Polarization and spectral energy distribution in OJ 287 during the 2016/17 outbursts

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Introduction

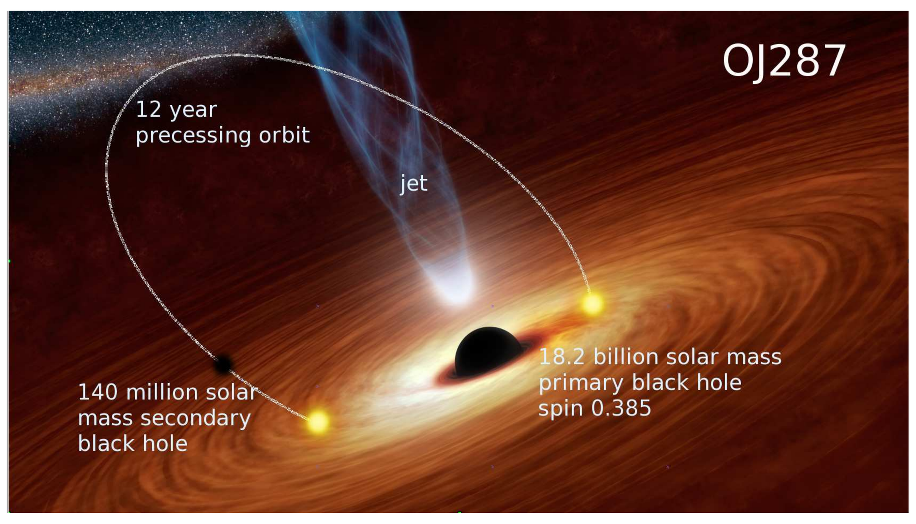

Figure 1: The coalescing binary black hole model of OJ287. The current period of 12.055 yr decreases by 38 days per century.

OJ 287 is one of the best candidates to host a SMBH binary. It has a high level of optical activity every 12 years, which has been observed since 1888 by using old photographic plates, and more recently, in optical photometry (Sillanpää et al 1988, ApJ, 325, 628; Hudec et al. 2013, A&A, 559, 20). One of the key features of this activity is the fact that it comes in pairs of outbursts which are separated by at least 1.1 years, with the separation being a function of the cycle number. This systematic behavior leads to a model of a high mass ratio (> 100) binary black hole system where the high brightness episodes arise from the impact of the secondary on the accretion disk of the primary (Lehto & Valtonen 1996, ApJ, 460, 207; Valtonen 2007, ApJ, 659, 1074).

After the General Relativity Centenary flare, which began on November 25, 2015, OJ 287 has stayed at 30 year record levels in optical brightness, divided into two episodes in 2016. Here we report optical photometry and polarimetry showing its 2016 - 2017 behavior. While the Centenary flare was limited only to the optical/UV region, and had a low level of polarization, the follow-up flares in 2016 had high polarization, and the outburst energy extends to X-rays with almost constant optical/X-ray spectral index of 2.7±0.1. This type of separation in the properties of the outbursts was predicted within the coalescing binary black hole model of OJ287. While the Centenary flare arises directly as the result of the impact of the secondary black hole onto the accretion disk of the primary, the follow-up flares occur in the jet of the primary. They are induced by transport of perturbations from the site of impact to the center of the accretion disk. The new observations allow the determination of the propagation speed. We also present the prediction of the blazar brightness in the coming years.

Observations: Photometry

Predicted by the SMBHs binary model, the Centenary flare in OJ287 was well covered in optical band by a campaign with more than 20 participating sites (Valtonen et al. 2016, ApJ, 819, L37). After this event we continued the monitoring of the blazar at several sites including the SKYNET Robotic Telescope Network achieving almost daily coverage. Observations were stopped for the summer 2016 when OJ287 was in conjuction with the Sun and we resumed monitoring its brightness as soon as it became accessible at the end of August 2016, taking data in the wide band R filter. The observations were reduced soon after they were taken in a standard way by calibrating the frames for bias, dark and flatfield.

