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Memorie della

OJ287 binary black hole system

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Abstract. The light curve of the quasar OJ287 extends from 1891 up today without major gaps. This is partly due to extensive studies of historical plate archives by Rene Hudec and associates, partly due to several observing campaigns in recent times. Here we summarize the results of the 2005 - 2010 observing campaign in which several hundred scientists and amateur astronomers took part. The main results are the following: (1) The 2005 October optical outburst came at the expected time, thus confirming the general relativistic precession in the binary black hole system. This result disproved the model of a single black hole system with accretion disk oscillations, as well as several toy models of binaries without relativistic precession. In the latter models the main outburst would have been a year later. (2) The nature of the radiation of the 2005 October outburst was expected to be bremsstrahlung from hot gas at the temperature of 3×10^5 °K. This was confirmed by combined ground based and ultraviolet observations using the XMM-Newton X-ray telescope. (3) A secondary outburst of the same nature was expected at 2007 September 13. Within the accuracy of observations (about 6 hours), it started at the correct time. Thus the prediction was accurate at the same level as the prediction of the return of Halley's comet in 1986. (4) Further synchrotron outbursts were expected following the two bremsstrahlung outbursts. They came as scheduled between 2007 October and 2009 December. (5) Due to the effect of the secondary on the overall direction of the jet, the parsec scale jet was expected to rotate in the sky by a large angle around 2009. This rotation may have been seen at high frequency radio observations. OJ287 binary black hole system is currently our best laboratory for testing theories of gravitation. Using OJ287, the correctness of General Relativity has now been demonstrated up to the third Post-Newtonian order, at higher order than has been possible using the binary pulsars.

Key words. quasars: general - quasars: individual (OJ287) - BL Lacertae objects: individual (OJ287)

1. Introduction

In 1982 Aimo Sillanpää put together the historical light curve of OJ287 based on published measurements. There appeared to be a 12 year outburst cycle (see Figure 1), and moreover, it was obvious that the next cyclic outburst was due very shortly. Indeed, OJ287 produced the expected event in the following

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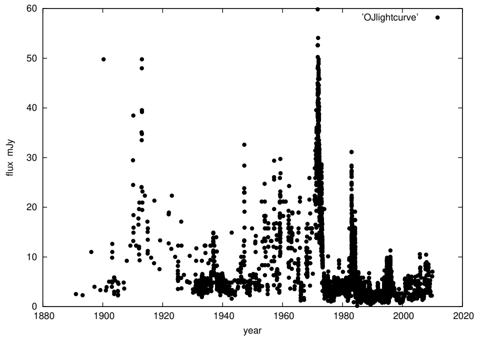

Fig. 1. The optical light curve of OJ287 from 1891 to 2010. It includes unpublished data from R.Hudec and M.Basta

January (Haarala et al 1983, Sillanpää et al. 1985). Observations showed a sharp decline in the percentage polarization during the outburst maximum, indicating that the outburst was produced essentially by unpolarized light (Smith et al. 1987). This is different from ordinary outbursts in OJ287 which are characterized by an increase of the percentage polarization at the maximum light. Radio outbursts were found to follow the optical outbursts with a time delay of between 2 months and a year, depending on the observing frequency (Valtaoja et al. 1987).

Sillanpää et al. (1988) suggested that OJ287 is a binary black hole system where a smaller companion perturbs periodically the accretion disk of a massive primary black hole. The next expected outburst was in 1994; it came as scheduled (Fiorucci et al. 1994, Sillanpää et al. 1996a). In the binary model there should be two disk crossings per 12 yr orbital period. Thus the 1994 outburst should have an equal pair whose timing was calculated to be at the beginning of 1995 October (Valtonen 1996, Lehto & Valtonen 1996, Sundelius et al. 1996). This prediction was also verified (Sillanpää et al. 1996b).

