

The FAST Galactic Plane Pulsar Snapshot Survey. VIII. 116 Binary Pulsars Postprint

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Abstract

Finding pulsars in binaries is important for measurements of the masses of neutron stars (NSs), for tests of gravity theories, and for studies of star evolution. We are carrying out the Galactic Plane Pulsar Snapshot survey (GPPS) by using the Five-hundred-meter Aperture Spherical radio Telescope (FAST). Here we present the Keplerian parameters for 116 newly discovered pulsars in the FAST GPPS survey and obtain timing solutions for 29 pulsars. Companions of these pulsars are He white dwarfs (WDs), CO/ONe WDs, NSs, main sequence stars and ultra light objects or even planets. Our observations uncover eclipses of eight binary systems. The optical counterpart for the companion of PSR J1908+1036 is identified. The Post-Keplerian parameter $\dot{\gamma}$ for the double NS systems PSR J0528+3529 and J1844-0128 have been measured, with which the total masses of the binary systems are determined.

Full Text

Preamble

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Black Hole Mass and Optical Radiation Mechanism of the Tidal Disruption Event AT 2023clx

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Abstract

We present the optical light curves of the tidal disruption event AT 2023clx in the declining phase, observed with Mephisto. Combining our light curve with ASAS-SN and ATLAS data from the rising phase and fitting the composite multi-band light curves with MOSFiT, we estimate the black hole mass for AT 2023clx to be between $10^{5.67}$ and $10^{5.82}M_{\odot}$. This event may be caused by either a full disruption of a $0.1M_{\odot}$ star or a partial disruption of a $0.99M_{\odot}$ star, depending on the data adopted for the rising phase. Based on these fit results and the non-detection of soft X-ray photons in the first 90 days, we propose that the observed optical radiation is powered by stream-stream collision. We speculate that soft X-ray photons may gradually emerge 100–600 days after the optical peak, when the debris is fully circularized into a compact accretion disk.

Key words: galaxies: nuclei –(galaxies:) quasars: supermassive black holes – radiation mechanisms: thermal

1. Introduction

A star that comes too close to a supermassive black hole (SMBH) shall be disrupted by the overwhelming tidal force from the SMBH, causing a tidal disruption event (TDE). Such an event gives rise to a flare that can last from months to years (Rees 1988). TDEs can occur around black holes (BHs) of any mass, making them promising probes for detecting SMBHs residing in the centers of galaxies and putative intermediate-mass black holes (IMBHs) in dwarf galaxies and globular clusters (see, for example, Lin et al. 2018 for a possible TDE that occurred around an IMBH). The critical distance to the SMBH for destroying a star is on the order of a few to tens of gravitational radii, $r_g = GM_{\text{BH}}/c^2$, where G , M_{BH} , and c are the gravitational constant, BH mass, and speed of light, respectively. Since a TDE and the subsequent accretion process happen so close to the SMBH, they are suitable for probing the properties of the SMBH (especially its mass) and accretion physics.

To fulfill this purpose, various tools have been developed and published to the community. Most notable are the Modular Open Source Fitter for Transients (MOSFiT) (Guillochon et al. 2018; Mockler et al. 2019), TiDE (Kovács-Stermeczky & Vinkó 2023a), and TDEmass (Ryu et al. 2020). MOSFiT and TiDE work with multiband light curves (mainly in ultraviolet (UV)/optical

bands), while TDEmass uses the peak bolometric luminosity and the associated effective temperature. These three codes are based on different physical models and assumptions: MOSFiT adopts a luminosity-dependent photosphere with blackbody spectral energy distribution (SED) (detailed in Section 3.1); TiDE adopts an accretion disk and reprocessing layer (RL) as the source of the emissions; TDEmass assumes that optical/UV photons are emitted from the stream-stream collision region. Therefore, the three codes may report different values for the SMBH mass and stellar mass, though they are in agreement in terms of order of magnitude (see, e.g., the comparison done by Kovács-Stermeczky & Vinkó 2023b; Hammerstein et al. 2023). Zhou et al. (2021) proposed another method to compute the SMBH mass, based on the eccentric accretion disk model developed by Liu et al. (2021), taking the total emitted energy and the peak bolometric luminosity as input. Zhou et al. (2021) demonstrated that their results are in good agreement with the SMBH mass estimated from the $M_{\text{BH}}-\sigma_*$ relation, though the code is currently unavailable to the public.

In the last decade, the number of (candidate and confirmed) TDEs has accumulated at a pace of roughly 2 per year (Graham et al. 2019), with most discovered in the optical band thanks to ground-based optical surveys. The discovery rate was pushed up to a few dozen per year by the Zwicky Transient Facility (ZTF; Bellm et al. 2019) and will be further boosted with upcoming survey facilities, such as the Legacy Survey of Space and Time (LSST) at the Vera Rubin Observatory (VRO) (Ivezić et al. 2019).

