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Repeated Tidal Disruption: an Unluckiest Star

1 Introduction

If a star comes close to a supermassive black hole, the size of the star cannot be neglected, the star feels a tidal force that squeezes it. If it comes too close and crosses the tidal radius, the black hole's tidal forces dominate over the star's self-gravity. The star will be torn apart. The shatters will form an accretion disk. See figure 1. The tidal radius is given by

$$R_{\rm t} = R_* \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3} \tag{1}$$

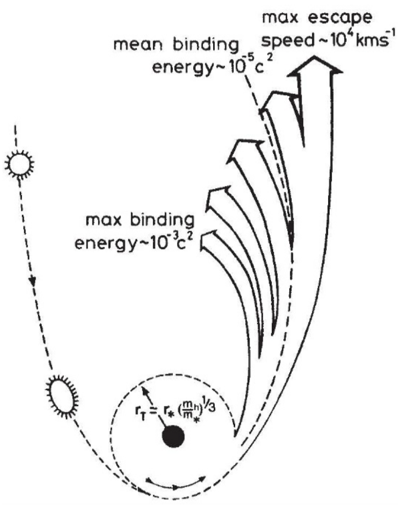

Figure 1: A solar-type star approaching a massive black hole on a parabolic orbit with pericenter distance r_T is distorted and spun up during infall, and then tidally disrupted.

One should note that if the SMBH is more massive than $\approx 10^8 M_\odot$, the tidal radius lies within the event horizon and no TDE can occur. Another useful parameter is the penetration factor or strength of encounter.

$$\beta \equiv \frac{r_t}{r_p} \tag{2}$$

where r_p is the pericenter distance. If a star has enough energy and only grazes the tidal radius with relatively less penetration, a fraction of the stellar mass will be accreted in a **partial TDE** (pTDE). However, if the star's kinetic energy is somehow dissipated, and the star is captured and bounded to the black hole, the remainder can continue orbiting and may re-disrupted whenever passing through pericenter after completing a next cycle, causing a **repeated pTDE** (or simply repeated TDE, since repeated TDE must be partial TDE). One may ask if we can distinguish the pTDE and the full TDE by finding a critical penetration value. However, β is not the main factor to determine if it is a partial TDE or full TDE.

According to the simulation result, the criterion depends on the density profile of the star cluster [1] and the stellar structure.

2 Observation

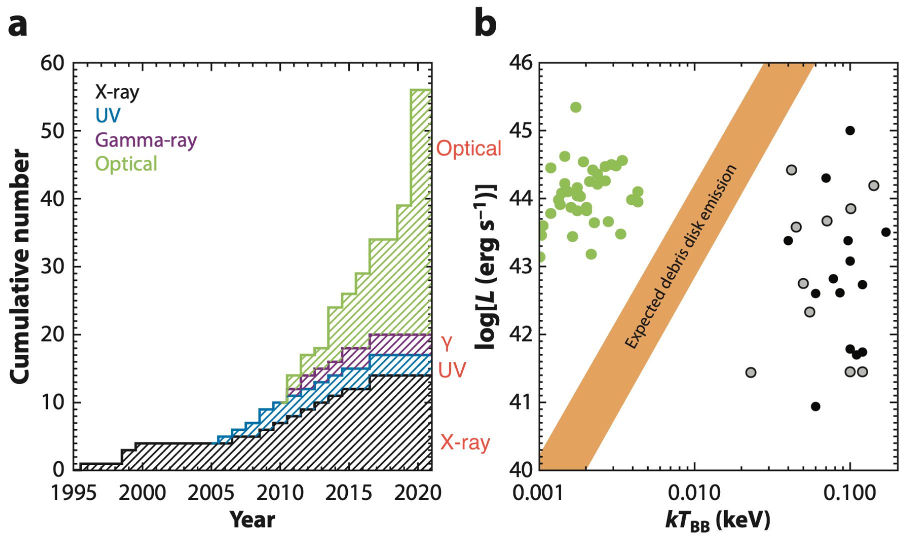

Figure 2: (a) Cumulative histogram of TDEs reported in the literature, color-coded by the wavelength in which they were discovered: X-ray (*black*), UV (*blue*), gamma-ray (*purple*), and optical (*green*). (b) Peak luminosity versus blackbody temperature for 56 TDEs reported in the literature, color-coded by the wavelength in which they were discovered: UV-optical (*green*), X-ray (*black*), and 10 of the UV-optically selected TDEs with detected X-ray components (*gray*) [2]

