Tidal Disruption Flares from Stars on Bound Orbits


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Outline

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   Standard theory and past observations
   Our scenario (Eccentric TDEs)

2. Our model
   1. Numerical modeling of a star-black hole system
   2. Simple General relativistic (GR) precession treatment

3. Result
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   2. Accretion disk formation

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Introduction
Tidal disruption events

Standard picture of tidal disruption events
Rees (1988)

\[
\begin{align*}
\epsilon &= \text{kinetic energy} + \text{potential energy} + \text{thermal energy} \\
&\sim \text{kinetic energy} + \text{potential energy} \\
\text{if } \epsilon \geq 0 &\quad \text{if } \epsilon < 0
\end{align*}
\]

Stellar debris flies away from the black hole
Stellar debris is bounded by the black hole’s gravity and falls back to black hole

Tidal disruption radius (self-gravity force=tidal force):

\[
r_t = \left( \frac{M_{\text{BH}}}{m_*} \right)^{1/3} r_*
\]

Scientific motivation

1. Evidence for quiescent supermassive black holes
2. Contribution to black hole growth
3. One of gravitational wave source candidates (EMRIs)
Differential mass-energy distribution of stellar debris

\[ \frac{dM}{dt} = \frac{dM(\epsilon)}{d\epsilon} \left| \frac{d\epsilon}{dt} \right| \quad (\epsilon < 0) \]

Specific energy:

\[ \epsilon \approx -\frac{GM_{BH}}{2a} \]

Its time derivative:

\[ \frac{d\epsilon}{dt} = -\frac{1}{3} \left(2\pi GM_{BH}\right)^{2/3} t^{-5/3} \]

(by using Keplerian third law)

\[ \frac{dM}{dt} \propto t^{-5/3} \]

Rees’s conjecture (1988)
Mass fallback rate

\[ \propto t^{-5/3} \]

Rees’s conjecture is consistent with numerical simulations

Evans & Kochanek (1989)
Numerical Simulations

Past Observations

- 15 Tidal disruption event (TDE) candidates (cf. Maksym +2010; Burrows +2011)

- Some observed light curves match theoretical expectations proposed by Rees (1998).

- Event rate: $10^{-4} \sim 10^{-5}$ per galaxy [1/year] (Donley + 2002)
Approaching stars are on parabolic orbits?

- Historically, TDE theory considers parabolic orbits:
  
  Well-motivated for 2-body scattering (bulge), large-scale triaxiality (galaxy)

- More exotic contributions to TDE rate have been proposed recently:
  
  - Binary star separation (Amaro-Seoane+2012, Bromley+ 2012)
  
  - Recoiling SMBH (Stone & Loeb 2011)
  
  - Binary SMBHs (Chen+2009,2012; Seto & Muto 2010,2011)
  
  - These mechanism makes smaller eccentricities possible than $e=1$.

Eccentricity of disrupted stars could be widely distributed over $0.1 < e < 1$. 
Our Goal

A schematic picture of "Eccentric TDEs"

To find differences between standard TDEs and TDEs of stars on eccentric orbits
Our *original* theoretical expectation

All of stellar debris are bounded by black hole even after the tidal disruption, when $\Delta \epsilon = \epsilon_{\text{orb}}$

**mass distribution**

All of disrupted mass can fall back to black hole **if** $e < e_{\text{crit}}$.

\[
\begin{align*}
\Delta \epsilon &= \frac{GM_{\text{BH}}}{r_{\text{t}}^2} r_*, \\
\epsilon_{\text{orb}} &\approx -\frac{GM_{\text{BH}}}{2r_{\text{t}}} \beta (1 - e_*)
\end{align*}
\]

\[
e_{\text{crit}} \approx 1 - \frac{2}{\beta} \left( \frac{M_{\text{BH}}}{m_*} \right)^{-1/3}
\]
More predictions

1. There is a cut-off time in mass fallback rate, because all of stellar masses fall back to the black hole.

2. Mass fallback rate is bigger than that of standard TDE, because the fallback time is shorter. $t \propto \epsilon^{-3/2}$

Finite and more intense accretion

Next, we test them by numerical simulations
Numerical Model
**Smoothed Particle Hydrodynamics (SPH)**

Lucy (1977); Monaghan & Gingold (1977)

1. Mesh-free Lagrangian methods in Computational Fluid Hydrodynamics
2. Treating fluid as ensemble of discrete elements (SPH particles)

A physical quantity in SPH:  
\[
\langle f(r) \rangle = \sum_j m_j \frac{f_j}{\rho_j} W(|r - r_j|, h)
\]

- \(m_j\): SPH particle mass; \(\rho_j\): Density of SPH particle; \(W\): Kernel function

- **●**: SPH particle  
- **h**: Smoothing length

![Diagram showing SPH particles and smoothing length](image)
Method

1. Modeling a star by SPH (Benz(1990); Bate et al.(1995))
2. Simulating a star-black hole system
3. Incorporating Pseudo-Newtonian potential (Wegg 2012) into SPH code to treat general relativistic (GR) effect

**BH mass:** \( M_{bh} = 10^6 M_\odot \)  \( \beta = r_t / r_p = 1, 5 \)  polytropic index : \( n=1.5 \)
**Stellar mass:** \( M_{\text{star}} = 1 M_\odot \)  Stellar Orbital eccentricity: \( e=1, 0.98, 0.8 \)

We will show simulation results with \( N_{\text{SPH}}=10^5 \)
GR Effects (Schwarzschild space-time)

Why do we consider GR effects?

