

Diverse Emission Patterns from Precessing Super-Eddington Disks Formed in Tidal Disruption Events

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ABSTRACT

A tidal disruption event (TDE) occurs when a star passes within the tidal radius of a supermassive black hole (SMBH). In TDEs it is expected that the orbital angular momentum of the disrupted star is generally misaligned with the SMBH spin axis, which should result in a misaligned super-Eddington disk precessing around the SMBH spin axis due to the Lense-Thirring effect. In this paper, we investigate the distinct observational signatures produced from such TDE disks, by performing radiative transfer calculations upon previous super-Eddington disk simulations. We demonstrate that the precession of the disk and wind drive time-dependent obscuration and reprocessing of X-ray radiation. Depending on the orientation of the viewing angle of the observer and the tilt angle of the disk, four main types of variability are induced: 1) The smooth-TDEs: The emissions from these TDEs show no fluctuations; 2) The dimmer: The main emission type (X-ray or optical) stays the same, with small to moderate modulations of brightness; 3) The blinker: X-ray and optical emissions take turns to dominate in one cycle of precession, with dramatic changes in the X-ray fluxes. 4) The siren: X-ray and optical emissions take over each other twice per cycle, possibly with two different peak X-ray fluxes within one cycle. In all three scenarios, we observe an inverse correlation between X-ray and optical emissions. Our model provides a unified physical framework for interpreting TDE multi-wavelength variability through disk precession dynamics and gives an alternative interpretation to the interesting case of J045650.3-203750 which was suggested to be a repeated partial TDE previously.

Keywords: Hydrodynamical simulations; Tidal disruption; Black hole physics; Galaxies; Accretion

1. INTRODUCTION

More than a hundred tidal disruption event (TDE) candidates have been discovered through optical and X-ray surveys. TDEs offer valuable insights not only for estimating the mass and spin of massive black holes (BHs) in the centers of galaxies but also for probing accretion physics, particularly in the context of a super-Eddington accretion disk (L. Strubbe & E. Quataert 2009; G. Lodato & E. M. Rossi 2011; L. Dai et al. 2018).

The newly formed TDE disk is thought to accrete at super-Eddington rates, generating strong radiation and/or magnetic pressure-driven outflows. These outflows are thinner along the polar direction and thicker in the equatorial plane, allowing X-rays from the inner disk to escape preferentially along the polar axis. At higher

angles of inclination, more X-ray emission is absorbed and the absorbed energy is reprocessed into optical/UV radiation (L. Dai et al. 2018).

In typical TDEs, the angular momentum of the disrupted star's initial orbit is misaligned with the BH's spin, causing the resulting accretion disk to tilt relative to the BH. Under the influence of general relativity, the tilted disk undergoes Lense-Thirring (LT) precession (J. Lense & H. Thirring 1918). For standard thin disks, the Bardeen-Petersen effect will align the inner part of the disk relatively quickly (J. M. Bardeen & J. A. Petterson 1975; J. C. B. Papaloizou & J. E. Pringle 1983; G. Lodato & D. J. Price 2010). However, a typical TDE disk is expected to be thick and accrete at super-Eddington rate, allowing it to precess as a rigid structure (P. C. Fragile et al. 2007; M. Liska et al. 2018).

X-ray variability, particularly quasi-periodic oscillations (QPOs), is commonly observed in the light curves of accreting black hole systems such as BH X-ray bina-

ries (BHXRBS, P. C. Fragile et al. 2001; J. M. Miller & J. Homan 2005; D. Altamirano & T. Strohmayer 2012), ultra-luminous X-ray sources (ULXs, T. E. Strohmayer & R. F. Mushotzky 2003; P. Mucciarelli et al. 2006) and TDEs (R. C. Reis et al. 2012; C. J. Saxton et al. 2012; R. D. Saxton et al. 2012; D. R. Pasham et al. 2019, 2024a; J.-H. Chen et al. 2022; Y. Wang et al. 2024b). Some of this variability can be attributed to the LT precession in a tilted disk. For example, a jetted TDE Swift J1644 (D. N. Burrows et al. 2011), and two TDE candidates, ASASSN 14li and AT 2020ocn, display QPO on their X-ray light curves, potentially indicative of precessing jet and disk structures, respectively (D. R. Pasham et al. 2019, 2024a).

Another class of intense periodic transients, quasi-periodic eruptions (QPEs), has been identified in galactic nuclei by their very-large-amplitude and periodic X-ray bursts (G. Miniutti et al. 2019; M. Giustini et al. 2020; R. Arcodia et al. 2021; J. Chakraborty et al. 2021). Similarly to QPOs, QPEs may also arise from a precessing disk associated with an active galactic nucleus (AGN) or a TDE accreting at super-Eddington rate (M. Middleton et al. 2025), although alternative scenarios have been proposed. These include collisions between an orbiting body and the accretion disk surrounding a massive black hole (P. Suková et al. 2021; J. Xian et al. 2021; A. Franchini et al. 2023; I. Linial & B. D. Metzger 2023; H. Tagawa & Z. Haiman 2023; I. Linial & B. D. Metzger 2024; C. Zhou et al. 2024; I. Vurm et al. 2024; W. Guo & R.-F. Shen 2025), disk instabilities (X. Pan et al. 2022; K. Kaur et al. 2023), or repeating TDEs (A. King 2022; J. H. Krolik & I. Linial 2022; M. Wang et al. 2022; J.-H. Chen et al. 2023).

Interestingly, the recently reported nuclear transient eRASS1 J045650.3-203750 (hereafter, J0456-20, Z. Liu et al. 2023, 2024), identified by extended ROentgen Survey with an Imaging Telescope Array (eROSITA) in a quiescent galaxy, exhibits long-term decay with superimposed short-term quasi-periodic X-ray variability. Notably, its near-UV (NUV) and X-ray light curves display a subtle inverse relationship, a feature that is difficult to explain in the context of repeating TDEs. This behavior may instead arise from a precessing thick disk with a declining accretion rate.

In this paper, we integrate the viewing angle dependence of spectral characteristics for the super-Eddington TDE disk, as explored in L. Dai et al. (2018) and L. L. Thomsen et al. (2022), with a precessional effect to comprehensively investigate the dynamical and radiative features of a precessing disk in TDE. Different precession patterns exhibit diverse observational signatures, which can be compared with current TDE candidates

and inform future observations. To our knowledge, this is the first precessing TDE disk model that incorporates the prediction of multiwavelength light curve behavior.

The structure of the paper is as follows: In Section 2, we describe our method to calculate the spectral dependence on the viewing-angle. In Section 3, we explore the dynamical properties of a precessing super-Eddington disk. We then compute the light curve of a precessing TDE disk based on the combined radiative spectra and precessional effects in Section 4. Sections 5 and 6 provide a discussion and summary of the results. Throughout this paper, we adopt a flat Λ CDM cosmology with $H_0 = 67.7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $\Omega_m = 0.308$ (Planck Collaboration et al. 2020).

2. METHODOLOGY

In this study, we do not simulate a physically realistic precessing super-Eddington accretion disk in TDEs. Instead, we adopt the spectral dependence on viewing angle and disk geometry for an aligned super-Eddington disk, based on simulations by L. Dai et al. (2018) and L. L. Thomsen et al. (2022). We then impose an artificial precession by varying the viewing angle over time. However, the spectral-viewing angle relationship for a genuinely precessing, tilted disk would differ significantly. Future work should include full simulations of precessing super-Eddington TDE disks to accurately characterize their spectral properties. We describe our method in the following sections.

2.1. Super-Eddington accretion disk in TDE

Following the disruption of a star, the newly formed disk initially enters a super-Eddington accretion state. In this phase, intense radiation pressure and/or magnetic pressure propel the gas outward, generating a powerful outflow. This outflow is nearly axisymmetric; due to azimuthal motion, the density of the outflow is greater near the equatorial plane, where the velocity is slower, while it is lower near the polar regions, where the velocity is faster. The gas in the outflow can absorb and scatter X-ray emissions from the inner disk, subsequently re-emitting them in the optical/UV bands. This configuration results in a significant dependence of radiation on the viewing angle: an observer looking directly at the face of the disk will detect strong X-rays, whereas an observer viewing the disk edge-on will detect optical/UV emissions with weak X-rays (L. Dai et al. 2018), as illustrated in Figure 1.

Here, we utilize simulation results of a super-Eddington accretion disk from L. L. Thomsen et al. (2022), conducted using the general relativistic radiation magnetohydrodynamic (GR-RMHD) code HARM-RAD (J. C. McKinney et al. 2014). In the simulation,

the SMBH is assumed to have a mass of $10^6 M_\odot$ and a dimensionless spin parameter of $a = 0.8$. A quasi-steady state was achieved in the inner regions of the disk, with a mass accretion rate of $\dot{M}_{\text{acc}} \simeq 12 \dot{M}_{\text{Edd}}$, where the Eddington mass accretion rate is defined as $\dot{M}_{\text{Edd}} \equiv L_{\text{Edd}}/(\eta_{\text{NT}} c^2)$, with L_{Edd} being the Eddington luminosity and $\eta_{\text{NT}} \simeq 0.12$ the nominal accretion efficiency for a Novikov-Thorne thin-disk solution (I. D. Novikov & K. S. Thorne 1973).

2.2. Spectra in different inclinations

To determine the escaped luminosity at different wavelengths, we utilize the result in L. L. Thomsen et al. (2022), obtained by the Monte Carlo radiative transfer code SEDONA (D. Kasen et al. 2006) to perform radiation transport calculations.

