Astron. Astrophys. 342, L29–L31 (1999)

ASTRONOMY
AND
ASTROPHYSICS

LETTER

Letter to the Editor

Probing the jet in the binary black hole model of the quasar OJ287

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Received 2 November 1998 / Accepted 21 December 1998

Abstract. A binary black hole model has been used to calculate the optical light curve of the quasar OJ287 in the 1990's. So far the model has been successful in predicting three outbursts and one fade; an accidental probability of correct predictions is less than one part in a million. Thus we may use the model to probe the structure of the quasar below 10^{-6} arcsec resolution. The most important information in this respect comes from the 1989 and 1998 fades which are interpreted as eclipses in the model. The time delays from radio to optical in 1989 may be used to position the emission regions in the jet, and the 1998 fade provides further constraints on the model. A high relativistic Lorentz factor ($\gamma \simeq 10^2$–10^3) is suggested, in agreement with microvariability data by Dreher et al.. A direct link between the jet emission regions and the accretion disk is suggested by matching the radio and optical light curves with the transfer rates of matter in the accretion disk at different radial distances. This link may be provided by magnetospheric field lines.

Key words: galaxies: jets – galaxies: BL Lacertae objects: individual: OJ287

1. Introduction

OJ287 reached the lowest flux levels ever recorded in this quasar in May 1989 both in optical-near infrared and in high frequency radio bands (Takalo et al. 1990). At that time there were many possible interpretations of this fade. In the binary black hole model (Sillanpää et al. 1988, Lehto & Valtonen 1996, Sundelius et al. 1977 and Valtonen & Lehto 1997) it was noted that this fade more or less coincided with the crossing of the secondary over the pole (or jet direction) of the primary. Therefore it was suggested that a fade should happen again in February 1998 when the alignment of the secondary relative to the primary is the same as it was in May 1989. The fade happened as expected in optical but was not seen in radio flux (Pietilä et al. 1999). This was the fourth successful prediction by the binary black hole model; considering the nature and the frequency of the events, the probability that the events should have happened accidentally within the given time range is below one part in 10^6.

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In this letter we discuss the significance of these observations and the model parameters which can be derived from them.

2. Jets and fades

The most straightforward explanation for a fade is an eclipse. Then we have to consider the optically thick disks about the black holes which may block radiation from the emission regions. The two black holes have masses $1.5 \cdot 10^{10} M_\odot$ and $0.93 \cdot 10^8 M_\odot$ in the model (Pietilä 1999), and they are likely to be surrounded by disks. Using the standard α_g-disk model (Sakimoto & Corotini 1981) for the accretion disks, we may estimate that the repeated passing of the disks through each other will truncate the disk of the secondary to the radius of about 10^{-3} pc. As this disk is optically thick it will block radiation from regions behind it. If it happens that the radiating regions are compact ($\lesssim 10^{-3}$ pc) and that the secondary passes over them in its 12 yr orbital path, then an eclipse is observed.

The emitting regions should lie on the axis of the primary disk at some distance from primary black hole (see Fig. 1). The exact distance R_0 is unknown.

Tateyama et al. (1996) have studied the core and the jet of OJ287 at 43 GHz and 100 GHz, and find that the core component is slightly resolved at 0.025 mas resolution which corresponds to 0.07 h^{-1} pc if the Hubble constant $H_0 = 100$ h km s^{-1} Mpc^{-1}. The pc-scale jet component A is found at the distance of 0.63 mas from the core and its size is 0.39 mas. In a jet with a constant opening angle we would thus estimate that the distance $R_0 \simeq 0.064 \cdot R_A$, where R_A is the distance of the jet component A from the core. We only know the projection of R_A into plane of the sky which is 1.8 h^{-1} pc. Thus the estimate from the observations at the best resolution available at present is $R_0 \lesssim 0.1$ h^{-1}/sin θ pc where θ is the viewing angle of the jet. Tateyama et al. (1996) argue that the smallest viewing angle consistent with observations is $\theta = 12^\circ.2$ h which makes $R_0 \lesssim 0.5$ h^{-2} pc.

