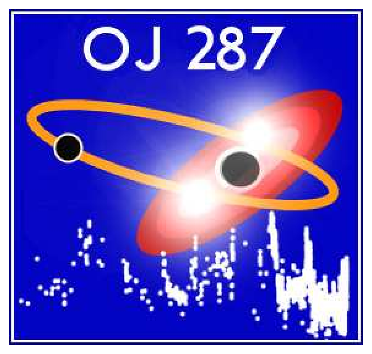

Time-domain analysis of blazar OJ 287 and the binary supermassive black hole conjecture

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Abstract

The proper understanding of blazar time-domain variability at the various electromagnetic spectral bands is one goal of multifrequency astrophysics. In this frame a peculiar and controversial phenomenology is the periodicity, postulated for long-term radio or optical flux light curves of about a dozen of blazars. The well-known BL Lac object OJ 287 (PKS 0851+202, S3 0851+20, PG 0851+202, z=0.306) is not only a high-variable, peculiar, extragalactic source with hints for approximately cyclical optical outbursts, but it also represents a case of substantial intensive and extensive (long-term) multi-frequency archive of observations. This rich, gold-mine, database allow us a deeper analysis based on a wide range of variability timescales.

OJ 287 light curve timing and GR binary model

A sub-parsec binary supermassive black hole (SMBH) interpretation is proposed for OJ 287 (Fig. 1 and 2). The timing and clocking of the optical and multifrequency light curves constrain this model. In general 10^8-10^9 years is the timescale from two galaxy merger to their central SMBH merger. The OJ 287, supposed, sub-parsec binary system has <10^5 years to merge. Sub-parsec scale means unresolved binary and strong field General Relativity regime. Timing is spin-sensitive meaning the accurate timing of the secondary BH impact flare constrained the Kerr parameter (spinning BH) of the primary BH with a fraction of percent accuracy. Hot bubble of gas is torn of accretion disc by impact of the secondary, and is not Doppler boosted.

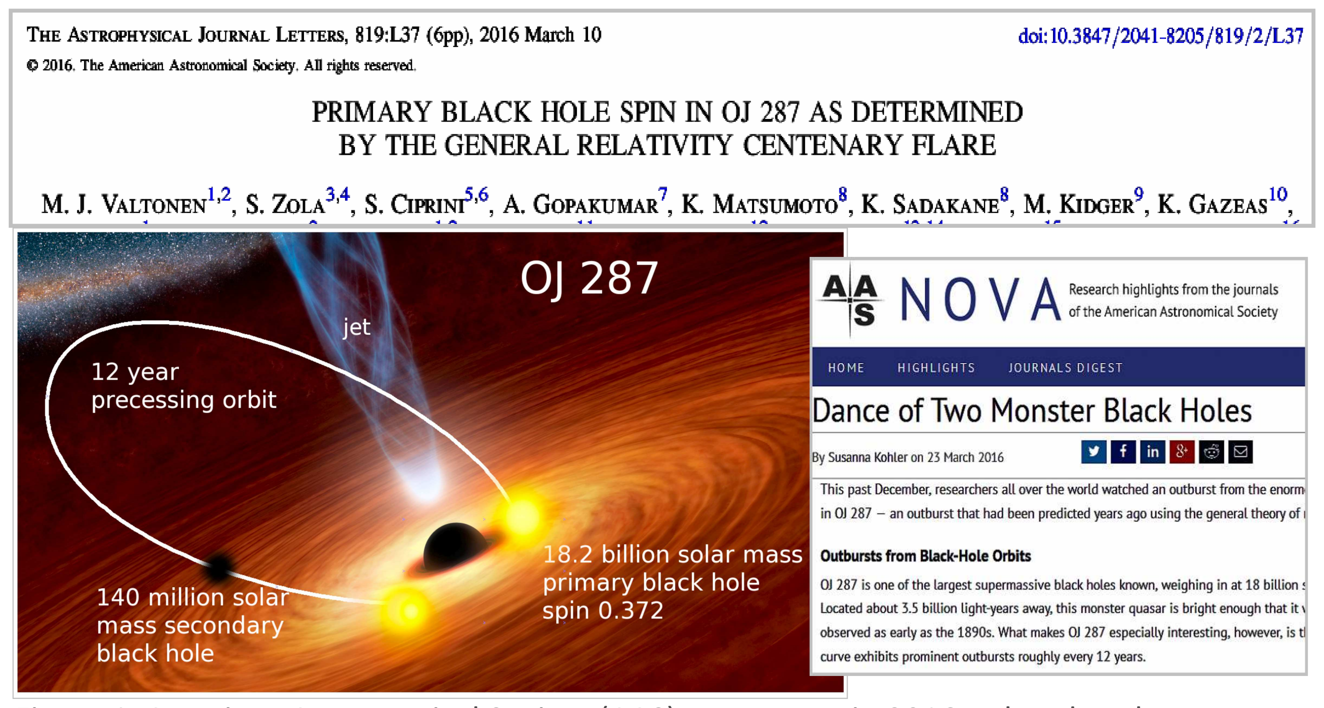
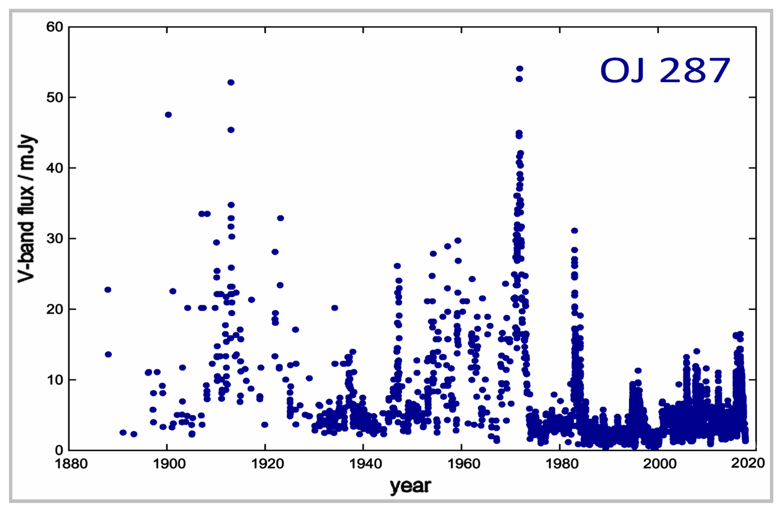