Following the method in L. L. Thomsen et al. (2022), we explore the spectra for a range of inclinations, from 15° to 70° . For each inclination, the gas density, temperature, and velocity are averaged within $\pm 5^\circ$ of the inclination from the GR-RMHD simulation, to generate a spherical input profile for SEDONA. The results are shown in Figure A.1, which highlights the 0.2–10 KeV X-ray band and the blackbody fitting in the optical band.

Figure 1 illustrates the X-ray luminosity in the 0.2–10 KeV band ($L_{\text{X},0.2-10 \text{ KeV}}$), and the optical luminosity ($L_{\text{o,bb}}$), derived from blackbody fitting the *Swift*/UVOT band (v, b, u, UVW1, UVM2, and UVW2 filters), as a function of the viewing angle. In particular, as the viewing angle exceeds $\sim 50^\circ$, the X-ray luminosity undergoes a sharp decline, while $L_{\text{o,bb}}$ exhibits a slight increase. The X-ray luminosity evolves more rapidly than the optical emission, while the optical luminosity exhibits minimal changes within the $0^\circ - 50^\circ$ and $55^\circ - 70^\circ$ ranges.

In the following sections, we proceed under the assumption of a rigidly precessing disk exhibiting the aforementioned viewing angle dependency to calculate the corresponding radiative features.

3. VIEWING-ANGLE MODULATION OF A PRECESSING SUPER-EDDINGTON DISK

The disruption of a star by an SMBH typically forms a super-Eddington accretion disk with powerful disk winds (L. Strubbe & E. Quataert 2009; G. Lodato & E. M. Rossi 2011; L. Dai et al. 2018). As demonstrated by L. Dai et al. (2018), the viewing angle plays a crucial role in observational signatures: near-polar orientations allow direct detection of inner-disk X-ray emission, while near-edge-on views lead to X-ray absorption by the thick outflow, with reprocessed emission dominating the optical/UV bands (see also E. Qiao et al. 2025).

The nascent accretion disk is typically misaligned with the SMBH’s spin axis because of the random orientation of the stellar orbit. This misalignment induces LT precession via general relativistic effects (J. Lense & H. Thirring 1918). Simulations suggest that thick, super-Eddington disks can precess coherently as rigid bodies (P. C. Fragile et al. 2007; M. Liska et al. 2018).

The observed flux modulation amplitude from such a precessing disk depends on the viewing angle between the observer’s line of sight and the disk, as well as the spin orientation of the SMBH, as illustrated in Figure 2.

As the disk precesses, the observed flux evolves with the angle θ between the line of sight and the disk orientation. From geometric considerations, $i(t)$ evolves as

$$\cos[i(t)] = \cos\varphi \cos\theta + \sin\varphi \sin\theta \cos(\omega t), \quad (1)$$

where φ is the angle between the observer’s line of sight and BH’s spin axis, θ is the disk tilt angle relative to the spin axis, and ω is the precession angular velocity. In a precession cycle, $i(t)$ ranges from

$$i_{\min} = |\varphi - \theta| \text{ to } i_{\max} = \min(\varphi + \theta, 2\pi - \varphi - \theta), \quad (2)$$

where $\theta \in [0, 180^\circ]$ and $\varphi \in [0, 180^\circ]$.

The observed variability strongly depends on the geometry of the system. For a small tilt angle ($\theta \sim 0^\circ$), the disk remains nearly aligned with the black hole’s spin axis, resulting in minimal precession. When the observer’s line of sight is nearly aligned with the spin axis ($\varphi \sim 0^\circ$), the viewing angle remains approximately constant. In both cases, the flux variations induced by disk precession are negligible.

When both φ and θ are large enough, $i(t)$ can exceed 90° during precession. This causes the opposite side of the disk to become visible, leading to more pronounced variability.

Figure 2 demonstrates the evolution of the viewing angle for different configurations θ and φ . For the small θ case, the viewing angle variation remains small as the disk maintains approximate alignment with the SMBH’s spin axis. In the extreme case where the viewing angle crosses 90° , observers see both faces of the disk during each precession cycle, resulting in two edge-on orientations per period.

4. RADIATIVE FEATURES

4.1. X-ray and optical luminosity modulation in a precession cycle

The observed emission properties are critically dependent on both the disk structure and the viewing geometry. For a standard thin disk, the flux follows a simple dependence of $\propto \cos\theta$ with minimal spectral changes.

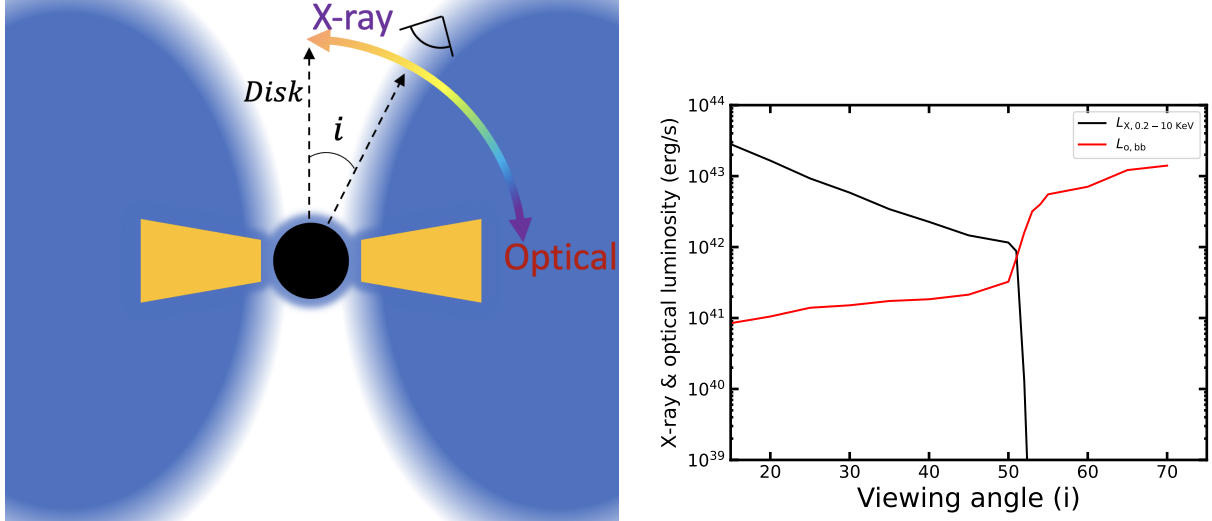


Figure 1. Left: Schematic of a super-Eddington accretion disk with outflowing material (blue shaded region). When the observer's line of sight aligns with the outflow-cleared funnel, bright X-ray emission is detected. Conversely, observations along the equatorial plane are dominated by optical emission due to reprocessing. Right: $L_{X,0.2-10 \text{ KeV}}$ and optical luminosity $L_{o,bb}$ versus viewing angle i .

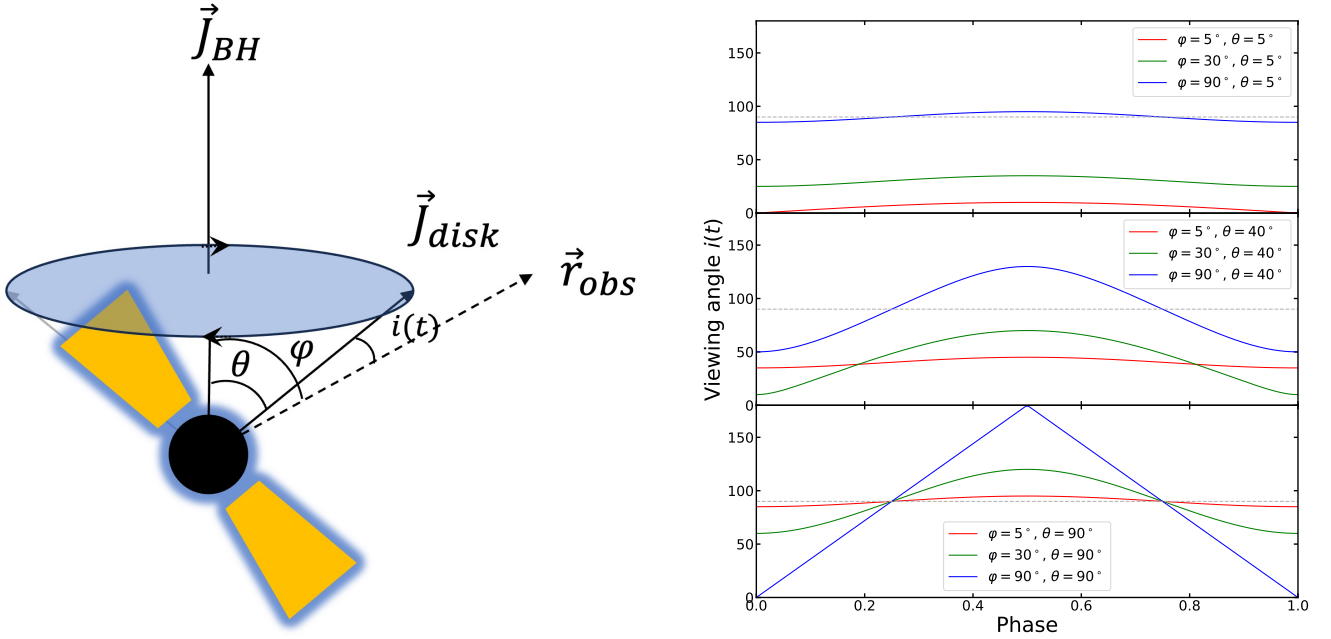


Figure 2. Left: Sketch of disk precession geometry. As the disk precesses around the BH's spin vector ($\vec{J}_{BH}$), the viewing angle $i(t)$ between the observer's line of sight ($\vec{r}_{obs}$) and the disk orientation ($\vec{J}_{disk}$) varies. The angle θ denotes the inclination between $\vec{J}_{BH}$ and $\vec{J}_{disk}$, while φ represents the angle between $\vec{J}_{BH}$ and $\vec{r}_{obs}$. Both θ and φ remain nearly constant during the precession cycle. Right: Evolution of viewing angle $i(t)$ of a precessing disk over one precession period. Upper, middle and lower panels illustrate the small, medium and large θ cases, respectively. The dashed gray line indicates the 90° viewing angle, beyond which the opposite side of the disk becomes visible as the disk viewing angle crosses this value. The blue line in the lower panel corresponds to the most extreme case with $\theta = \varphi = 90^\circ$.

