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J1048+7143: Signatures of a Supermassive Binary Black Hole Close to Merger?

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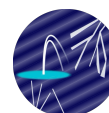
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The blazar J1048+7143 (a.k.a. J1044+71) is a promising candidate for harboring a supermassive binary black hole (SMBBH) inspiral on the verge of merging. Its gamma-ray, optical and radio light curves show consistent quasi-periodic oscillations (QPOs) with a period in the range of ~ 3 years. The flares in gamma rays, optical and infrared consist each of two sub-flares, while in radio, the emission follows a Gaussian-like structure.

Here, we show that the spin-orbit coupling of the leading jet in a SMBBH at the center leads to jet precession, which can produce the observed flaring signatures. Using our jet precession model, we successfully predicted the timing of the last flare observed between 2022 and 2024, whereas a spine-sheath model of the jet explains the different signature in radio compared to the other wavelengths. In this contribution we present the complete multi-wavelength dataset in context of our model that we use to constrain the mass ratio on the SMBBH, allowing a prediction of the merger time, which will happen in $\sim 17 - 37$ years. In addition, we model the characteristic strain of its expected gravitational wave emission until the time of the merger.

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1. Introduction

Blazars are among the most powerful objects in the Universe. They are characterized by a central supermassive black hole (SMBH) reaching up to billions of solar masses, which launches a relativistic jet in the line of sight direction of Earth. The observed signal is highly variable, with variabilities ranging from days to years. Repeating flaring signatures of such a blazar can be caused by a variety of effects like the lighthouse effect [1] or pulsation accretion flow instabilities [2]. Are these quasi-periodic oscillations (QPOs) appearing on scales of years and are constant or decreasing with time, then they could reveal an ongoing inspiral of a supermassive binary black hole (SMBBH) at the blazar center (see e.g. [3]).

In [4], a QPO with a period of 3.06 ± 0.43 yrs was found in the gamma-ray light curve of the flat spectrum radio quasar (FSRQ) J1048+7143 at a significance level of $\sim 3.6\sigma$. In [5], a jet precession model, which explains quasi-periodic signatures with the spin-orbit coupling of the leading jet, was applied to the gamma-ray light curve of J1048+7143, covering the first three main-flares only. This work predicted the timing of the fourth flare. In [6], it was shown that the occurrence of the fourth flare in gamma rays aligned with the predicted time by the jet precession model.

Here, we expand the multi-messenger picture of J1048+7143 by adding optical data and radio data covering the last three main-flares observed in gamma-rays and apply the jet precession model to the flare characteristics derived from both additional light curves.

2. Light curves

2.1 Gamma rays

The gamma-ray light curve of 4FGL J1048+7143 was generated using archival data taken with the Large Area Telescope (LAT) instrument onboard the Fermi Gamma-ray Space Telescope around the coordinates $RA_{J2000} = 162.1067^\circ$, $DEC_{J2000} = 71.7297^\circ$ [7]. Here, we analyzed 16 years of Fermi-LAT data in the time range 2008 Aug 4 – 2024 Aug 22 and energy range 100 MeV – 800 GeV. Analogously to [5] and [6], a binned likelihood analysis of the data was performed using the `fermipy` v1.0.1 and `ScienceTools` v2.0.8 packages (see [5] for technical details). We applied adaptive binning with a relative flux error threshold of 5% and an energy cut at 168 MeV to ensure that no background photons from the Galactic and extragalactic backgrounds are accidentally captured. The gamma-ray photon flux of J1048+7143 is plotted as a function of time in the top panel of Fig. 1.

2.2 Optical

The optical light curve was generated using V-band and g-band data collected with the All-Sky Automated Survey for Supernovae (ASAS-SN), which consists of 24 telescopes distributed around the world [8, 9]. The V-band data covers the time range from 2014 Jan 25 – 2018 Nov 13 and the g-band from 2017 Dec 16 to 2023 Apr 19. In addition, the V-band data collected by the American Association of Variable Star Observers (AAVSO, [10]) in the time range 2016 June 1 – 2023 Jul 7 was added to the light curve.

The combined data set was binned into 20 days to smooth out short-time variations. The optical flux of J1048+7143 is plotted as a function of time in the middle panel of Fig. 1.