Another approach is to use Eq. 21 from Marscher and Gear (1985) and to substitute in it the parameters from Tateyama et al. (1996) and Valtaoja et al. (1988). One obtains $R_0 \lesssim 0.2$ h$^{-1.4}$ pc. This is an upper limit since $R_0 \propto \delta^{-0.6}$ and the Doppler boosting factor $\delta \simeq 8.9$ used in these calculations is

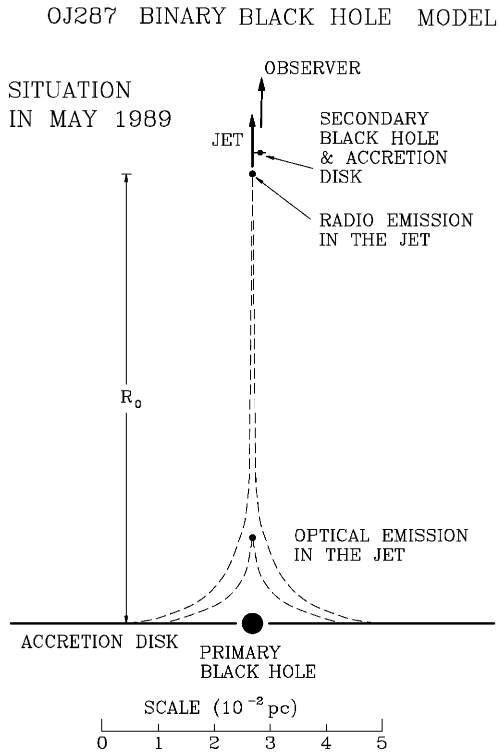

Fig. 1. A close-up view of OJ287 in a plane perpendicular to the primary accretion disk. The adopted distance R_0 between the primary black hole and the radio emitting region is 0.08 pc. The size (= Schwarzschild radius) of the secondary black hole is drawn 30 times larger than its real size; otherwise the illustration is a scale drawing. The warping of the primary accretion disk has been neglected. The magnetic field line connection between the accretion disk and the jet (dashed line) is schematic; the true situation is likely to be much more complex.

a lower limit based on the assumed inverse-Compton origin of the X-ray emission (Madau et al. 1987).

In order that an eclipse is possible, $R_0 < 0.085$ pc, which is the distance of the secondary from the primary at the time of the 1989 eclipse. On the other hand, since no radio fade was seen in 1998, $R_0 > 0.065$ pc since 0.065 pc is the primary – secondary interval one period later. The interval has decreased because of the precession of the binary orbit. Thus 0.065 pc $\lesssim R_0 \lesssim 0.085$ pc. Alternatively, the radio emitting region may have moved outwards between 1989 and 1998.

The limits for R_0 are somewhat lower than the above estimates. But considering that these estimates are upper limits, and anyhow depend on several uncertain assumptions, we cannot exclude the possibility that R_0 is indeed smaller than $\simeq 0.08$ pc. It would appear that a rather large value of the Lorentz factor $\gamma \simeq 10^2$–10^3 for the approaching jet (as may be the case in several quasars, Ghisellini et al. 1993) together with a very small viewing angle θ, i.e. looking more or less straight down on the jet, may allow models where $R_0 \lesssim 0.08$ pc. In such a situation we have the effective jet cone angle $\phi \approx \gamma^{-1}$ and $\delta \approx \gamma$ which by Eq. 21 of Marscher and Gear (1985) leads to a substantial reduction of R_0 when $\gamma > 10^2$. Further work is required to study such situations.

Table 1. Periods of maximum activity in OJ287: particle transfer rates through the 13 Schwarzschild radius circle and periods of high level of activity in radio

	Theoretical		Observed	
Event	Duration	Max count	Duration	Max flux (Jy)
1972	1971.2–1972.9	13	1971.5–1972.5	6.5
1973	1973.1–1973.3	3	1972.5–1974.1	7.5
1975	1974.5–1975.3	4	1974.8–1975.4	5
1983	1983.2–1984.2	13	1983.2–1984.3	10
1985	1984.6–1986.6	13	1985.1–1986.5	12.5
1995	1995.7–1995.9	7	1995.7–1996.0	3.5
1996	1996.7–1996.9	5	1996.7–1996.9	2.5
2007	2007.3–2007.4	3	–	
2010	2010.8–2011.0	3	–	

The high Lorentz factor is also suggested by the microvariability data which give brightness temperatures in the range of 10^{16}–10^{20} K deduced from the observed variability time scales (Dreher et al. 1986). It would thus appear that the small value of R_0 is consistent with the variability time scales in OJ287, and together with the high Lorentz factor could in fact be the explanation for the observed microvariability.

