The April–June 2020 super-outburst of OJ 287 and its long-term multi-wavelength lightcurve with Swift: binary supermassive black hole and jet activity

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ABSTRACT

We report detection of a very bright X-ray-UV-optical outburst of OJ 287 in April–June 2020; the second brightest since the beginning of our Swift multi-year monitoring in late 2015. It is shown that the outburst is predominantly powered by jet emission. Optical-UV-X-rays are closely correlated, and the low-energy part of the XMM-Newton spectrum displays an exceptionally soft emission component consistent with a synchrotron origin. A much harder X-ray powerlaw component (Γx = 2.4, still relatively steep when compared to expectations from inverse-Compton models) is detected out to 70 keV by NuSTAR. We find evidence for reprocessing around the Fe region, consistent with an absorption line. If confirmed, it implies matter in outflow at ∼0.1c. The multi-year Swift lightcurves show multiple episodes of flaring or dipping with a total amplitude of variability of a factor of 10 in X-rays, and 15 in the optical–UV. The 2020 outburst observations are consistent with an after-flare predicted by the binary black hole model of OJ 287, where the disk impact of the secondary black hole triggers time-delayed accretion and jet activity of the primary black hole.

Key words: galaxies: active – galaxies: jets – galaxies: nuclei – quasars: individual (OJ 287) – quasars: supermassive black holes – X-rays: galaxies

1 INTRODUCTION

The last few years have seen the first direct detection of high-frequency gravitational waves (GWs) from merging stellar-mass black holes (e.g. Abbott et al. 2016, 2019). Coalescing supermassive binary black holes (SMBBHs), formed in galaxy mergers, are the loudest sources of low-frequency GWs in the universe (Centrella et al. 2010). Therefore, an intense electromagnetic search for wide and close systems in all stages of their evolution is currently ongoing (review by Komossa & Zensus 2016). While wide pairs can be identified by spatially-resolved imaging spectroscopy, we rely on indirect methods of detecting the most compact, evolved systems. These are well beyond the “final parsec” in their evolution (Begelman et al. 1980; Colpi 2014), in a regime where GW emission contributes to orbital shrinkage. Semi-periodicity in lightcurves has been a major tool for selecting small-separation SMBBH systems.

OJ 287 is a nearby, bright, and massive blazar at redshift z = 0.306 (Dickel et al. 1967), and among the best candidates to date for hosting a compact SMBBH (Sillanpaa et al. 1988; Valtonen et al. 2016). Its unique optical lightcurve spans more than a century, dating back to 1891. It shows pronounced optical double-peaks every ~12 years, which have been interpreted as arising from the orbital motion of a pair of SMBHs, with an orbital period on that order (~9 yrs in the system’s rest frame).

While different variants of binary scenarios have been discussed in the past (e.g. Lehto & Valtonen 1996; Katz 1997; Villata et al. 1998; Liu & Wu 2002; Britzen et al. 2018; Dey et al. 2019), the best explored model explains the double peaks as the times when the secondary SMBH impacts the disk around the primary twice during its 12.06 yr orbit (“impact flares” hereafter). The most recent orbital two-body modelling is based on 4.5 order post-Newtonian dynam-
ics and successfully reproduces the overall long-term lightcurve of OJ 287 until 2019 (Valtonen et al. 2016; Dey et al. 2018; Laine et al. 2020) (and references therein). It requires a compact binary with a semi-major axis of 9300 AU which is subject to GR precession of $\Phi = 38$ deg/orbit, on an eccentric orbit ($e = 0.7$), with a massive primary of $1.8 \times 10^{10} M_\odot$, and a secondary of $1.5 \times 10^9 M_\odot$. Independent evidence for a massive primary comes from the host galaxy of OJ 287 and other arguments (e.g. Wright et al. 1998; Kushwaha et al. 2018a; Nilsson et al. 2020). We are carrying out a multi-year, multi-frequency monitoring program of OJ 287, in order to search for epochs of outbursts and explore facets of the binary SMBH model (for first results see Komossa et al. 2017, 2018; Myserlis et al. 2019; Komossa et al. 2020a). Independent of the binary’s presence, OJ 287 is a nearby bright blazar, and dense multi-frequency monitoring and high-resolution X-ray spectroscopy are powerful diagnostics of jet and accretion physics in blazars.