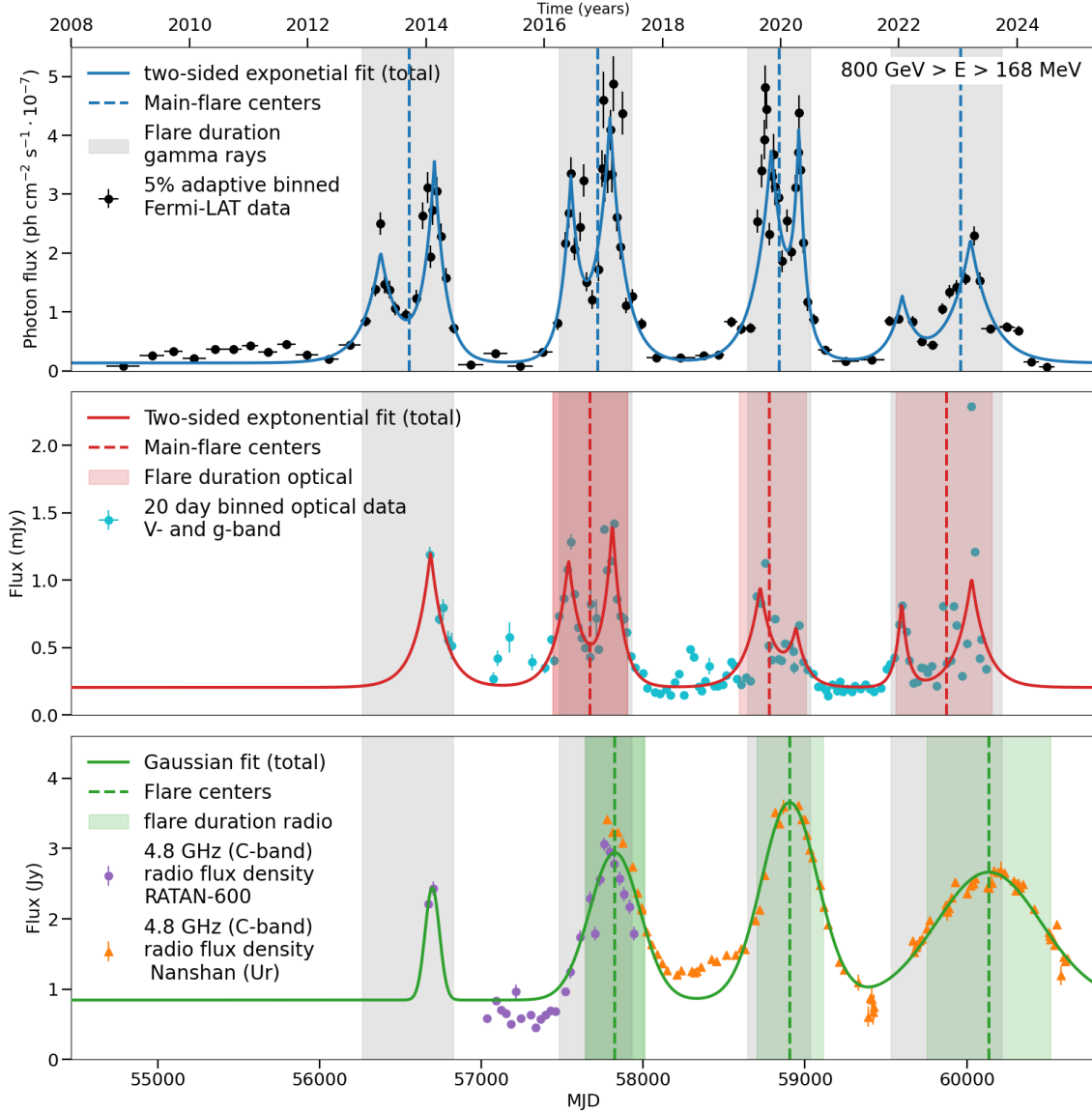


Figure 1: Gamma-ray, optical and radio light curves of J1048+7143. Top: 5% adaptively binned Fermi-LAT gamma-ray light curve (black). Each sub-flare was fitted by a two-sided exponential function. The blue continuous line displays the sum of these fits and together with the baseline. Grey areas show the duration of each main-flare determined with the centroid method and the blue dashed vertical lines show the position of the main-flare centers. Middle: Combined 20-day binned optical light curve in the V- and b-bands (cyan). Analogous to the gamma-ray light curve, the sub-flares were fitted by two-sided exponential functions. The sum of baseline and the fits is shown as the red continuous line. Red areas display the flare durations of the main-flares, determined with the centroid method and red dashed vertical lines show the position of the main-flare centers. Bottom: Radio flux density in the C-band as a function of time. Each flare is fitted by a Gaussian fit. The sum of the contributions is shown as the green continuous line. Green areas show the flare durations in radio and the green dashed vertical lines show the position of the flare centers. Grey areas in the middle and bottom panels show the flare durations determined in gamma rays as comparison.

Table 1: Fit parameters of the gamma-ray, optical and radio light curves of J1048+7143. First column describes the parameter (see text). The columns $F_{i,j}$ corresponds to the j -th ($j=1$ or $j=2$) of the i -th main flare (from 1 to 4). The fitted baseline is $a_0 = (0.13 \pm 0.02) \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}$ for the gamma-ray, $a_0 = (0.21 \pm 0.03) \text{ mJy}$ for the optical and $a_0 = (0.85 \pm 0.06) \text{ Jy}$ for the radio light curve.

Parameter	$F_{1,1}$	$F_{1,2}$	$F_{2,1}$	$F_{2,2}$	$F_{3,1}$	$F_{3,2}$	$F_{4,1}$	$F_{4,2}$
Gamma rays ($\chi^2_{\text{red}} \approx 9$)								
$a (\times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1})$	1.86 ± 0.24	3.35 ± 0.38	2.92 ± 0.39	4.15 ± 0.36	3.62 ± 0.27	3.39 ± 0.41	1.06 ± 0.36	2.11 ± 0.23