The discovery of TDE has been limited by their relatively low occurrence rate of about 10^{-4} – $10^{-5}\text{galaxy}^{-1}\text{yr}^{-1}$. From the late 1990s to the late 2000s, only ~ 10 TDEs had been discovered. Most of them are identified in the X-ray bands. The plan of detecting the repeated TDE was paid less attention by the telescopes, which also caused the low rate of discovery. In the last decade, however, more TDEs have been discovered by wide-field optical surveys, such as the All Sky Automated Survey for Supernovae (ASAS-SN), the Asteroid Terrestrial-impact Last Alert System (ATLAS) survey, and the Zwicky Transient Facility (ZTF), and the current number of TDEs has greatly increased to ~ 100. See in figure 2. Most of these TDEs are bright in optical/UV wavelengths but much fainter in X-rays, contrary to those earlier discovered TDEs. The origin of optical/UV emission is still under debate. As a result, there is not a mature and standard method of identifying a repeated pTDE. The identification of optical/UV TDEs is empirical, relying on the features of the former samples.

2.1 The identification of AT2022dbl

Confirmation of a repeated pTDE requires not only evidence to rule out other types of transients but also proof that only one star is involved, as TDEs from multiple stars can also produce similar flares. Very recently in this summer, a group claimed to identify the first spectroscopically confirmed repeated pTDE: AT 2022dbl [3]. Their identification is inspired by Somalwar et al. [4] We follow their work to go through the classification process.

The discovery of the first flare was in 2020. The UV and optical band spectrum of the first flare mainly came from Swift Ultra-Violet/ Optical Telescope (UVOT). There is no bright X-ray, radio, or mid-infrared counterparts. The recurring flare is observed on 2024 January 22. Its rise stage is well covered by the ZTF

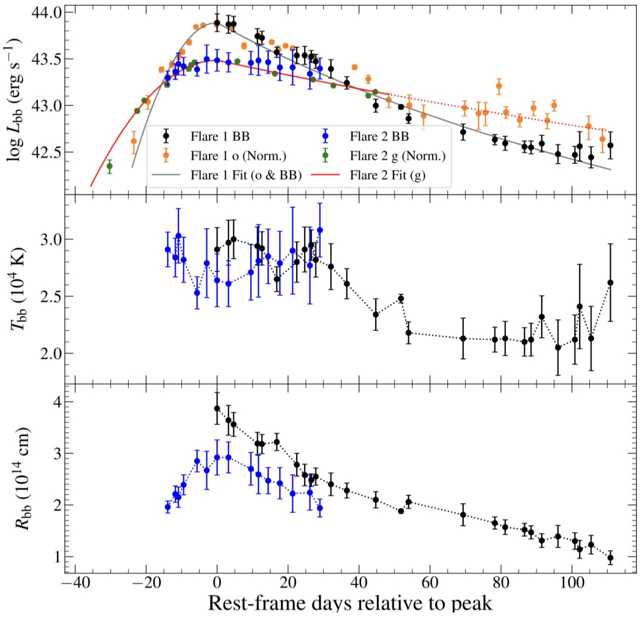

Figure 3: Luminosity, temperature and radius variation of AT2020dbl [3].

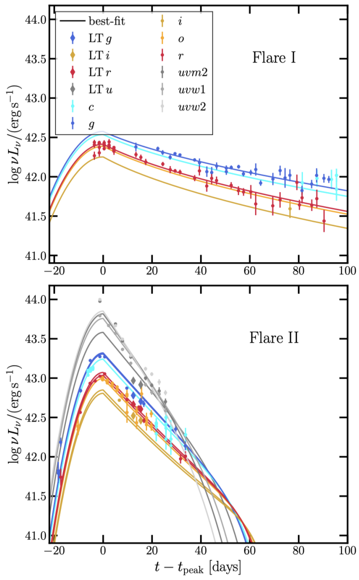

Figure 4: The light curve of AT2020vdq. The shape and the peak luminosity of the two flares are highly different, which seems not to be a repeated TDE [4].

and Las Cumbres Observatory (LCO) g band. However, Swift has unfortunately entered safe mode since 2024 March 15, which was exactly when the source left the peak. Therefore, the decline stage is sparsely covered by the ZTF g and ATLAS o bands.[1]