Yunnan University built the Multi-channel Photometric Survey Telescope (Mephisto) in September 2022, located at Lijiang Observatory, Yunnan, China, at longitude 26°41'42" North and altitude 3200 m. The telescope has a 1.6 m primary mirror and covers a field-of-view (FOV) of 2° in diameter. It is capable of imaging the same FOV in three optical bands simultaneously and delivering real-time, high-quality colors of unprecedented accuracy for surveyed celestial objects. The 2° FOV, in cooperation with the 3-channel simultaneous exposure, makes its survey efficiency competitive with other survey telescopes. Mephisto is currently equipped with two commercial Oxford Instruments/Andor Technology iKon-XXL single-chip CCD cameras for the blue and yellow channels, allowing imaging with uv and gr filters, respectively. Each camera employs an e2v CCD231-C6 6144 × 6160 sensor with a pixel size of 15 μm (corresponding to 0.429" projected on the sky) and covers an area of about a quarter of the full FOV. Mephisto is equipped with six optical filters, implemented in blue (uv), yellow (gr), and red (iz) channels.

In this paper, we present the light curve of AT 2023clx, a TDE that took place in the nucleus of the galaxy NGC 3799, obtained with Mephisto. There is no previous information about the central SMBH mass of NGC 3799, except for the value recently reported by Zhu et al. (2023) via the empirical relationship between BH mass and galaxy mass. Hence, AT 2023clx provided a unique opportunity to measure the central SMBH mass in NGC 3799. The observations and data reduction process are described in Section 2. We briefly introduce

the light curve modeling of MOSFiT, which is used in this work to extract the physical parameters of AT 2023clx (Section 3). The fitting results are presented in Section 4.1. Based on the fitted BH mass, stellar mass, and observed optical penetration factor, we explain that emissions are powered by stream-stream collision (Section 4.2), and accordingly address the reason for the non-detection of soft X-ray photons during the observed optical flare stage (Section 4.3). Finally, we summarize our work in Section 5.

2. Observations and Data Reduction

2.1 Mephisto Data

AT 2023clx was first detected by the All Sky Automated Survey for SuperNovae (ASAS-SN; Shappee et al. 2014) on 2023 February 22. We performed the first follow-up observation in the u , v band on February 24. The observation was then interrupted for 2 days due to the installation of the yellow channel camera. Taguchi et al. (2023) took an optical spectrum on February 26; the bluish continuum and broad Balmer emission lines led the authors to suspect that this event might be a TDE. After completing the yellow channel camera installation, we immediately resumed follow-up observations. However, the yellow channel camera suffered from hardware problems and was replaced with the red channel camera on March 10. Since then, Mephisto worked in two-channel mode, with only the blue and yellow channel cameras operating.

Whenever weather and observation conditions permitted, we performed exposures in the $uvgr$ bands on the same night. The observation campaign ended in June when the rainy season began.

The optical light curve was obtained by performing point-spread function (PSF) photometry on difference images. As a first step, reference images were selected from the observational database. Then image subtraction between the PSF-convolved science and reference images, along with PSF photometry on the difference images, was performed with the Python package Photutils. The corresponding PSF models were constructed with PSFEx, which uses star profiles selected from science and reference images.

Mephisto is a newly built telescope, so this was the first time we obtained images of NGC 3799, which caused some problems in selecting appropriate reference images. Since the TDE fades with time, we used the latest images from the observation campaign as reference images (ug : June 4; vr : June 1). However, the TDE was not completely faded in these reference images, and the difference flux f_{diff} obtained from PSF photometry is lower than the true flux. The intrinsic flux of the TDE in the reference image, f_{ref} , should be added to f_{diff} to obtain the real flux. To estimate f_{ref} in the reference images in the $uvgr$ bands, we used the bolometric luminosity ($L_{\text{bol}} = 10^{41.5} \text{ erg s}^{-1}$) and effective temperature ($T_{\text{eff}} = 12,500 \text{ K}$) near MJD 60100 reported by Zhu et al. (2023).

Finally, the multiband light curves were corrected for galactic extinction with

$E(B - V) = 0.027$ mag (Schlegel et al. 1998; Schlafly & Finkbeiner 2011). The galactic extinctions in each band are 0.133 mag (u band), 0.124 mag (v band), 0.087 mag (g band), and 0.072 mag (r band).

2.2 Pre-peak Data

The rising part of the light curve is critical for constraining the SMBH mass (Mockler et al. 2019). Although we began observing AT 2023clx immediately after receiving the notification from TNS, the rising part of the light curve was still missed. Fortunately, pre-peak observations were available from ASAS-SN and the Asteroid Terrestrial impact Last Alert System (ATLAS; Tonry et al. 2018; Smith et al. 2020). We retrieved the host-subtracted g band light curve from the ASAS-SN Sky Patrol photometry pipeline (Shappee et al. 2014; Kochanek et al. 2017) and the c , o band light curve from the ATLAS forced photometry service. For the purpose of constraining the starting time and rising part of the light curve, we only use the ASAS-SN and ATLAS data before MJD 60000.

The full multiband light curves of AT 2023clx are presented in Figure 2 [Figure 2: see original paper], together with the mock light curves generated from the fitting results (details are in Section 4.1). Initially, we used both the available ASAS-SN and ATLAS data but found some inconsistency in the apparent peak time between them. We therefore constructed four groups of composite light curves, each with different data sources for the rising phase: AS (ASAS-SN g band only), ATc (ATLAS c band only), AS+ATc (ASAS-SN g band + ATLAS c band), and AS+ATco (ASAS-SN g band + ATLAS c , o bands).

Charalampopoulos et al. (2024) and Hoogendam et al. (2024) also used MOSFiT to fit the light curve of AT 2023clx.