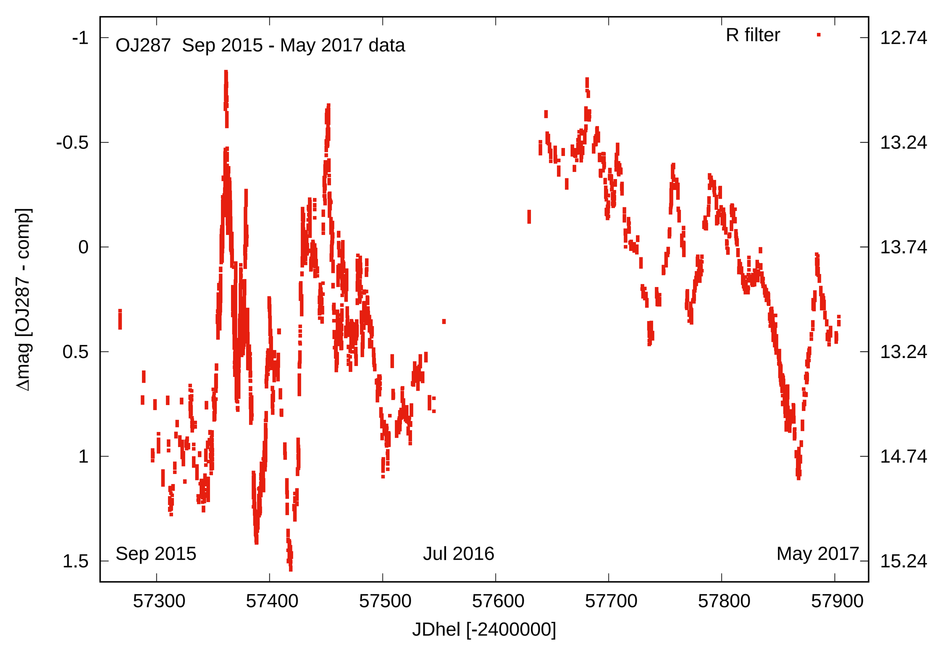

Figure 2: Light curve of OJ 287 observed in 2015/16 and 2016/16 seasons. The gap in summer 2016 is due to the conjunction with the Sun.

Data taken with the SKYNET telescopes were calibrated with the network pipeline. Magnitudes were extracted using the aperture method with the CMunipack program (Hroch, 1998) which is a graphical interface for the DAOPHOT II code. The photometric light curve of OJ 287 taken until the end of May 2017 in the wide band R filter is presented in Fig. 2.

Observations: Polarization

The fully autonomous and robotic Liverpool Telescope (LT) simultaneously houses 7 instruments, and any one can be accessed on a given night (Steele et al. 2004, Proc. SPIE, 5489, 679). RINGO3 is the current polarimeter on the LT (Arnold et al. 2012, Proc. SPIE, 8446, 84462J). It consists of a rotating Polaroid (at 0.4 Hz) which modulates the incoming beam of light. The light is then split into three wavebands using dichroic mirrors, 350-640 nm, 650-750 nm and 760-1000 nm. Images are captured at 8 different Polaroid rotor angles by three electron multiplying charge coupled device (EMCCD) cameras (one for each waveband). The measured counts at the 8 different Polaroid angles are combined using equations from Clarke & Neumayer 2012 (A&A, 383, 360) to calculate the Linear Stokes Parameters q and u, whilst stacking the 8 images from the different rotor angles gives the Linear Stokes Parameter I. Using the Linear Stokes Parameters the degree of polarisation and polarisation angle can be calculated as described in Jermak et al. 2016 (MNRAS, 462, 4267).