Figure 1. American Astronomical Society (AAS) press news in 2016, related to the paper: Valtonen, Zola, Ciprini, Gopakumar, et al. 2016, ApJ Lett, 819, 37: "Primary Black Hole Spin in OJ 287 as Determined by the General Relativity Centenary Flare". Press news are published by: ASI (Italian Space Agency); INAF (Italian National Institute forAstrophysics); TIFR Mumbai India; University of Turku, Finland; Jagiellonian University, Poland.



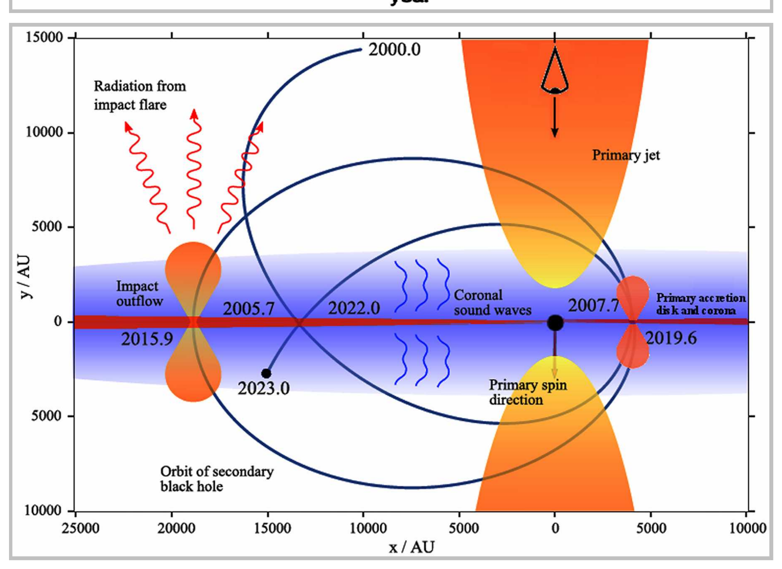


Figure 2. Quasi-periodic pattern of prominent outbursts in >100 year historical optical light curve: 12 identified main outbursts, not strictly periodic, and several probable secondary outbursts. Outbursts seem to come in pairs separated by 1 or 2 years. 