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Multiwavelength astrophysics of the blazar OJ 287 and the project MOMO

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Abstract

We are carrying out the densest and longest multiyear, multiwavelength monitoring project of OJ 287 ever done. The project MOMO (Multiwavelength Observations and Modeling of OJ 287) covers wavelengths from the radio to the high-energy regime. A few selected observations are simultaneous with those of the Event Horizon Telescope (EHT). MOMO aims at understanding disk-jet physics and at testing predictions of the binary black hole scenario of OJ 287. Here, we present a discussion of extreme outburst and minima states in context, and then focus on the recent flux and spectral evolution between 2021 and May 2022, including an ongoing bright radio flare. Further, we show that there is no evidence for precursor flare activity in our optical–UV–X-ray light curves that would be associated with any secondary supermassive black hole (SMBH) disk impact and that was predicted to start as thermal flare on December 23, 2021.

KEYWORDS

AGN, black holes, blazars: Individual (OJ 287), jets, supermassive binary black holes

1 | INTRODUCTION

Blazars are characterized by their powerful, collimated, long-lived jets of relativistic particles that often extend beyond the host galaxies. The jets are launched in the immediate environment of the supermassive black holes (SMBHs) at the blazars' centers (Blandford et al. 2019). The accretion disk—jet interface represents one of the most extreme astrophysical environments where special and general relativistic effects play a major role in shaping the multiwavelength (MWL) radiation of these systems. Hence, blazars are excellent laboratories for understanding matter under strong gravity and the disk-jet coupling.

OJ 287 is a nearby bright blazar of BL Lac type at redshift $z = 0.306$, and highly variable across the electromagnetic spectrum (e.g., Abdollahi et al. 2022; Komossa et al. 2022). During epochs of outbursts (Figure 1) it reveals

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a bright and supersoft X-ray emission component, making it one of the few blazars of its type that has contributions from both the synchrotron and inverse-Compton (IC) emission component present in its X-ray spectrum below 10 keV (Komossa et al. 2020). OJ 287 therefore offers the rare chance of studying the relation of both spectral components simultaneously in single-band observations.

Among the main EHT targets, OJ 287 is the only source observed with XMM-Newton and EHT quasi-simultaneously in 2018 (M87 and SgrA* were unobservable with XMM-Newton at the epochs of EHT observations).

Based on repeated bright optical outbursts in the 1970 s to 1990 s, it was suggested that OJ 287 hosts a binary SMBH (Sillanpää et al. 1988). Different variants of binary SMBH models were then proposed. The amplitude of the brightest optical outbursts of OJ 287 ("main flares" hereafter) decreased in recent years (e.g., Dey et al. 2018; Komossa et al. 2021c; Laine et al. 2020), making it more difficult to distinguish between blazar-driven activity and hypothetical binary-driven activity. A broad wavelength coverage and high-cadence monitoring are therefore important when testing model predictions.

The project MOMO (Multiwavelength Observations and Modeling of OJ 287) was initiated in late 2015 (Komossa et al. 2021c, and references therein). It covers OJ 287 densely from the radio to the X-ray regime in dedicated observations with the Effelsberg telescope (between 1 and 40 GHz) and with the Neil Gehrels Swift observatory (Swift hereafter; in three optical bands, three UV bands, and in the 0.3–10 keV X-ray regime). Public data from the Submillimeter Array SMA (~230 GHz; Gurwell et al. 2007) and the Fermi satellite (0.1–100 GeV; Kocevski et al. 2021) are added. At selected epochs, deep follow-up observations with XMM-Newton and NuSTAR and at other wavebands were taken, including during a few epochs of EHT observations of OJ 287. MOMO provides MWL timing information, spectra, and broad-band spectral energy distributions (SEDs) at all activity states of OJ 287. When new remarkable flux or spectral states of OJ 287 are discovered, the community is alerted rapidly in form of Astronomer's Telegrams (e.g., Komossa et al. 2021).

Previous publications of results from the MOMO project focused on (1) our discovery with Swift of a bright X-ray–UV–optical outburst that started in 2016 (Komossa et al. 2017),(Komossa et al. 2020), (2) our discovery with Swift of a second bright X-ray–UV–optical outburst in 2020 that we followed up with XMM-Newton and NuSTAR (Komossa et al. 2020), (3) a detailed analysis of all XMM-Newton X-ray spectra of OJ 287 including one quasi-simultaneous with EHT (Komossa et al. 2021), (4) a study of the complete Swift optical–UV–X-ray light curve of OJ 287 covering all activity states of this blazar (Komossa et al. 2021c), and (5) selected multi-frequency Effelsberg radio observations of OJ 287 since 2015 (Komossa et al. 2015; Myserlis et al. 2018) (Komossa et al. 2021b)(Komossa et al. 2022).