2.1.1 Photometric analysis

Characterize the light curves of both flares by the rest frame rise time from half-peak luminosity to peak luminosity ($t_{1/2,\text{ rise}}$) and the decline time from peak luminosity to half-peak luminosity ($t_{1/2,\text{decline}}$). To extract these two timescales, a traditional way is to fit the light curves with a Gaussian rise and a power-law decline [4]:

$$L(t)=L\left(t_{\text{peak}}\right)\times\begin{cases}e^{-\left(t-t_{\text{peak}}\right)^2/\left(2\sigma^2\right)}, & t<t_{\text{peak}}\\ \left(\frac{t-t_{\text{peak}}+\tau}{\tau}\right)^\alpha, & t\geqslant t_{\text{peak}}\,.\end{cases} \tag{3}$$

As shown in figure 5, the rise and the decay time of both two flares are only a dozen days, which highly disfavor the origin of AGN. (Actually, the absence of a strong X-ray band counterpart of the flare can help us rule out a turn-on AGN, which usually lasts for several to hundred years) If we know its luminosity L_{BB}, perhaps the most convenient way is to treat the transient as a blackbody and get the black body temperature T_{BB} and blackbody radius R_{BB}. The best-fit results are displayed in figure 3. T_{BB} slowly declines from 3×10^4K to 2×10^4K. R_{BB} smoothly declines from 4×10^{14}cm to 1×10^{14}cm.

Flare (No.)	t_{peak} (MJD)	$L_{\text{BB,peak}}$ (log (erg s^{-1}))	$T_{\text{BB,peak}}$ (10^4 K)	$R_{\text{BB,peak}}$ (10^{14} cm)	$t_{1/2,\text{rise}}$ (days)	$t_{1/2,\text{decline}}$ (days)
1	59637.6	43.89 ± 0.10	2.91 ± 0.19	3.87 ± 0.31	10.6 ± 0.5	15.7 ± 0.8
2	60346.6	43.48 ± 0.12	2.64 ± 0.23	2.92 ± 0.34	16.8 ± 0.5	36.9 ± 2.4

Note. $t_{1/2,\text{rise}}$: the rest-frame rise time from half-peak luminosity to peak luminosity. $t_{1/2,\text{decline}}$: the rest-frame decline time from peak luminosity to half-peak luminosity.

Figure 5: The Best-fit Light-curve Parameter for the Two Flares [3].

[1]While originally designed for the study of gamma-ray bursts, Swift now functions as a general-purpose multi-wavelength observatory, particularly for the rapid follow-up and characterization of astrophysical transients of all types.

2.2 Optical spectroscopic Analysis

This is the most important part of identification. There are five spectra in figure6. The top three spectra are from the first flare and the bottom 2 are from the second. Both flares show broad Hα emission with FWHM(Full Width at Half Maximum) $> 10000\text{km}\cdot\text{s}^{-1}$ and declining blackbody radii after the peak, which disfavor the origin of supernovae.

All of the features that disfavor AGNs and supernovae are nevertheless characteristic of TDEs, including the timescales of both flares, the fairly steady blackbody temperatures of (2–3) $\times$ 10^4 K, the value and evolution of the blackbody radii, and the very broad Hα emission. How do we know that the two flare of two independent TDEs? Both flares display highly similar broad Hα, $\sim 4400-5200$Å (Hβ and possible N III and He II), and ~ 4100Å (N III and possible Hδ) features. Moreover, **the intensity of ~ 4100Å is comparable to that of Hα, which is rare among all TDEs**. This helps us rule out the possibility of two independent TDEs. At last, they concluded that AT2022dbl went through repeated partial TDEs.