2015-2016 outburst confirms the established General Relativity properties of the system such as the loss of orbital energy to gravitational radiation at the 2% accuracy level, and it opens up the possibility of testing the black hole no-hair theorem with 10% accuracy during the next decade. The requirement that the disc is stable in spite of the binary action puts a lower limit on the mass of the primary.
Binary SMBH masses: 1.5X10^8 M_sun, 1.8X10^10 M_sun, orbital eccentricity 0.7.

XMM-Newton and Swift time-domain experiment

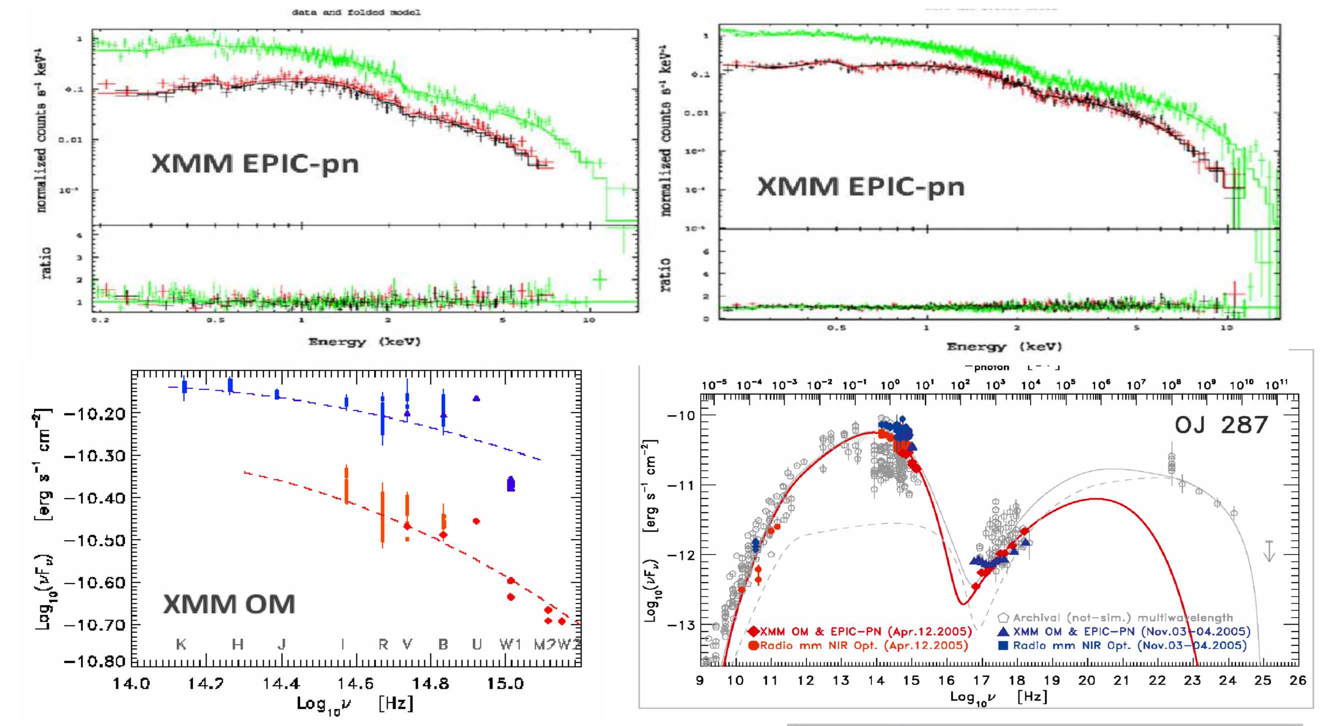
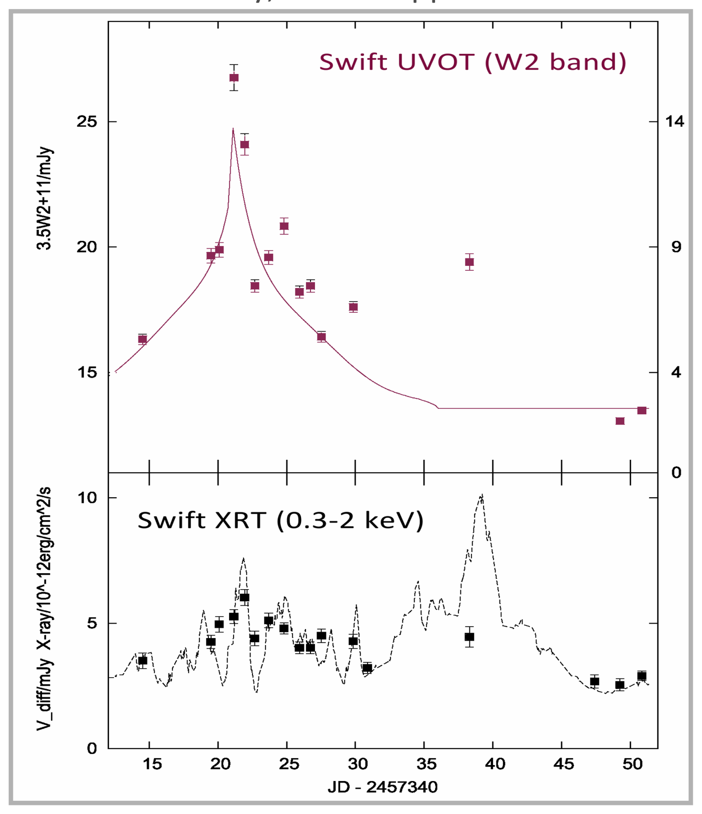