3. Disks and outbursts

The mass transfer in the disk is not uniform in the binary model, but happens in episodes related to the phase of the binary orbit. Also the transfer rate varies with the radial distance in the accretion disk of the primary. The following table (Table 1) summarizes the particle transfer rates (counts) in the numerical simulations (Sundelius et al. 1997) and compares them with the observed high frequency radio light curves (Aller et al. 1985, Aller et al. 1992, 1996, Teräsranta et al. 1992, Valtaoja 1998).

Note that the maximum flux for the 1973–1975 events is given at 8 GHz and for later events at 22 GHz and that the flux at 22 GHz is about 50% higher than at 8 GHz (Takalo 1994). The theoretical period of activity is measured when the counting level is above 2 units (Sundelius et al. 1997), and the observed period of activity is defined such that the measured flux is primarily above a given flux limit during this period. The limits used are: 4 Jy at 8 GHz prior to 1981, 8 Jy at 22 GHz in 1981–1994.5, and 2.5 Jy at 22 GHz after 1994.5. Fig. 2 shows the most recent radio data from Metsähovi (H. Teräsranta, private communication) and compares them with the particle transfer rate through the 13 Schwarzschild radius circle in the accretion disk. Naturally the exact value of 13 Schwarzschild radii is not important; it could vary about 10% on either side of 13 without significant change in the result. The radio flux variations show more detail than can be explained by the model. For example, the 1998 flux rise has no obvious explanation in our model. In this context one might consider the effect of the secondary on the jet and its stability, but this is beyond the present letter.

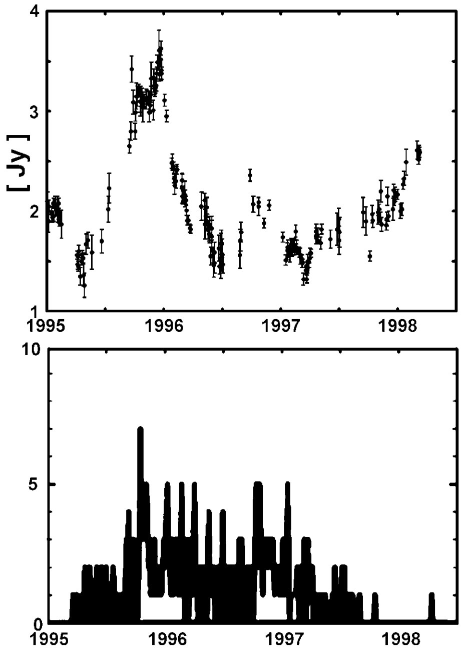

Fig. 2. A comparison of the particle transfer rate in the accretion disk through the 13 Schwarzschild radius circle (*lower panel*) and the 22 GHz radio flux measurements of OJ287 at Metsähovi (*upper panel*).

4. Discussion

Even though the periods of peak activity in the model and in the observations correspond to each other fairly well, the drop in the general level of activity from 1980's to 1990's is not explained by the model (as reflected in the flux limits used to define the period of activity). But even a very modest change in the direction of the jet by about 1° per period is enough to explain this general flux level change. The precession of the primary black hole or its disk does not appear sufficient for such changes in jet orientation (Begelman et al. 1980, Katz 1997). The change in the jet orientation may also be caused by the warping of the accretion disk and its variation due to the precession of the major axis of the orbit of the secondary (Sundelius et al. 1977). It is also possible that the change in the radio flux has to do with variations in the mass transfer rate in the jet. These alternatives can be differentiated after a longer timespan in the radio monitoring of OJ287.

Rather modest radio outbursts are expected during and after the next pericentre passage at 2007.

It was previously pointed out that the optical mean flux correlates fairly well with particle transfer rate through the 10 Schwarzschild radius circle in the disk of the primary (Sundelius et al. 1977). It now seems that the radio flux also has a correlation with the mass transfer rate, but at a larger radius. This suggests that somehow the accretion disk at 10-13 Schwarzschild radii is connected with the jet at similar distances from the central black hole. This is also supported by the observed periodicity in the radio flux of OJ287 at the period of 1.67 yr which is the rotation period of the accretion disk at 11.7 Schwarzschild radii (Aller et al. 1994). Perhaps the particle transport happens via magnetic fields directly from the halo above the disk to the jet (Camenzind 1989). Particles originating from the inner edge of the disk flow to the base of the jet and radiate at high frequencies; particles originating from the outer parts of the disk end up higher in the jet and radiate at low frequencies.

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