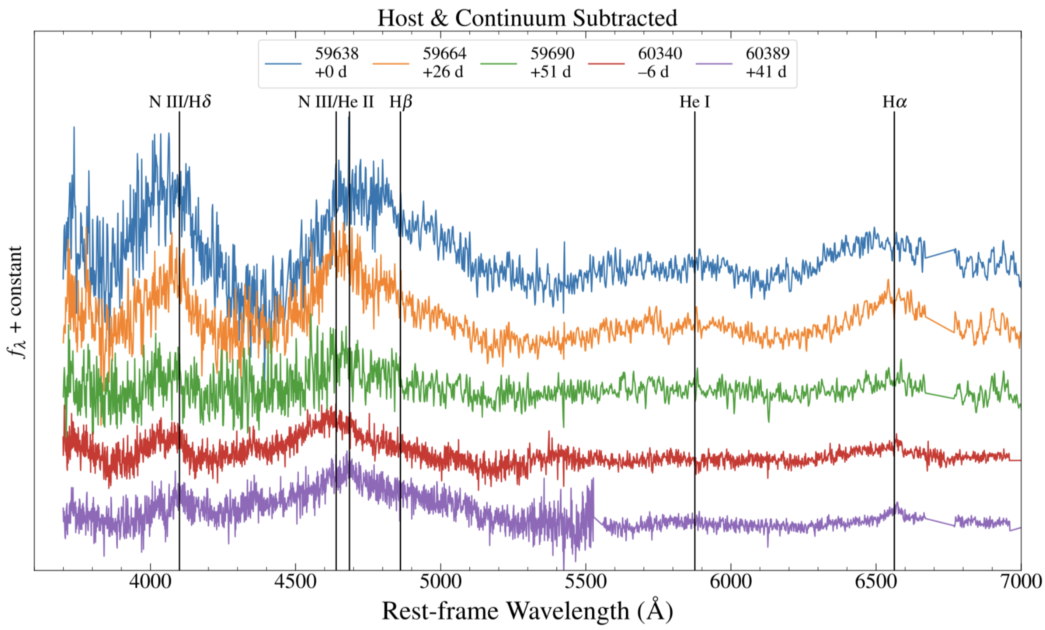

Figure 6: Five Spectra from two flares of AT2022dbl. The top three are from Flare I. The last 2 are from Flare II. All of the spectra show a significant broad Balmer line and NIII line. [3]

2.3 Comparison of other TDEs

As I said, the method used by Lin et al. for identifying AT2022dbl is drawn heavily from Somerlwar et al. who use it to identify AT2020vdq [4]. They examined the case of AT 2020vdq and believe that the evidence is not robust to identify AT2020vdq as a repeated TDE. They pointed out that the light-curve evolution shapes and the peak luminosity of two flares of AT2020vdq are highly different (see figure 4). The most critical issue is that they lack some data to find the spectroscopic connections between the two flares, such as the similar FWHW of the broad Balmer and NIII lines. AT2020vdq system is in a host galaxy that has a relatively higher tidal disruption rate. Somalwar et. al are also aware of these opposing evidence and admitted that in an extreme case, the probability of detecting two independent TDEs within $\sim$ 3yr can be as high as 30%, which implies **AT2020vdq may not be a repeated TDE.**

Nevertheless, we are still free to hold an opposing opinion of the identity of AT2022dbl. The light curves can provide limited information on the judgment of repeated pTDEs by now, as there is currently a lack of reliable optical/UV repeated pTDEs for comparison. A third flare can provide conclusive evidence for a repeated pTDE classification, which might occur in the next couple of years. That is why the author appeals for a more careful plan for multi-wavelength observations of TDEs in the future.

3 Theoretical Model for repeated TDE

3.1 Hills Mechanism

Hills mechanism was originally used to testify the existence of SMBH in the center of our galaxy. It was recently proposed to produce a fast repeated TDE: ASASSN-14ko [5]. A binary star of semimajor axis $a_\star$ and primary mass $M_\star$ that nears an SMBH of mass $M_{\rm BH}$ will be destroyed if it enters the Hills radius of the SMBH,

$$r_{\rm t} = a_\star \left(\frac{M_{\rm BH}}{M_\star}\right)^{1/3}. \tag{4}$$

What makes things different is that the binding energy will be redistributed between the binary. The captured star transports the gravitational energy to another binary, causing its twins to be accelerated with an extremely high velocity (thousands of km/s, which has been discovered in 2019 [6]). Meanwhile, the left one lost more kinetic energy and is tightly bounded by the SMBH with a short period, whose semimajor axis is

$$a_\bullet \simeq \frac{a_\star}{2}\left(\frac{M_{\rm BH}}{M_\star}\right)^{2/3} \tag{5}$$

and period is

$$P_\bullet \simeq P_\star \left(\frac{M_{\rm BH}}{M_\star}\right)^{1/2}. \tag{6}$$

with $P_\star \simeq \pi a_\star^{3/2}/\sqrt{2GM_\star}$. If the captured one is finally placed inside the tidal radius, it will be tidally disrupted. Compared to the period of a single star (cf eq(1)), binaries will naturally orbit more quickly than single stars with a short period. In order to yield a companion star with a fast period of 144 days, they built a feasible parameter set which has the binary star's separation of $a_\star = 0.005\text{au}(1.1R_\odot)$, the black hole of $M_{BH} = 10^7 M_\odot$, and the mass captured star of $M_\star = 1M_\odot$. They change the initial periastron of the binaries (β ranging from 2 to 4, beyond which will cause the capture of both the binaries), and perform a three-body integration to get a statistical result of the circular motion. Their simulation shows that the most probable value of the simulations meets the theoretical analysis very well and that the results are not sensible to the initial given β. This is the evidence that favors the Hills mechanism explanation for fast repeated TDEs.