However, super-Eddington accretion disks exhibit more complex behavior as a result of their powerful outflows. When viewed pole-on, observers detect strong X-ray emission from the inner disk and potentially jets. At higher inclinations, the outflow obscures X-rays, leading to optical/UV-dominated emission through reprocessing.

We identify three distinct precession modes based on φ and θ configurations, as illustrated in Figure 3

Small tilt angle ($\theta \simeq 0^\circ - 10^\circ$): Spin-aligned observer ($\varphi \simeq 0^\circ$): X-ray-dominated emission with minimal variability (e.g., some TDEs with steady X-ray emission). Intermediate φ : Simultaneous X-ray and optical emission with low variability (e.g., ASASSN-14li S. T. Holoien et al. 2015; J. Brown et al. 2017) and ASASSN-20qc (D. R. Pasham et al. 2024b). Notably, these sources show quasi-periodic X-ray variability that potentially indicates precession. Edge-on observer ($\varphi \simeq 90^\circ$): Optical-dominated and X-ray-weak emission without variability (e.g., ASASSN-14ae T. Holoien et al. 2014).

Moderate tilt angle ($\theta \simeq 30^\circ - 60^\circ$): Spin-aligned observer: Similar to small- θ case with mixed X-ray/optical emission in the medium inclination. Intermediate φ : exhibit periodic transitions between X-ray-bright and optical-dominated states during the precession cycle (e.g., J0456-20 Z. Liu et al. 2024). Edge-on observer: Optical-dominated emission with variability (e.g., ASASSN-14ko A. V. Payne et al. 2021, 2022; C. Liu et al. 2023).

Large tilt angle ($\theta \gtrsim 60^\circ$): Spin-aligned observer: Optical-dominated with minimal variability, similar to the small θ case in the vertical direction. Intermediate φ : optical-dominated TDE with a large modulation amplitude in optical, similar to the medium θ case in medium inclination. Edge-on observer: Both X-ray and optical emissions undergo extreme flux modulation. As the accretion disk transitions between face-on and edge-on orientations, the emission alternates between being X-ray-dominated and optical-dominated, respectively.

Subsequently, we employ these results to model the observed light curve from a precessing disk, where the viewing angle varies periodically. If the viewing angle can be extended to $\lesssim 15^\circ$ or $\gtrsim 70^\circ$, it is crucial to understand the relationship between luminosity and angle within these angle ranges. Unfortunately, acquiring spectra directly at these extreme viewing angles is not feasible. At high inclinations, approaching an edge-on orientation, the optical depth becomes excessively large, rendering post-processing with SEDONA impractical. In contrast, at low inclinations, the results are compromised by contamination from the jet component, thus

undermining their reliability. Instead, we must make assumptions to extrapolate the luminosity-angle relationship to these ranges. Here, we assume that the luminosity within $0^\circ - 15^\circ$ is equal to the value at 15° , and the luminosity within $70^\circ - 90^\circ$ is equal to the value at 70° .

In Figure 3, we see that the precession mode depends on both θ and φ , with some modes exhibiting similar radiative characteristics. The luminosity evolution is directly dependent on the viewing angle range during a precession cycle. When the viewing angle range is small, i.e., $i_{\max}/i_{\min} \lesssim 2$, and does not cross the rapid transition point at 50° , the X-ray luminosity varies by less than one order of magnitude, resulting in weak modulation. Otherwise, the modulation is more pronounced. Based on these radiative characteristics, we can classify the precession modes into several patterns according to $i_{\min}$ and $i_{\max}$, as shown in Figure 5. The left and right panels depict the no/weak and large/extreme large modulation patterns, respectively. These different patterns are illustrated in Figure 4.

For cases with weak modulation, if the viewing angle is small, the dominated emission is X-ray; otherwise, it is optical. These cases correspond to X-ray or optical TDEs with minimal variability. For cases with a medium/large modulation amplitude, if $i_{\max} \lesssim 50^\circ$, we see medium modulation amplitude in the X-ray light curve. If the viewing angle crosses 50° , we see a large amplitude of modulation in the X-ray band and a slight increase in the optical band when the X-ray emission drops. If the viewing angle range is even larger and crosses 90° , we can observe the disk edge twice during a cycle, leading to two optical peaks in one phase.

These findings elucidate the radiative evolution of a precessing disk in a stable stage. However, in the context of TDE, the accretion rate undergoes a rapid increase followed by a gradual decline. Consequently, the light curve should reflect the interplay between these two effects. In the forthcoming section, we will delve into the analysis of the light curve emanating from a precessing disk in a declining accretion rate.

4.2. Light curve with declining accretion rate

The evolution of multiwavelength emission, particularly X-ray and optical emission, in observed TDE candidates is complex, as these emissions do not always follow the same trend. For simplicity, we assume that their overall behavior adheres to a $-5/3$ power-law decay, consistent with the typical mass fallback rate observed in TDEs. We express the X-ray luminosity and optical luminosity with declining accretion rate as fol-

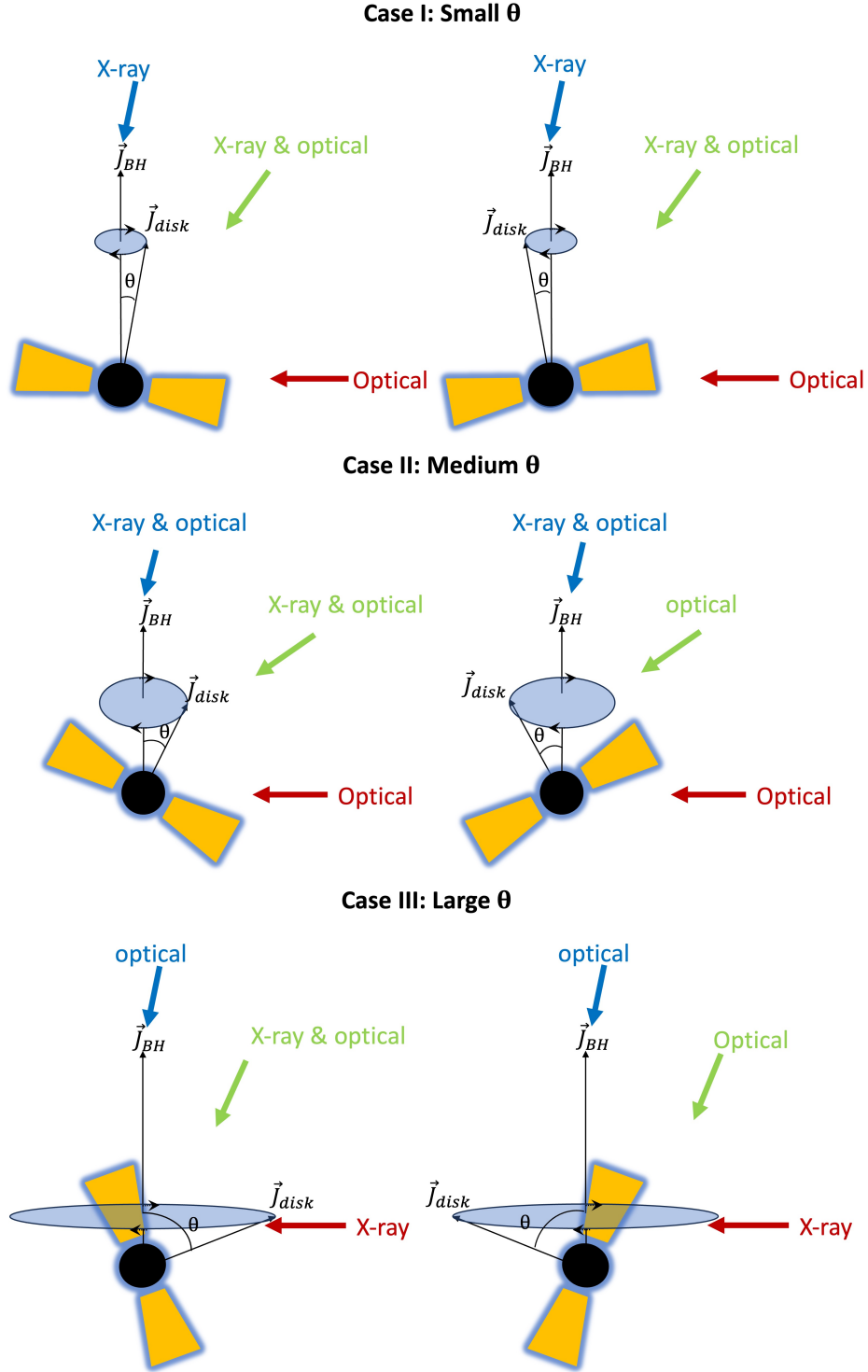
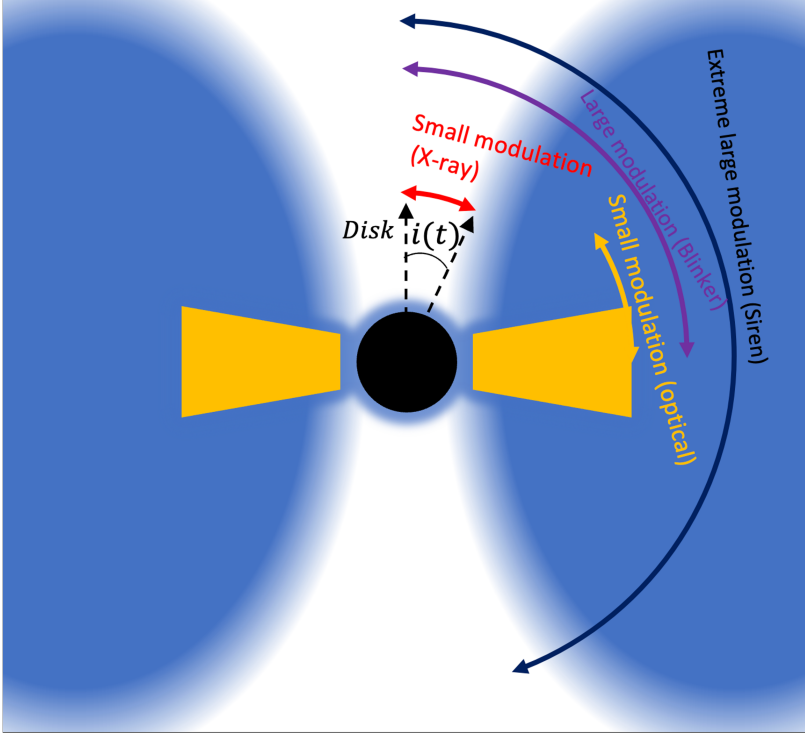


