PROCEEDINGS OF SCIENCE

The OJ 287 black hole binary: witness of the validity of the General Relativity

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From several years different hypotheses have been suggested to connect, at least at low-accretion regimes, the physical processes regulating the conversion of an accretion flow into radiative energy and jet properties and the black hole activity, in some universal relations across all the decades of black hole masses. The proper understanding of blazar variability at the various electromagnetic spectral bands is one important mechanism for these scenarios. In particular a peculiar and controversial phenomenology is the periodicity, postulated for long-term radio or optical flux light curves of few AGNs. The well-known BL Lac object OJ 287 (PKS 0851+202, S3 0851+20) is a high-variable extragalactic source with hints for approximatively cyclical optical outbursts. Also for this reason OJ 287 represents a case of substantial intensive and extensive multifrequency data allowing, under the strong assumption of a binary supermassive black hole central engine, to clock some General Relativity model predictions and properties of this object.

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1. The fundamental plane of accreting black holes

Accretion and jets connect accretion processes to ejection in black holes, neutron stars, white dwarfs, supermassive black holes. Collimated jets underline relativistic systems and are applicable to a wider variety of astrophysical objects like young stellar objects, super-soft X-ray binaries, low/high-mass X-ray binaries, cataclysmic variable stars, symbiotic stars, pulsars, planetary nebulae, tidal disruption events, gamma-ray bursts, active galactic nuclei (AGNs). There are a number of distinctive signatures of accreting black hole-powered activity (relativistic jets, luminous and compact power-law X-ray emission and other), with a couple of relevant facts established in the last two decades.

The discovery of correlations between massive black hole masses in the nuclei of nearby galaxies and the global properties of galaxies, as the bulge luminosity, bulge mass or the central velocity dispersion [16], suggesting a direct link between the physical processes that contribute to the central black holes growth and the formation of their host galaxies.

The determination of a universal scaling law of black hole activity, namely the so called, "Fundamental Plane" representing a tight relation between the radio luminosity of radio-loud AGNs with core dominated jets and the combination of their X-ray luminosity and black hole mass in logarithmic scale $\log_{10} L_R = 0.6 \log_{10} L_X + 0.78 \log_{10} M_{BH} + 7.33$ [12]. The correlation appears to extend over many decades of black hole mass and accretion luminosity, applicable both to star masses black holes (hereafter BH) in X-ray binaries and to supermassive analogs in AGN (hereafter SMBHs). Variability in the disc and jet however hinders the inversion of the relation to determine disk properties. The physical processes regulating the conversion of an accretion flow into radiative energy could anyway be universal across the entire black hole mass scale, at least at low-accretion rates [6, 15, 13].

Relations between BH mass, accretion rate and timing variability properties are also suggested (e.g. [11]). A scaling law appear also to connect the observing and emission rest frames in beamed/jetted sources, with a correlation between the intrinsic broad-band radio luminosity and the black hole mass, extending over nine orders of magnitude from blazars (SMBHs) down to microquasars (BH) scales [9]. This can allow independent estimations of the bulk Doppler factor of jets also in systems of tens-of-solar mass BHs like are the first cases of gravitational waves bursts of BH binary mergers discovered by LIGO. There are also some examples of qualitatively similar variability patterns between AGNs like, for example 3C 111, and X-ray binaries or microquasars like GRS 1915+105, both with claimed correlations among superluminal radio ejections, radio-optical flares and X-ray flux dips and power spectrum breaks [2]. The jet of Cyg X-1 could be produced by extraction of the BH spin energy via a magnetically arrested disk accretion flow, a physical process that could work also for the low power and turbulent jets of BL Lac objects.

2. 130-year observations of the blazar OJ 287

Blazars, divided into the two classes of Flat Spectrum Radio Quasars (FSRQs) and BL Lac objects (BL Lacs), constitute unique laboratories to study extreme astrophysics, from relativistic magnetohydrodynamics and shocks, to particle acceleration, ultra-high energy cosmic rays, neutrino production, and nano-Hz gravitational waves in the cases of sub-parsec SMBHs binaries. Spe-

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cial relativity effects dominate their emission from radio to γ-rays, extreme variability is present across all the wavebands, and γ-ray loudness makes them the largest detected source population of the *Fermi* Large Area Telescope [1].