2.3 Historical Variability in the Nuclear Region of NGC 3799

NGC 3799, the host galaxy of AT 2023clx, is classified as a LINER galaxy, so the nucleus may exhibit some low-level activity. The g , r band light curves presented by the ALeRCE ZTF Explorer showed many spikes in the past. By visual inspection of the scientific images available in the NASA/IPAC Infrared Science Archive (IRSA), we found that the quality of the images corresponding to these spikes is usually poor. To exclude the possibility that AT 2023clx is an AGN flare, we retrieved the pre-flare ZTF g and r band images from IRSA. These ZTF images cover roughly 5 years before AT 2023clx and were selected based on the following criteria: airmass less than 1.5 and limiting magnitude greater than 20 mag.

The earliest images available in the database were used as reference images in each ZTF band. The difference fluxes f_{diff} in later exposures relative to the reference image were measured by performing PSF photometry on the difference images. The fluxes of the nuclei in the reference images f_{base} were obtained via aperture photometry with a diameter of 3 .

Figure 1 [Figure 1: see original paper] shows the historical light curve of the nucleus of NGC 3799, with the apparent magnitude computed by $m = -2.5 \log_{10}[(f_{\text{base}} + f_{\text{diff}})/\text{ZP}]$, where ZP is the photometric zero-point recorded in the header of the reference FITS file. The temporal variations of g and r magnitude are smaller than 0.05 mag in the last five years. For comparison, the brightness of the nuclear region increased by a maximum of 0.3 mag above the quiescent level during the flare. Thus AT 2023clx is unlikely to be caused or affected by AGN activity.

3. Light Curve Fitting

Many valuable pieces of information are encoded in the light curve of a TDE. In particular, we are interested in the mass of the disrupting SMBH and the mass of the disrupted star. As mentioned in Section 1, there are three open-source software packages that can determine the BH mass from the light curve. TDEmass requires the peak luminosity and the associated effective temperature; unfortunately, we did not catch the peak of the light curve. We therefore turn to MOSFiT, which generates Monte Carlo ensembles of a semi-analytical light curve, fits them to the observed data using Bayesian inference, and obtains parameter posteriors. It has been used in many studies (Mockler et al. 2019; Gomez et al. 2020; Nicholl et al. 2020; Mockler & Ramirez-Ruiz 2021; Hammerstein et al. 2023).

3.1 Light Curve Modeling in MOSFiT

In this subsection, we briefly describe the key parameters involved in the light curve model; more details can be found in Mockler et al. (2019).

The modeling starts with the mass fallback rate \dot{M}_{fb} measured from hydrodynamic simulations (Guillochon & Ramirez-Ruiz 2013). In this model, the mass fallback rate is determined by three key parameters: the SMBH mass M_{BH} , the stellar mass m_* , and the penetration factor β . Guillochon & Ramirez-Ruiz (2013) adopted two polytropic stellar models: $\gamma = 4/3$ (suitable for $1M_{\odot} \lesssim m_* \lesssim 15M_{\odot}$) and $\gamma = 5/3$ (suitable for $m_* \lesssim 0.3M_{\odot}$ and $m_* \gtrsim 22M_{\odot}$). In the other parts of the mass ranges, a hybrid fallback function is adopted, constructed as a linear combination of the $\gamma = 4/3$ and $\gamma = 5/3$ fallback functions; the fractional contributions from the two γ models are determined by the stellar mass.

The penetration factor β is defined as the ratio between the tidal radius r_t and the pericenter distance r_p . For simplicity, the tidal radius is computed by $r_t \approx r_*(M_{\text{BH}}/m_*)^{1/3}$, where r_* is the stellar radius. One can regard β as a proxy for the strength of the tidal field; i.e., higher β means the orbital pericenter is closer to the event horizon and more stellar mass shall be stripped from the star. Hence the amount of stripped mass depends on β .

Guillochon & Ramirez-Ruiz (2013) found that mass stripping starts at β_p and

full disruption happens at β_d . Accordingly, TDEs can be divided into two categories: partial ($\beta_p \leq \beta < \beta_d$) and full ($\beta \geq \beta_d$) TDEs. Note that β_p and β_d take different values in different stellar models. To avoid confusion in interpreting the results, MOSFiT maps the conventional β to the scaled penetration factor b : $b = 0$ means no disruption, $0 < b < 1$ means the star is partially disrupted, $b \geq 1$ means the star is completely disrupted, and $b = 2$ corresponds to the maximum β that is simulated by Guillochon & Ramirez-Ruiz (2013).

The accretion rate that actually powers the luminosity should differ from the fallback rate due to viscous delay in the accretion disk. In MOSFiT, this process is controlled by the viscous timescale t_ν . Increasing t_ν could prolong the rising and declining timescales of the light curve and suppress the peak luminosity. Note that only in the limit of $t_\nu \rightarrow 0$ does the accretion rate equal the mass fallback rate. The exact formula for transforming the fallback rate to the accretion rate can be found in Mockler et al. (2019).

The bolometric luminosity is computed by $L_{\text{bol}} = \eta \dot{M}_{\text{acc}} c^2$, where η is the radiation efficiency. The range of η is set between 10^{-4} and 0.4; the upper limit is the radiation efficiency for a maximally spinning BH, while the lower limit comes from the minimum value achievable for the eccentric accretion disk model (Zhou et al. 2021).

