PRIMARY BLACK HOLE SPIN IN OJ 287 FROM THE GR CENTENARY FLARE

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ABSTRACT

OJ 287 is a quasi-periodic quasar with roughly 12 year optical cycles. It displays prominent outbursts which are predictable in a binary black hole model. The model predicted a major optical outburst in December 2015. We found that the outburst did occur within the expected time range, peaking on 2015 December 5 at magnitude 12.9 in the optical R-band. Based on SWIFT/XRT satellite measurements and optical polarization data, we find that it included a major thermal component. Its timing provides an accurate estimate for the spin of the primary black hole, $\chi = 0.315 \pm 0.025$. The present outburst also confirms the established general relativistic properties of the system like the loss of orbital energy to gravitational radiation at the 2% level and it opens up the possibility of testing the black hole no-hair theorem at the 10% level during the present decade.

Subject headings: quasars: general — quasars: individual (OJ 287) — quasars: supermassive black holes — black hole physics — BL Lacertae objects: individual (OJ 287)

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1. Introduction

OJ 287 is recognized as a quasar with roughly 12 year cycles in optical brightness, observed since 1890's (Sillanpää et al. 1998). Its light curve is definitely not periodic (Hudec et al. 2013) but the deviations from periodicity are systematic and predictable in a model that contains a gravitational wave driven inspiralling spinning binary black hole system as its central engine (Valtonen et al. 2008, 2010a; Ryrd et al 2015) The prediction for the 2015/6 observing season was that OJ 287 should have a major optical outburst in December 2015, brightest optical level in 30 years (see Figure 1 in Valtonen et al. 2011a for the

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future light curve), coinciding with the centenary of General Relativity. The exact timing of the optical outbursts may be used to test predictions of the general relativistic binary black hole model (Valtonen & Lehto 1997; Valtonen et al. 2010b).

The quasi-periodic pattern of optical outbursts of OJ 287 was explained in 1995 by a model where a secondary black hole in a 12 year orbital period impacts the accretion disk of the primary black hole at regular intervals (Lehto & Valtonen 1996; Sundelius et al. 1997). Due to the quasi-Keplerian nature of binary black hole orbits in general relativity, the impacts and their associated electro-magnetic radiation events cannot occur in a strictly periodic manner (Damour & Schäfer 1988; Memmesheimer et al. 2004). Attempts to use purely Newtonian orbit models, ignoring post-Newtonian corrections, have failed (Valtonen et al. 2011; Valtonen & Ciprini 2012). For a pictorial depiction of binary black hole orbits in general relativity, see animations by S. Drasco at www.tapir.caltech.edu/∼sdrasco/animations.

However, it is indeed possible to find a unique mathematical description for the orbit in the post-Newtonian approximation to general relativity, provided a long enough record of past radiation outbursts is available. The solution is sensitive to the loss in gravitational binding energy due to gravitational wave emission and the Lense-Thirring effect that forces the binary black hole orbital plane to precess, mainly due to the spin of the primary black hole (Damour & Schäfer 1988; Barker & O'Connell 1975) An essential feature of the model is that the impact outbursts are generated by expanding bubbles of hot gas which have been shocked and pulled out of the accretion disk (see Figure 1). The process is astrophysically rather simple (Lehto & Valtonen 1996; Ivanov et al. 1998; Pihajoki 2016) and the resulting radiation emanates from the vicinity of the impact site. Thus these thermal radiation events are excellent markers for tracing the orbital motion of the secondary around the primary black hole. In contrast, the shocks in jets which also arise as a consequence of the influence of the secondary, have a complicate route from cause to effect. These 'tidal' outbursts (Sillanpää et al. 1998; Sundelius et al. 1997; Valtonen et al. 2011, 2009) are also predictable in the binary model, but cannot be used to construct the orbit as accurately as using the record of thermal events. In other systems the regularly repeated events in a jet may be a more likely alternative than thermal events (Ackermann et al. 2015).