Figure 3. XMM-Newton (Guest Observer proposal PI S. Ciprini) observed OJ 287 during two active optical states of the source in 2005 for the first time. An enduring, symmetrical, and time structured optical outburst is observed in Oct.-Nov. 2005, around the 2nd XMM pointing. Broken power law component (break about 0.7 keV, synchrotron tail/thermal component and inverse Compton). X-ray break signature typical of interm. energy peaked blazars. April 2005: an optical secondary impact pre-outburst state. November 2005: the main about 12 year cycle secondary impact outburst. Optical-to-UV range has a thermal Bremsstrahlung spectral energy distribution consistent with gas at 3×10^5K temperature. Hot bubble of gas which is torn of the accretion disc by the impact of the secondary, is not Doppler boosted.



Swift monitor (time experiment) program led by SSDC: Oct.2015-Feb.2016 PI **S. Ciprini** (several repeated ToO proposals) and accurate and quick XRT/UVOT analysis by **M. Perri** and **F. Verrecchia**

Figure 4. A dedicated time-domain experiment with Swift (through several ToO proposed observations) was performed in 2015 and 2016 for the first time by Swift on the object OJ 287, in order to obtain simultaneous X-ray and UV flux light curves on daily-weekly timescales to be compared to the intensive optical monitor data by ground based telescopes. Swift UV emission measured by UVOT followed the optical emission rather well as expected by a unique dominating bremsstrahlung emission component by the secondary BH impact. Remarkably the X-ray flux (0.3-2 keV) light curve does not show a corresponding flare in agreement with the separation between the thermal, orphan, impact binary outburst emission and the stocastic erratic in-jet non-thermal emission (X-ray band and beyond). Optical binary SMBH model line, shifted to the UV-W2 band follows these UVOT data rather well.

First dedicated X-ray observations of OJ 287 by XMM-Newton (two snapshots in 2005, further two in 2006 and 2007) with related intensive coordinated multifrequency campaign (Fig. 3 and 5) organized and performed. Insights on cross-correlated variability, spectral energy distribution (SED) and separation of emission components. In 2015-2016 for the first time a OJ 287 binary/periodic outburst was temporally monitored on daily-weekly scales also by a X-ray satellite (a Swift time domain experiment). Swift UVOT UV-W1 and UV-M2 light curves in agreement with the binary model line. Separation of the disk thermal impact bremsstrahlung emission of the secondary BH on the primary BH from synchrotron flares (erratic jet variability). X-ray emission modeled as entirely erratic in-jet emission. Non-presence of a simultaneous strong X-ray outburst (orphan optical-UV outburst) → evidence for extra optical-UV (non-jet) emission component (the predicted binary model thermal outburst).