The optical SED of TDEs is generally described by blackbody radiation with effective temperature T_{eff} . The total bolometric luminosity is the product of the area of the emitting surface, αR_{ph}^2 , and the energy flux per unit area $\sigma_{\text{SB}} T_{\text{eff}}^4$, where R_{ph} is the so-called photosphere radius, σ_{SB} is the Stefan-Boltzmann constant, and α is a dimensionless geometric factor (in the case of a spherical photosphere, $\alpha = 4\pi$; there is also another choice, e.g., in the model of Ryu et al. 2020, $\alpha = 2\pi$). After some simple algebra, the expression for the effective temperature reads $T_{\text{eff}} = (L_{\text{bol}}/\alpha\sigma_{\text{SB}}R_{\text{ph}}^2)^{1/4}$. Then the observed SED is $F_\nu = (\pi B_\nu[T_{\text{eff}}]/D_L^2)R_{\text{ph}}^2$, where B_ν is the Planck function and D_L is the luminosity distance.

Many observations of TDEs have found that the effective temperature varies little near the peak and tends to increase at late times. To model this SED behavior in MOSFiT, a power-law scaling relation between R_{ph} and L_{bol} is adopted: $R_{\text{ph}} = R_{\text{ph},0}(L_{\text{bol}}/L_{\text{Edd}})^l a_p$, where $R_{\text{ph},0}$ is a normalization of the photosphere radius, a_p is the semimajor axis of the material corresponding to the maximum fallback rate, and L_{Edd} is the Eddington luminosity. Substituting this relation into the equation for T_{eff} results in $T_{\text{eff}} \propto L_{\text{bol}}^{(1-2l)/4}$; hence in the special case of $l = 1/2$, the effective temperature will not vary with time. Jiang et al. (2016) studied the stream-stream collision process and also found a power-law relation between R_{ph} and the rate of mass injection into the collision region, with a power-law index close to 1.

To compare the mock light curve generated by the MOSFiT TDE module to the observations, a conversion from bolometric luminosity to AB magnitude in

different bands is performed. This is done using the filter transmission function $T(\lambda)$ and the following equation: $m_{\text{AB}} = -2.5 \log_{10} \left[\frac{\int F(\lambda) T(\lambda) \lambda d\lambda}{\int T(\lambda) \lambda d\lambda} \right] - 48.6$. Finally, a logarithmic likelihood score $\log \mathcal{L}$ is computed for the mock light curve (see Equation (3) of Guillochon et al. 2018). This score is used to assess the goodness of fit, in the sense that the higher the score, the better the mock light curve matches the observation.

3.2 Parameter Settings

The ranges of the aforementioned fitting parameters and the types of their prior distributions are listed in Table 1. The rest of the fitting parameters use their default settings. To initialize the Markov Chain Monte Carlo (MCMC) fitting procedure, the model parameters are randomly drawn from the prior distributions. To accelerate the convergence of the fitting procedure, we narrowed the ranges of the priors for the SMBH mass and stellar mass. Zhu et al. (2023) reported that the SMBH in the nucleus of NGC 3799 has a mass of $10^{6.26 \pm 0.28} M_{\odot}$, derived from the relationship between the central BH mass and total galaxy mass (Reines & Volonteri 2015). We thus made the searching area roughly 1 dex above and below this value, i.e., $10^{5.26} \leq M_{\text{BH}}/M_{\odot} \leq 10^{7.26}$.

The spectrum of the nucleus taken before the TDE indicates that the stellar population is relatively old; hence we restricted the search range of stellar mass to the low-mass range, i.e., $0.08 \leq m_{*}/M_{\odot} \leq 3$, and the priors are drawn from the Kroupa initial mass function (Kroupa et al. 1993). We also constrained the start time of the TDE to be within 30 days before the peak, which is determined from the last non-detection in the ZTF survey. The other fitting parameters take the default ranges and empirical distribution types shipped with MOSFiT. The luminosity distance is set to 47.8 Mpc, derived from the redshift of NGC 3799, with $z = 0.011$, in a flat universe ($H_0 = 69.6 \text{ km Mpc}^{-1}$, $\Omega_M = 0.286$). The fitting procedure stops when the potential scale reduction factor (PSRF) value drops below 1.1, which is the default value in MOSFiT and indicates that the Monte Carlo chain has converged to the target distribution.

MOSFiT uses the ‘‘Watanabe-Akaike information criterion (WAIC)’’ to assess the goodness of fit, which is defined as: $\text{WAIC} = \langle \log \mathcal{L} \rangle - \text{var}(\log \mathcal{L})$, where $\langle \log \mathcal{L} \rangle$ is the mean of the logarithmic likelihood score and $\text{var}(\log \mathcal{L})$ is the variance, using samples from the ensemble. According to this definition, models with higher WAIC values are more appropriate for the observed data. We present the WAIC values for the four models in Table 2.

4. Results and Discussion

4.1 Fitting Results

The mock light curves generated by the fitting results and the observed data points are plotted in Figure 2 [Figure 2: see original paper]. The BH mass, stellar mass, and scaled penetration factor b are listed in Table 2, and the

posterior distributions of these fitting parameters are shown in Figure 3 [Figure 3: see original paper].

