTS IN OJ 287: A NEW TEST FOR THE GENERAL THEORY OF RELATIVITY

MAURI J. VALTONEN AND HARRY J. LEHTO
Tuorla Observatory University of Turku, Väisäläntie 20, FI-21500 Piikkiö, Finland
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ABSTRACT

The quasar OJ 287 has a light curve extending over 100 years. It has been photographed accidentally since 1893. In recent years, systematic monitoring has been carried out, e.g., by the large monitoring campaign OJ-94, which was set up to check whether the quasar brightens above the usual brightness level in 1994 as it has done regularly at 12 yr intervals since at least 1910. The large outburst in 1994 came as expected. A detailed analysis of the light curve led to a binary black hole model that predicts all future outbursts with the expected accuracy of 1 week. The first prediction of the new model was a second outburst that should have begun in 1995 November and should have extended until 1996 January. The outburst came on time, which thus confirms the expectations of the binary black hole model. Because of the strong gravitational fields involved in the supermassive binary black hole model, the timing of future outbursts will provide a sensitive test to the general theory of relativity in very strong gravitational fields, exceeding by a factor $\sim 10^4$ the gravitational fields present in the binary pulsar PSR 1913+16.
Subject headings: accretion, accretion disks — black hole physics — quasars: individual: (OJ 287) — relativity

1. INTRODUCTION

OJ 287 shows recurring outbursts approximately every 12 yr. This was initially explained as a tidal triggering of mass inflow in the accretion disk of a primary black hole that is perturbed by a less massive secondary black hole (Sillanpää et al. 1988). However, the exact timings of the outbursts were not purely periodic, but they seemed to come sometimes before the pericenter passage and sometimes after the pericenter passage with phase angles varying up to $\pm 90°$ from one pericenter passage to another.

The solution to this problem came from the realization that large bursts of radiation are expected whenever the secondary hits the disk of the primary (Lehto & Valtonen 1996). The points of impact are typically $\pm 90°$ from the pericenter passage in phase angle. In this model, we expect two outbursts near each pericenter passage, which is shown clearly by the 1970–1972 and 1983–1984 events. The lack of obvious pairs in older outbursts can be accounted for by missing data in the earlier rather sparse record.

A unique orbit determination for the black hole binary is possible, except for the unknown orientation, when five disk passages are well timed (Lehto & Valtonen 1996). The five events were normalized such that the reference time of the 1983 January outburst is 1983.00, in which case the other four events were 1947.29, 1972.99, 1984.16, and 1994.77, with an accuracy of ± 0.01 yr. Two solutions were found: the first one assumed that the time delay from the moment of crossing the central plane of the accretion disk to the radiation outburst is independent of the radial distance of the point of impact from the center of the disk. This model predicted the reference time for the 1995 outburst at 1995.83. In the second case, a time delay between the disk passage and the outburst was calculated using an α_g-disk model (Sakimoto & Coroniti 1981), and it was found to be a function of the radial distance. This function was used in the second solution, which gave the reference time of 1995.87 for the 1995 November outburst.

Besides explaining the above five outbursts, the model gave a correct value for the 1959.22 event (within the accuracy of 0.01 yr) and gave a general account of the events around 1912, 1955, 1963, and 1971. The observations are not dense enough in these years for a definite verification of the model even though the agreement is good. Other outbursts were also predicted at the times of a complete lack of observations.

2. THE 1995 NOVEMBER EVENT

The 1995 November outburst began with a sharp rise in the flux between 1995.845 and 1995.865 by 2.5 mJy in the V band. It was quite comparable to the flux rise between 1984.15 and 1984.165, which marked the beginning of the 1984 outburst (Sillanpää et al. 1996). Since we use the reference time of 1984.16 for the latter event, the reference time of the 1995 event is thus 1995.86. Figure 1 shows time-averaged light curves of the 1994 (Lehto & Valtonen 1996) and 1995 events.

The reference time for the 1995 event can also be determined in relation to the 1994 event. The cross-correlation (Edelson & Krolik 1988; Hufnagel & Bregman 1992) of the two light curve events is shown in Figure 2. The maximum correlation occurs around 1.1 yr time difference, which again leads to the reference time of 1995.87.