Here, we discuss the 2016–2020 outbursts (Figure 1) and deep fades of OJ 287 in context. We then focus on the recent MWL flux and spectral evolution between 2021 and May 2022 that includes the detection of the second-brightest radio flare since the start of the MOMO project. Further, we comment on a recent speculation (Valtonen et al. 2021) that a disk impact of a secondary SMBH in OJ 287 might produce detectable precursor flare activity in the optical–UV regime in late 2021 or beyond.

2 | OUTSTANDING FLUX AND SPECTRAL STATES

2.1 | 2016/2017 and 2020 outbursts

With Swift we detected a bright X-ray–UV–optical outburst in 2016–2017 (Komossa et al. 2017) (Komossa et al. 2020). It reached its peak in X-rays in February 2017. These observations motivated a VERITAS (Very Energetic Radiation Imaging Telescope Array System) observation of OJ 287 that was carried out near the X-ray maximum, leading to the first weak detection of VHE (very high energy) emission (> 100 GeV) of OJ 287 at the level of ~ five standard deviations above the background (O'Brien 2017). Surprisingly, in the Fermi γ − ray band, no accompanying sharp flaring activity was observed. MOMO radio observations during this epoch reveal that the X-ray–optical outburst is accompanied by a strong radio outburst in 2016–2017 detected at all frequencies, reaching the highest radio fluxes at high frequencies (up to ~ 11 Jy at 36 GHz in 2017 February) during our ongoing monitoring between 2015 and 2022. All previous and new observations clearly establish non-thermal synchrotron emission as the origin of this radio–X-ray flare.

A second bright outburst was detected during the MOMO observations of OJ 287 in 2020 with Swift. XMM-Newton and NuSTAR follow-ups were triggered and caught OJ 287 while it was still near maximum (Komossa et al. 2020). XMM-Newton observations revealed the extremely soft X-ray spectrum of the outburst (Figure 2). Its synchrotron nature was established through multiple independent arguments including: variability faster than the last stable orbit (assuming an SMBH mass of order 10^{10} $M_\odot$), SED arguments, small optical–UV lags $\leq$ 1d, and the association with radio flaring. Along with BL Lac (e.g., D'Ammando 2022), OJ 287 exhibits the steepest known X-ray spectra among blazars of its kind.