The fitting results from the four composite light curves fall into two cases: (a) full disruption ($b > 1$) of a low-mass star ($\sim 0.1M_{\odot}$); (b) partial disruption ($b < 1$) of a near solar-mass star. Additionally, the rising time of case (a) is longer than that of case (b) (see column 2 of Table 3), and the BH mass in case (a) is slightly lower than that in case (b). Nevertheless, all BH masses are lower than that reported by Zhu et al. (2023). Our BH mass results are also lower than that found by Hoogendam et al. (2024) but roughly agree with the result of Charalampopoulos et al. (2024). Moreover, we note some inconsistency between ASAS-SN and ATLAS data. In cases where the rising part contains only one data source (e.g., AS and ATc), the rising part is well fitted (the observed data points fall on the mock light curves). In contrast, in cases where the rising part adopts data from both ASAS-SN and ATLAS (e.g., AS+ATc and AS+ATco), the rising part is not well fitted.

Recently, some interesting TDEs have been observed whose light curves show re-brightening features in the declining phase after the first peak. The separation between the first and second peaks spans a range from a few hundred days (in the sample of Yao et al. 2023) to a few years (Somalwar et al. 2023). The nature of this phenomenon remains an open question, with possible models including repeated partial TDEs produced by the same star (Somalwar et al. 2023) and two subsequent TDEs produced by two different stars following the tidal breakup of a binary (Mandel & Levin 2015).

In the case of AT 2023clx, the scaled penetration factor b obtained from the four composite light curves differs: while the composite light curves AS and AS+ATco report complete disruption of the intruding star ($b > 1$), the other two light curves (ATc, AS+ATc) report partial disruptions ($b < 1$). However, in the latter cases, b is very close to 1, so the surviving remnant core is unlikely to produce a second TDE, given its extremely low mass (hence the tidal radius is very small) and the possibility of ejection from the SMBH (see, for example, Zhong et al. 2022). In either case, we speculate that there would be no further TDE flare from this galaxy until another star falls within the tidal radius.

Although MOSFiT has been successful in fitting the UV/optical light curves of many TDEs, the code still has limitations that may affect our measurements. The radiation efficiency η is fixed throughout the lifetime of a TDE. However, in the long-term evolution, as new dissipation processes are added, η should vary with time (see Section 4.2). Therefore, MOSFiT should be applied to a limited segment of the light curve in which the η value can be taken as constant, but it is hard to identify this time segment in advance. The mock light curves in the decline phase are generally well matched with the observational data, so we think a fixed η value is appropriate in the fitting procedure, although some small deviations are noticeable.

Mockler & Ramirez-Ruiz (2021) found degeneracy between η and m_* in the fit-

ting results of MOSFiT. They reduced the lower limit of the η prior distribution and re-fitted the TDEs presented in Mockler et al. (2019). They found that for the same TDE light curve, lowering the η value by a factor of 10 results in a stellar mass roughly 10 times heavier. Our fitting results also show that lower η_{fit} corresponds to higher m_* ; however, we argue that this behavior is not due to parameter degeneracy. The difference among the four fitted m_* values is ~ 10 , so the difference in η_{fit} caused by parameter degeneracy should also be ~ 10 , but the results only show a factor of ~ 2.7 difference.

The viscous timescale (column 4 in Table 3) is much shorter than the fallback time (column 3 in Table 3), indicating that the bolometric light curve well represents the mass fallback rate. Therefore, the accuracy of estimations of M_{BH} , m_* , and β depends on the mass fallback rate model. MOSFiT adopts the mass fallback rate obtained from the disruption of stars modeled by polytropes (Guillochon & Ramirez-Ruiz 2013). The $\gamma = 5/3$ polytrope is a good approximation for an $m_* \sim 0.1M_{\odot}$ star (obtained from the AS, AS+ATco light curves), and the stellar structure hardly changes within the age of the Universe. However, for an $m_* \sim 1M_{\odot}$ star (obtained from the ATc, AS+ATc light curves), the stellar structure becomes more centrally concentrated than the $\gamma = 4/3$ polytrope as it ages, and the fallback rate should be modified (Law-Smith et al. 2020). The age of the disrupted star cannot be obtained from the light curve alone, since there is a degeneracy with β (Law-Smith et al. 2020). The chemical abundance of the tidal debris is promising for determining the age of the disrupted star (Law-Smith et al. 2019). Unfortunately, we do not have spectral data to study the age and/or type of the disrupted star. The parameters fitted from the ATc, AS+ATc light curves should be treated with caution, although they have higher WAIC scores.

4.2 What Process Powers the Optical Radiation of AT 2023clx

After a star is disrupted, the debris bound to the SMBH is not immediately accreted. Instead, the debris spends some time settling into an accretion disk. The specific orbital energy of the bound debris is spread between $-\epsilon$ and 0 (Evans & Kochanek 1989). Therefore, different portions of the debris return to the pericenter at different times. Due to general relativistic apsidal precession of the orbit, the outgoing stream is deflected toward the fallback stream and will collide with it at some location. Such collisions could dissipate the orbital energy of the debris and promote the formation of an accretion disk (Kim et al. 1999; Jiang et al. 2016). In the classic picture of TDEs, it is assumed that the debris can quickly form a compact circular accretion disk (radial size $\sim 2r_p$), and the SED of this disk peaks in the soft X-ray or extreme ultraviolet (EUV) band (Rees 1988). The accretion rate at the early stage should exceed the Eddington accretion rate for $M_{\text{BH}} < 10^7 M_{\odot}$, so the disk could launch radiation-driven outflows, which obscure the central accretion disk and form an RL that converts X-ray/EUV photons into UV/optical photons (Strubbe & Quataert 2009; Metzger & Stone 2016). However, the assumption that an accretion disk is quickly

formed has been questioned by later numerical and theoretical works (Piran et al. 2015; Shiokawa et al. 2015), because the strength of energy dissipation during stream-stream collision is too mild to circularize the debris in a short period.