Figure 3. Upper, middle and lower panels depict three distinct cases corresponding to different tilted angle θ . The left and right panels illustrate the disk's positions at the two antipodal points of the precession cycle. The direction of precession is indicated by a circular arrow. The colored and labeled arrows elucidate the radiation patterns detectable by an observer as they scan different directions within a precession cycle.



- X-ray TDE with small modulation (Dimmer)
- Optical TDE with small modulation (Dimmer), e.g., ASASSN-14ae
- Optical & X-ray TDE with large X-ray modulation (Blinker), e.g., J0456-20
- X-ray & optical TDE with extreme large modulation (Siren)

Figure 4. Schematic of observed precession patterns in an super-Eddington accretion disk. As the viewing angle varies across different ranges, the observer detects distinct signatures of disk precession, as indicated by the double arrows. A summary of these patterns is provided in Table 1.

Table 1. Summary of the precession patterns of TDEs

Name	Type	Viewing angle	Num. of modulation
Smooth-TDEs	No modulation	$i_{\min} \sim i_{\max}$	0
Dimmer	Small modulation in X-ray	$i_{\min} < i_{\max} \lesssim 50^\circ$ or $130^\circ \lesssim i_{\min} < i_{\max}$	1
	Small modulation in optical	$50^\circ \lesssim i_{\min} < i_{\max} \lesssim 130^\circ$	1
Blinker	Large modulation	$i_{\min} \lesssim 50^\circ$ and $50^\circ \lesssim i_{\max} \lesssim 130^\circ$	1
Siren	Extreme large modulation	$i_{\min} \lesssim 50^\circ$ and $i_{\max} \gtrsim 130^\circ$	2

NOTE—We classify the four precession patterns as listed in Column 1. Columns 2-4 specify the modulation type, the corresponding viewing angle range, and the number of modulation peaks per precession cycle, respectively. Figure 4 illustrate these four patterns.

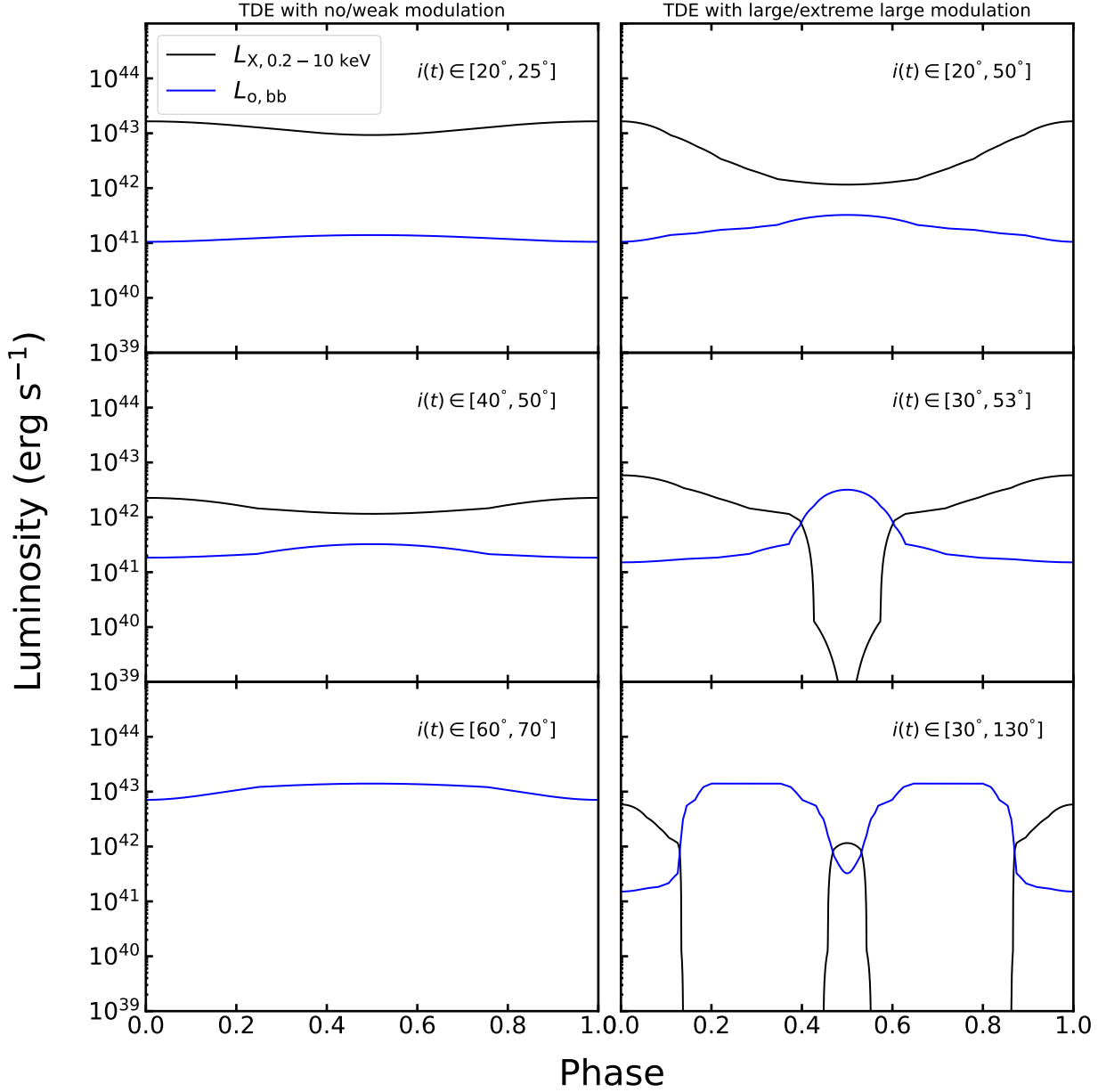


Figure 5. Characteristic examples of the evolutions of X-ray luminosity $L_{X,0.2-2 \text{ KeV}}$ (black lines) and optical luminosity $L_{o,bb}$ (blue lines) due to disk precession over one precession period. Each panel shows the results corresponding to distinct viewing angle ranges. The left and right panels present the no/weak and large/extreme large modulation patterns, respectively. A narrow range of viewing angles arises when observing a precessing disk due to Small θ or small φ , resulting in the no/weak modulation. Otherwise, the wide range of viewing angles leads to large/extreme large amplitude of modulation.

lows:

$$\tilde{L}_{X,0.2-2 \text{ KeV}}(t) \simeq L_0 \left(\frac{t + t_{fb} - t_0}{t_{fb}} \right)^{-5/3} \times L_{X,0.2-2 \text{ KeV}} \quad (3)$$

$$\tilde{L}_{o,bb}(t) \simeq L_0 \left(\frac{t + t_{fb} - t_0}{t_{fb}} \right)^{-5/3} \times L_{o,bb}. \quad (4)$$

Here, constant L_0 is the re-scale factor for luminosity, while t_0 , t_{fb} denote the zero-point time and the timescale of mass fallback, respectively. t_{fb} depends on the black

hole mass, pericenter radius, stellar mass and stellar structure, and can be estimated by

$$t_{fb} \simeq 41 M_6^{1/2} r_*^{3/2} m_*^{-1} \text{ day}, \quad (5)$$

where $M_h = M_6 \times 10^6 M_\odot$, $M_* = m_* \times M_\odot$ and $R_* = r_* \times R_\odot$ represent the black hole mass, stellar mass, and radius, respectively.

Note that for the sake of simplicity, we calculate the light curve assuming a declining accretion rate by proportionally reducing the luminosity while preserving the

spectral shape. In reality, super-Eddington outflows can obscure a greater proportion of X-rays in higher accretion rate (L. Dai et al. 2018). However, we choose not to incorporate this effect in the current study, reserving its exploration for future research endeavors.