b (MJD, days)	56378 ± 10	56710 ± 6	57553 ± 6	57795 ± 6	58792 ± 7	58963 ± 3	59601 ± 17	60023 ± 10
c (days)	111 ± 20	70 ± 10	58 ± 12	91 ± 10	105 ± 11	38 ± 7	81 ± 29	130 ± 19
Optical ($\chi^2_{\text{red}} \approx 183$)								
a (mJy)	–	1.01 ± 1.50	0.94 ± 0.25	1.20 ± 0.27	0.75 ± 0.08	0.39 ± 0.23	0.64 ± 0.23	0.82 ± 0.17
b (MJD, days)	–	56687 ± 125	57539 ± 14	57810 ± 10	58723 ± 9	58945 ± 25	59598 ± 10	60030 ± 13
c (days)	–	92 ± 337	84 ± 43	61 ± 18	90 ± 28	62 ± 42	40 ± 19	93 ± 36
Radio ($\chi^2_{\text{red}} \approx 120$)								
	F_1		F_2		F_3		F_4	
a (Jy)	1.60 ± 0.21		2.10 ± 0.09		2.81 ± 0.11		1.82 ± 0.08	
b (MJD, days)	56697 ± 12		57825 ± 8		58905 ± 7		60136 ± 14	
c (days)	45 ± 5		156 ± 10		174 ± 9		324 ± 18	

2.3 Radio

For the radio light curve, we show the RATAN-600 C-band data as described in [5] covering the time range between 2014 Jan 15 and 2017 July 10. The Nanshan (Ur) C-band was expanded compared to the data set in [6] and now contains data in the time range 2017 Jan 24 – 2024 Nov 5. The radio flux density of J1048+7143 is plotted as a function of time in the bottom panel of Fig. 1.

3. Multi-Wavelength Analysis of J1048+7143

As was shown in [5] and [6], the gamma-ray light curve of J1048+7143 consists of four main-flares, each made up by two sub-flares and separated by quiescent phases. In the following, the main-flare is meant when *flare* is mentioned. The sub-flares were fitted with two-sided exponential functions in the form of

$$F_{i,j}(t) = a_0 + a_{i,j} \times \exp \left[\frac{-|t - b_{i,j}|}{c_{i,j}} \right], \quad (1)$$

with t being the time. The index i describes the main flares and runs from 1 to 4, while j is 1 or 2 for the sub-flares of the i -th main flare. The baseline is measured by a_0 , the height by $a_{i,j}$, the location of the peak by $b_{i,j}$, and the slope of the exponential function by $c_{i,j}$. The resulting fit parameters (for the updated gamma-ray light curve shown) are displayed in Table 1.