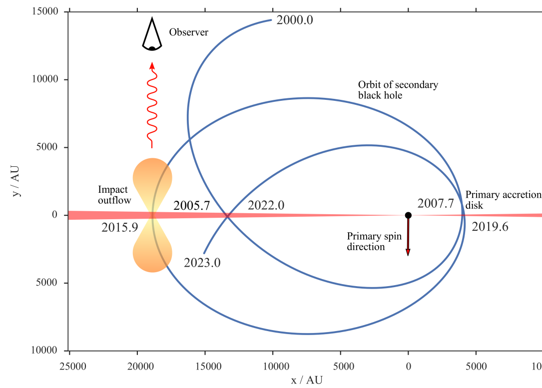

Fig. 1.— The orbit of the secondary black hole in OJ 287 from year 2000 to 2023. The present thermal outburst comes from the disk crossing prior to 2015 while the non-thermal flux arises from a jet, parallel to the primary spin axis. The next two thermal outbursts are due in 2019 and 2022, following the crossing of the secondary black hole through the accretion disk of the primary black hole.

2. OBSERVATIONS

In anticipation of the predicted outburst, we organized a mulitisite observing campaign aimed at getting photometric and polarimetric data of OJ 287. Both professional astronomical observatories and amateur observers (AMAT in Fig. 2) took part in taking photometric data from the very beginning of the 2015/2016 season. Some of the telescopes of the amateur astronomers who took part in the current campaign are listed in Valtonen et al. (2008).

Photometric observations were carried out by the following observatories: Tuorla Observatory in Finland, Astronomical Observatory of the Jagiellonian University (in Fig. 2, KRK) and Mount Suhora Observatory of the Pedagogical University (SUH) in Poland, University of Athens (GR) in Greece, Mount Abu Infrared Observatory (MIRO) in India, and Liverpool Telescope (LIV), Kungliga Vetenskapliga Akademien Telescope (KVA) and the Nordic Optical Telescope situated at Observatorio del Roque de Los Muchachos in La Palma, Canary Islands, Spain (see Pihajoki et al. (2013) for details). Other telescopes participating in the campaign were 0.41 m PROMPT5 (PROM in Fig. 2) telescope in Chile (Reichart et al. 2005), the 0.6 m SARA telescope at Cerro Tololo, the 0.51 m reflector in Osaka Kyoiku University, the 0.90 m Schmidt telescope of the Jena Observatory, the 0.60 m and 1.22 m reflectors of the Canakkale Onsekiz Mart University Observatory (COMU), the 0.60 m telescope of the University of Adiyaman (ADYU) and the 0.60 m telescope at the TUBITAK National Observatory, Turkey. In the continental US the photometric data were gathered with the 0.9 m SARA telescope at Kitt Peak, the 0.40 m telescope of Florida International University, the 0.76 m Katzman Automatic Imaging Telescope (KAIT) at the Lick Observatory, the 0.40 m University of Alabama campus telescope and the 0.40 m Arizona State University campus telescope. OJ 287 was measured through the wide band R filter in most sites. Only the KAIT data were taken without any filter and transformed into the R band. We performed differential photometry on images calibrated for bias, dark and flatfield with the aperture method. We used GSC 1400-222 (R=13.74^m) as the comparison, while GSC 1400-444 as the check star, respectively.

Polarimetric observations were taken with Ringo3 (LIV), Nordic Optical Telescope (NOT) in La Palma, Dipol-2/T60 in Maui, Hawaii, Mt. Suhora, Poland, and with ARIES in India. Measurements with the DIPOL-2 polarimeter (Piirola et al. 2014) installed on the remotely controlled, 0.60 m telescope at the Haleakala observatory (Tohoku University, Maui, Hawaii) were carried out on 13 nights in the interval 2015 Nov 30 - Dec 15. Simultaneous observations in three passbands (B, V, R) were made by using dichroic beam splitters to divide the light into the different spectral bands, recorded by three CCD cameras. With the simultaneous observations in the different passbands, rapid variations in the blazar polarization have no effect on the observed wavelength dependence. On each night, 32x30 s exposures of OJ 287 were made at different orientations (22.5 deg steps) of the superachromatic half-wave retarder used as the polarization modulator. The fluxes of the target images on the CCD frames were extracted by