Quasi-periodic oscillations (QPOs, typically 1-10 Hz) of high-mass X-ray binaries, if produced in accretion flows coupled to the jet, could have a similar analogy in blazars on time-scales of years, with linear scaling of time-scales with BH mass. If this hypothesis is true candidate blazar and AGN flux periodicity would be analogous to X-ray binary QPOs, intrinsic to the accretion flow rather than attributed to binary SMBHs motion. In general periodicity in extragalactic objects (galaxies or AGN) is a peculiar and controversial phenomenology claimed, for example, for radio/optical flux light curves of very few blazars. Estimates of periodicity significance, the red-noise estimation, gaps in light curves, weak multiwavelength cross-correlations and systematics, generally makes the results weaker for blazars/AGN sources with respect to QPOs of star-sized BHs (X-ray binaries).

A particular case in literature is the BL Lac object OJ 287 (also historically known as PKS 0851+202, S3 0851+20, B2 0852+20, PG 0851+202 and as 1ES 0851+203, RX J0854.8+2006, 3EG J0853+1941, 3FGL J0854.8+2006 in high-energy bands). OJ 287 (Fig. 1) is an intermediate synchrotron-energy peaked and optically high-variable BL Lac object (variations > 3 mag), with redshift $z = 0.306$, and a large database of radio-/optical flux data [18, 7]. From the earlier 11/12-year optical periodicity claims, the current theory for OJ 287 points to a more complex, non-strictly periodic, scenario, with double outburst events (separated by one/two years) and orbital precession in a binary SMBHs system and shrinking as clear signatures in the observed optical flux light curves [19, 21, 23].

Coordinated, and both intensive and long-term, observing programs devoted to OJ 287 were organized and accomplished in the past years: the 1993-1997 OJ-94 monitoring project[1]; the 2005-2008 ENIGMA and WEBT projects with the related long-term and intensive multifrequency ob-

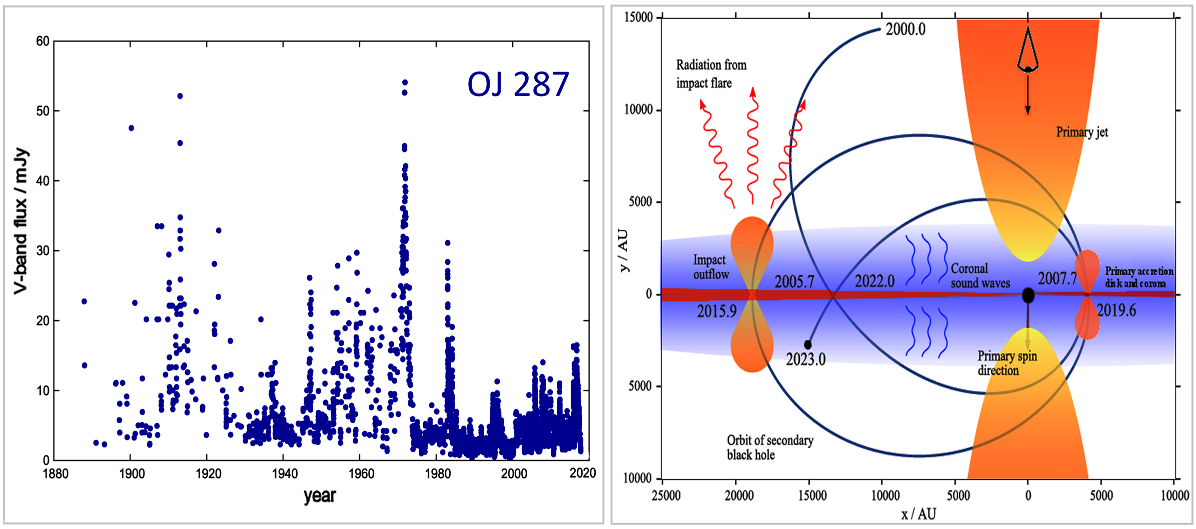

Figure 1: Left panel: about 130-year optical light curve of OJ 287. Right panel: Pictorial representation of the orbit of the secondary SMBH in OJ 287 from 2000 to 2023. Optical outbursts are seen every time the secondary SMBH impacts/perturbs the accretion disk of the primary SMBH (adapted from [23]).

[1] `http://www.astro.utu.fi/research/oj94/`

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serving campaigns[2]; the 2006-2017 optical long-term monitoring project[3].

The postulated approximatively cyclical temporal modulation of the optical flux emitted by OJ 287 has been interpreted, for example, by a precessing jet, a rotating helical jet or, as cited above, a binary SMBH system with sub-parsec separation and high-mass ratio (100 : 1) [17, 19, 23]. The presence of a binary SMBH system with sub-parsec separation in OJ 287 is based on the approximatively periodical optical flares observed and arising, in this hypothesis, from the secondary BH perturbing or piercing (Fig. 1) the accretion disk of the primary, about every 11-12 years, with nine identified episodes since 1913. Under this hypothesis the General Relativity orbital precession of the secondary BH naturally explains the approximatively periodic modulations of the optical light curve of OJ 287 [19, 23].