However, the problem is that **the reduction in the orbital period of the captured star owing to gravitational-wave emission for their set of parameters did not meet the observations and also did not meet the simulation very well**. Observations gives $\dot{P} = -0.002$ but theoretical results gives $\dot{P} \simeq -10^{-6}$ for $\beta = 2$. Although increasing the penetration parameter will reduce the reduction rate of period, $\beta = 4$ still gives a factor of 10 larger than the observed value. For this, they explain that the period decay in ASASSN-14ko is related to a distinct physical origin, such as the interaction between the star and the active galactic nucleus disk.

Apparently, this model is not so complete but the correct prediction to the period ASASSN-14ko via Hills mechanism is a success. A successive research on the elliptical pTDE model based on Hills mechanism can be found in Lu & Quataert 2023 [7]. There are still a lot of blanks in this direction.

3.2 Eccentric Kozai-Lidov Mechanism

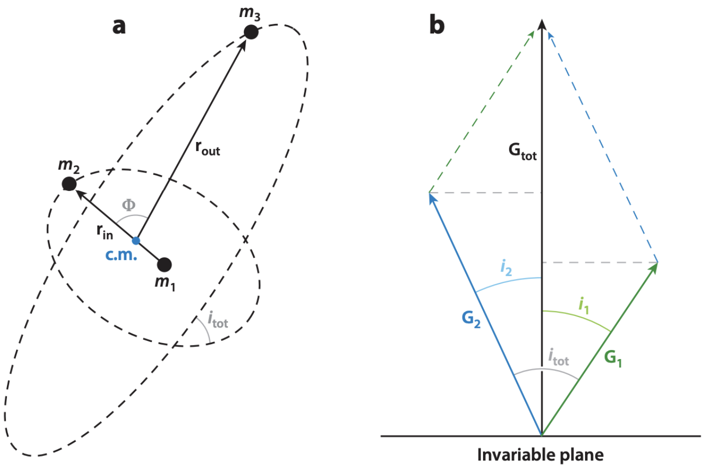

Figure 7: A hierarchical system for Kozai-Lidov mechanism. A farther black hole(perturber) orbits around the center of the disruptor-star system with a large mutual inclination. The perturber tends to shorten the angle, inducing the eccentric of the inner orbit [8].

Recently, the research on the secular perturbations of hierarchical system brought some revelations to the formation of TDE/rTDE. Imagine that a supermassive black hole binaries with a star in their vicinity form a triple system (see figure 7). The second black hole is far away from the BH-star binaries and thus orbits around the center of the mass of the binaries. Such a system has a Hamiltonian in the form like

$$\mathcal{H} = \frac{k^2 m_1 m_2}{2a_1} + \frac{k^2 m_3 (m_1 + m_2)}{2a_2} + \frac{k^2}{a_2} \sum_{n=2}^{\infty} \left(\frac{a_1}{a_2}\right)^n M_n \left(\frac{r_1}{a_1}\right)^n \left(\frac{a_2}{r_2}\right)^{n+1} P_n(\cos\Phi) \tag{7}$$

whereas a_1, a_2 represents the semi-major axis of inner and outer orbit. Φ is the angle between the c.m. and m_3 and the line joining m_1 and m_2. The first term is the energy of m_1 and m_2 doing circular motion. The second term is the energy of m_3 orbiting around the binaries. The third term represents the individual contributions of m_3, m_1 imposed on m_3 and is proportional to the ratio of a_1 and a_2, i.e., $\alpha \equiv a_1/a_2$.