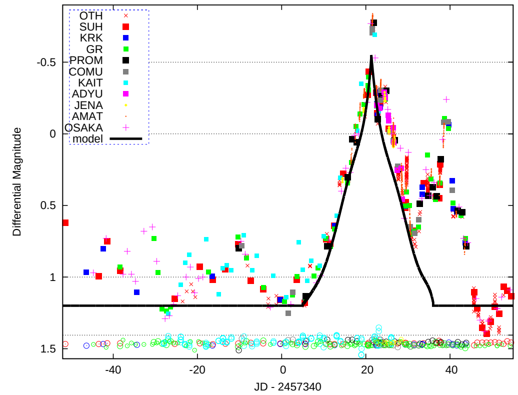

Fig. 2.— Optical photometry of OJ 287 from October to December 2015. The optical R-band magnitude is given with respect to a non-variable comparison star (GSC 1400-222). The symbols refer to observations made at different observatories. At the bottom (circles) we show the differences between our comparison star and another nearby non-variable star (GSC 1400-444, shifted by 2.05 mag). The theoretical line which we use to separate the presumed thermal and non-thermal components of the November-December outburst is also shown. It was calculated prior to the campaign by one of authors (P.P.; presented in a conference but not published) with two small modifications explained in the text.

using a circular aperture of 4 - 6 arcsec radius, depending on the atmospheric conditions.

Polarization and photometry observations of OJ 287 were taken on 20 nights (89 altogether) in the interval 2015 November 28 to 2015 December 31 with the RINGO3 polarimeter (Arnold et al. 2012) on the fully robotic and autonomous Liverpool Telescope on La Palma, Canary Islands (Steele et al. 2010). Simultaneous observations (120 seconds in total) in three passbands (blue: 3500-6400 Å, green: 6500-7600 Å and red: 7700-10000 Å) were taken using the rapidly rotating (once per 4 seconds) polaroid which modulates the incoming beam of light in 8 rotor positions, for the photometry the 8 frames are stacked. The beam is split by 2 dichroic mirrors to three low noise electron multiplying (EM) CCD cameras simultaneously. The fluxes of the O J287 images on the EMCCD frames were extracted using circular apertures with radii of 4 arcseconds. By combin-

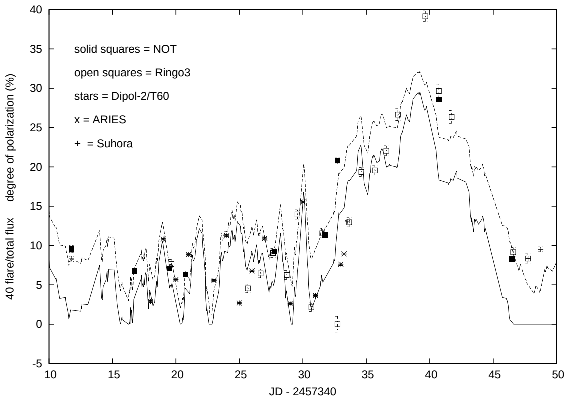

Fig. 3.— The degree of polarization in the optical R-band. The curve represents the expected degree of polarization if the excess non-thermal component, above the line in Figure 2, is 40% polarized and the rest of the radiation is unpolarised. The dashed line assumes that in addition the base level flux makes a 10% contribution to the degree of polarization. Nightly median values are plotted for the Ringo3 observations.

ing the flux from the 8 rotor positions using equations from (Clarke & Neumayer 2002) the Linear Stokes Parameter were measured and used to calculate the degree and angle of polarisation. The data were corrected for the effects of instrumental polarisation and depolarisation by observation of standard stars from Schmidt et al. (1992).