MOSFiT does not assume any specific optical radiation mechanism. Instead, it adopts a dynamical photosphere whose size evolves with the bolometric luminosity. In addition, as mentioned by Mockler et al. (2019), MOSFiT allows a wide range of radiation efficiency, so it could cover various radiation models, including accretion disk and stream-stream collision. Note that in the case of orbital energy being dissipated in stream-stream collisions, \dot{M}_{acc} should be substituted with \dot{M}_{inflow} and interpreted as the mass inflow rate to the collision region (see, for example, Jiang et al. 2016).

Based on the fitting results, we discuss the possible energy source of AT 2023clx. The b values indicate that the penetration factor β is very close to β_d . From these parameters, we find that the pericenter distance r_p is much larger than the Schwarzschild radius of the central SMBH. Therefore, the relativistic apsidal precession effect on the trajectories of the tidal debris is mild. According to the self-intersection model of Dai et al. (2015), we find that in AT 2023clx the stream-stream collision happens far from the SMBH (order of 10^{13} - 10^{14} cm; for comparison, the pericenter distance is on the order of 10^{12} cm). The shocks in the collision region dissipate orbital energy into thermal energy, and part of it may eventually radiate away. The amount of dissipated energy can be estimated with the semimajor axis of the debris before and after the collision: $\Delta E = GM_{\text{BH}}m_*/2a_{\text{mb}} - GM_{\text{BH}}m_*/2a_{\text{pc}}$, where a_{mb} is the semimajor axis of the most bound debris (Equation (4) of Dai et al. 2015) and a_{pc} is the post-collision semimajor axis of that debris (Equation (11) of Dai et al. 2015).

This dissipated energy sets the upper limit for the radiation luminosity powered by stream-stream collision, and we define the corresponding efficiency as $\eta_{\text{sh}} = \Delta E/(m_*c^2)$. In the case of AT 2023clx, the maximum η_{sh} value is a few times 10^{-3} (see the sixth column of Table 2). The radiation efficiency reported from all the fittings (the seventh column of Table 2) is smaller than the η_{sh} values derived above and also much lower than the typical radiation efficiency of a standard accretion disk (~ 0.1). The rest of the dissipated energy may be converted into the kinetic energy of a mild collision-induced outflow (CIO) (Lu & Bonnerot 2020; Ryu et al. 2023).

Note that in the stream-stream collision scenario, the optical photons do not directly come from the collision region, since the temperature of the shock region and post-shock gas could reach 10^6 K (Ryu et al. 2023). Instead, they are generated in the photosphere embedded in the CIO (Jiang et al. 2016).

So far, we have only considered energy dissipation in the first collision. The post-collision debris still moves on a highly eccentric orbit and might experience more collisions. Bonnerot et al. (2017) and Chen et al. (2022) have analytically studied the long-term evolution of the debris stream. They find that successive

collisions should dissipate more orbital energy, so η_{sh} should evolve with time—a feature not captured by MOSFiT. The calculations of Bonnerot et al. (2017) and Chen et al. (2022) assume the debris strictly follows the trajectory modeled by a succession of elliptical orbits with decreasing orbital energy (and angular momentum if magnetic stress is applied) and relativistically precessed pericenters. However, numerical simulations show that after the first stream-stream collision, the post-collision streams may not follow the theoretical elliptical trajectory due to the redistribution of angular momentum by the shocks (Shiokawa et al. 2015). Instead, the post-collision stream quickly forms an eccentric disk whose inner edge is still far from the accretion radius of the BH. The shocks formed inside the eccentric disk could dissipate more orbital energy into heat, although the efficiency is low (Piran et al. 2015; Shiokawa et al. 2015).

On the other hand, Liu et al. (2021) proposed that the optical emission from an eccentric disk is powered by accretion onto the BH instead of self-crossing shocks. In this model, viscous friction at the disk pericenter region works as a new heating source. The disk is geometrically thin but optically thick, and the emission region for optical photons lies in the disk surface around the apocenter region. Zhou et al. (2021) estimated the total radiation efficiency for this viscous dissipation process and the stream-stream collision process. According to our fitted BH mass, stellar mass, and penetration factor, we read from Figure 1 of Zhou et al. (2021) that the total radiation efficiency is around 2.5×10^{-3} , which brings the luminosity to sub-Eddington, so no strong outflow is expected. This η is higher than our fitting results, sufficient to power the optical luminosity, but there is no outflow or disk expansion to absorb the rest of the dissipated energy, so this model may overestimate the dissipated energy and is disfavored.