Intensive & extensive (long-term) multifrequency campaigns

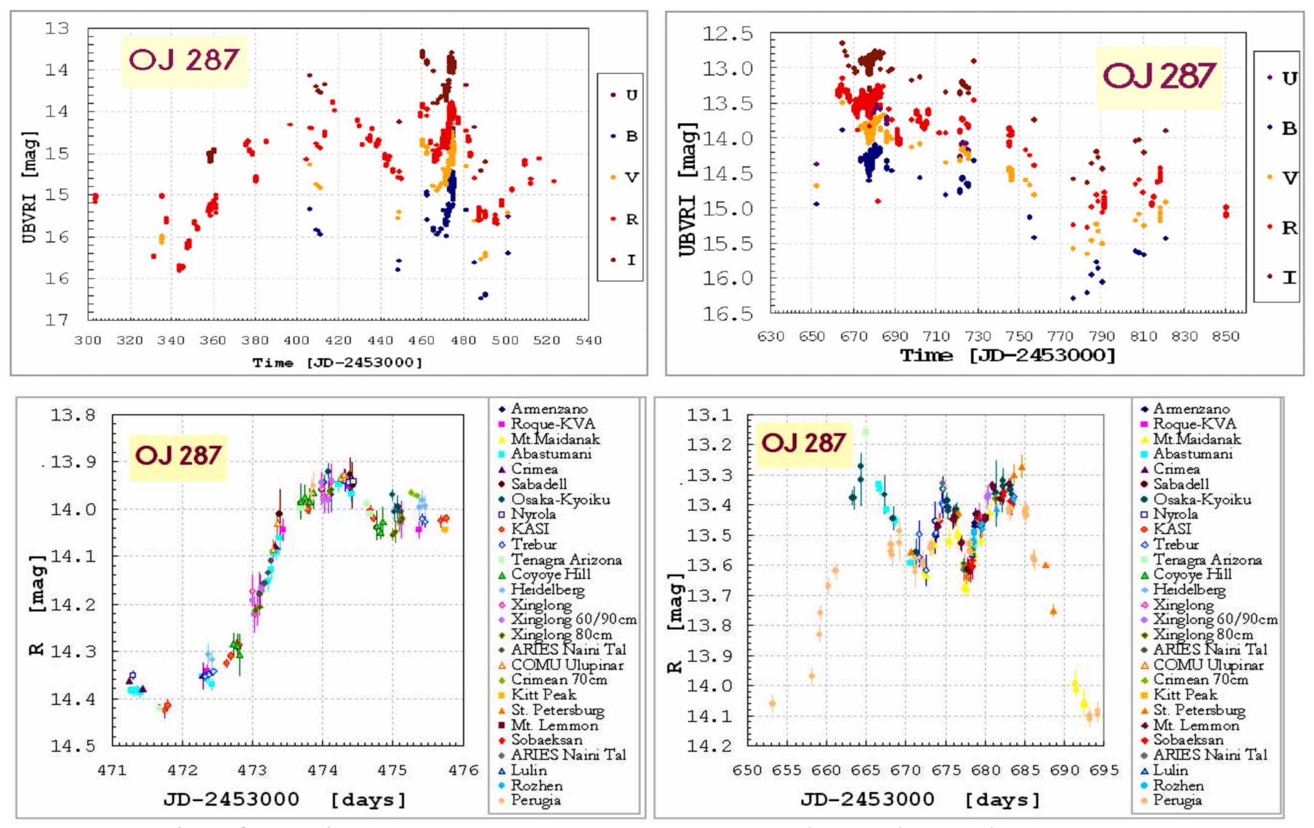


Figure 5: plots from the 2004-2007 WEBT intensive and coordinated campaigns and long-term monitoring (from ENIGMA European research training newtwork institutes/observatories, and further independent observations). About 3700 data points collected only in the R-band. XMM-Newton observed OJ 287 during two active optical states of the source. An enduring, symmetrical, and time structured optical outburst observed in Oct.-Nov. 2005, around the 2nd XMM pointing. Radio flux on the average and any outburst observed. Radio IDV (3%) found. Frequency dependence of the mean structural position angle of the radio-jet in VLBA maps, consistent with jet precession.