3. Some recent results

The last two, and best monitored, optical outbursts phases of OJ 287 occurred at the end of 2005, (with a secondary event in 2007), and in the period between winter 2015 and summer 2016. The optical monitor and multifrequency data obtained with coordinated observing campaigns[2] performed in the years between 2005 and 2008 [3] allowed, in particular, to test the Einstein's General Relativity (GR) theory in strong-field conditions [19] through light curve timing (clocking). Such data also corroborated the sub-parsec binary SMBH hypothesis, where optical/UV/X-ray data have evidenced the separation between un-boosted (non relativistically beamed) spectral component dominated by thermal bremsstrahlung emission from hot (3×10^5 °K) gas and the relativistically beamed in-jet, non-thermal, X-ray emission. The results where obtained thanks to XMM-*Newton* EPIC and OM observations [3, 21, 20], and to more recent *Swift* XRT and UVOT [4, 25, 23] data based on Guest Observer programs and a whole series of subsequent ToO proposals that represented one of the most relevant time-domain experiment performed with the *Swift* mission. The dedicated *Swift* temporal monitor continued since winter 2015 trough 2016 and 2017 thanks to additional observing proposals and ToOs. Fig. 2 (left panel) shows the different temporal shape between UV and X-ray data during the impact bremsstrahlung outburst of Nov.-Dec. 2015. Other observing programs confirmed the thermal spectral bump dominating from UV to near-IR bands during this epoch [8], in agreement also with optical polarization data showing a low-polarization (thermal) component during the impact epoch [22, 26, 23].

General Relativity three-body calculations and simulations demonstrates that a SMBH surrounded by a gas disk (the third body as an ensemble of particles) and possessing a companion SMBH can create a quasi-periodic signal. From the light curve clocking is possible to determine the secondary orbit and the sub-parsec binary SMBH system parameters. The secondary passes through the accretion disk of the primary with Keplerian orbit and post-Newtonian GR corrections at the third order expansion. Specifically post-Newtonian equations of motion for compact SMBH inspiralling binaries with high-mass ratio are adopted, with Lagrangian and Hamiltonian formalisms, and numerical computations of the gravitational reaction self-force. The loss in gravitational binding energy is caused by low frequency gravitational wave (GW) emission and the Lense-Thirring effect: the binary orbital plane precess, mainly due to the spin of the primary

[2] `http://www.astro.utu.fi/OJ287MMVI/`

[3] `http://www.as.up.krakow.pl/sz/oj287.html`

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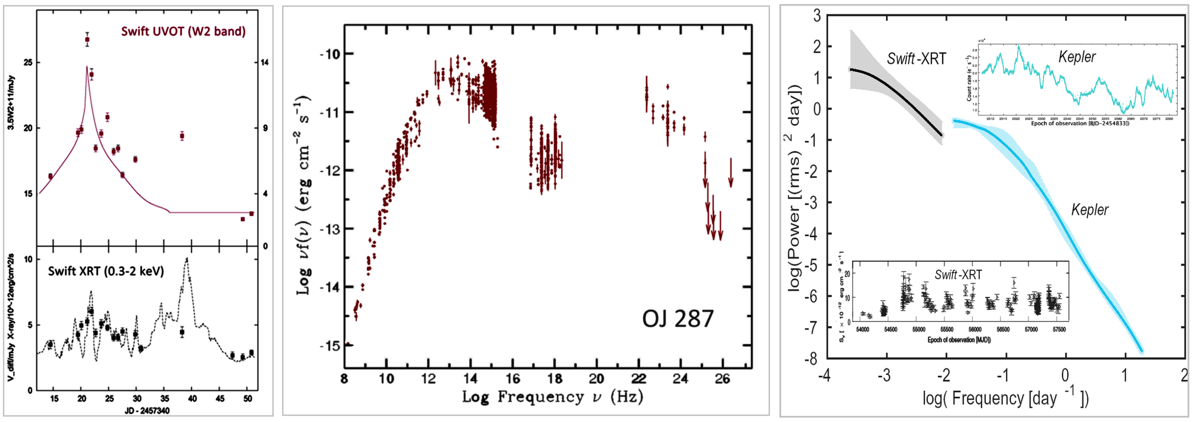

