Disk formation versus disk accretion—what powers tidal disruption events?

TSVI PIRAN[1], GILAD SVIRSKI[1], JULIAN KROLIK[2], ROSEANNE M. CHENG[2], AND HOTAKA SHIOKAWA[2]
[1] Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem 91904, Israel
[2] Physics and Astronomy Department, Johns Hopkins University, Baltimore, MD 21218, USA

Speaker：Xu Xian

2024.4.12

- ***Introduction***

- ***TDE model – disk formation***

- ***Comparison with observations***

- ***Summary***

Introduction

- When a star passes close enough to a supermassive black hole (SMBH), it will be tidally disrupted. —TDE

the pericenter distance r_p smaller than the tidal radius r_T

$$r_\mathrm{T} = R_\mathrm{star}\left(\frac{M_\mathrm{BH}}{M_\mathrm{star}}\right)^{1/3} \quad \longleftarrow \quad \frac{GM_\mathrm{BH}R_\mathrm{star}}{r^3} = \frac{GM_\mathrm{star}}{R_\mathrm{star}^2}$$

- Motivation—a growing number of TDE candidates have been recently discovered in the optical. But the recent optical TDE observations are difficult to reconcile with theoretical expectations, in which the optical signal is due to accretion onto the black hole.

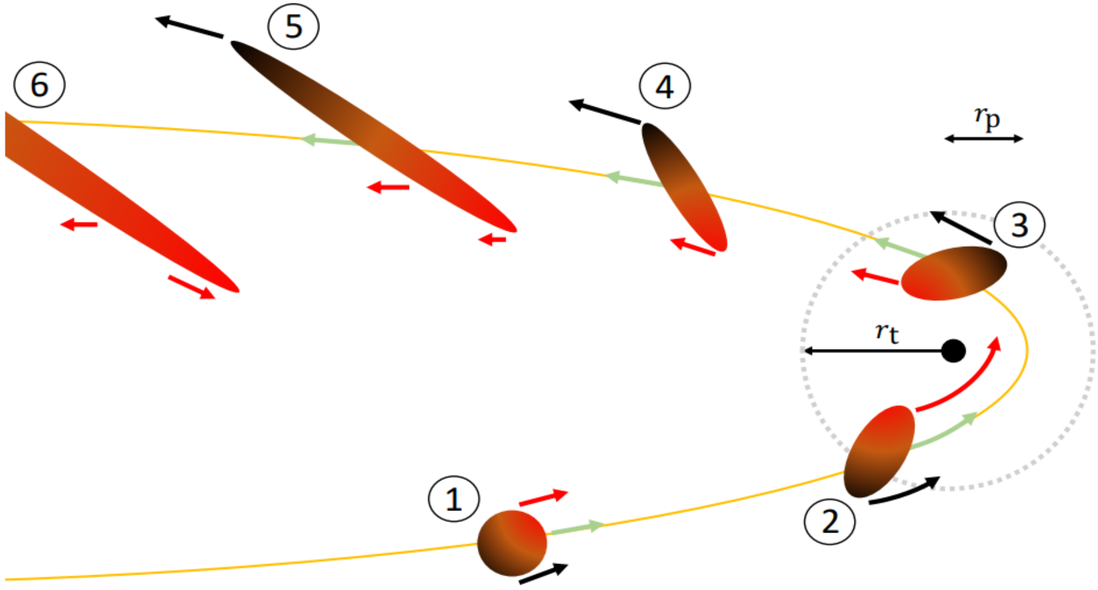
Introduction

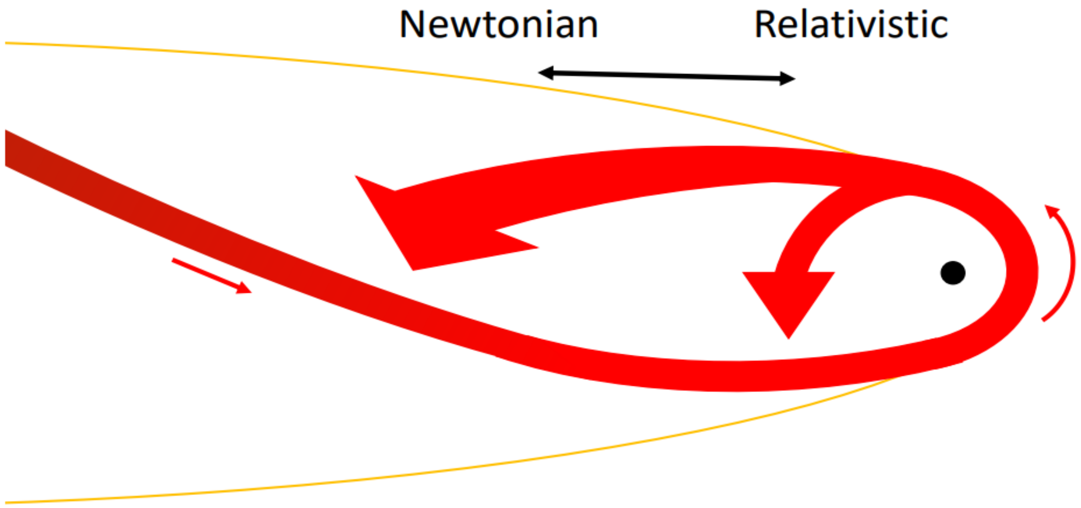
- classical TDE picture

the semimajor axis of the most bound matter

$$a_{\min} \simeq (1/2)R_T^2/R_* \sim (M_{\rm BH}/M_*)^{1/3}R_T \gg R_T$$

the most bound debris returns, turns around the black hole, and collides with a newly returning stream. The collision occurs at shorter distances as relativistic apsidal precession becomes stronger





(Wevers T. & Ryu T., 2023, arXiv:2310.16879)

Introduction

- classical TDE picture

Streams returning at different times to shock against each other and dissipate sufficient orbital energy to compress these very extended, highly elliptical orbits into approximately circular orbits with radii ~2 r_p.
The inflow time through the accretion disk that then forms is estimated to be ≪ t0, so that the accretion rate onto the black hole closely tracks the mass return rate of the tidal streams.

$$T = \frac{\pi G M_{BH}}{\sqrt{2}}(-e)^{-3/2} \quad \rightarrow \quad \frac{de}{dt} = \frac{(2\pi G M_{BH})^{2/3}}{3t^{5/3}}$$

$$\frac{dm}{dt} = \frac{dm}{de} \cdot \frac{(2\pi G M_{BH})^{2/3}}{3} \cdot t^{-5/3}$$

If so, the bolometric light curve should peak at