The low efficiency could also be due to the low BH mass. Davis & Laor (2011, hereafter DL11) reported a relation between accretion efficiency and BH mass, $\eta_{\text{DL11}} = 0.52(M_{\text{BH}}/10^9 M_{\odot})^{-0.52}$, from 80 Palomar-Green quasars. They defined the accretion efficiency as $\eta_{\text{DL11}} = L_{\text{bol}}/\dot{M}_{\text{BH}}c^2$, where L_{bol} is the bolometric luminosity integrated from infrared to X-ray band and \dot{M}_{BH} is derived from the UV/optical SED based on the fully relativistic thin accretion disk model (Dexter & Agol 2009). When disk wind is taken into account, the normalization of the above relation should be reduced by roughly 0.5 dex, according to Figure 10 [Figure 10: see original paper] of Laor & Davis (2014). In MOSFiT, η solely accounts for the bolometric luminosity of optical bands. Hence the η_{DL11} value derived from the DL11 relation should be further reduced by roughly 1 dex (see Figure 12 [Figure 12: see original paper] of DL11) to compare with our results. Inserting our fitted BH mass into the DL11 relation and applying corrections for disk wind and the different definitions of bolometric luminosity, we find η_{DL11} is lower than η_{fit} . In addition, the aforementioned works use the thin accretion disk model in their calculations, which is generally not realized in TDE accretion flows. Therefore, we think the DL11 relation is not likely responsible for the low η_{fit} value. We also note that there are suspicions related to the DL11 relation in the literature: it may be an artifact of selection effects (Raimundo et al. 2012)

and uncertainty in BH mass estimation (Wu et al. 2013).

The fallback rate could exceed the Eddington accretion rate for smaller BHs. In the context of a standard accretion disk with $\eta \sim 0.1$, radiation-driven outflows could reduce the actual accretion rate to $f_{\text{acc}}\dot{M}_{\text{fb}}$, with $f_{\text{acc}} = 1$ (Strubbe & Quataert 2009; Metzger & Stone 2016). In this case, the η_{fit} reported by MOS-FiT is actually $\eta/f_{\text{acc}} = 0.1$. We think this situation is unlikely to have occurred in AT 2023clx because (1) the time needed to form a standard accretion disk is longer than our observation time (see Section 4.3); (2) the peak bolometric luminosity is only about $0.1L_{\text{Edd}}$ (Zhu et al. 2023).

In summary, the low η_{fit} values support the conjecture that the optical luminosity is powered by energy released in stream-stream collisions. Another clue comes from the viscous timescale t_{ν} : in all the fittings, t_{ν} is much smaller than the fallback timescale, so the light curve closely follows the mass fallback rate, which aligns with the explanation that the luminosity (around the peak) is powered by stream-stream collision.

4.3 Reason for the Non-detection in Soft X-Ray Band

Zhu et al. (2023) report non-detection of soft X-ray photons with Swift/XRT observation of AT 2023clx within 90 days after the optical peak. According to the discussion in the previous paragraphs and assuming the soft X-ray photons are solely emitted from the compact accretion disk (because the soft X-ray SEDs from other non-jetted TDEs indicate a thermal origin, Saxton et al. 2020), we conjecture that the non-detection is simply because the compact accretion disk has yet to form. In fact, many optical TDEs exhibit later brightening of soft X-ray emissions long after the optical peak, e.g., ASASSN-15oi (Gezari et al. 2017; Holoiu et al. 2018), AT2019azh (van Velzen et al. 2021; Liu et al. 2022), and OGLE16aaa (Kajava et al. 2020), suggesting that the accretion flow eventually settles into a compact standard circular accretion disk.

Numerical simulations suggest that circularization happens roughly $\sim 10t_{\text{mb}}$ after the disruption, where t_{mb} is the orbital period of the most bound debris (Shiokawa et al. 2015). More specifically, we estimate the time to circularization (t_{circ}) using the dimensionless circularization efficiency \mathcal{C} defined by Wong et al. (2022), which is the ratio of energy loss during the first stream-stream collision to the total energy that needs to be dissipated before circularization finishes. The quantity $1/\mathcal{C}$ gives a rough estimate of the number of collisions needed to circularize the debris, hence $t_{\text{circ}} \sim t_{\text{mb}}/\mathcal{C}$. The values of t_{mb} and \mathcal{C} derived from our fitting results are presented in Table 3. For parameters obtained from the AS and AS+ATco light curves, $t_{\text{mb}} \sim 13$ days and $\mathcal{C} \sim 0.129$, so it takes ~ 100 days to form the compact accretion disk. For parameters obtained from the ATc and AS+ATc light curves, $t_{\text{mb}} \sim 28$ days and $\mathcal{C} \sim 0.042$, extending the timescale to ~ 600 days. Until then, X-ray photons emitted from the inner disk region (near the innermost stable circular orbit, ISCO) could be observed. Our estimated timescales are roughly consistent with the duration of

non-detection (within 90 days after optical peak). We also note that an XMM-Newton detection at MJD 60095 was reported by Hoogendam et al. (2024) (the X-ray luminosity is 2 orders of magnitude fainter than the UV/optical bolometric luminosity), which roughly agrees with our estimations.