In a hierarchical system, this parameter α is small. If we expand it as a power series of a_1/a_2, the lowest order of approximation, which is proportional to $(a_1/a_2)^2$, is called the **quadrupole term**. Most of the research on Kozai-Lidov Mechanism is based on the assumption that the inner binary is a test particle (Test Particle Quadrupole, TPQ approximation). When only considering quadratic level, Jacobian frame shows that the angular momentum of the inner orbit is a conserved quantity and bridges the eccentricity of the inner orbit e_1 and the inclination angle i_{tot},

$$J_z = \sqrt{1 - e_1^2} \cos i_{\text{tot}} = \text{Const.} \tag{8}$$

The high inclination nature of the plane of the perturber's orbit concerning the inner orbit plane tends to be reduced, which increases the eccentricity of the inner orbit. The pericenter distance, defined as $r_{\min} = a_1(1 - e_1)$, also decreases. In the end, this effect causes an oscillation of pericenter distance about a constant value, which in turn leads to a periodic exchange between its eccentricity and inclination. The total effect is that large mutual inclinations between bodies can excite eccentricities from near-circular. It can even flip an initially moderately inclined orbit between a prograde and a retrograde motion. The process occurs on timescales much longer than the orbital periods.

Although the Eccentric Kozai-Lidov mechanism was obtained in the 1970s, it was largely ignored for many years. Recently, Naoz et al. [9] showed that relaxing of TPQ assumptions leads to qualitatively different dynamical evolution. Considering systems beyond the test particle approximation requires the next level of approximation, called the octupole level of approximation.

$$\text{octupole term} \propto (\frac{a_1}{a_2})^3 = \frac{a_1}{a_2}\frac{e_2}{1-e_2^2}. \tag{9}$$

This also means the perturber's orbit is not circular. Under this condition, the angular momentum is not conserved but is **transferred between the inner orbit and the outer orbit**. This transfer shrinks the minimum of the minimum of the oscillation of the eccentricity. As a result, the pericenter distance will go through a secular descent until reaches the minimum determined by the minimum inclination angle($\cos i_{\rm tot,min} \approx \sqrt{3/5}$). In this place,

$$e_1 = e_{1,max} \approx 1 - \frac{5}{3}J_z^2 \tag{10}$$

Now, if the minimum of the pericenter distance falls into the tidal radius of the disruptor, a TDE occurs. Moreover, this change is also a period behavior, which means if the star survived in the first encounter, the angular momentum will be given back, and the pericenter distance will go through secularly ascents and descents. Every time it reaches the minimum of $r_{\rm min}$, it will be striped by the black hole. This forms the repeated TDE. The calculation of pericenter distance when considering octupole terms is shown in figure 8.

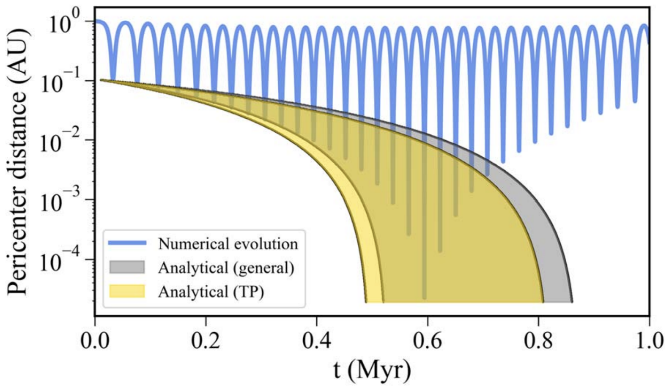

Figure 8: The variation of the pericenter distance($\equiv a_1(1-e_1)$) calculated from eccentric Kozai-Lidov mechanism. The blue line is the oscillation accompanied by the extraction and injection of the angular momentum from the perturber black hole. If the star falls in the tidal radius and survives in the first encounter, it will go back in the next cycle and form a repeated TDE. Weldon et al built models to follow the minimum of each oscillations [10].

Nazo's student, Weldon, tried to find two analytical models for the form and timescale of the secular descent [10]. One is suitable for the large inclination initial condition, another is for the general condition. The strength of the first analytical model lies in this ability to estimate the changes in eccentricity and pericenter distance during each cycle, which can be pieced together to approximate the full secular descent. Both the first and the second model could predict the minimum eccentricity of each oscillation. The spread in the shaded regions represents the $\sim 25\%$ variations in the numerical factor obtained from Monte Carlo simulations. This model has a lot of space to improve since their error from the numerical simulation is quite large.

However, the most important question of this work is that they didn't give a clear connection between the repeated tidal disruption event and their models. The paper also didn't cite any observational results to testify the models. This is partially due to the less evidence and the difficulty of recognizing repeated pTDEs. Anyway, secular perturbation is not always the main reason to generate a TDE. This model is insightful for studying the pericenter evolution of the star near the black holes, and it gives a new perspective on studying the theory of repeated pTDE.