Equations (3) – (4) suggest that the overall light curve exhibits a power-law decay, whereas the multi-wavelength emissions undergo periodic modulation due to precession.

In Figure 6, we present five different representative cases with varying parameters in different rows. All cases share the same $t_0 = 0$, $t_{\text{fb}} = 300$ day and $L_0 = 10$, but differ in their precession parameters, as indicated in each panel. In the following, we describe the characteristics of each case, presented in order from top to bottom.

1. This case illustrates a TDE with rapid and minor variability in the X-ray light curve, like the QPO signal, while the optical emission shows little variability and follows the X-ray decay. We designate this case as the “*Dimmer*”. This behavior resembles the TDE candidate ASASSN-14li (S. T. Holoien et al. 2015; J. Brown et al. 2017), which exhibits both X-ray and optical emissions, with X-rays displaying a QPO signal attributed to a precessing disk (D. R. Pasham et al. 2019). Another candidate, ASASSN-20qc, also shows minor X-ray variability, possibly due to quasi-periodic outflows from a binary black hole TDE modulating the X-ray emission (D. R. Pasham et al. 2024b).
2. In this case, the viewing direction is close to the disk edge, resulting in optical-dominated emission with small variability. We also designate this case as the “*Dimmer*”. A similar source is ASASSN-14ko, which displays periodic optical flares (A. V. Payne et al. 2021, 2022). However, the overall luminosity of ASASSN-14ko does not show a discernible decreasing trend, suggesting that recurring flares are more likely to be attributable to repeated TDE rather than to a single TDE with modulation (C. Liu et al. 2023; S. Huang et al. 2023). Interestingly, the host galaxy of ASASSN-14ko is classified as an AGN (T. W. S. Holoien et al. 2014). Therefore, we consider that the recurring flares of ASASSN-14ko may arise from the precession of the AGN disk, but the rigid-body precession period could be too long for detection. Alternatively, the AGN disk may not be undergoing rigid-body precession due to its large size, instead, a warp wave-like disturbance could be propagating within the disk, inducing periodic vari-

ability (Y.-C. Peng et al. 2024). This warp may develop during the accretion of surrounding gas onto the disk or arise from the torque exerted during close encounters with a black hole companion, approaching from a non-coplanar direction (J. C. B. Papaloizou & C. Terquem 1995), from non-coplanar direction.

3. This scenario depicts a TDE characterized by significant variability in the X-ray light curve, whereas the optical light curve exhibits smaller, inversely correlated variations. We designate this case as the “*Blinker*”. This behavior resembles J0456-20, whose overall X-ray light curve adheres to a $-5/3$ power-law decay, typical of a TDE, and presents several rapid rise-and-decay outbursts approximately 200 days apart. Similarly, its UV light curve displays a gradual decline accompanied by slight periodic fluctuations. Notably, the UV and X-ray light curves exhibit an inverse relationship, where dips in the UV light curve coincide with peaks in the X-ray light curve. We will dive deeper into modeling this source in Section 5.1.
4. In this scenario, the viewing angle evolves over a wide range, even crossing the 90° , leading to repeated transitions from optical-dominated ($\theta \sim 90^\circ$) to X-ray-dominated emission. Notably, it has two optical peaks in a precession cycle. This occurs because the tilted angle is exceptionally large, enabling the observer to observe the disk in an edge-on direction twice during a single precession cycle. Given that the disk is observed edge-on at certain times, this type of precessing disk ought to be optical-dominated during those intervals. Subsequently, as the optical emission diminishes, the system could transition to being X-ray bright. The modulation pattern of this case is similar to that of the “*Blinker*”, but an ‘abac’ pattern where the two X-ray peaks differ within a precession cycle. Thus, we refer to it as the “*Siren*”. However, to the best of our knowledge, no such TDE has been observed to date. This absence could imply the presence of potential selection biases or some physical reasons, as discussed in Section 5.1.
5. When the precession period exceeds the mass fallback timescale, that is, when $T_{\text{pre}} = 2\pi/\omega \gtrsim t_{\text{fb}}$, we cannot see the periodic variability in the light curve. Instead, we may observe an X-ray brightening at late times as the viewing angle aligns with the near-polar direction of the disk as a result of the precession effect. This phenomenon could possibly explain the sharp late-time rise in X-rays ob-

served in certain TDEs, such as ASASSN-15oi (A. Hajela et al. 2025), AT 2019azh (X.-L. Liu et al. 2022), and OGLE16aaa (J. J. E. Kajava et al. 2020). However, it is important to note that late-time X-rays in TDEs have also been attributed to delayed accretion or outflow-torus interactions (J. Zhuang & R.-F. Shen 2021; G. Mou et al. 2021). If the late-time X-ray emission stems from the precession effect, we might anticipate a second X-ray flare at a later stage. Conversely, if the alignment process occurs more rapidly than the precession, we may not observe this secondary flare. Similarly, if the disk’s polar direction is initially facing the observer, early X-ray emission could be detected at the very beginning, but it would soon diminish as the disk shifts to other directions due to slow precession. If the polar direction subsequently aligns with the observer again, a late-time X-ray rebrightening would be observed. A TDE candidate exhibits very early X-ray emission, AT 2022dsb (A. Malyali et al. 2024), may belong to this case.

The precession signal can be decomposed into rapid and slow scenarios, with the former producing periodic modulations and the latter enabling detection of late-time X-ray transitions. Cases 1–4 correspond to rapid precession and are illustrated in Figure 4 and summarized in Table 1.

It is noteworthy that as the accretion rate declines to a sub-Eddington state in later stages, the disk transitions into a geometrically thin disk. The viscous torque induces rapid alignment of the tilted disk, as documented in previous studies (J. M. Bardeen & J. A. Petterson 1975; R. P. Nelson & J. C. B. Papaloizou 1999; N. Stone & A. Loeb 2012). We give a detailed calculation on the alignment timescale in appendix C. Alternatively, it may tear the disk apart, leading to a fast precession of the inner portion and subsequent alignment, while the outer part remains tilted. Therefore, we would not detect the light curve modulation in late time of TDEs.

5. DISCUSSION

5.1. Where are the Blinkers?

The recently reported nuclear transient eRASSt J045650.3-203750 (hereafter, J0456-20, Z. Liu et al. 2023, 2024), identified by extended ROentgen Survey with an Imaging Telescope Array (eROSITA) in a quiescent galaxy at redshift of $z \sim 0.077$, exhibits long-term decay with superimposed short-term quasi-periodic X-ray variability. We suggest that this behavior may be due to a precessing thick disk with a declining accretion rate.

The X-ray and UV light curves of J0456-20 are shown in Figure 7, where the X-ray data are obtained from Z. Liu et al. (2024).

The overall X-ray light curve exhibits a $-5/3$ power-law decay, consistent with the characteristic behavior of a typical TDE. However, it also displays several rapid rise-and-decay outbursts, separated by about 200 days, which deviate from the standard TDE profile. Similarly, the NUV light curve shows a gradual decay with slight periodic variations. Notably, the NUV and X-ray light curves show an inverse relationship: dips in the NUV light curve coincide with the peak in the X-ray light curve.

These observational characteristics are consistent with the “*Blinker*” as discussed in Section 4.2. Therefore, we propose that it arises from emissions originating in a precessing tilted disk, formed as a result of the TDE.

The model light curve is shown in Figure 7, with parameters $t_{\text{fb}} \simeq 108$ days, $t_0 \simeq 59258$ MJD, $L_0 \simeq 63$, $\varphi \simeq 12^\circ$ (40.3°), $\theta \simeq 40.3^\circ$ (12°). The results indicate a precession period of about 200 days. The viewing angle evolves from 28° to 52° in each precession cycle.

Furthermore, the overall light curve decay timescale $t_{\text{fb}} \sim 108$ days is approximated to the fallback timescale of a TDE, i.e., $t_{\text{fb}} \simeq 130(M_{\text{h}}/10^7 M_\odot)^{1/2}(R_*/R_\odot)^{3/2}(M_*/M_\odot)^{-1}$ days (M. J. Rees 1988), where M_* and R_* are the stellar mass and radius, respectively. Here we adopt the $10^7 M_\odot$ SMBH mass, which is estimated by the $M - \sigma$ relation (Z. Liu et al. 2023).

In conclusion, the precessing TDE disk model provides a comprehensive interpretation of the multiwavelength behavior of J0456-20. However, the scarcity of detected *Blinker* candidates raises a critical question: What fraction of TDEs host precessing disks with significant tilt angles?

If the disk tilt angle θ and the mutual inclination φ between the observer’s line of sight and the SMBH’s spin direction are randomly oriented in space, the most probable configuration would be $\theta \sim \varphi \sim 90^\circ$ (i.e., both the disk and observer’s line of sight are perpendicular to the SMBH’s spin). In this scenario, we would expect most TDEs to exhibit strong modulation due to precession. However, this contradicts observations, which show that the majority of TDEs display smooth light curves or only weak modulation. This discrepancy may arise from intrinsic physical factors or observational selection biases.

There are several unconsidered physical effects. Stars may preferentially disrupt in the SMBH’s equatorial plane, aligning the disk with the SMBH spin axis. For example, axisymmetric nuclear stellar clusters (e.g.