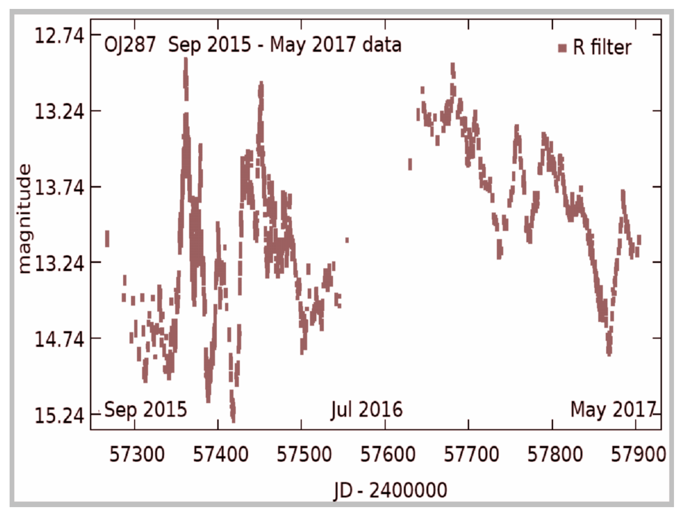
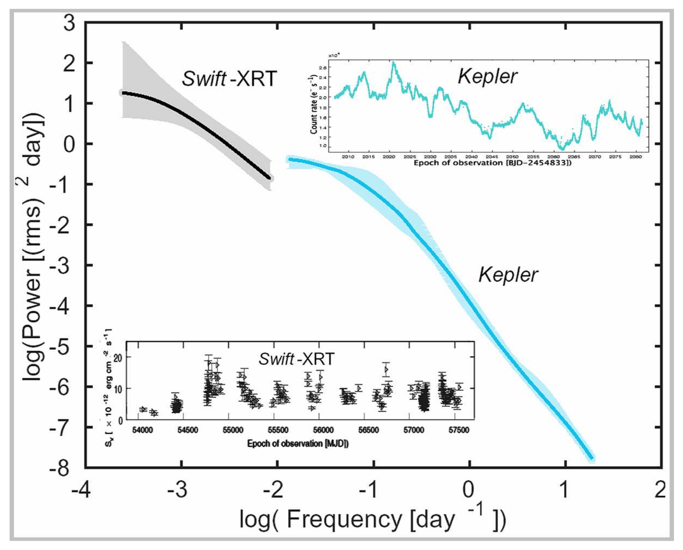


Figure 6: 2015-2017 optical intensive campaign led by Astron. Obs. of Jagiellonian Univ., Poland, providing a clocking of the predicted impact outburst. The timing constraint provide outburst began on JD 2457342.5+/-2.5 day (2015.874, Dec.5 2015). Using the calculated correlation with the spin the Kerr parameter of the primary SMBH is obtained (0.313+/-0.01). Optical polarization data confirmed the major thermal impact (low-polarization) component.



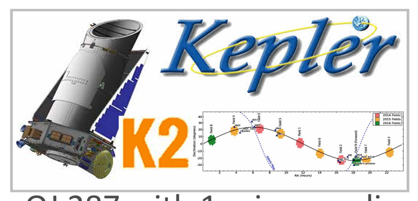


Figure 7: Kepler K2 Campaign 5. light curve of OJ 287 with 1 min sampling at >90% duty cycle and high S/N (Apr.27-Jul.13 2015). There are not statistically significant periodicities detected in the range from some minutes to 30 days. Power density spectra PDS of Swift-XRT data and Kepler K2 optical data with light curve model as continuous-time auto regressive moving average (CARMA) process.

Post Newtonian approx. to General Relativity (massive BHs and strong-field) predictions are observed in optical data, and corroborated by UV/X-ray data. Loss of orbital energy due to nano-Hz gravitational wave (GW) radiation at 2% accuracy level. Test BH no-hair theorem at 30% accuracy. Lense Thirring precession (orbital plane and pericenter). Huge masses: 1.5X10^8 M_sun, 1.8X10^10 M_sun, orbital eccentricity 0.7. Primary Kerr SMBH spin parameter is 0.313+/-0.01. More GR tests possible after 2019.

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