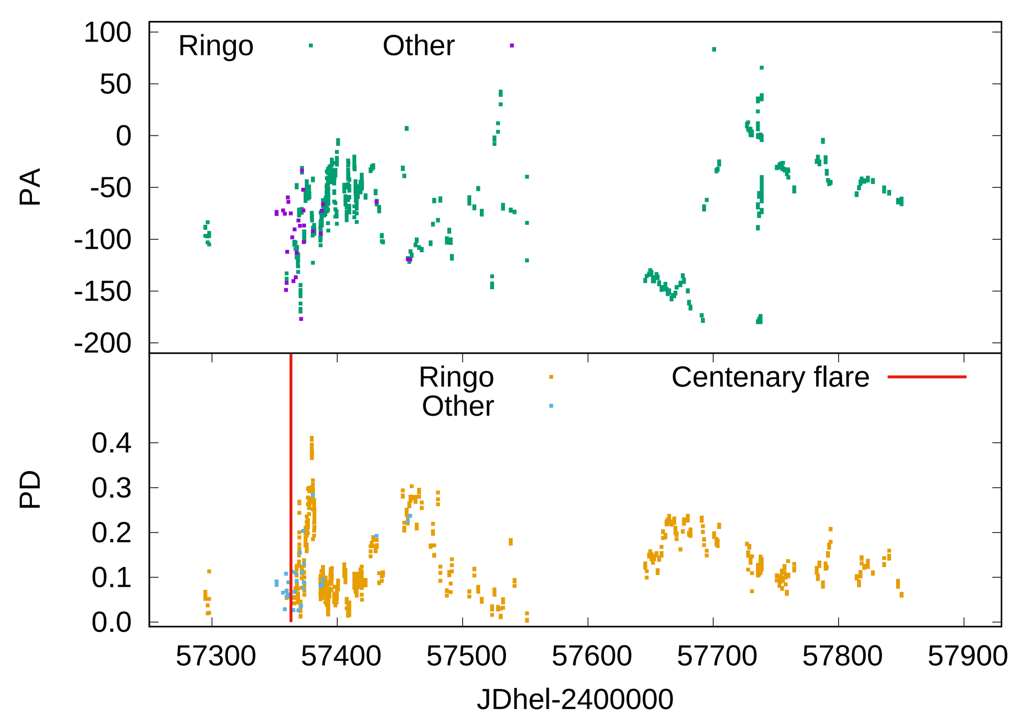

Figure 3: Polarimetric data for OJ 287 from Sep 2015 to May 2017.

The measurements performed for OJ 287 (linear polarization degree and position angle) are shown in Fig. 3. In this figure we also plotted data reported in Valtonen et al. (2016). Except for the December 2015 flare (marked by the red vertical line) for which the polarization degree was at the level of 0.1 or below, the subsequent brightenings were highly polarized.

Propagation of perturbations

We started the 2015/2016 observing campaign for the purpose of getting accurate data on the outburst predicted to occur in December 2015. The optical flux rose above its normal level of variations of 14.5 mag in R band, on the exact date of the Centenary of General Relativity; thus its name Centenary flare (Valtonen et al. 2016).

For the first time this campaign obtained polarization and UV/X-ray data over the whole light curve of an OJ287 primary flare, in addition to optical photometry. The campaign has continued in order to monitor the follow-up flares which have been observed as a rule in OJ 287 previous outburst episodes (Sillanpää et al. 1996, A&A, 305, 17, A&A, 315, 13; Valtonen et al. 2009, ApJ, 698, 781; Valtonen & Ciprini 2012, MNRAS, 427, 77), the follow-up flares which comes directly from the impact, is of low polarization and is limited to optical/UV region (Valtonen et al. 2008, Nature, 452, 821; Valtonen et al. 2012, MNRAS, 427, 77), the follow-up flares are highly polarized and extend to X-ray region of the spectrum (Smith et al. 1985, AJ, 90, 1184; Seta et al. 2009, PASJ, 61, 1011). Therefore in the current campaign both polarization measurements and UV/X-ray data have been in central role in determining the likely origin of the different light curve features.

Prior to this campaign the speed of the transmission of perturbations from the impact site to the jet was an open question. In the 1994/1996 flares it was determined that it takes 0.25 years for the transit (Valtonen et al. 2006), while in the 2007 flare the time was 0.02 years (Valtonen et al. 2009). From these two data points alone it is difficult to determine the transmission speed, even though qualitatively they are consistent with the greater distance of the 1994/1995 impacts (about 5500 AU on average) from the center of the accretion disk than the distance of the 2007 impact point (about 3200 AU from the center). One solution based on these data is that the transit speed is about $(1+z)/6c$ down to 3000 AU, at which point the perturbation is quickly transmitted to the jet. The transit time is then = (distance from the center in 1000 AU − 3)/10. Using this formula, we expected that the transit time from the 2013 impact place (at the distance of about 18 000 AU from the center) is 1.5 years, and the two main peaks in the follow-up light curve occur at 2016.1 and 2016.8, both with a rather broad (± 0.2 year) width (Pihajoki et al. 2013, ApJ, 764, 5). Thus the follow-up outbursts were expected very soon after the primary outburst at 2015.9, and they were anticipated to carry on through April 2016, and then reappear around August 2016 and last until the end of 2016.