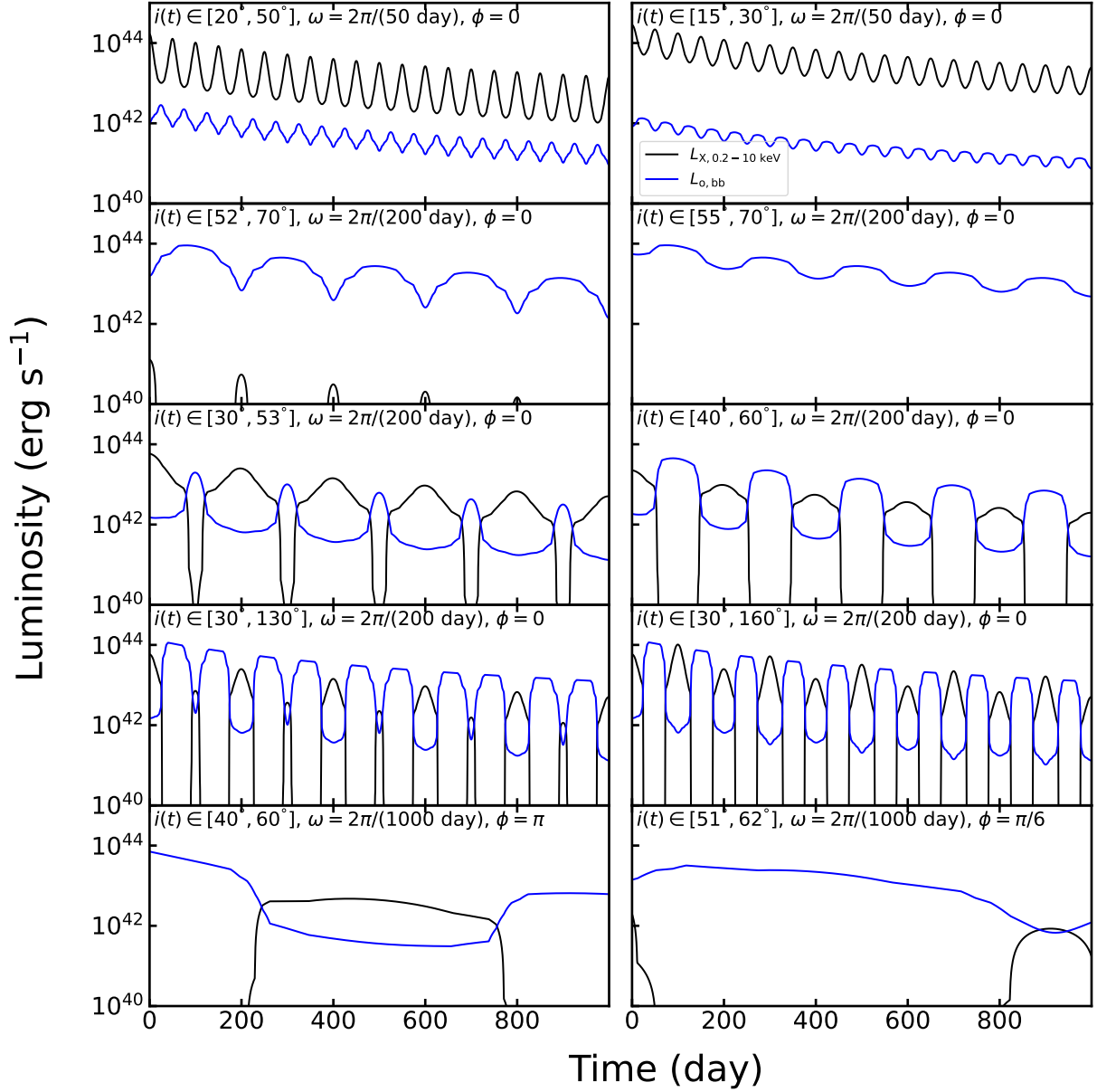


Figure 6. Characteristic examples of evolutions of X-ray luminosity $\tilde{L}_{X,0.2-2\text{ KeV}}$ (black lines) and optical luminosity $\tilde{L}_{o,bb}$ (blue lines) are represented, combining the effect of disk precession and declining accretion rate. Each panel shows the results obtained with distinct parameters, as labeled in the figure. Panels in columns 1-4 correspond to rapid precession, while column 5 illustrates the slow precession case. A detailed discussion on these findings can be found in Section 4.2.

saucer-like structures from galaxy mergers) could confine disruptions to the equatorial plane (S. Zhong et al. 2015). Additionally, a pre-existing accretion disk surrounding the SMBH may capture stars via dynamical friction, enhancing TDE rates and further biasing disruptions toward the equatorial plane (Y. Wang et al. 2024a). Another physical mechanism arises from the inefficient formation of disks in TDEs. If a star's orbit is significantly tilted relative to the SMBH's equatorial plane, the returning debris stream may fail to intersect, preventing stream-stream collisions. This inefficient disk

formation leads to fainter TDEs (L. Dai et al. 2013; J. Guillochon & E. Ramirez-Ruiz 2015; Y. Jiang et al. 2016; T. Jankovič et al. 2024).

Despite these potential suppression effects, the light curves of *Blinker* and *Siren* would still differ markedly from typical TDEs, potentially causing them to be overlooked in surveys. Future observational campaigns with improved sensitivity and cadence are essential to detect and characterize these rare systems.

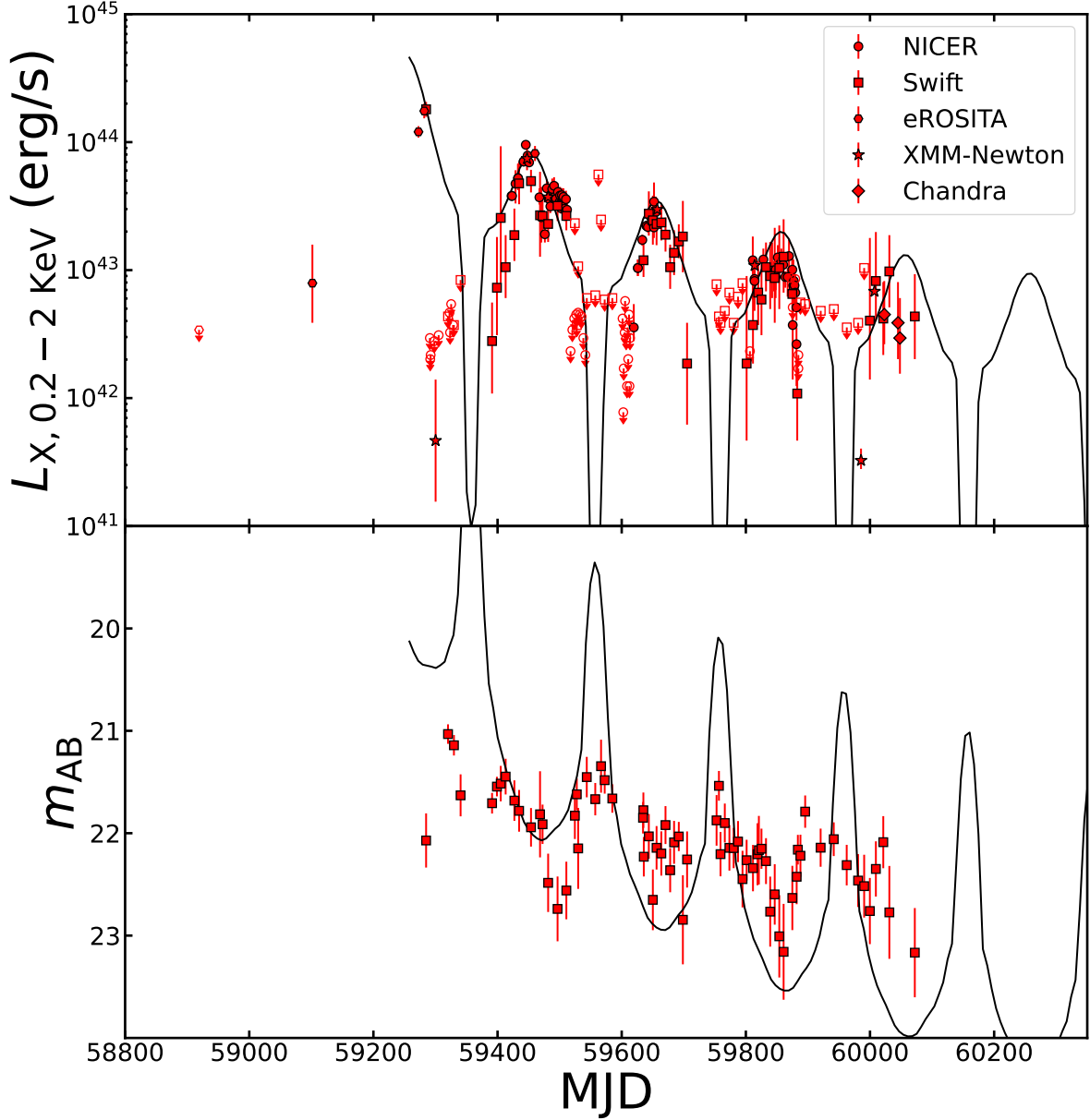


Figure 7. X-ray and NUV data of J0456-20 on top of the modeled light curves. The model parameters are $t_{\text{fb}} \simeq 108$ day, $t_0 \simeq 59258$ MJD, $L_0 \simeq 63$, $\varphi \simeq 12^\circ$ (40.3°), $\theta \simeq 40.3$ (12°). The corresponding viewing angle $i(t)$ evolves from 28° to 52° .