Alternative explanations were also put forward. Quasiperiodic oscillations in an accretion disk were suggested (Igumenshchev & Abramowicz 1999), and several binary toy models without relativistic precession were also proposed (Katz 1997, Villata et al. 1998, Valtaoja et al. 2000). The latter models all predicted the next main outburst of OJ287 in the autumn of 2006 while the precessing binary model gave a prediction one year earlier, at the beginning of 2005 October (Sundelius et al. 1997, Kidger 2000). The second major outburst was expected in late 2007 in all binary models while in the oscillating accretion disk model there was no reason to expect a second major outburst. In the precessing binary model the date was given with high accuracy, with the last prediction prior to the actual event being 2007 September 13 (Valtonen 2007, 2008a). In the oscillating accretion disk model and in non-precessing binary models the nature of the radiation at these outbursts should have been polarized synchrotron radiation while the precessing binary model predicted unpolarized bremsstrahlung radiation (Lehto & Valtonen 1996). In addition, the precessing binary model predicted a series of further outbursts for the interval 2007 - 2010 (Sundelius et al. 1997). In this model the companion black hole should also affect the disk of the primary in a predictable way, leading to the wobble of the jet (Valtonen et al. 2006).

With these predictions in mind, a multiwavelength campaign of observing OJ287 during 2005 - 2010 was set up.

2. Five 'smoking gun' results

In the following we describe five 'smoking gun' observations which produced expected results from the point of view of the precessing binary black hole model but which were surprising and unexpected in other theories.

2.1. Timing the 2005 outburst

The 2005 outburst was well covered by altogether 2329 observations in V and R-bands. The points in Figure 2 are daily averages, 92 in all.

According to Sundelius et al. (1996), the impact causing the 2005 outburst was expected 22.3 years after the impact of the 1983 outburst. In addition, Lehto & Valtonen (1996) estimated that the 2005 outburst should be delayed after the impact. Also the 1983 outburst

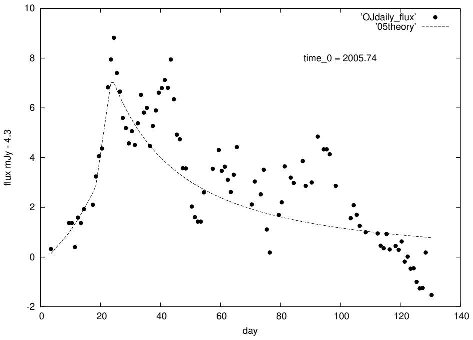

Fig. 2. The optical light curve of OJ287 during the 2005 outburst. The dashed line is the theoretical fit based on Lehto & Valtonen (1996)

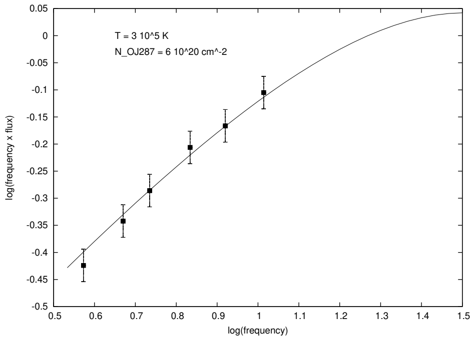

Fig. 3. The optical - UV spectrum of OJ287 during the 2005 outburst. The solid line is the bremsstrahlung fit as predicted in Lehto & Valtonen (1996). The observational points are corrected for the internal extinction in OJ287 as well as for the extinction in our Galaxy.

is delayed but not as much, the difference being 0.44 yr. The rapid flux rise started in the latter outburst at 1983.00; thus the corresponding rapid flux rise of the 2005 outburst was expected at 1983.00 + 22.30 + 0.44 = 2005.74. Actually, the outburst was one week late and did not begin until 2005.76 (Valtonen et al. 2008c), but anyway the timing was well within the error limits. Only a few polarization measurements were carried out at that time, and unfortunately, even those happened during secondary flares. Thus the polarization state of the primary outburst is not known.

The timing confirmed the precession of 39.1° per period. It is so much higher that e.g. in binary pulsars (by a factor of 10^4) that we immediately realise the importance of OJ287 in testing General Relativity.

2.2. Nature of radiation at the 2005 outburst

The impact outbursts are expected to consist of bremsstrahlung radiation and thus the optical polarization of OJ287 should go down during them. As mentioned above, the polarization information for the basic 2005 outburst is not available. However, bremsstrahlung may be recognized also by it spectrum, and this is the part of the campaign that was successfully carried out.