The polarimetric observations at the NOT telescope (Principal Investigator K.N.) were carried out in the manner described in Valtonen et al. (2009). Polarization observations with the 0.60 m Cassegrain telescope at Mt. Suhora Observatory were carried out on 7 nights using four polarimetric filters transmitting light of the polarization plane 0, 45, 90 and 135 degrees. One series of measurements in all four filters allow the determine degree of polarization and the position angle. At least 7 full series were performed each night with exposure times between 30 and 90 seconds, depending on weather conditions and brightness of the target. Fluxes were extracted by using the IRAF apphot package. Finally, the degree of polarization and and position angles were obtained by the n-polarizers method proposed by Sparks & Axon (1999).

Two polarimetric observations were obtained using the Aries Imaging Polarimeter (AIMPOL; Rautela et al. 2004), mounted on the 1.04 m Sampurnanand Telescope (Sinvhal et al. 1975) at ARIES, Nainital, India, coupled with a TK 1024x1024 pixels CCD camera.

Several *Swift* UVOT and XRT instruments pointings were performed, observing at UV filters W1, M2 and W2, and at the 0.3-10 keV X-ray energy band, repspectively (Pricipal Investigator SC). Here we report primarily the results from the optical R-band and UV W2 band where the results were more complete than in other channels, in addition to X-rays. *SWIFT* XRT data were taken in Photon Counting mode for a total exposure of about 20 ksec divided in daily observations. Each single X-ray spectrum (0.3-10 keV) can be fit by an absorbed single (or broken) power-law model, with an HI column density consistent with the Galactic one in the direction of the source (nH = 2.56×10^{20} cm^{-2}, Kalberla et al. 2005). The X-ray spectra have photon indexes between about 1.4 and 1.9. The preliminary corresponding unabsorbed (0.3-2.0 keV) integral daily fluxes are reported here, together with simultaneous dereddened UVOT flux density values obtained with the 3 UV filters.

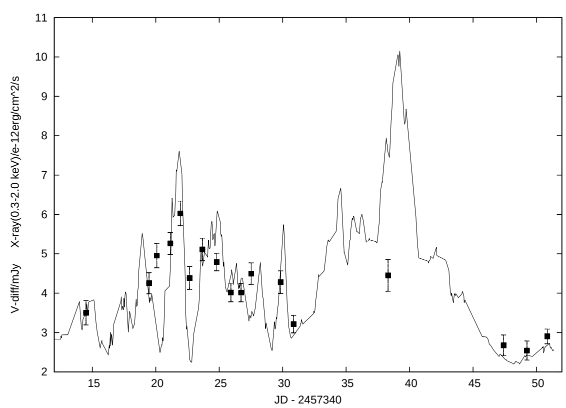

Fig. 4.— A comparison of X-ray observations by *Swift* XRT in the 0.3-2 keV energy band in ergs cm^{-2} sec^{-1} with the excess ('jet') emission above the line of Figure 2. Compared with the optical outburst, the X-ray flare was rather modest, consistent with the view that the thermal component makes no detectable contribution in X-rays.

After starting an intensive photometric monitoring of OJ 287 in September 2015, series of

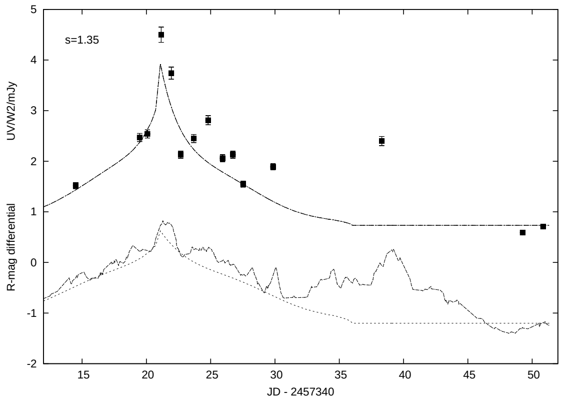

Fig. 5.— *Swift* UVOT observations in the UV W2 band (central wavelenght 1928 Å) shown as points with errorbars. The broken line below represents optical light curve from Figure 2, while the smooth dashed line below it is the corresponding line in Figure 2. This line has been shifted to the W2 band by using the spectral index of 1.35.