Thus, it seems that the models without time delays (or with a constant time delay) can be excluded. On the other hand, the disk model used in Lehto & Valtonen (1996) seems quite appropriate, at least in explaining the radial dependence of the time delays.

So far we have assumed that the period of the binary is constant or that its change is negligible. We have carried out further new calculations in which the energy losses to gravitational radiation are included. It turns out that we can find new solutions that are consistent with the observed outbursts with the secondary mass in the range $5 \times 10^7\, M_\odot \lesssim m_2 \lesssim 10^8\, M_\odot$.

The next outburst event in the spring of 2006 will be an excellent opportunity to test the model and in particular the shortening of the period. The model without gravitational radiation predicts an outburst at 2006.36, i.e., around mid-May of the year. The best models with radiation ($m_2 \simeq 7 \times 10^7\, M_\odot$)

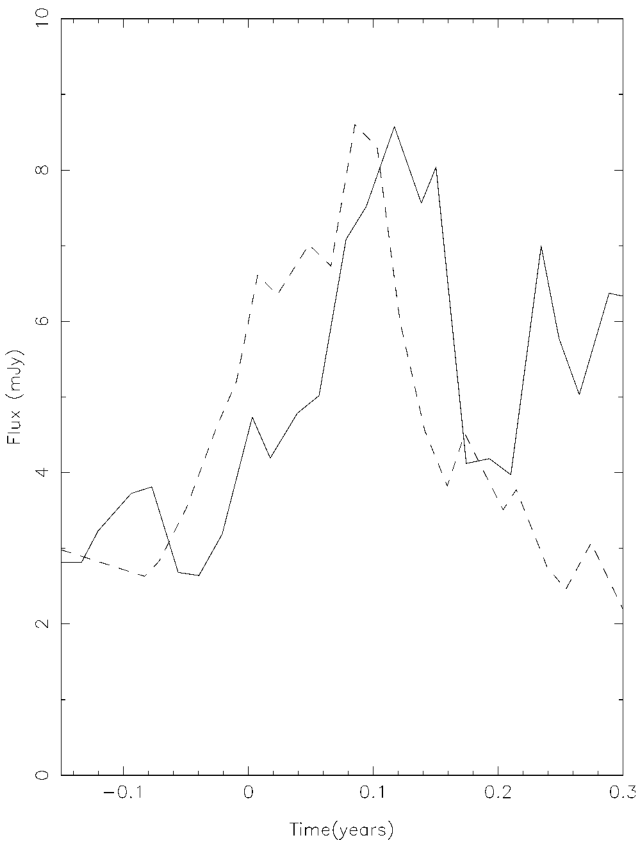

FIG. 1.—One week averaged light curves of the 1994 and 1995 outbursts. The ordinate is flux density in the optical V band. The abscissa is time in years from the onset of the outburst. The dashed line represents the 1994.77 outburst, and the continuous line the outburst beginning at 1995.87.

predict the event at 2006.23, i.e., 7 weeks earlier in late March. Thus, the detection of the loss of energy of the binary orbit should be quite easy. The subsequent outburst at 2007.73 (no radiation) or 2007.69 (with radiation) is an even more clear-cut test of the effects of gravitational radiation, since the timing is practically independent of the α_g-disk model.

The best solution for the binary orbit (including gravitational radiation) has eccentricity $e = 0.67$, precession rate of $33\overset{\circ}{.}3$ per period, and (the redshifted) period 12.07 yr. From these we obtain the semimajor axis $a = 0.056$ pc and the mass of the primary black hole $17.7 \times 10^9\ M_\odot$. The gravitational fields in this binary system are a factor $\sim 10^4$ times stronger than in the binary system PSR 1913+16. For the first time, general relativity can be tested in the regime of very strong gravitational fields.