Figure 2: Left panel: *Swift* XRT X-ray and UVOT UV light curves during the predicted impact outburst epoch for OJ 287 of Nov.-Dec. 2015. The model foreseen the separation of the disk bremsstrahlung (optical and UV flux) from erratic in-jet synchrotron/inverse-Compton beamed variability (X-ray flux). The orphan optical-UV outburst strengthened the evidence for an extra, optical-UV, out of the jet, emission (adapted from [23]). Central panel: radio-to-gamma-ray spectral energy distribution of OJ 287 built with public data archived at the ASI SSDC. Right panel: temporal variability power density spectrum of OJ 287 constructed with *Kepler* space telescope data (1-minute sampling optical light curve from Apr. 27 to Jul. 13, 2015, K2 mission, Campaign #5) and *Swift* data (adapted from [5]).

SMBH [19, 23]. At the impact of the secondary on the accretion disk, a hot bubble of gas is extracted from the disk and expands at its internal sound speed. When it becomes optically thin during the expansion a burst of optical-UV radiation occurs.

The timescale from two galaxy merger to their central SMBH merger is usually of the order of $10^8 - 10^9$ years, and at the OJ 287 sub-parsec scale the time to merge is $< 10^5$ years. The estimated parameters of the system are: SMBHs masses $m_1 = (1.84 \pm 0.01) \times 10^{10}$ M$_\odot$; $m_2 = (1.40 \pm 0.03) \times 10^8$ M$_\odot$; $\Delta\phi = (39.1 \pm 0.1)^\circ$; primary Kerr SMBH spin $\chi = (0.313 \pm 0.01)$; $e = 0.66 \pm 0.01$; $q = 1.0 \pm 0.8$ [20, 21, 23]. In particular the orbital motion is measurably different if the primary BH has no "hair" (no-hair theorem of General Relativity) or if it has some "hair". The external gravitational field depends strictly only on the mass and the spin (net electric charge not expected in astronomical BHs). The occurrence of the optical outburst within the expected time window, using the high-mass ratio compact binary model is consistent with the no-hair theorem at the second post-Newtonian order, and confirms the energy losses by GW radiation in agreement within a few percents with the prediction by GR. The binary modeling of OJ 287 also indicated that the primary Kerr SMBH should spin approximately at quarter of the maximum spin rate allowed in GR, with a unique mathematical solution and prediction for impact flare outburst, that was observed on Dec. 2015. Its clocking is spin-sensitive, and this accurate light curve timing allowed us to constrain the Kerr spin parameter of the primary $\chi = (0.313 \pm 0.01)$ [23]. In this model the primary SMBH in OJ 287 is a black hole described by General Relativity with 30% accuracy of the no-hair theorem and the outburst clocking also confirmed the energy loss by radiation of very low-frequency gravitational waves.

OJ 287 can represent an optimal, indirect, laboratory for General Relativity in strong field conditions (masses, orbital parameters, no-hair theorem, precession, gravitational wave radiation losses). On the other hand the big effort in temporal time-domain monitor and multi-frequency observations allows us, in general, to perform several studies about the spectral and temporal behavior

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of this blazar, on both short and long time scales, and during different brightness states.

The search for different physical mechanisms responsible for the variability is not necessarily related only to the binary system underlying, deterministic, mechanism. High-energy observations at X-ray bands (*Beppo*SAX, XMM-*Newton*, *Suzaku*, *Swift*, [10, 3, 23]) and γ-ray bands (*Fermi* all-sky survey monitoring the source since Aug. 2008) are now contributing to enlarge the physical picture on this blazar.

Optical flux light curves during the 2015-2016 observing season where also recently analyzed searching for quasi-periodic oscillations (QPOs) corresponding to the innermost stable circular orbit (ISCO) timescale of the primary SMBH [26]. Previously, the long-term (2005-2008) observing campaign data evidenced the possible existence of a $\sim$ 50-day quasi periodic primary ISCO [14]. The optical flux and polarization data of the following 2016-2017 observing season indicated a persisting activity with high levels of polarization degree indicating a synchrotron emission from the primary SMBH jet, explained as in-jet stochastic flares induced by accretion perturbations following the Nov. 2015 impact [24].

An intensive and continuous three-month observing campaign of OJ 287 was performed by the *Kepler* space telescope, with 1 minute sampling at >90% duty cycle and high S/N, during the K2 Campaign #5 (Apr.27-Jul.13 2015, [26, 5] and Fig. 2, right panel). No statistically significant QPO was detected in the range from minutes to 30 days.