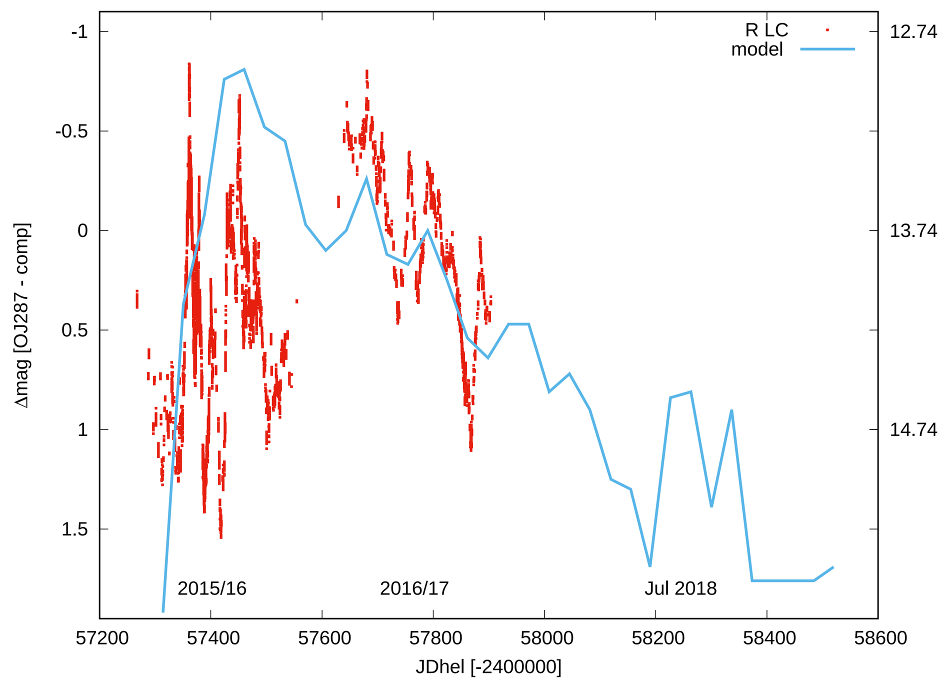

Figure 4: Prediction of OJ 287 brightness changes.

Using the Pihajoki et al. (2013) model, we can compare the blazar observed brightness level after the December 2015 flare, in 2016 and 2017, as the result of disturbances propagating through the disk towards the primary SMBH. This comparison as well as the predicted behaviour in the future is shown in Fig. 4. We would like to point out that the strength of the second jet outburst at the end of 2016 is underestimated in the model of Pihajoki et al. (2013). This is due to an artificial truncation of the accretion disk at 21 600 AU in the model. Without this truncation, the late 2016 outburst theoretically would have a somewhat greater brightness than the early 2016 one.

Conclusions

We have observed the predicted two peaks in the follow-up light curve of OJ 287. Optically they are both highly polarized and the optical/X-ray spectrum is consistent with the synchrotron radiation. It is therefore likely that the emission originates in the jet of the primary black hole. The transmission time of the perturbations is confirmed as 1.5 years. Since distance is 15 000 AU, the speed is $\sim(1+z)/6c$. It has been previously estimated that this is the sound speed in the corona of the accretion disk (Pihajoki et al. 2013, ApJ, 764, 5); thus it appears that the perturbations are transmitted via the corona to the inner parts of the accretion disk at about 3000 AU (∼8.3 Schwarzschild radii of the primary). From there, the perturbations appear to influence the jet without further delay.

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