Here, we present the detection of a bright outburst of OJ 287 in April–June 2020 with the Neil Gehrels Swift observatory (Swift hereafter; Gehrels et al. 2004); even brighter in UV–X-rays than the observed part of the 2015 “centennial” impact flare, and the second brightest in X-rays since the beginning of Swift observations of OJ 287 in 2005. XMM-Newton and NuSTAR X-ray spectroscopy was used in order to understand the nature of this outburst. (The long-term Swift lightcurve will be analyzed further in upcoming work; Paper II hereafter). We use a cosmology (Wright 2006) with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$ and $\Omega_\Lambda = 0.7$ throughout this paper.

### 2 DATA ANALYSIS AND SPECTRAL FITS

#### 2.1 Swift

We have monitored OJ 287 since December 2015 (Tab. 1, Fig. 1, which also includes some Swift data sets from other programs and PIs). The April-May 2020 outburst was typically covered with a cadence of 1–3 days, while the cadence was $\sim 2-10$ days at other epochs. Long gaps of several months occur each year when OJ 287 is in Swift sun constraint.

Most of the time, the Swift X-ray telescope (XRT; Burrows et al. 2005) was operating in photon counting mode with typical exposure times of 0.5-2 ksec. For X-ray analysis, source photons were extracted within a circle of radius 47$''$ (equivalent to 20 detector pixels). The background was determined in a nearby circular region of radius 236$''$. X-ray spectra in the band (0.3-10) keV were generated and then analyzed with the software package XSPEC (version 12.10.1f; Arnaud 1996).

Spectra were fit with single powerlaws of photon index $\Gamma_X$ adding Galactic absorption with a column density $N_{\text{H,Gal}} = 2.49 \times 10^{20}$ cm$^{-2}$. Photon indices range between $\Gamma_X = 1.6-3.0$ (Fig. 1, 2), with a general trend of steepening as OJ 287 becomes X-ray brighter.

We also observed OJ 287 with the UV-optical telescope (UVOT; Roming et al. 2005) and typically in all six filters [V (5468Å), B (4392Å), U (3465Å), UVW1 (2600Å), UVW2 (2246Å), UVM2 (1928Å)]; where values in brackets are the filter central wavelengths in order to obtain reliable spectral energy distribution

| mission | band (keV) | date ($t_{\text{start}}$) | MJD | $\Delta t$ (ksec) |
|---------|------------|---------------------------|-----|------------------|
| Swift XRT | 0.3-10 | 2015 Nov.–2020 June | 57354–59012 | 0.5-2 |
| XMM-Newton | 0.2-10 | 2020 April 24 | 58963 | 15 |
| NuSTAR | 3-79 | 2020 May 4 | 58973 | 29 |
Table 2. Results from XMM-Newton and NuSTAR spectral fits. Absorption was fixed at the Galactic value $N_H,\text{Gal}$, except when noted otherwise. Parameters and abbreviations are as follows: (1) Models: pl = powerlaw, bbdy = black body, logpar = logarithmic parabola model; (2) absorption in units of 10$^{20}$ cm$^{-2}$; (3) powerlaw photon index; (4) unabsorbed powerlaw or log-parabola flux from 0.5–10 keV in units of 10$^{-12}$ erg/cm$^2$/s; (5) $kT_{\text{BB}}$ in units of keV; (6) bbdy emission in units of 10$^{-5} \times (L/10^{39}$ erg/s)/[(D/10kpc)]$^2$; (7) $f_{\gamma}$; (8) unabsorbed powerlaw or log-parabola flux from 0.5–10 keV in units of 10$^{-12}$ erg/cm$^2$/s; (9) goodness of fit $\chi^2$ and number of degrees of freedom. For NuSTAR data, the pl flux is given from 3–50 keV. When no errors are reported, the quantity was fixed.