We used the centroid method (for a thorough discussion of the method, see [5]) to determine the centers and durations of the main-flares. The main-flare centers were determined in MJD as 56555 ± 25 , 57720 ± 15 , 58834 ± 10 and 59925 ± 42 , while the durations were determined in days as 564 ± 50 , 450 ± 31 , 387 ± 31 and 685 ± 72 . The main-flare centers are marked as vertical, dashed blue lines and durations as gray areas in Fig. 1.

We define the time elapsed between each main flare as the time elapsed between consecutive main-flare centers. They are shown in Table 2 as $P_{i \rightarrow (i+1)}$ for the time between main-flare i and next main flare $i + 1$.

Since the flares in the optical light curve resemble the ones in the gamma-ray light curve, we apply the same fitting of the sub-flares (Eq. 1). This delivered a better description of the data ($\chi_{\text{red}}^2 \approx 183$) than a fitting of main-flares with one exponential function (instead of two, $\chi_{\text{red}}^2 \approx 261$) or a Gaussian function ($\chi_{\text{red}}^2 \approx 275$). The fit parameters are shown in Table 1. Since the data partly cover the first main-flare between 2013 and 2014, only the sub-flare $F_{1,2}$ could be fitted and, as seen in Table 1, the fit describes this flare not sufficiently. This is why only the other 3 main-flares are considered in the further analysis.

Analogously to the gamma-ray light curve, we apply the centroid method and obtain the flare centers starting from the second main-flares in MJD as 57671 ± 47 , 58778 ± 42 and 59874 ± 51 (vertical, dashed red lines in Fig. 1). The flare durations of these main-flares are determined in days as 474 ± 94 , 416 ± 65 and 594 ± 53 , and shown as red areas in Fig. 1. As is seen, the fourth main-flare probably continues longer than covered by the time range of the optical light curve. Comparing the starts of the optical main-flare with the starts in gamma-rays (in gray), it is also noticeable that, for the second and third main-flare, the optical flares begin earlier than the flare in gamma-rays. This time shift is not observed for the fourth main flare, but could be caused by the limited data set after the fourth flare and could change with more data.

Unlike the other light curves, the radio light curve does not indicate main-flares consisting of two sub-flares, but has rather a single peak. This is why the flares were fitted by a Gaussian fit:

$$F_i(t) = a_0 + a_i \times \exp \left[\frac{-(t - b_i)^2}{2 c_i^2} \right]. \quad (2)$$

The parameters are the same as in Eq. (1), except that no parameter j is needed, and the parameter c_i describes the standard deviation here. The fit parameters are shown in Table 1.

The flare centers are described by the row b in Table 1 and are shown in Fig. 1 as vertical, dashed green lines. However, since only two data points were available at the time of the first flare, its fit parameters are shown here, but the flare is omitted in the further discussion. The flare durations were determined by calculating the full width at half maximum (FWHM) and determining the crossing of the fitted light curve with a parallel line at the FWHM for each flare, respectively. The values in days starting from the second flare are 367 ± 24 , 410 ± 21 , and 762 ± 42 , and are shown as green areas in Fig. 1. Comparing them with the main-flare durations in gamma-rays shows that the radio flares are following the gamma-ray flare in time.

4. Spin-Orbit precession of the Jet

Quasi-periodic flaring emissions as seen in the light curves in Fig. 1 can be caused by the spin-orbit precession of the leading jet in a SMBBH system. This precession is caused by the realignment of the SMBH spins and thus change in jet directions due to gravitationla wave (GW) emission. We use the jet precession model presented in [5], which describes the directional angle of the leading spin, ϕ , as a function of the time remaining until the binary merger, ΔT_{GW} :

$$\phi(\Delta T_{\text{GW}}, q) = -\frac{2(4+3q)}{(1+q)^2} \left(\frac{5c}{32 G^{1/3} M^{1/3}} \cdot \frac{(1+q)^2}{q} \right)^{3/4} (\Delta T_{\text{GW}})^{1/4} + \psi. \quad (3)$$

Here, q is the mass ratio, defined as $q = m_2/m_1 < 1$ with the masses of the SMBHs m_1 and m_2 and the total mass $M = m_1 + m_2$. The parameter G is the gravitational constant, c the speed of light, and ψ an integration constant, which describes the direction of the jet at the beginning of the inspiral stage, during which most of the orbital energy of the system is removed via GWs.