$$\sim t_0 \sim 2 \times 10^6 M_{BH,6.5}^{1/2}\ \mathrm{s}$$

after the star is destroyed, reaching a maximum luminosity

$$\sim 2 \times 10^{46} M_{BH,6.5}^{-3/2}\ \mathrm{erg\ s^{-1}}$$

and then decay

$$\propto (t/t_0)^{-5/3}$$

within this model, the effective temperature of the peak would be

$$\sim 4 \times 10^7 M_{BH,6.5}^{-7/2}\ \mathrm{K}$$

Introduction

This simple model now faces serious problems when confronted with observations of optical TDE candidates.

Although optical light curves of these events show (in rough terms) the expected $t^{-5/3}$ decline. The observed temperature and bolometric luminosity are significantly lower than predicted. $\sim 2\text{–}3 \times 10^4$ K, $\sim 10^{43}\text{–}10^{44}$ erg s^{-1}

The assumptions behind the classical TDE picture have been criticized by many authors.

Introduction

the assumption that the gas circularizes immediately upon returning to the vicinity of the black hole, and that it does so on the scale of the tidal radius

→ Shiokawa et al. (2015) took up this question using detailed numerical simulations.

They found that the circularization process is slower than previously thought

$$\simeq (5 - 10) t_0$$

and leaves most of the debris at radii closer to $a_{\rm min}$ than $r_{\rm T}$ because the principal shocks are located at that scale.

And demonstrated that circularization may remain incomplete even at the end of the event.

TDE model – disk formation

- several parameters

$$R_* = R_\odot \mathcal{M}_*^{1-\xi} \qquad \mathcal{M}_* \equiv M_*/M_\odot$$

f : the ratio of the gravitational binding energy of the star to GM_*^2/R_*

k : the apsidal motion constant

fiducial value $k/f = 0.08$

$$\rightarrow \quad R_T \approx 6.7 \times 10^{12} \left(\frac{k/f}{0.08}\right)^{1/6} \mathcal{M}_*^{2/3-\xi} M_{\mathrm{BH},6.5}^{1/3} \ \mathrm{cm}$$

$$t_0 \approx 1.8 \times 10^6 \left(\frac{k/f}{0.08}\right)^{1/2} \mathcal{M}_*^{(1-3\xi)/2} M_{\mathrm{BH},6.5}^{1/2} \ \mathrm{s}$$

$$a_{\min} \approx 3.2 \times 10^{14} \left(\frac{k/f}{0.08}\right)^{1/3} \mathcal{M}_*^{1/3-\xi} M_{\mathrm{BH},6.5}^{2/3} \ \mathrm{cm}$$

$$\dot{M}_0 \approx \frac{M_*}{3t_0}$$

the maximal mass return rate

$$\approx 3.6 \times 10^{26} \left(\frac{k/f}{0.08}\right)^{-1/2} \mathcal{M}_*^{(1+3\xi)/2} M_{\mathrm{BH},6.5}^{-1/2} \ \mathrm{gm\ s^{-1}}$$