| model       | $N_H$  | $\Gamma$ | $f_{\gamma}$ | $f_{\gamma}$ | $f_{\gamma}$ | $kT_{\text{BB}}$ | $f_{\gamma}$ | $f_{\gamma}$ | $f_{\gamma}$ | $f_{\gamma}$ | $\chi^2$/dof |
|-------------|--------|----------|--------------|--------------|--------------|-----------------|--------------|--------------|--------------|--------------|--------------|
| XMM         |        |          |              |              |              |                 |              |              |              |              |              |
| pl          | 2.49   | 2.82 ± 0.01 | 38.5 ± 0.1   | -            | -            | -               | -            | -            | -            | -            | -            |
| pl + pl     | 2.49   | 2.84 ± 0.01 | 38.1 ± 0.2   | 0.0 ± 0.4    | 0.8 ± 0.2    | -               | -            | -            | -            | -            | -            |
| pl + pl, $N_H$ free | 3.4$^{+0.5}_{-0.6}$ | 2.49 | 3.1 ± 0.1   | 38.0 ± 1.0   | 1.7 ± 0.3   | 5 ± 0.1        | -            | -            | -            | -            | -            |
| pl + bbdy   | 2.49   | 2.70 ± 0.01 | 35.2 ± 0.3   | -            | -            | 0.152 ± 0.003  | 8.0 ± 0.7   | -            | -            | -            | -            |
| logpar + pl | 2.49   | 2.76 ± 0.03 | 35.6 ± 0.3   | 0 ± 1        | 0.6 ± 0.2    | 0.16 ± 0.01    | 6.0 ± 1.0   | -            | -            | -            | -            |
| NuSTAR      |        |          |              |              |              |                 |              |              |              |              |              |
| pl          | 2.49   | 2.36 ± 0.06 | 6.1 ± 0.2    | -            | -            | -               | -            | -            | -            | -            | -            |
| pl (> 10 keV) | 2.49  | 2.2 ± 0.2 | -            | -            | -            | -               | -            | -            | -            | -            | -            |

(SED) information of this rapidly varying blazar. Observations in each filter were co-added using the task involutions. Source counts in all six filters were then selected in a circle of radius 5$''$ and the background was determined in a nearby region of radius 20$''$. The background-corrected counts were then converted into fluxes based on the latest calibration as described in Poole et al. (2008) and Breiveld et al. (2010). The UVOT data were corrected for Galactic reddening of $E_{B-V}$=0.0248 (Schlegel et al. 1998), with a correction factor in each filter according to Equ. (2) of Roming et al. (2009) and based on the reddening curves of Cardelli et al. (1989).

2.2 XMM-Newton

Our XMM-Newton (Jansen et al. 2001) observation of OJ 287 was carried out in small window mode for 15 ksec from 2004-04-24 21:13:18 to 2004-04-25 01:23:18 UTC when OJ 287 was near the maximum of its outburst (observation id 0854591201). The effective exposure time was 9 ksec, after removing an epoch of flaring particle background.

The XMM-Newton data were reduced using the Science Analysis Software (SAS) version 18.0.0. EPIC-pn and EPIC-MOS spectra were extracted in a circular region of 20$''$ centered on the source position and background photons were collected in a nearby region of ~ 50$''$ for the pn and ~ 100$''$ for the MOS instruments. A lightcurve analysis of the 2020 data did not reveal significant short-time variability beyond the 3 sigma level, and therefore the spectra were analyzed as a whole without splitting into different flux states. Inspection of the RGS spectrum did not reveal significant narrow spectral features, and the data were not analyzed further.