We had XMM-Newton observations both before the 2005 outburst (2005 April), and

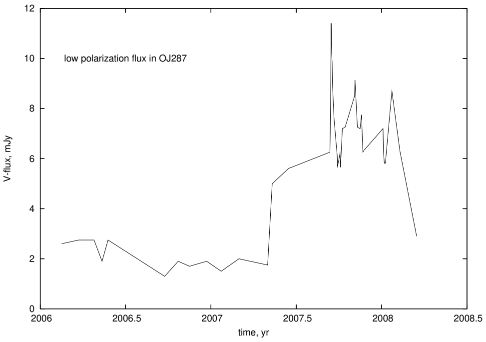

Fig. 4. The optical light curve of OJ287 during 2006-2008. Only low polarization (less than 10%) data points are shown.

during the outburst (2005 November 3-4). Fortunately the November observation happened at the time when the source was at its basic outburst level, in between two secondary bursts. Thus we would expect to see an additional pure bremsstrahlung spectrum above the underlying synchrotron power-law. A preliminary report of these observations has appeared in Ciprini et al. (2007), and a more detailed report is under preparation.

In Figure 3 we show the difference between the 2005 November flux and the 2005 April flux. The values have been corrected for the Galactic extinction and for the extinction in the OJ287 host galaxy. For the latter, we use the

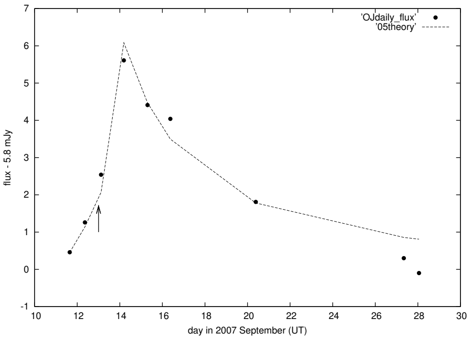

Fig. 5. The optical light curve of OJ287 during the 2007 September outburst. Only low polarization (less than 10%) data points are shown. Data points are based on Ref. 22. The dashed line is the theoretical fit based on Ref 9. The arrow points to September 13.0, the predicted time of origin of the rapid flux rise.

measuments in Gosh & Soundararajaperumal (1995) and the standard Galactic extinction curve (Draine 2003). The solid line shows the bremsstrahlung spectrum at the expected temperature of 3×10^5 °K. Note that a raised synchrotron spectrum, as one might have expected in some other theories, would have a downward slope toward higher frequencies, and it is entirely inconsistent with observations.

2.3. Timing and nature of the 2007 September 13 outburst

The 2007 September 13 outburst was an observational challenge, as the source was visible only for a short period of time in the morning sky just before the sunrise. Therefore a coordinated effort was made starting with observations in Japan, then moving to China, and finally to central and western Europe.

Four outbursts of various sizes were detected in 2007 September. In three of them the degree of polarization was above 15% while the fourth and the biggest one had polarization below 10% (Valtonen et al. 2008b). Thus it is not difficult to decide which one was the expected bremsstrahlung event. Later in the year there were more highly polarized outbursts, but if we look at the light curve composed of low polarization states only (Figure 4), the September 13 outburst clearly stands out as a sharp spike. The light curve has been plotted with a better resolution in Figure 5. A theoretical light curve is also drawn, and an arrow points to the expected moment of the beginning of the sharp flux rise. We see that the observed flux rise coincides within 6 hours with the expected time. The accuracy is about the same with which we were able to predict the return of Halley's comet in 1986!

2.4. 2007 - 2010 outbursts

Sundelius et al. (1997) gave a detailed prediction of the whole light curve of OJ287 during the campaign period. In addition to the two impact outbursts, it was expected that the tidal forcing mechanism of Sillanpää et al. (1988) would create a long hump in the light curve, starting in the middle 2007 and continuing until the middle of 2009. This hump is clearly seen in Figure 5, together with the 2007 September 13 spike. Seta et al. (2009) carried out multifrequency observations of OJ287 at the hump (2007 November 7-9) and compared the flux values with earlier observations before the hump (2007 April). They find that the excess radiation at the hump is neither due to increased magnetic field strength nor increased Lorentz factor, but likely results from an increase in electron energy density. This is what is expected in the tidal model.