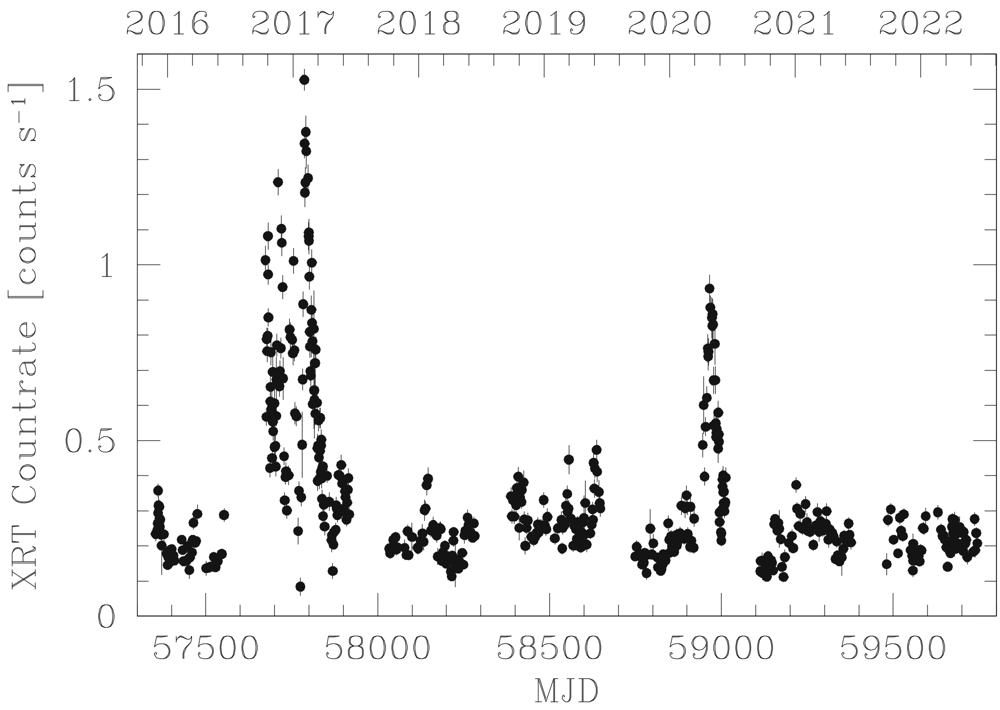

FIGURE 1 Swift X-ray telescope (XRT) light curve of OJ 287 between 2015 December and 2022 May. The large majority of the data were taken in the course of the MOMO program. Bright outbursts were detected in 2016–2017 and 2020 that came with a strong softening of the X-ray spectra

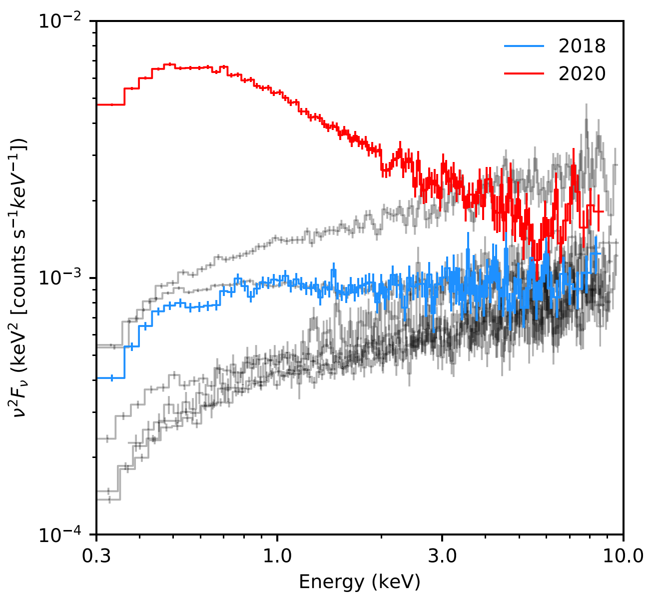

FIGURE 2 All eight XMM-Newton spectra of OJ 287 taken between 2005 and 2020. Most of the time, OJ 287 is in a relatively flat X-ray spectral state. However, during its 2016/2017 outburst (not covered by XMM-Newton but in our Swift observations) and during its 2020 outburst (red color), an additional supersoft spectral component was discovered that is exceptionally steep for blazars. When all the spectra are fit with a double power-law model, the soft X-ray photon index Γ_x ranges between −2.8 in the softest state in 2020, −2.1 in the intermediate state in 2018, and −1.5 in the hardest state in 2005. The XMM-Newton observation obtained quasi-simultaneously with EHT is marked in blue. Adopted from Komossa et al. (2020). OJ 287 was found in an intermediate flux and spectral state at that epoch

The 2016/2017 and 2020 outbursts share some similarities with previous, bright, double-peaked, optical outbursts of OJ 287 in the 1970 s-1990 s (e.g., Sillanpää et al. 1988; Valtaoja et al. 2000), albeit with lower amplitudes. However, they do not match a pattern of approximately constant separation between the double-peaks of approximately 1 year (0.5–2 years; e.g., Valtaoja et al. 2000).

The 2020 outburst timing is consistent within a few months with predictions of an after-flare predicted by a binary SMBH model of OJ 287 (Sundelius et al. 1997). In this model, after-flares are produced when new jet activity is launched following a secondary SMBH impact of the disk around the primary, after the disk disturbance has traveled to the inner disk and the accretion rate changes. However, any such model comes with many assumptions and free parameters, including the physics of the launching of a new jet component, its interactions with the interstellar medium, and the timing when it becomes detectable at multiple frequencies. Alternatively, the 2020 outburst could represent a bright synchrotron flare that is independent of a binary's presence.