If the jet pointing multiple times at Earth, then the following connection can be established:

$$\phi(\Delta T_{\text{GW}}, M, q) = \phi(\Delta T_{\text{GW}} - P_{i \rightarrow (i+1)}, M, q) \pm \zeta, \quad (4)$$

with $P_{i \rightarrow (i+1)}$ the time interval between the flare i and consecutive flare $i + 1$ and the half-opening angle of the jet ζ . So the time remaining until the coalescence of the binary decreases by the complete spin-orbit precession period, which is $P_{i \rightarrow (i+1)}$.

Inserting Eq. (3) into Eq. (4) and utilizing a total mass of $10^{9.16 \pm 0.2} M_\odot$ [11], ΔT_{GW} can be determined in dependence of the mass ratio q . By inserting the value for the time until merger in Eq. (4), another unknown period $P_{(i+1) \rightarrow (i+2)}$ between the flares $i + 1$ and $i + 2$ can be determined by subtracting it from ΔT_{GW} on the right side of Eq. (4) and solving the equation. This way, predictions for the next periods, and thus flares, can be made and it can be tested whether a flare is explainable by the jet precession model in dependence of the mass ratio (if the whole flare is inside the predicted region for a mass ratio range). One consequence of this model is, due to the continuous realignment of the jet direction in the direction of the total angular momentum, that the time intervals between the flares decrease the closer the SMBBH gets to merger.

The time intervals (or periods) determined between the main-flares as described in Sec. 3 are shown in Table 2. While for the gamma-ray and optical light curves, a slight decrease of the period is possible inside the error bars (a linear fitting to the gamma-ray periods results in a slope of -0.11 ± 0.03 yrs, but a fitting of two periods in optical is redundant), in radio it seems that the periods between the flares increase (see $P_{2 \rightarrow 3}$ and $P_{3 \rightarrow 4}$). However, this behavior might result from the longer duration of the fourth flare, as seen in all wavelengths, in combination with the different fitting of the radio light curve compared to the other wavelengths. If comparing the timings between the beginnings of the radio flares, instead of the flare centers, we obtain a similar behavior as with gamma-ray and optical flares (in yrs): 2.90 ± 0.05 between the start of flare 2 and 3 and 2.89 ± 0.08 between the start of flare 3 and 4.

In [6], utilizing all 4 main-flares of the gamma-ray light curve, it was shown that, in order to agree with the jet precession model, the mass ratio of the SMBBH must lie between $0.062 < q < 0.088$. Here, we apply this model to the last 3 main-flares of the optical and radio light curves and can put upper limits to the mass ratio q in these wavelengths. Using the same half opening angle of $\zeta = 8.3^\circ$ as for the gamma-ray predictions (see [6]), we receive $q \leq 0.19$ with optical data. For radio data, we use $\zeta = 20^\circ$, as the half-opening angle is expected to be larger in radio than in other wavelengths, and receive $q \leq 0.10$. Since the mass ratio ranges received overlap among the wavelengths, all light curves shown are in agreement with a SMBBH origin caused by jet precession. We note that these results are dependent on the half-opening angle and the flare duration assumed in the initial conditions, and serve to showcase that the jet precession model agrees among all wavelengths.

Following the tightest mass ratio constraint from the gamma-ray flux, the merger of the SMBBH will happen between 2042 Oct 30 and 2062 Dec 9 (see left side of Fig. 2).

Table 2: Time intervals between successive flare centers using the centroid method (gamma-ray and optical light curve) or Gaussian fitting (radio light curve).