frames (about 10 images per night) were taken to measure the brightness of the target every clear night. Nightly means were calculated and posted on the campaign's web page. After November 14, a steady rise of the object flux was noticed, and by November 25 it was apparent, that it may develop into a major outburst, in the category observed only twice in twelve years. We extended our observations by making them as long as possible each night, measuring also colors at some sites. The source kept brightening very rapidly until it was brightest in 30 years in the optical band. After the December 5 maximum the source declined in stages, until it arrived at its pre-outburst level on December 30 (see Figure 2).

The major outbursts in OJ 287 are recognized by a rapid rise to a narrow peak and then a slower decline with multiple smaller flares. The curve in Figure 2 is based on a theoretical calculation (Pihajoki 2016) with an added initial slowly rising part (seen generally in observations) and with an additional peak on top of it that is based on previous experience with similar flares, especially in the well observed outburst in 1983 (Smith et al. 1987). The information on the nature of radiation at different stages of the outburst has been limited up to now. In 2007 a good coverage of the outburst was achieved in polarization; it showed that the major component of the outburst was unpolarized, superposed on a lower level of polarized synchrotron emission (Valtonen et al. 2008). In 1983 the degree of polarization decreased close to zero at the high point of the light curve (Smith et al. 1987). Therefore we have reasons to believe that an underlying unpolarized component, like the curve in Figure 2, exists also in the 2015 outburst, in addition to the usual polarized flares.

Figure 3 shows the evolution of the degree of polarization at different stages of the 2015 outburst. We superpose on the data the expected degree of polarization, by using the theoretical line in Figure 2 to separate the thermal and non-thermal components of the outburst. The solid line gives the ratio of the excess radiation above the theoretical line to the total flux, multiplied by 40. This is what one might expect if the radiation below the theoretical line is unpolarized, as thermal bremsstrahlung should be, and superposed on it we have synchrotron flares with 40% polarization. This simple concept seems to work reasonably well. If our separation of the bremsstrahlung from synchrotron flares in the model is correct, then the X-ray emission, coming entirely from the jet, should follow the optical excess emission. The optical excess emission is defined as the total optical flux minus the bremsstrahlung flux, the latter separated from the total flux according to the line in Figure 2. Figure 4 shows that this is indeed the case. The X-ray flare is rather modest, much smaller that the optical outburst on the whole, but correlates very well with the excess flare emissions. The flares arising at this time are not different from flares observed during the campaigns of the previous twelve months (Edelson et al. 2015). There the X-ray flux was $(4.0\pm)1\times10^{-12}$ ergs cm^{-2} sec^{-1}, while during our campaign it has been $(4.4\pm1)\times10^{-12}$ ergs cm^{-2} sec^{-1}, only slightly enhanced. The UV emission has followed the optical emission rather well in previous campaigns, using the 1.35 spectral index between the two wavelength ranges (based on data from the Edelson et al. 2015 campaign) we have transferred the theoretical line from Figure 2 to the W2 band of *Swift* UVOT, by using the same spectral index. The figure shows that the new line in the W2 channel underlines the data rather well. Above the thermal components there are the same non-thermal flares that are seen in optical. The lower part of the figure gives a comparison to Figure 2. The *Swift* W1 and M2 channel results are entirely consistent with Figure 5. A more careful study is required to determine the temperature of the bremsstrahlung component at this time (Valtonen & Ciprini 2012).