5.2. Precession: Rapid or Slow?

In Section 4.2, we conducted a comprehensive analysis of two distinct precession regimes in TDE accretion disks, rapid precession characterized by periodic modulation in the light curve, and slow precession, which manifests itself as gradual, secular changes in X-ray emission.

The precession timescales are governed by the interplay of critical system parameters, including the SMBH's spin, disk density, and disk size. The detailed calculation is given in Appendix B.

For a rapidly spinning SMBH and a compact, mass-concentrated accretion disk, the Lense-Thirring torque induces rapid precession, with timescales as short as minutes to days. Conversely, in systems with a slowly rotating SMBH, or an extended, outer-mass-dominated disk, precession is weakened, leading to slower evolution over months to years.

5.3. Jet Formation and Precession in TDEs

A super-Eddington accretion disk in a TDE can launch a relativistic jet powered by either the Blandford-Znajek (BZ) mechanism (R. D. Blandford & R. L. Znajek 1977), which extracts rotational energy from the

spinning SMBH, or the Blandford-Payne (BP) mechanism (R. D. Blandford & D. G. Payne 1982), which taps into the disk’s rotational energy. BZ-powered jets are expected to align with the SMBH’s spin axis, as they originate from the ergosphere where frame-dragging effects dominate. Thus, in the absence of disk-jet coupling, such jets should not precess. BP-powered jets, however, are anchored to the accretion disk and would naturally precess if the disk itself is warped or misaligned with the SMBH spin. Interestingly, some simulations suggest that even BZ-powered jets can align with the disk axis (M. Liska et al. 2018, 2023; S. M. Ressler et al. 2023), potentially due to strong disk outflows exerting torques that reorient the jet. The exact alignment mechanism remains debated.

There is some observational evidence for jet precession. The nearby active galaxy M87 exhibits coprecession of its jet and compact accretion disk (Y. Cui et al. 2023; Y. Cui & W. Lin 2025). Additionally, variability in some GRB light curves has been attributed to jet precession (W. H. Lei et al. 2007; T. Liu et al. 2010; Z. Zhang et al. 2023). Swift J1644+57, a strong evidence of jetted TDE, discovered by Swift (D. N. Burrows et al. 2011), showed X-ray variability interpreted as jet precession (W.-H. Lei & B. Zhang 2011; W.-H. Lei et al. 2012). EP250702a, detected by the Einstein Probe (H. Q. Cheng et al. 2025), this fast X-ray transient is spatially and temporally associated with multiple GRBs (GRB250702D, B, E; E. Neights et al. 2025b,a). Its light curve and multiwavelength spectrum suggest a jet-powered TDE with an intermediate-mass black hole, where multiple GRBs may arise from precession (A. J. Levan et al. 2025).

Despite these cases, most TDEs show no clear jet signatures, likely due to intrinsically only a small fraction of TDEs producing relativistic jets, narrow jet opening angles may miss our line of sight, or the jet could be choked by the disk outflow, as the jet precesses (W. Lu et al. 2024; H.-Y. Yuan et al. 2025).

6. CONCLUSION

In this paper, we model the radiative properties of a super-Eddington disk which is misaligned with the black hole spinning axis and therefore undergoing Lense-Thirring precession. The results are applied to explain and predict multiwavelength light curve or variation behavior of TDEs. Our key findings are as follows:

1. A super-Eddington accretion disk naturally produces both X-ray emissions at polar directions and reprocessed optical/UV emissions at moderate to large inclinations, as previously demonstrated (L. Dai et al. 2018). We find that the UV/optical

fluxes remain rather insensitive to the viewing angle for a wide range of inclinations, while the X-ray emission varies faster with the viewing angle. As a result, as the disk undergoes precession, the X-ray light curve will display a more significant amplitude of modulation than its optical light curve.

2. The modulation pattern and amplitude of the multi-wavelength light curves during a precession cycle are governed by the variation of the viewing angle with respect to the disk, which is in turn governed by two key parameters: the disk tilt angle θ relative to the spin axis of the SMBH, and the inclination φ between the observer’s line of sight and the SMBH’s spin direction. The viewing angle range during a precession cycle is described by Equation (2).
3. Different combinations of θ and φ lead to three main precession patterns, as illustrated in Figure 4 and summarized in Table 1. We give a brief summary as follows.
 - (a) When either $\theta = 0^\circ$ or $\varphi = 0^\circ$, the observer will detect a TDE without precession, consistent with TDE candidates showing no fluctuations, which we classify as “*Smooth-TDEs*”.
 - (b) The *Dimmer*: When the viewing angle range falls within the outflow-cleared funnel in the polar direction or the thick outflow in the equatorial direction, it results in minor fluctuations in the light curve in the X-ray and optical/NUV bands, respectively. This specific scenario corresponds to TDE candidates that show little variability, such as ASASSN-14li.
 - (c) The *Blinker*: When the viewing angle spans a moderate range and crosses $\sim 50^\circ$, it induces intense variability in the X-ray light curve. X-ray emission may disappear when the viewing angle is $\gtrsim 50^\circ$, while optical and NUV emissions have a slight increase. This inverse relationship between the X-ray and optical/UV light curves aligns with observations of the TDE candidate J0456-20 (Z. Liu et al. 2023, 2024).
 - (d) The *Siren*: For extremely large tilt angles and φ , the viewing angle can span a range from $\sim 0^\circ$ to 180° . This sweeping motion carries the observer’s line of sight from one side of the polar direction to the opposite side, resulting in extreme large modulations

in both optical/UV and X-ray light curves. During a single precession cycle, both optical and X-ray emissions are observed to exhibit two peaks. Moreover, the two X-ray peaks can be distinct in flux and other characteristics.

Our work provides a valuable tool for modeling the multiwavelength emission properties of TDEs with precessing disks, through which our understanding of the geometry and dynamics of precessing thick disks can be greatly advanced. Furthermore, detecting and analyzing precession-induced modulations in the light curves of TDEs can provide crucial constraints on two key physical parameters: the viewing angle of the accretion disk relative to the observer and the tilt angle of the disk with respect to the spin axis of the SMBH. Last but not least, the properties of the precession-induced modulation can offer promise in constraining the spin of SMBHs.

With the advent of upcoming and newly operational time-domain telescopes conducting sensitive all-sky sur-

veys, we anticipate detecting more TDEs with precession signals, providing deeper insights into the underlying physics of TDEs and precessing disks, and testing principles of general relativity. For instance, the Einstein Probe X-ray telescope can discover numerous TDEs and conduct follow-up observations in the soft X-ray band. The Imaging X-ray Polarimetry Explorer (IXPE) can detect X-ray polarization, offering a powerful tool for studying precessing disks in TDEs. The upcoming optical telescopes, such as the China Space Station Telescope (CSST) and the Legacy Survey of Space and Time (LSST) by the Vera C. Rubin Observatory, are expected to discover hundreds to thousands of TDEs per year in the optical band (K. Bricman & A. Gomboc 2020), significantly expanding the TDE sample. By combining X-ray and optical telescopes, one can observe TDE emission across multi-wavelengths and constrain their precession patterns, using which one can test precessing disk theories and constrain SMBH spin properties.

APPENDIX

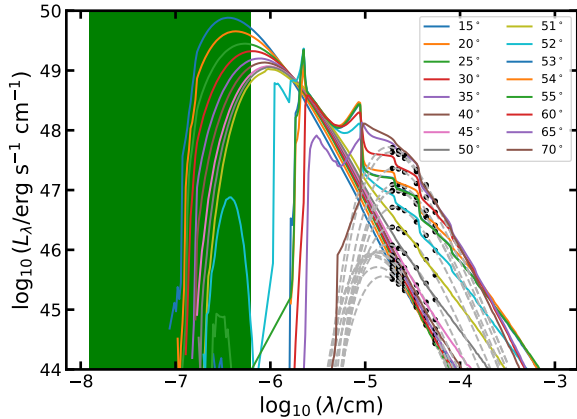


Figure A.1. Escaped continuum emission spectra of a super-Eddington disk with an accretion rate of $\dot{M}_{\text{acc}} = 12 \dot{M}_{\text{Edd}}$. The different colors represent various viewing angle. The green shade area highlights the 0.2 – 10 KeV X-ray band, while the black points denote L_{λ} for the *Swift*/UVOT bands (v, b, u, UVW1, UVM2 and UVW2 filters). The dashed gray lines indicates the blackbody fitting in optical/NUV bands.

A. SPECTRA OF A SUPER- EDDINGTON DISK IN DIFFERENT INCLINATIONS

B. PRECESSION TIMESCALE

The combined LT torques across different regions of the disk drive its precession. The precession period de-

pends on the density of the disk surface ($\Sigma(R) \propto R^{-\zeta}$), the inner and outer radii of the precessing disk (R_{in} and R_{out}), as well as the mass and spin of the SMBH (N. Stone & A. Loeb 2012; J.-H. Chen et al. 2022). It can be expressed as:

$$T_{\text{pre}} \simeq \frac{\pi c^3}{|a| G^2 M_{\text{h}}^2} \frac{\int_{R_{\text{in}}}^{R_{\text{out}}} R'^{3/2} \Sigma(R') dR'}{\int_{R_{\text{in}}}^{R_{\text{out}}} R'^{-3/2} \Sigma(R') dR'} \quad (\text{B1})$$

$$= T_{\text{LT}} g(r_{\text{out}}, \zeta),$$

where

$$T_{\text{LT}} = \frac{\pi c^3}{|a| G^2 M_{\text{h}}^2} R_{\text{in}}^3 \quad (\text{B2})$$

represents the LT precession period for a gas particle located in the innermost circular orbit R_{in} . Here, M_{h} denotes the SMBH's mass, and a is the dimensionless spin parameter. The function

$$g(r_{\text{out}}, \zeta) = \frac{\int_{r_{\text{in}}}^{r_{\text{out}}} r'^{3/2} \Sigma(r') dr'}{\int_{r_{\text{in}}}^{r_{\text{out}}} r'^{-3/2} \Sigma(r') dr'} \quad (\text{B3})$$

depends on the ratio $r_{\text{out}} \equiv R_{\text{out}}/R_{\text{in}} \gg 1$ and the power-law index of the surface density ζ .