If the primary is a Kerr black hole, the period of the innermost stable orbit in a corotating accretion disk is 8 days. Finding this time structure would bring further support to the model. The angular size of the binary in the sky is about 10^{-5} arcsec, which is perhaps resolvable in future space (or Earth-Moon) VLBI if both components are strong radio sources.

The precession of the orbit is such that the pattern of disk crossings starts to repeat itself approximately after 60 yr. This may be the explanation of the two long-lasting high brightness states seen in the historical light curve of OJ 287: one at 1910–1913, and the second one at 1970–1973. This idea can be tested observationally in 2030–2033. The high brightness states have been explained qualitatively as being due to varying tidal transfer rates during the precession cycle, and the same theory also explains why the slowly varying part of the high brightness state moves relative to the sharp disk crossing events from one pericenter passage to the next (Sundelius et al. 1997).

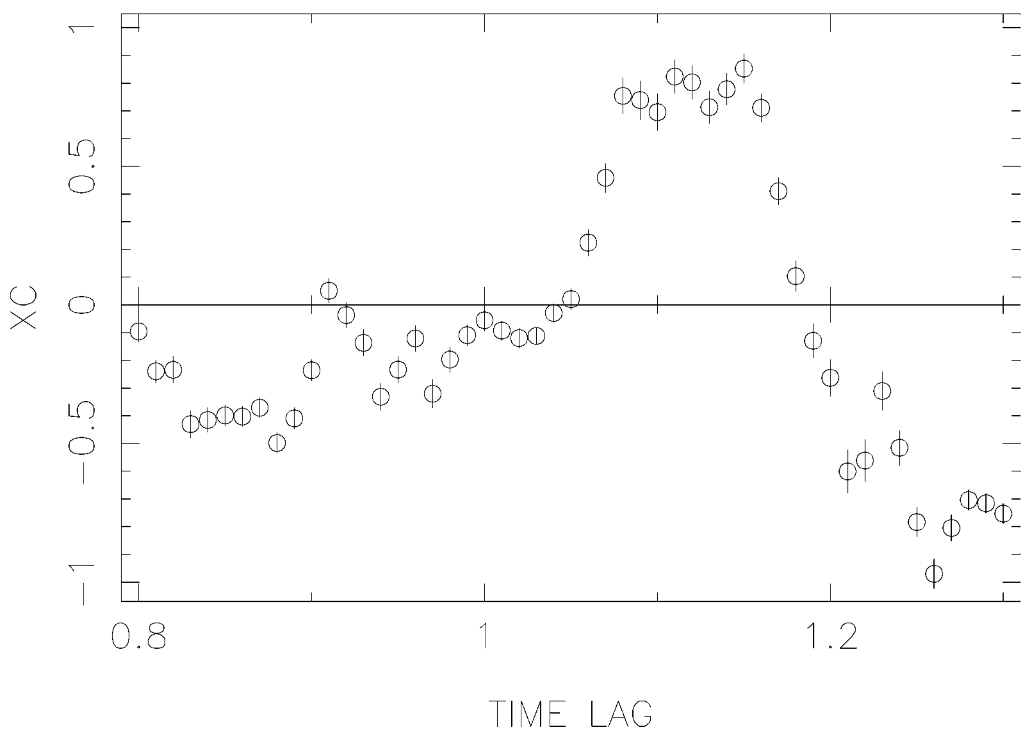

FIG. 2.—A discrete cross-correlation between 1994 and the 1995 outbursts. The peak at 1.1 yr indicates the temporal separation of the two outbursts. The ordinate gives the correlation coefficient, and the abscissa is time lag in years.

In conclusion, the black hole binary model has now successfully predicted two well-defined outburst events in OJ 287. The first prediction had an accuracy of only 1 year, and thus its correctness could have been accidental at $\sim$10% likelihood, considering that such outbursts are seen roughly once in 10 yr. The second prediction was accurate within 1/25 of a year, and its accidental likelihood is about 1/250. Thus, the probability that the model has made correct predictions by accident is currently less than 10^{-3}. It is likely that OJ 287 is a supermassive binary black hole system.

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Please direct correspondence and requests for materials to Harry J. Lehto (email: hlehto@astro.utu.fi).

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