3. DISCUSSION

The timing signals are extracted from the optical light curve by identifying the start of the outburst. From Figure 2 it appears that the outburst began on JD 2457342.5±2.5 which in years and their fractions is 2015.874±0.007. Using the previously calculated correlation with the spin (Valtonen et al. 2011a), we get for the Kerr parameter $\chi = 0.313 \pm 0.003$. The scatter in the models is greater than the timing uncertainty: solutions found for this timing value range beteen 0.29 and 0.34 (see Figure 6 of Valtonen et al. 2010a). Thus we may say that the dimensional spin value of the primary black hole, the Kerr parameter $\chi = 0.315 \pm 0.025$. This is a considerable improvement with respect to the previous value $\chi = 0.28 \pm 0.08$ (Valtonen et al. 2010a).

For a comparison with black hole spin determinations by X-ray spectroscopy, see Reynolds & Fabian (2008) and Reynolds (2014). These are based on determining the innermost stable orbit of the accretion disks in Seyferts or low-z QSOs, which are in the radio-quiet realm, or in X-ray binaries. Some of the spins are comparable to the spin of OJ 287, others are close to the maximal value of unity. In contrast to the X-ray spectroscopy method, in this blazar we are not dependent on understanding the physics of accretion disks close to the innermost stable orbit; in this sense the orbital torque method is complementary to X-ray spectroscopy.

The present outburst timing firmly confirms the correctness of the binary black hole central engine model for OJ 287 within its specified parameter ranges, namely primary mass $(1.84 \pm 0.01) \times 10^{10}$ solar mass, secondary mass $(1.4 \pm 0.1) \times 10^{8}$ solar mass and orbital eccentricity (as defined by using the apocentre/pericentre ratio) 0.700±0.001.

The present χ estimate opens up the possibility of measuring the dimensionless quadrupole moment of the primary black hole (q_2) at the 10% level during the next thermal outburst, predicted to happen in July 2019 (see Figure 1). This should allow one to test the black hole no-hair theorem by verifying the relation $q_2 = -\chi^2$ at that level (Carter 1970; Thorne & Hartle 1985). However, observing the predicted July 2019 thermal outburst from the Earth will be difficult due to the proximity of OJ 287 to the Sun.

Additionally, as demonstrated earlier (Valtonen et al. 2010b, 2011a), the occurrence of the outburst within the expected time window confirms the loss of energy by gravitational radiation within 2% of the prediction by General Relativity and is consistent with the no-hair theorem of black holes within an accuracy of 30%. The energy loss by impacts on the accretion disk is four orders of magnitude smaller than the energy loss by gravitational radiation and thus plays no role in the binary model.

Finally we note that an exceptionally large amount of gas has been pulled away from the primary disk during this impact which occurred close to the apocentre of the binary orbit (Pihajoki et al. (2013) see Figure 1). This gas is expected to feed the two black holes for some time to come, and keep OJ 287 active with flares.

The highly polarized (39% polarization) flare near JD 2457480 is interesting in this respect. Its degree of polarization is the highest ever measured in OJ 287. The previous record was 36% polarization measured in the secondary peak of the 1984 major event (Smith et al. 1987). This suggests that the secondary flare is closely connected with the first, unpolarized outburst. One possibility is the activation of the jet of the secondary black hole at these times. The secondary black hole is in the vicinity of the expanding cloud of plasma and will definitely accrete a major part of it, that is, the part which is expanding to its direction. It will be interesting to search for other evidence to associate the secondary flare with the secondary black hole.

In summary, we have shown that the outburst in OJ 287 in November-December 2015 agrees with the binary black hole model, both with regard to the timing and the expected brightness as well as in that a major component in this outburst is thermal. The fact that such thermal outbursts are excellent trackers of the secondary black hole orbit allowed us to estimate the spin value of the primary more narrowly than before, $\chi = 0.315 \pm 0.025$. This outburst firmly confirms the presence of an inspiralling massive black hole binary in OJ 287. Therefore, this November-December flare makes a fitting contribution to GR centenary celebrations of 2015.

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