Wavelength	$P_{1 \rightarrow 2}$ (yrs)	$P_{2 \rightarrow 3}$ (yrs)	$P_{3 \rightarrow 4}$ (yrs)
gamma rays	3.19 ± 0.08	3.05 ± 0.05	2.99 ± 0.12
optical		3.03 ± 0.17	3.00 ± 0.18
radio		2.96 ± 0.03	3.37 ± 0.04

5. Expected Gravitational Wave Signal

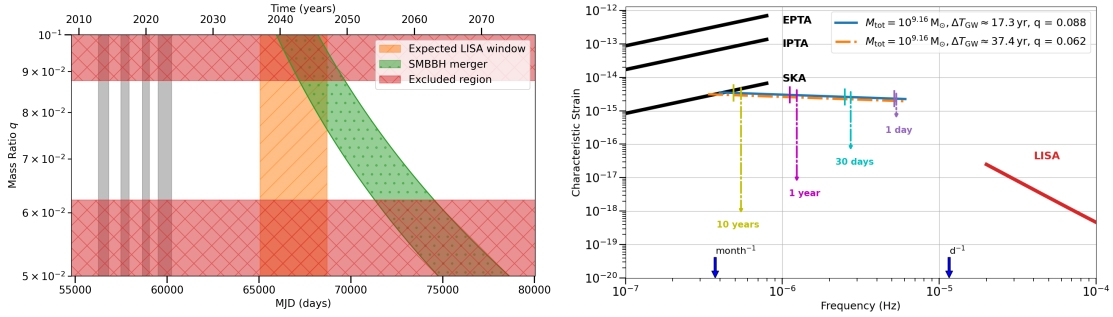


Figure 2: Left: Time of the merger in case of a SMBBH at the core of J1048+7143 as a function of its mass ratio q . Red areas mark the excluded mass ratios based on the occurrence of the gamma-ray main-flares (gray areas). Orange area show an assumed LISA observational window set between 2037 and 2047. Right: Expected gravitational wave signals from J1048+7143. The blue solid and orange dashed-dotted lines show the expected characteristic strain with the mass ratios $q = 0.088$ and $q = 0.062$, respectively. Vertical solid ($q = 0.088$) and dashed-dotted ($q = 0.062$) lines indicate the respective gravitational wave frequency emitted and characteristic strain induced at the respective time prior to merger. Red line shows the sensitivity curve of LISA [12], while the black lines show the sensitivity curves from the detectors SKA, IPTA and EPTA [13].

With the mass ratio further constrained compared to [5] in case of a SMBBH inspiral at the center of J1048+7143, we update the expected characteristic strain h_c . For this, we model it analogously to [5]. The expected characteristic strain is shown on the right side of Fig. 2 for the mass ratios $q = 0.062$ (blue solid line) and $q = 0.088$ (orange dashed-dotted line). These lines represent the evolution of the characteristic strain and GW frequency emitted with time: The left edge represents both on 2025 Jul 1, with a distance of $6.9 M_S$ ($q = 0.088$) and $7.8 M_S$ ($q = 0.062$), respectively, M_S being the Schwarzschild radius. After the time until merger passes, indicated in the legend, the binary reaches the innermost stable circular orbit (ISCO), which is represented by the right edge of the lines. The sensitivity curves of some PTAs and the Laser Interferometer Space Antenna (LISA) are also shown in this figure to indicate that no currently planned GW observatory will be able to detect J1048+7143 in GWs.

6. Conclusions

We show that the flaring behavior of J1048+7143 in the gamma-ray, optical and radio light curves agrees with a SMBBH origin caused by a jet precession due to spin-orbit coupling of the leading jet. Due to a more complete data set in gamma rays, the mass ratio is most severely constrained using flare characteristics inferred from this wavelength and lies inside the larger range of mass ratios determined with the optical and radio flare characteristics.

In addition, the light curves of all wavelengths show agreement with a spine-sheath model of the jet in combination with a target along our line of sight (e.g. broad-line region cloud), which the jet quasi-periodically crosses: In such a model, the sheath is mostly made up of protons, electrons and positrons, while the spine consists of electrons and positrons only. Whenever the sheath interacts with the target, we see sub-flares in the gamma-ray flux as a result of p-p and p- γ interactions, and, at the same time, an optical flaring. The synchrotron radiation from electrons in the sheath creates the raising (or falling) radio flux. When the proton-less spine hits the target, the gamma-ray and optical main-flares reach a minimum due to the lack of p-p and p- γ interactions, while the electron synchrotron radiation reaches a peak due to the jet reaching the smallest inclination angle to the line of sight and thus the largest Doppler boost towards the observer.

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