3.3 Combination of Two-body Relaxation and EKL Mechanism

Two-body relaxation is an important mechanism in a system with many stars (galactic nucleus or star clusters, figure 9 is a diagram). The overall gravitational potential is influenced by all the stars, creating a "smooth background potential". However, the background potential does not directly cause relaxation. Instead, relaxation is driven by *deviations* from the smooth potential, which arises from local two-body interactions. Thus, the smooth potential governs the general motion of stars, while (tow-body) relaxation encounters introduce long-term changes and drive the system towards a more statistically uniform or thermally "relaxed" state. It can alter the angular momentum of stars at large distances and place them into nearly radial orbits, thus driving them to disruption. Although the relaxation has a timescale much longer than the timescale of EKL and is always neglected in previous research, the change rate of the angular momentum relaxation is quite comparable. The change in angular momentum h is $h/\Delta h \approx t_{\rm EKL}/P_\star$ for the EKL mechanism and $h/\Delta h \approx \sqrt{t_{\rm rlx}/P_\star}$ for two-body relaxation [11].

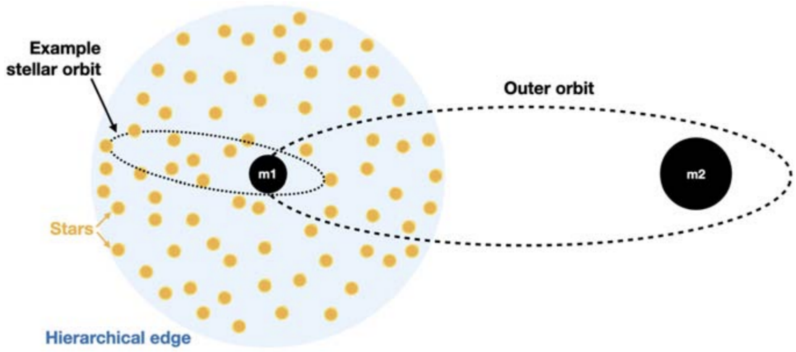

Figure 9: Diagram of two body relaxation and EKL mechanism [12].

Thus, Melchor et al. combined the Effects of Two-body Relaxation and the Eccentric Kozai–Lidov Mechanism [12]. Compared with the previous model that included the higher order perturbation, they used the traditional test particle quadratic term and didn't consider the octupole effects of EKL mechanism. Their simulations show that for a system that never had its eccentricity excited to cause a TDE when only considering EKL, in the EKL and two-body relaxation scenario, the star's pericenter crossed the tidal radius, signifying a TDE. Moreover, the star will repeatedly reach the tidal disruption radius if it does not enter the dead zone totally(The figure is not shown here paper, see the original paper [12]).

As mentioned before, Hill's Mechanism also boosts the probability of repeated TDE. Figure 10 shows their efforts in trying to sort the recognized TDE with different mechanisms. They claimed to find the corresponding minimum period for a repeated TDE caused by Hills Mechanism by simply taking the semimajor axis as 2 times the radius of the binary members. This value seems to be 1000 years in the figure(the initial time value of the shade). They believe that the long-period J1331 could have originated from the Hills mechanism, while the other potential rTDEs seem to be consistent with the channel described here. However, in their figure, the ASASSN-14ko is classified as a TDE induced by EKL and two-body relaxation. This is evidently contradicted to the result and motivation mentioned in the previous section, which used Hill's Mechanism to explain the fast repeated TDEs ASASSN-14ko. They insist that there is a lower limit of the period that was generated by Hills Mechanism, which is determined by the minimum