For further analysis, spectra were binned to a signal-to-noise ratio of at least 6, and to oversample the instrumental resolution by a factor of 3, and fit with several emission models (Tab. 2) with absorption fixed to the Galactic value (modeled with TBnew; Wilms et al. 2000) or left free (at $z = 0.3$). OJ 287 is a very bright X-ray source. Fitting is based on $\chi^2$ statistics. Overall, the spectrum shows a very soft emission component, a harder component up to 10 keV, and possible spectral structure in the Fe-line region (Fig. 3, 4). The latter is independently present in both, the EPIC-pn and EPIC-MOS data. It is best fit by an absorption line of EW = 0.1 keV, at a restframe energy of 7.45 ± 0.05 keV. This would correspond to an outflow with a velocity of 0.067c assuming the line is produced by iron Fe XXVI or 0.1c if it is produced by Fe XXV. Adding a Gaussian absorption line to the best fit model improves the fit by $\Delta \chi^2 = 17$, for two degrees of freedom, which corresponds to a significance of ~ 3.7$\sigma$. However, after correcting for the number of trials, assuming 20 resolution elements between 7 and 10 keV for the EPIC cameras, the false alarm probability is raised to 4%, so the line significance is ~ 2$\sigma$. Therefore, its presence has to be confirmed in deeper future observations. While single-component broad-band models are unsuccessful, the XMM-Newton spectrum is best fit by the curved log-parabola plus flat powerlaw model with cold absorption at the Galactic value (Tab. 2).

For comparison, previous observations of OJ 287 between 2005 and 2020 (corrected for effective area of the detector, and without applying any model fits). Our 2020 and 2018 data are highlighted in red and blue, respectively. A strong soft emission component dominates the 2020 spectrum.

![Figure 3. Comparison of all XMM-Newton (EPIC-pn) spectra of OJ 287 between 2005 and 2020 (corrected for effective area of the detector, and without applying any model fits). Our 2020 and 2018 data are highlighted in red and blue, respectively. A strong soft emission component dominates the 2020 spectrum.](image-url)
long-lasting 2016-2017 flare which was the brightest in X-rays with Swift and with a soft spectrum (Verrecchia et al. 2016; Grupe et al. 2017; Komossa et al. 2017; Kushwaha et al. 2018b; Kapanadze et al. 2018). The event was accompanied by a VHE detection (Mukherjee et al. 2017). A sharp and symmetric deep low-state in late 2017 in all optical (Valtonen et al. 2020) and UV bands which is absent in X-rays (to be discussed further in Paper II). (4) The April 2020 outburst, where OJ 287 reached the second-brightest X-ray state during the Swift monitoring. Here, our focus is the 2020 outburst, and X-ray analysis has been done with the following key questions in mind:

What does the variability imply about the emission site? At 1.8 × 10^{10} M_\odot, an innermost stable orbit of R_{ISCO} \sim 3R_S$ corresponds to a minimum restframe lightcrossing timescale of 6.3 days, which is larger than observed. Daily changes including a factor 1.7 drop in flux within 2 days during the 2020 outburst (Fig. 2) therefore imply an emission site smaller than the last stable orbit of the primary SMBH of OJ 287, then indicating jet activity. Is there any wavelength-dependent delay in the peak time of the flare? UV-optical lightcurves follow each other closely and reach their peak quasi-simultaneously (see paper II for details), implying co-spatial emission and small opacities. X-rays follow substructure in the April flare closely, but the two-week flat plateau does not allow to locate the peak precisely.

Which mechanism drives the softness of the X-ray spectrum: accretion or jet (synchrotron) activity? The very soft X-ray emission component could potentially represent emission associated with the inner accretion disk; either a high-energy tail of the big blue bump or reprocessing/reflection of coronal photons off the inner disk. Near the peak of the 2020 flare, the observed powerlaw flux corresponds to an isotropic X-ray luminosity of 10^{45} erg/s, which would imply an X-ray Eddington ratio of L/L_{Edd} = 4 \times 10^{-4} \times (8 \times 10^{-7}) for a BH of mass 1.8 × 10^{10} M_\odot (10^8 M_\odot) if it was accretion driven. Given the rapid variability, it then has to be the disk of the secondary BH. However, there is no other evidence so far for a long-lasting disk around the secondary, and the quasi-simultaneous variability in all bands from the optical to X-rays strongly argues for a synchrotron origin of the emission.