2.2 | 2017 deep fade

Most of the time, OJ 287 is highly variable with new (lower-amplitude) flares every 1–4 weeks. However, in 2017 we detected with Swift a long-lasting low-state in form of a symmetric fading and recovery of the UV and optical flux that lasted 2 months (Komossa et al. 2021c), not followed by the X-rays. A previous similar optical deep fade in 1989 was speculated to be perhaps linked to the passing of a secondary SMBH near the jet of the primary SMBH leading to a temporary jet deflection (Takalo et al. 1990). However, using binary model predictions from Valtonen et al. (2021), the system's geometry in 2017 did not match with a secondary SMBH's location in front of the disk of the primary SMBH at the time of the deep fade. An occultation event by a dusty gas cloud can be ruled out as well, given the lack of UV reddening (and the lack of X-ray absorption). A possible explanation is a temporary jet dispersion or deflection in the core region, or in a radio-bright off-center quasi-stationary jet feature (e.g., Hodgson et al. 2017; Zhao et al. 2022) that was interpreted as either a recollimation shock or a region of maximized Doppler factor in a bent jet.

2.3 | Recent MWL flux evolution and the bright ongoing 2021–2022 radio flare

We recorded a strong rise in radio emission in 2021 that peaked in November and then rose again in January (Figure 3 at 36 GHz), keeping high flux levels until at least May 2022. This is the second-brightest radio flare since the start of our monitoring in late 2015. Unlike the bright 2016/2017 outburst, the radio is not immediately accompanied by large, long-lasting flaring activity in the optical–UV band where the overall emission level is very low at least until early January 2022 (Figure 4).

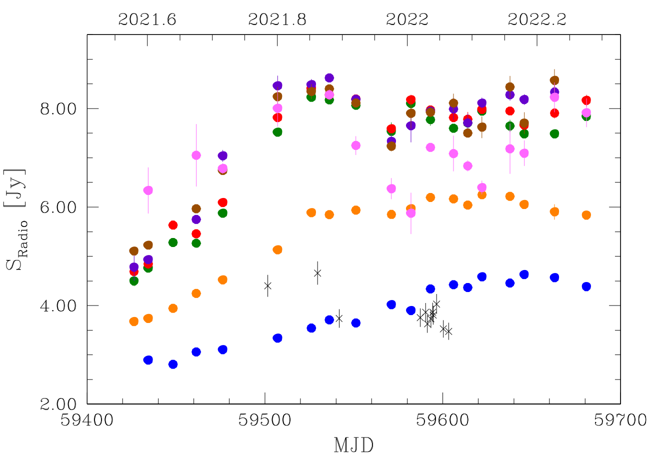

FIGURE 3 Recent Effelsberg radio observations of OJ 287 obtained in the course of the MOMO project between 2021 August and 2022 May. During this time interval, the second-brightest radio flare was recorded since the start of the monitoring program, lasting at least until May (colors: blue: 2.6 GHz, orange: 4.85 GHz, green: 10.45 GHz, red: 14.25 GHz, purple: 19.25 GHz, brown: 24.75 GHz, pink: 36.25 GHz, black crosses: SMA data around 230 GHz)

For the year 2021, the fractional rms variability amplitude $F_{\rm var}$ was computed according to Vaughan et al. (2003) for all radio frequencies between 2.6 and 43.75 GHz, following Komossa et al. (2021c). It ranges between $F_{\rm var} = 0.105 \pm 0.001$ at 2.6 GHz and 0.295 ± 0.019 at 43.75 GHz. The increase of $F_{\rm var}$ with frequency can be traced back to decreasing opacity.

Two short, sharp $\gamma-$ray flares of OJ 287 were detected with Fermi in 2021 October and December; the brightest observed in the last few years (Figure 4). These may be associated with the bright radio flare, matching a pattern reported by (Agudo et al. 2011). On the other hand, the even brighter radio flare of 2016/2017 that was accompanied by the brightest X-ray outburst of OJ 287 so far recorded (Komossa et al. 2020) lacked a bright Fermi $\gamma-$ray counterpart (e.g., Figure A1 of Komossa et al. 2022). These observations strongly suggest multiple $\gamma-$ray emission sites in OJ 287.

3 | RECENT BINARY (PRECURSOR-FLARE) ACTIVITY?