The non-detection of X-ray photons could also be understood in the framework of the TDE unified model (Dai et al. 2018). This model employs an outflow-launching super-Eddington accretion disk, and the outflow plays the role of the RL that absorbs soft X-ray photons emitted from the accretion disk and re-emits them in the UV/optical band. The geometric shape of the RL is non-spherical (R_{ph} varies with inclination angle), so the soft X-ray to optical flux ratio varies with the inclination angle i between the line-of-sight and the rotation axis of the accretion disk. Thomsen et al. (2022) studied the SEDs of this model with different accretion rates and investigated the temporal evolution of post-peak blackbody temperature ($T_{O,BB}$) inferred from optical emission, as well as the optical to soft X-ray flux ratio viewed from different inclination angles at different times. In the case of AT 2023clx, the post-peak $T_{O,BB}$ increases slowly with time (as discussed in Section 3.1, this can be inferred from the value of l ; all four composite light curves report l values between 0.7 and 1.1). According to Thomsen et al. (2022), such temporal evolution of $T_{O,BB}$ can be reproduced in moderate inclination angle cases (e.g., $i = 30^\circ$ and $i = 50^\circ$). For these inclination angles, their calculations show that as the accretion rate declines, the observable soft X-ray flux increases (Figure 4 [Figure 4: see original paper] of Thomsen et al. 2022) because the density of the outflow falls.

The TDE unified model assumes a compact circular accretion disk as the source of the outflow and soft X-ray photons. Swift formation of such a disk is feasible only if $\beta > 3$ when $M_{\text{BH}} < 5 \times 10^6 M_\odot$ (Dai et al. 2015). However, as we have shown, it takes 100–600 days to form such a compact circular accretion disk. In addition, the mass fallback rate might fall below the Eddington accretion rate at that time. Hence, it is unlikely that the outflow launched from a super-Eddington accretion disk is responsible for the optical emission and the non-detection of X-ray photons in the early stage.

Another problem for the formation of a compact circular disk comes from magnetic stress operating in the stream-stream collision and subsequent accretion process, since every disrupted star should possess a magnetic field. Magnetic stress can transport angular momentum outward in the stream (Svirski et al. 2017). Bonnerot et al. (2017) found that in the case of strong magnetic stress, the post-collision stream may lose angular momentum significantly, resulting in ballistic accretion in a short period when the pericenter of the stream falls below the radius of an unstable circular orbit. Consequently, a circular accretion disk will never form. Unfortunately, our observational data cannot constrain the role of magnetic stress in AT 2023clx.

We encourage continued monitoring of the nucleus of NGC 3799 in the soft X-ray band to further test our conjecture.

5. Summary

In this paper, we present the optical light curves of AT 2023clx in the declining phase, observed with Mephisto in the *uvgr* bands. Combining our light curves with ASAS-SN and ATLAS data from the rising phase, we obtain full composite light curves. We then use the light curve fitting software MOSFiT to extract physical parameters for this particular TDE, especially the BH mass, stellar mass, and penetration factor. We construct four groups of composite light curves, each using different data for the rising phase.

The four fitted BH masses are close to each other ($10^{5.67}-10^{5.82}M_{\odot}$), but they are all lower than the estimate made from the SMBH-galaxy mass relation ($10^{6.26\pm 0.28}M_{\odot}$, Zhu et al. 2023). The other parameters clearly divide into two categories: either a full disruption of a low-mass star or a partial disruption of a near solar-mass star (Section 4.1). This discrepancy is mainly caused by inconsistency between the rising phases of ASAS-SN and ATLAS data, which shows the importance of obtaining good measurements in the rising phase. If the rising phase were well sampled and measured (for example, if the full light curve were obtained with Mephisto), the fitting result would be improved.

The origin of optical emissions in TDEs remains an open question (Gezari 2021). The major origins of optical photons include: (1) an RL embedded in the outflow launched from the accretion disk during the super-Eddington accretion phase (Strubbe & Quataert 2009; Metzger & Stone 2016); (2) a photosphere embedded in the CIO launched from the location of stream-stream collision (Jiang et al. 2016; Lu & Bonnerot 2020; Ryu et al. 2023); and (3) the surface layer in the apocenter portion of an eccentric accretion disk (Liu et al. 2021). Using the physical parameters obtained from light curve fitting, we explain that the observed optical emission (i.e., before MJD 60100) should be powered by the stream-stream collision process and emanate from the photosphere embedded in the CIO, due to the low radiation efficiency and the long timescale needed to circularize the debris. Hence it is unlikely to launch a disk outflow that creates the RL. Moreover, because a compact accretion disk did not form during the observation campaign, emission in the soft X-ray band should be weak or even absent. The structure of the debris flow should evolve with time, and other mechanisms may take over from stream-stream collision and become the main engine of optical luminosity in the future.

However, we do not have the opportunity to test these aspects for AT 2023clx in long-term evolution because it is the faintest TDE observed to date (Zhu et al. 2023), and the optical luminosity already falls below the host galaxy background. Nevertheless, we still have a chance to detect soft X-ray photons when the debris becomes circularized into a compact accretion disk.

Although the stream-stream collision and CIO can explain the optical emissions of AT 2023clx, we note that this model still has a caveat. The high-temperature collision region is enshrouded by the CIO, making it difficult to produce thermal soft X-ray flux (Jiang et al. 2016). Therefore, it cannot be applied to X-ray-

selected TDEs or TDEs that have comparable X-ray and optical fluxes. For such TDEs, the TDE unified model (Dai et al. 2018; Thomsen et al. 2022) is more feasible.

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