A prominent outburst was also expected at the end of 2009 and it was observed (Valtonen et al. 2011a).

2.5. Jet reorientation

The accretion disk as a whole is also affected by the companion in its 12 year orbit. If the jet and the disk are connected the jet direction should be influenced by the companion.

There are three periodicities that could be expected to show up: the 12 yr orbital cycle, the 120 yr precession cycle (or half of it due to symmetry) and the Kozai cycle (Innanen et al. 1997) which also happens to be $\sim$ 120 yr. The 12 yr orbital cycle produces the tidal en-

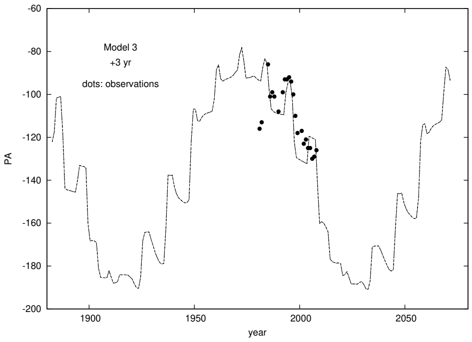

Fig. 6. The observed position angle of the radio jet of OJ287 (points) compared with the binary model, with a 3 year jet response time to the reorientation of the disk.

hancements in accretion flow, and the enhancement can be stronger or weaker depending on where we are in the precession cycle. These two tidal effects explain the overall appearance of the light curve (Sundelius et al. 1997). In addition, there is a modulation in the long term base emission level due to the jet wobble which follows the Kozai cycle.

The jet wobble shows up in observations in several ways. First, the mean angle of optical polarization varies (Sillanpää 1991). The binary model predicts, among other things, a quick change in the optical polarization angle by nearly 90° around 1995 which has been observed (Villforth et al. 2010). In radio, we should see a similar rapid change in the position angle of the parsec scale jet. Depending on the delay in radio jet reorientation, the change could be already under way (Figure 6), or it may be delayed by another 12 yr cycle (Valtonen et al. 2011b). There are recent observations which suggest the first alternative (Agudo et al. 2011), but the interpretation of these observations is not yet clear-cut.

3. Testing General Relativity

Using the OJ287 binary, we may test the idea that the central body is actually a black hole. One of the most important characteristics of a black hole is that it must satisfy the so called no-hair theorem (Misner et al. 1973). A practical test was suggested by Thorne (1980). In this test the quadrupole moment Q of the spinning body is measured. If the spin of the body is S and its mass is M, we determine the value of q in

$$Q = -q\frac{S^2}{Mc^2}. \qquad (1)$$

For black holes $q = 1$, for neutron stars and other possible bosonic structures $q > 2$ (Wex & Kopeikin 1999, Will 2008)

We have studied the distribution of q-values in orbits which give the correct timing of 9 outbursts within the range of measurement accuracy. We find that the distribution peaks at $q = 1$, thus confirming the no-hair theorem. The parameter values $q = 0$ or $q = 2$ can be rejected at the 3 standard deviation level at present. This is the first time that it has been possible to study general relativity at higher than the 1.5PN order.

4. Conclusions

Prior to the 2005 - 2010 multiwavelength campaign there were several ideas about the nature of OJ287. Fortunately, these models made completely different predictions about the behaviour of OJ287. The result of a scientific enquiry is seldom as clear-cut as this: the outbursts satisfied the expectations of the precessing binary model in every respect while the alternative ideas failed. Therefore we are confident that OJ287 can be used as a test laboratory for theories of gravitation. Our first results strongly support general relativity as the correct theory.

5. Discussion

FRANK RIEGER: (1) What is the gravitational lifetime of the system? I presume it is short. (2) You seem to need that the secondary crosses the primary disk twice per orbit. I remember that Ivanov et al. (1999) found that the co-alignment (orbital plane vs. disk plane) happens relatively quickly. Did you check for that?
MAURI VALTONEN: (1) 10000 yr. (2) Observational evidence is that the disk and the orbital plane are at roughly 90 degree angle relative to each other. This comes primarily from

the so called “eclipses” which may arise when the secondary crosses the jet. Theoretically, the first order perturbation theory shows that the inclination can remain at 90 degrees if it has obtained a value close to it at some earlier time. Our numerical simulations confirm this.