In the context of the binary SMBH scenario, it is conceivable that the interaction of the secondary SMBH with matter of the disk and corona around the primary SMBH contributes emission to the light curve of OJ 287 at selected epochs; for instance, X-ray emission during epochs of gas accretion. It is interesting to search for such events, though it may be challenging to disentangle them from other flaring that goes on in blazars (and OJ 287 in particular) all the time, completely unrelated to any binary's presence. In particular, Pihajoki et al. (2013) and Valtonen et al. (2021) speculated that certain optical lower-amplitude flare activity in the past light curve of OJ 287 that was seen to precede the "main flares" by months was not due to the common blazar variability but was in an unknown fashion related to the binary's presence; for instance through temporary accretion or jet activity of the secondary SMBH, or due to leaky Bremsstrahlung emission from impact-driven streams or bubbles following the secondary's disk crossing. They then further suggested that these flares should repeat at similar epochs before new "main flares" (assuming that the complicated gaseous physics and magnetic fields involved in all these processes repeat in identical fashion during future secondary disk encounters decades later).

We have searched our recent MWL light curve of OJ 287 for any such "precursor flares", and do not find any evidence for these. First, Komossa et al. (2021c) searched for precursor flare activity of the kind suggested by Pihajoki et al. (2013) that was predicted to peak at 2020.96 ±0.1. No sharp flare (increase by ∼ 2 mag) was observed.

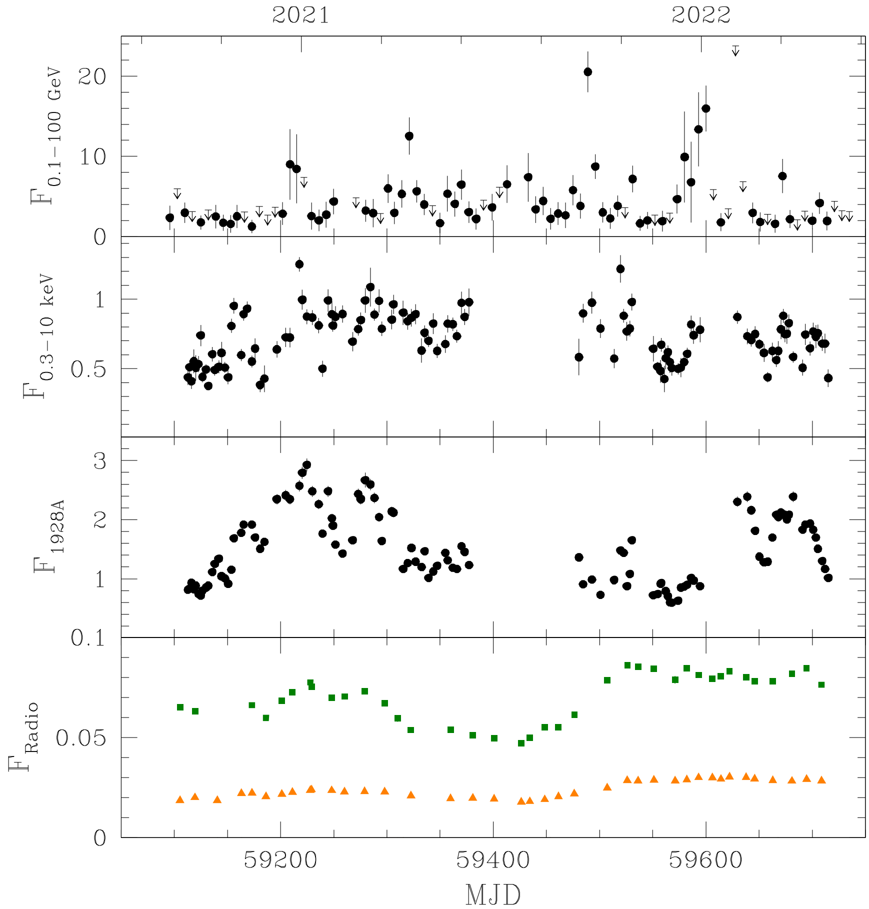

FIGURE 4 MWL flux light curve of OJ 287 between 2020 September and 2022 May. From top to bottom: Fermi γ − rays, Swift X-rays and UV (W2 filter at 1928 Å), and Effelsberg radio observations at selected frequencies (orange triangles: 4.85 GHz, green squares: 10.45 GHz). The γ − ray flux (observed 0.1–100 GeV band; one-week averages), the absorption-corrected X-ray flux (observed 0.3–10 keV band), the extinction-corrected UV flux at $\lambda_{\rm obs} = 1928$ Å, and the radio flux are in units of 10^{-11} erg s^{-1} cm^{-2}. The gap in Swift observations between mid-January to mid-February 2022 is due to a satellite safe mode during which no data were taken. The gap in Swift observations between June to September 2021 is due to the unobservability of OJ 287 with Swift (and from the ground) because of the blazar's close proximity to the Sun. Fermi and Effelsberg observations are not affected by this Sun constraint