Even though blazars often show a synchrotron component in the X-ray band (Urry et al. 1996; Donato et al. 2005), it is interesting to note that their synchrotron component is rarely as soft as in OJ 287 (see paper II for further discussion). We find that OJ 287 generally exhibits a "softer-when-brighter" variability pattern in our multi-year Swift lightcurve\footnote{also seen on long timescales when combining a few Einstein, EXOSAT, ROSAT, and ASCA data (Isobe et al. 2001); but see Seta et al. (2009))} – with the exception of the epoch around the 2015 impact flare when the X-ray spectrum was rather hard.

In summary, the various observations imply that the April 2020 outburst is not dominated by accretion-disk emission but rather by non-thermal emission from the jet, further corroborated by the Effelsberg detection of a (delayed) radio flare (Komossa et al. 2020b), and by the detection of high polarization of the optical flare of OJ 287 first reported by (Zola et al. 2020).

3.2 Binary black hole model

In the context of the binary SMBH model for OJ 287 as reviewed by Dey et al. (2019), there are several potential sites of UV–X-ray emission, which may become bright at different epochs: First, the impact flare (bremstrahlung) from the secondary, as it impacts the...
accretion disk around the primary, causing a two-sided expanding bubble (Ivanov et al. 1998). It was last observed in July 2019 (Laine et al. 2020) and none is predicted for 2020. Second, temporary accretion and perhaps jet emission of the secondary SMBH while and/or after passing the primary’s disk (Pihajoki et al. 2013). However, it is unlikely that any secondary SMBH of much lower mass and different spin, and with a temporary disk without large-scale magnetic field, will trigger synchrotron flares of very similar brightness and spectrum as the primary (see the long-term lightcurve in Fig. 1). Third, “after-flares” in form of changes in the accretion rate of the primary, after the impact disturbance has travelled to the inner edge of the accretion disk, then later followed by changes in jet activity in response.

Sundelius et al. (1997) (see also Valtonen et al. 2009) predicted the expected after-flares of OJ 287 tidally induced by the secondary. Based on their model, we expect major accretion after-flare activity in early January 2020. Identifying their predicted (accretion) peak in January 2020 with the (jet) outburst reported here in April requires a time delay of ~4 months between accretion disk and jet activity, and implies rapid communication between disk and jet. Factors which determine the actual delay between accretion and jet changes include the disk/corona properties and geometry, the magnetic field geometry, and shock formation in the jet (e.g. Marscher et al. 2018; Tchekhovskoy et al. 2014; Valtonen et al. 2019), which are not yet well understood, and we therefore cannot predict delays from first principles, but can compare with other extragalactic systems where delays were observed. Overall, the timescale observed in OJ 287 is consistent with the one seen in stellar tidal disruption events (Komossa & Zensus 2016) where accretion flares are typically followed by detectable radio-jet activity within days (e.g. Zauderer et al. 2011), and with the blazar 3C120 for which Marscher et al. (2002) reported a delay of 0.1 yrs between accretion and radio-jet activity.

4 SUMMARY AND CONCLUSIONS

We have monitored OJ 287 with Swift since December 2015, revealing multiple epochs of high-amplitude optical–X-ray variability. The bright April–June 2020 super-outburst of OJ 287 has one of the densest quasi-simultaneous optical-UV-X-ray coverages obtained so far for this blazar. We also presented the first XMM-Newton and NuSTAR broad-band X-ray spectroscopy of OJ 287 in outburst.

Several X-ray spectral features stand out: First, a steep low-energy component (Γx ~ 2.8) at peak, rarely that soft in blazars but consistent with a synchrotron origin. Across the flare, OJ 287 is softer when brighter, a pattern also seen in our long-term Swift lightcurve. Second, a power-law component detected up to ~ 70 keV (Γx ~ 2.4). Third, signs of reprocessing in the Fe-line region, which may represent a relativistic outflow if confirmed.

We find that the outburst is jet-driven and consistent with a binary SMBH model, where the disk impact of the secondary black hole triggers an after-flare in form of time-delayed accretion activity on the primary which is then followed by an increase in jet emission of the primary ~4 months later.

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