MANEL PERUCHO: There is tendency to associate the radio jet helical structures to precession caused by binary black hole systems. Could comment on this point? Is the periodicity you find in the jet of OJ287 the expected one from your model?

MAURI VALTONEN: Marcher and Jorstad (2011) have discovered that in the large scale X-ray and radio jet there are oscillations in the time scale of thousands of years. In our model the spin axis of the primary precesses with the period of about 1300 years (Valtonen et al. 2010). These two facts may be connected.

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References

Agudo, I. et al. 2011, ApJ, 726, L13

Ciprini, S. et al. 2007, Mem. Soc. Astron. Italia, 78, 741

Draine, B. T. 2003, Ann. Rev. Astron. & Astrophys., 41, 241

Fiorucci, M. et al. 1994, IAU Circ., 6104, 2

Ghosh, K. K. & Soundararajaperumal, S. 1995, ApJS, 100, 37

Haarala, S. et al. 1983, IAU Circ., 3764, 3

Igumenshchev, I. V. & Abramowicz, M. A. 1999, MNRAS, 303, 309

Innanen, K. A. et al. 1997, AJ, 113, 1915

Katz, J. I. 1997, ApJ, 478, 527

Kidger, M. R. 2000, AJ, 119, 2053

Lehto, H. J. & Valtonen, M. J. 1996, ApJ, 460, 207

Marscher, A. P. & Jorstad, S. G. 2011, ApJ, 729, 26

Misner, C.W., Thorne, K.S. & Wheeler, J.A. 1973, Gravitation, W.H.Freeman & Co, New York, p. 876

Seta, H. et al. 2009, PASJ, 61, 1011

Sillanpää, A. et al. 1985, A&A, 147, 67

Sillanpää, A. et al. 1988, ApJ, 325, 628

Sillanpää, A. 1991, A&A, 247, 11

Sillanpää, A. et al. 1996a, A&A, 305, L17

Sillanpää, A. et al. 1996b, A&A, 315, L13

Smith, P. S. et al. 1987, ApJS, 64, 459

Sundelius, B. et al. 1996, Blazar continuum variability, ASP Conf. Ser. 110, Proc. workshop in Miami 4-7 February 1996, San Francisco: ASP, ed. H. R. Miller et al., p.99

Sundelius, B. et al. 1997, ApJ, 484, 180

Thorne, K.S. 1980, Rev.Mod.Phys. D, 31, 1815

Valtaoja, E. et al. 2000, ApJ, 531, 744

Valtaoja, L., Sillanpää, A. & Valtaoja, E. 1987, A&A, 184, 57

Valtonen, M. J. 1996, Proc. workshop at Oxford 11-14 September, 1995. Tuorla Obs. Rep., No. 176. Ed. L. O. Takalo, Univ. of Turku, p.64

Valtonen, M. J. et al. 2006, ApJ, 646, 36

Valtonen, M. J. 2007, ApJ, 659, 1074

Valtonen, M. J. 2008a, The Nuclear Region, Host Galaxy and Environment of Active Galaxies: Proc. Meeting at Huatulco 18-20 Apr 2007 (Eds. E. Bentez et al.), Rev. Mex. Astron. Astrof. (Ser. Conf.) Vol. 32, 22

Valtonen, M. J. et al. 2008b, Nature, 452, 851

Valtonen, M. et al. 2008c A&A, 477, 407

Valtonen, M. J. et al. 2009, ApJ, 698, 781

Valtonen, M. J. et al. 2010, ApJ, 709, 725

Valtonen, M. J. et al. 2011a ApJ, 729, 33

Valtonen, M. J., Savolainen, T. & Wiik, K. 2011b, Jets at all Scales, Proc. IAU Symp. 275, p. 275

Villata, M. et al. 1998, MNRAS, 293, L13

Villforth, C. et al. 2010, MNRAS, 402, 2087

Wex, N. & Kopeikin, S.M. 1999, ApJ, 514, 388

Will, C. M. 2008, ApJ, 674, L25