TDE model – disk formation

the outer shock heating rate

$$\dot{E}_{\rm peak} \sim \frac{GM_{\rm BH}\dot{M}_0}{a_{\rm min}} \approx 5 \times 10^{44}\left(\frac{k/f}{0.08}\right)^{-5/6} \times \mathcal{M}_*^{1/6+5\xi/2} M_{\rm BH,6.5}^{-1/6}\ {\rm erg\ s^{-1}},$$

the blackbody temperature of the apocenter radiation

$$T \sim 5.1 \times 10^4\ {\rm K}\left(\frac{k/f}{0.08}\right)^{-3/8} \mathcal{M}_*^{-\frac{1}{8}+\frac{9\xi}{8}} M_{\rm BH,6.5}^{-3/8}$$

the typical relative velocity between shocking streams at the apocenter region

$$v \approx \left(\frac{GM_{\rm BH}}{a_{\rm min}}\right)^{1/2} \approx 11{,}000\ {\rm km\ s^{-1}}\left(\frac{k/f}{0.08}\right)^{-1/6} \times \mathcal{M}_*^{\xi/2-1/6} M_{\rm BH,6.5}^{1/6}.$$

TDE model – disk formation

- Model Predictions for TDEs with a Rise Time of a Month

Stellar Structure	k/f	$M_{\rm BH}$ ($10^6 M_\odot$)	$L_{\rm peak}$ (10^{43} erg s^{-1})	$T_{\rm BB}$ (10^4 K)	$R_{\rm BB}$ (10^{15} cm)	Line Width (km s^{-1})
Radiative	0.02	10	130	5.6	0.44	17000
Convective	0.3	1	20	4.8	0.23	7500
Fiducial	0.08	3	50	5.1	0.31	11000

Here assuming 100% efficiency of the shocks in converting gravitational energy to observed luminosity.

Shiokawa et al. (2015) suggests luminosities lower by a factor of ≈5 and temperatures lower by a factor of ≈1.5.

Comparison with observations

- Observed Properties of Optical TDE Candidates

Event	$M_{\rm BH}$ ($10^6 M_\odot$)	$L_{\rm peak}$ (10^{43} erg s^{-1})	$T_{\rm BB}$ (10^4 K)	$R_{\rm BB}$ (10^{15} cm)	Line Width (km s^{-1})
PS1–10jh[a]	4^{+4}_{-2}	$\gtrsim 22$	$\gtrsim 3$	~ 0.6	9000 ± 700
PS1–11af[b]	8 ± 2	8.5 ± 0.2	1.90 ± 0.07	~ 1.2	$\cdots$
PTF09ge[c]	$5.65^{+3.02}_{-0.98}$	85^{+50}_{-40}	3.1 ± 0.3	1.14 ± 0.2	10070 ± 670
		$5.8^{+5.3}_{-3.3}$[f]	2.2 ± 0.3	$0.59^{+0.16}_{-0.12}$	
SDSS TDE2[d]	$35.5^{+55.3}_{-25.8}$	$\gg 4.1$[g]	$1.82^{+0.07}_{-0.06}$		~ 8000[h]
ASASSN-14ae[e]	$2.45^{+1.55}_{-0.74}$	8.2 ± 0.5	2.2 ± 0.1	0.7 ± 0.03	17000–8000[h]
PTF09axc[c]	$2.69^{+0.66}_{-0.64}$	$1.9^{+3.3}_{-1.4}$[i]	$1.19^{+0.32}_{-0.17}$	$1.14^{+0.41}_{-0.43}$	11890 ± 220
PTF09djl[c]	$3.57^{+9.97}_{-2.96}$	$12.7^{+23.1}_{-10.4}$[j]	$2.7^{+0.7}_{-0.5}$	$0.58^{+0.24}_{-0.21}$	6530 ± 350
Prediction results of that model		$\boxed{L_{\rm peak} \sim 10^{44}\ {\rm erg\ s^{-1}}}$	$\boxed{\sim 4 \times 10^4\ {\rm K}}$	$\boxed{\sim 5 \times 10^{14}\ {\rm cm}}$	$\boxed{\sim 8000\ {\rm km\ s^{-1}}}$

Summary

- The authors suggest that the energy liberated during the formation of the accretion disk, rather than the energy liberated by subsequent accretion onto the black hole, powers the observed optical TDE candidates.
- The observed rise times, luminosities, temperatures, emission radii, and line widths seen in these TDEs are all more readily explained in terms of heating associated with disk formation rather than in terms of accretion.

Thanks!