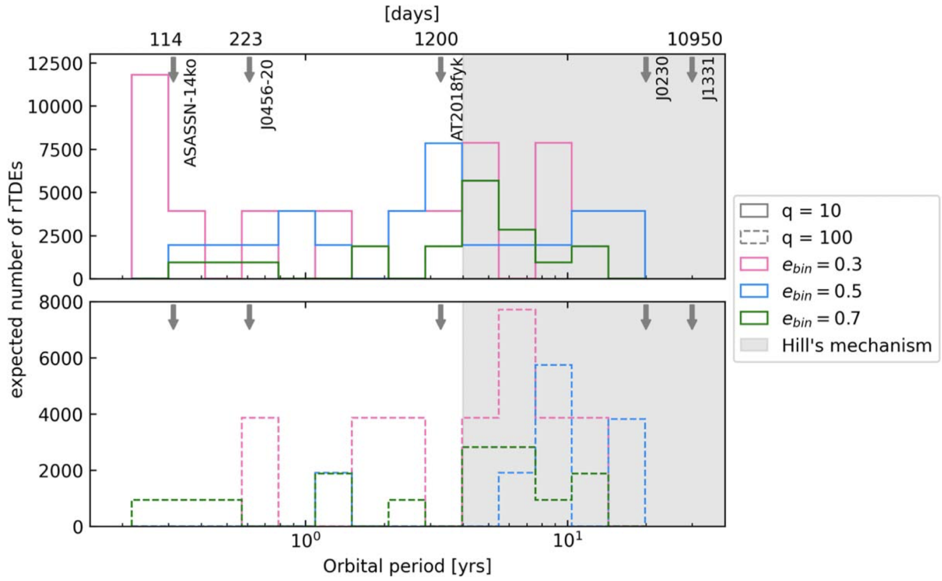

Figure 10: A controversial classification of repeated TDE based on the mechanism of formation. ASASSN-14ko is excluded from the Hill's mechanism zone, which is contradicted to the motivation of introducing Hills Mechanism [12].

distance of a tightly bounded binary(the diameter of the star for two identical twins). This criterion of classification in their paper lacks detailed derivation, which turns out to be puzzling and immature. The contradicted classification of ASASSN-14ko shows that we still know less about the formation of repeated TDE.

General relativity precession

What else factors affect the rate of TDE? In Melchor et al, they also mentioned the role of general relativity(GR). EKL mechanism excites the eccentricity but has a competitor—GR precession. The point of periastron shifts slightly with each cycle by an angle of

$$\Delta\phi \approx \frac{6\pi GM}{c^2 a(1-e^2)}.$$

Thus, GR precession will (always) suppress the eccentricity excitation from EKL. To determine which effect is the winner, they calculate the timescale of the EKL and GR precession. For $m_{\text{disruptor}} > m_{\text{perturber}}$, GR precession dominates the EKL eccentricity excitations, thus suppressing TDE formation. On the other hand, when $m_{\text{disruptor}} < m_{\text{perturber}}$, the EKL eccentricity excitation timescale is faster than GR precession. In their work, in order to excite the eccentricities more efficiently, they just choose $m_1 < m_2$ by a factor of 10 or 100. For example, the primary black hole is of mass $m_1 = 10^7 M_\odot$ with a secondary of $m_2 = 10^9 M_\odot$.

However, since the parameter is chosen to reduce the influence of GR precession, they are not believed to discuss this mechanism thoroughly. We may choose $m_1 > m_2$ (in which the timescales fall in the right part of Figure) such that GR precession is dominant, and combine the GR and Hills Mechanism caused by the tightly bounded binary stars, or consider the octupole term in EKL mechanism caused by the gravitational potential perturbation of a farther black hole. The combination of these different mechanisms may bring a different behavior for a star near the black hole.

4 Summary

We introduced the observational progress of identification of repeated TDE in this paper. By photometric and spectroscopic analysis, AT2022dbl is recognized to be an optical/UV repeated TDE. The same luminosity of NIII and Hα of the two flares strongly suggests its identical origin. Yet a third flare in the next several years may further testify this conclusion. This is a ground-breaking discovery in the area of repeated TDE.

Theoretical study falls far behind the observations. Several promising mechanisms are introduced to understand the formation of repeated TDEs. A binary star system which was destroyed in the vicinity of the black hole may form a tightly bounded star, but the gravitational wave emission rate doesn't match the theory. The perturbation of a third body with a large mutual inclination induces the secular descent and ascent of the pericenter distance and may cause a repeated TDE. Apart from that, the combination of the two-body relaxation and EKL shows the chaos of the oscillation of pericenter distance. These different factors all introduce many-body movements. But the classification based on different mechanisms is still highly debated.

Further theory model relies heavily on observations. With the assistance of high-cadence optical/UV/X-ray photometric and spectroscopic data, we can take the chance to collect important clues to the mechanism of optical/UV emission of TDEs. As the next-generation "TDE hunters" come into play, such as the Vera Rubin Observatory and the Wide Field Survey Telescope, the high-cadence multi-band surveys are expected to reveal a number of such pTDEs and accelerate the process of solving these puzzles in the near future.

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