The 77-day continuous *Kepler* light curve and the gapped 2015-2017 *Swift* light curve, allowed us to determine the temporal variability power density spectrum (PDS) of OJ 287 on more than four decades ([5] and Fig. 2 right panel). The overall optical PDS calculated with *Swift*-UVOT and *Kepler* data is mostly consistent with, stochastic, red noise process, with no significant QPOs and a hint for a mild break at 10-day timescale. The X-ray (*Swift*-XRT) PDS suggests a pure red noise description [5], with no breaks that may have hinted a stable periodicity.

There is not a strict theoretical upper limit to the mass grow of a black hole, it depends on its age and how fast is the accretion. The primary SMBH of OJ 287 is among the most massive known black hole in the universe ($m_1 = (1.84 \pm 0.01) \times 10^{10}$ M$_\odot$). OJ 287 can represent an indirect evidence for the existence of a compact binary spinning SMBH system emitting gravitational waves and, possibly, constituting an indirect test bench for General Relativity in strong field. This is encouraging for Pulsar Timing Arrays, especially the future large-scale SKA project, that will indirectly detect, very low frequency gravitational waves (typically 10^{-9} Hz) from such binary SMBHs in the early stages of inspiral, thanks to very high precision ($\lesssim$ 100 ns) timing of pulsars. Waiting for SKA more tests for the binary hypothesis in OJ 287 with optical and multifrequency flux light curve data will be possible in the next years.

References

[1] Ackermann, M., Ajello, M., Atwood, W. B., et al. 2015, ApJ, 810, 14

[2] Chatterjee, R., Marscher, A. P., Jorstad, S. G., et al. 2011, ApJ, 734, 43

[3] Ciprini, S., Raiteri, C. M., Rizzi, N., et al. 2007, Mem. SAIt, 78, 741

[4] Ciprini, S., Perri, M., Verrecchia, F., & Valtonen, M. 2015, ATel #8401

[5] Goyal, A., Stawarz, L., Zola, S., et al. 2018, submitted.

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[6] Heinz, S., & Sunyaev, R. A. 2003, MNRAS, 343, L59

[7] Hudec, R., Bašta, M., Pihajoki, P., & Valtonen, M. 2013, A&A, 559, A20

[8] Kushwaha, P., Gupta, A. C., Wiita, P. J., et al. 2018, MNRAS, 473, 1145

[9] Liodakis, I., Pavlidou, V., Papadakis, I., et al. 2017, ApJ, 851, 144

[10] Massaro, E., Giommi, P., Perri, M., et al. 2003, A&A, 399, 33

[11] McHardy, I. M., Koerding, E., Knigge, C., Uttley, P., & Fender, R. P. 2006, Nature, 444, 730

[12] Merloni, A., Heinz, S., & di Matteo, T. 2003, MNRAS, 345, 1057

[13] Mezcua, M., Hlavacek-Larrondo, J., Lucey, J. R., et al. 2018, MNRAS, 474, 1342

[14] Pihajoki, P., Valtonen, M., & Ciprini, S. 2013, MNRAS, 434, 3122

[15] Plotkin, R. M., Markoff, S., Kelly, B. C., Körding, E., & Anderson, S. F. 2012, MNRAS, 419, 267

[16] Richstone D., Ajhar E. A., Bender R., et al. 1998, Nature Suppl. Rev., 395, A14

[17] Sillanpää, A., Haarala, S., Valtonen, M. J., Sundelius, B., & Byrd, G. G. 1988, ApJ, 325, 628

[18] Takalo, L. O. 1994, Vistas in Astronomy, 38, 77

[19] Valtonen, M. J., Lehto, H. J., Nilsson, K., et al. 2008, Nature, 452, 851

[20] Valtonen, M., & Ciprini, S. 2012, Mem. SAIt, 83, 219

[21] Valtonen, M. J., Ciprini, S., & Lehto, H. J. 2012, MNRAS, 427, 77

[22] Valtonen, M., Zola, S., Gopakumar, A., et al. 2015, ATel #8378

[23] Valtonen, M. J., Zola, S., Ciprini, S., et al. 2016, ApJ Lett., 819, L37

[24] Valtonen, M., Zola, S., Jermak, H., Ciprini, S., et al. 2017 Galaxies, 5, 83

[25] Verrecchia, F., Ciprini, S., Valtonen, M., & Zola, S. 2016, ATel #9709

[26] Zola, S., Valtonen, M., Bhatta, G., Goyal, A., et al. 2016, Galaxies, 4, 41

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