Second, Valtonen et al. (2021) speculated that an optical flare seen in the 2005 light curve of OJ 287 was a precursor flare and would repeat in identical fashion, starting on December 23, 2021 with a thermal Bremsstrahlung spectrum in the optical–UV with spectral index $\alpha_\nu \sim -0.2$ (and without any X-ray or radio counterpart; their Section 3). However, we found OJ 287 in a deep optical–UV low-state throughout December 2021 and any optical–UV flaring activity at that time period can be excluded (Figure 4). Further, neither the rise in emission after the deep low-state, nor any other UV–optical flaring activity during the first months of 2022, shows the predicted spectrum of thermal Bremsstrahlung (Figure 5): Observed spectral indices $\alpha_{\nu,\rm opt-UV}$ (defined as $f_\nu \propto \nu^{\alpha_\nu}$, where the optical is measured at $\lambda_{\rm obs} = 5468$ Å and the UV at 1928 Å) range between −1.2 and −1.5 while the predicted thermal spectrum would have had $\alpha_\nu \sim -0.2$.

We also note that the pattern of optical-UV variability in late 2021 to early 2022 is very similar to the one in late 2020 to early 2021 (Figure 4), therefore excluding the possibility that any 2021–2022 flaring activity is driven by non-standard processes that repeated in an identical fashion from 2004 to 2005.

Third, we find, more generally, that none of the low-amplitude flaring activity of OJ 287 in recent years

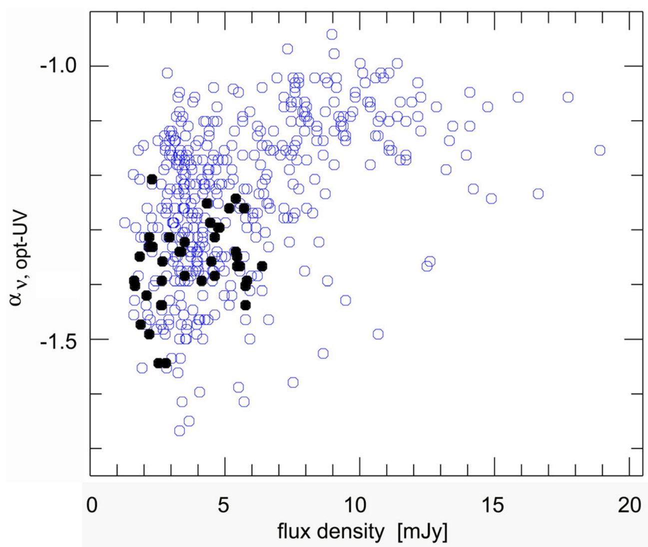

FIGURE 5 Optical–UV power-law spectral index α_ν between 2015 December and 2021 November (open circles), and during the period 2021 December to 2022 May (filled circles). The optical flux density f_V is measured at $\lambda_{\rm obs} = 5468$ Å in units of 10^{-26} erg cm^{-2} s^{-1} Hz^{-1}. OJ 287 displays a "softer-when-brightest" variability pattern. A thermal precursor flare with $\alpha_\nu \sim -0.2$ was predicted to happen in 2021 December. None was detected, neither a flare nor an event with $\alpha_\nu \sim -0.2$. Neither was an event with $\alpha_\nu \sim -0.2$ observed at any other time period

stands out. All of them, in X-rays, the optical and UV, show the spectral and variability properties that we see in a similar way in our long-term light curves of OJ 287 since 2015 (Figure 5; see Komossa et al. 2021c, for our Swift long-term lightcurve). Maximum amplitudes of variability in the optical–UV have been rather constant since 2015, with an amplitude of ~ 1.5 mag in the optical–UV, and variability between 0.1 and 0.5 cts/s in X-rays, with the single exception of the bright flares in 2016/2017 and 2020.

We conclude that there is no positive evidence for any binary-driven precursor flare activity in our Swift light curves. Does this finding falsify this particular variant of the binary SMBH model of OJ 287? It raises some doubts, but because the precursor flares are a more speculative and less-well developed ingredient of the model than the main flares, we do not yet reject the model. The presence or absence of the next predicted main flare (Valtonen et al. 2022) will constitute a very stringent test of this variant of the binary model of OJ 287 (Komossa et al., in prep.).

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