When $\zeta \gtrsim 5/2$, the function $g(r_{\text{out}}, \zeta)$ approaches unity. In this case, the inner part of the disk contributes the majority of the LT torques responsible for the precession, resulting in rapid precession with a period $T_{\text{pre}} \sim T_{\text{LT}}$. In contrast, if $\zeta \lesssim -1/2$, then

$g(r_{\text{out}}, \zeta) \simeq r_{\text{out}}^3$. Here, the outer part of the disk contributes most of the LT torques, leading to slow precession with a period $T_{\text{pre}} \sim T_{\text{LT}} r_{\text{out}}^3$.

The inner radius of the disk, R_{in} , can be approximated as the innermost stable circular orbit, which depends on the spin of the SMBH. For a prograde ($a > 0$) or retrograde ($a < 0$) orbit, it is given by:

$$R_{\text{in}} \simeq \left(3 + Z_2 - \frac{a}{|a|} \sqrt{(3 - Z_1)(3 + Z_1 + 2Z_2)} \right) R_g, \quad (\text{B4})$$

where $Z_1 = 1 + (1 - a^2)^{1/3} [(1 + a)^{1/3} + (1 - a)^{1/3}]$ and $Z_2 = (3a^2 + Z_1^2)^{1/2}$. For prograde and retrograde orbits with the maximum spin $|a| = 1$, $R_{\text{in}} = 1, 9R_g$, respectively, where $R_g = GM_h/c^2$ is the gravitational radius.

For a newly formed TDE disk, R_{out} is expected to be close to the circularization radius, roughly $2R_T$, while $R_T = R_*(M_h/M_*)^{1/3}$ being the tidal radius. Consequently, we obtain $r_{\text{out}} \simeq 10$ and $10^2(M_h/10^6 M_\odot)^{-2/3}(R_*/R_\odot)(M_*/M_\odot)^{-1/3}$ for prograde and retrograde orbits, respectively.

If the inner part of the disk governs the LT precession, the precession occurs rapidly with a period $T_{\text{pre}} \simeq T_{\text{LT}} \simeq 10$ to $10^3 |a|^{-1} (M_h/10^6 M_\odot)$ s. The lower and upper values correspond to the prograde and retrograde orbits, respectively. This could potentially explain some QPO-like signals observed in TDEs with short periods. In contrast, if the outer part of the disk dominates the LT precession, the precession is slow, with a period r_{out} times that of the previous one, spanning timescales from days to years.

C. ALIGNMENT TIMESCALE

Typically, the precession of a thick disk can persist for a long time, continuing until the disk becomes geometrically thin. Here, we examine two mechanisms that drive the alignment process, as outlined in A. Francini et al. (2016). The first mechanism involves viscous shear, which dissipates the disk's precession energy at a rate proportional to α , the dimensionless viscosity parameter. The corresponding alignment timescale is given by

$$t_{\text{Bate}} \simeq \alpha^{-1} \left(\frac{H}{R} \right)^2 \frac{\Omega}{\omega^2}. \quad (\text{C5})$$

Here, H/R represents the relative scale height, and $\Omega = (GM_h/R^3)^{-1/2}$ is the Keplerian angular velocity at the outer radius R_{out} , as detailed in M. R. Bate et al. (2000).

The second mechanism comes into play as the accretion rate decreases. The disk gradually cools to $\alpha \gtrsim H/R$, at which point the propagation of the warp within the disk becomes diffusive. This leads to rapid damping of any warps and subsequent alignment of the

disk, as discussed in J. M. Bardeen & J. A. Petterson (1975) and R. P. Nelson & J. C. B. Papaloizou (1999). For a thick disk, which is typical in TDEs, $\alpha \lesssim H/R$ initially holds true. Consequently, warp propagation is wave-like, resulting in rigid precession of the disk. This scenario was considered in N. Stone & A. Loeb (2012), where the alignment timescale was calculated as:

$$t_{\text{SL}} \simeq t_{\text{fb}} \left(15 \frac{f}{X} \frac{\dot{M}_{\text{peak}}}{\dot{M}_{\text{Edd}}} \frac{R_g}{R_{\text{out}}} \right)^{3/5}. \quad (\text{C6})$$

In this equation, $f = 1 - (R_{\text{in}}/R)^{1/2}$ and $X = \alpha/(1 - 8\alpha^2/3f)$. $\dot{M}_{\text{peak}} \simeq M_*/3t_{\text{fb}}$ is the peak mass fall-back rate with a corresponding timescale t_{fb} . $\dot{M}_{\text{Edd}}$ is the Eddington mass accretion rate defined as $\dot{M}_{\text{Edd}} \equiv L_{\text{Edd}}/(\eta_{\text{NT}} c^2)$, where L_{Edd} is the Eddington luminosity, and $\eta_{\text{NT}} \simeq 0.12$.

Combining these two mechanisms, the alignment timescale can be estimated as

$$t_{\text{align}} = \min(t_{\text{Bate}}, t_{\text{SL}}). \quad (\text{C7})$$

Assuming the outer radius of the precessing disk is $R_{\text{out}} \simeq 2R_T$ and that the disrupted star is a Sun-like star, Figure C.1 presents the alignment timescale for different SMBH mass and spin.

Generally, disk cooling is the main driver of alignment, resulting in $t_{\text{align}} \simeq t_{\text{SL}} \propto \alpha^{-3/5}$. The corresponding timescale typically ranges from one to several years. If the SMBH's mass is $\gtrsim 10^7 M_\odot$ and its spin is $|a| \gtrsim 0.2$, the viscous dissipation becomes efficient, leading to $t_{\text{align}} \simeq t_{\text{Bate}} \propto \alpha^{-1}$ and a faster alignment timescale of a few months. However, in reality, the inflowing debris stream can introduce additional misaligned angular momentum into the disk upon joining, potentially prolonging the alignment timescale.

The TDE candidate AT2020ocn is believed to have a precessing disk. Its quasi-periodic X-ray variability is associated with changes in viewing angle, exhibiting a 10-day period (Z. Cao et al. 2024). More intriguingly, its variability displays an overall decreasing trend over approximately 200 days, which implies the alignment process.

Magnetic forces also play a crucial role in disk alignment. Some studies demonstrate that magnetically arrested disks (MADs) are compelled to align with the black hole's spin axis due to the saturation of magnetic flux in the black hole's ergosphere and inner accretion disk. As the black hole rotates, it twists this saturated magnetic flux. In the MAD state, the magnetic field exerts a dominant influence on the dynamics of the inner disk. Consequently, the inner disk adjusts its orientation in accordance with the alignment of the magnetic

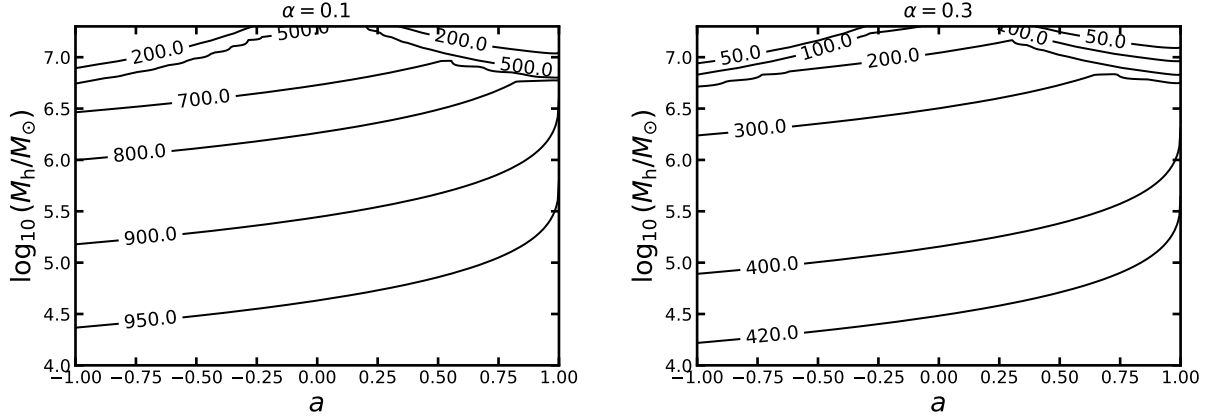


Figure C.1. Alignment timescale of a precessing disk, formed by the disruption of a Sun-like star by a SMBH with different mass and spin. The left and right panels represent the results with $\alpha = 0.1$ and $\alpha = 0.3$, respectively. The contour lines indicate the alignment timescale t_{align} in unit of day.

field (J. C. McKinney et al. 2013; S. M. Ressler et al. 2023; K. Chatterjee et al. 2023; P. C. Fragile & M. Liska 2024). However, the efficiency of this forced alignment depends on the strength and radial extent of the magnetic saturation. Currently, several key questions remain unanswered. For instance, it is uncertain whether the magnetic field strength in the thick disk formed during a TDE is adequate to maintain a MAD state. Additionally, the precise level of magnetic flux required for rapid alignment remains an open question.

ACKNOWLEDGMENTS

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