GR precession is strong for small periastron distances. We expect that it can cause the orbital crossing of the stellar debris.

How do we model GR effects?

For simple GR treatment, pseudo Newtonian potentials are incorporated into the SPH code. Wegg (2012):

$$ U(r) = c_1 \frac{GM_{\text{BH}}}{r} - \frac{(1 - c_1)GM_{\text{BH}}}{r - c_2 r_g} - \frac{c_3 GM_{\text{BH}} r_g}{r} $$

where $c_1 = -(4/3)(2+6^{1/2})$, $c_2 = 4*6^{1/2}-9$, $c_3 = -(4/3)(2*6^{1/2}-3)$

Newtonian if $c_1 = 1$, $c_2 = c_3 = 0$ : Paczynski-Wiita PN if $c_1 = c_3 = 0$, $c_2 = 1$

We modeled only GR precession effect by incorporating pseudo-Newtonian potential (Wegg 2012) into SPH.
Standard TDE ($e=1, \beta=1$) : Density map animation

The run time, $t$, is normalized by

$$P_* \equiv 2\pi \sqrt{\frac{r_*^3}{Gm_*}} \sim 3.2 \times 10^{-4} \left( \frac{r_*}{R_\odot} \right)^{3/2} \left( \frac{M_\odot}{m_*} \right)^{1/2} \text{ [yr]}$$

Tidal disruption radius

$$r_t = 100R_\odot \times \left( \frac{M_{BH}}{10^6M_\odot} \right)^{1/3} \left( \frac{1M_\odot}{m_*} \right)^{1/3} \left( \frac{r_*}{R_\odot} \right)$$

* The star moves in the x-y plane
* The surface density is measured in a range of the seven orders of magnitude in the logarithmic scale
Eccentric TDE: e=0.98 and β=5
Critical eccentricity: $e_{\text{crit}}=0.996$

1. $e < e_{\text{crit}}$ leads that mass is distributed in a range of negative energy
2. Mass fallback rate has clearly a finite cut-off time and is $\sim 200$ times larger than that of standard TDEs.
Comparison between Eccentric TDE case and p Parabolic TDE case

Parabolic TDE

$\dot{M} \propto t^{-5/3}$

Eccentric TDE

$\dot{M}$ [M$_\odot$ yr$^{-1}$]

Orbital period [yrs]
Summary I.

1. Eccentric TDEs has a critical value of eccentricity, below which all the mass is bounded by the black hole. Since fallback time is finite when \( e < e_{\text{crit}} \), the fallback rate substantially exceeds the Eddington rate.

2. Analytic expectation overestimates \( e_{\text{crit}} \), because the energy spread is wider as expected.

3. In standard TDEs, the mass fallback rate is consistent with \( t^{-5/3} \) law.

4. There are arguments whether an accretion disk is formed around the black hole after stellar debris falls back (Rees 1988, Cannizzo 1990, Kochenck 1994). But, there is poorly known how accretion disk is formed around black hole.
Accretion disk formation in eccentric TDEs
Newtonian potential simulation

\( (e=0.8, \beta=5) \)

- Dotted line shows the geodesic of a test particle
- Dashed circle shows the tidal disruption radius
- Central point represents the black hole

Stellar debris orbits around the black hole, following the Keplerian third law
Pseudo-newtonian potential simulation
(e=0.8, β=5)

- Dotted line shows the geodesic of a test particle
- Dashed circle shows the tidal disruption radius
- Central point represents the black hole

\[ \beta = \frac{r_t}{r_p} \]

Accretion disk is formed around the black hole due to shock energy dissipation of orbital crossings induced by GR precession
Comparison of two animations

Newtonian potential simulation (e=0.8, β=5)

Pseudo-Newtonian potential simulation (e=0.8, β=5)

General relativistic precession plays a crucial role in the accretion disk formation around supermassive black hole
Averaged specific energy and angular momentum

pseudo-Newtonian potential simulation (e=0.8, β=5)

\[ P_* \equiv 2\pi \sqrt{\frac{r_*^3}{Gm_*}} \sim 3.2 \times 10^{-4} \left( \frac{r_*}{R_\odot} \right)^{3/2} \left( \frac{M_\odot}{m_*} \right)^{1/2} \text{[yr]} \]

\[ \epsilon = \epsilon_{tp} \]

\[ \epsilon_t = GM_{BH}/r_t \]

\[ \epsilon_{tp} : \text{Specific energy of a test particle} \]

\[ l_{tp} : \text{Specific angular momentum of a test particle} \]

While specific energy is dissipated due to the orbital crossing, specific angular momentum is conserved
Dependence of error rate of precession angle on eccentricity of a test particle under the pseudo-Newtonian potential

\[
\text{Error rate [\%]} \equiv \frac{\Delta \phi_{GR} - \Delta \phi_{N}}{\Delta \phi_{GR}} \times 100
\]

\[
\Delta \phi_{GR} = 2 \int_{r_-}^{r_+} \left[ \frac{(E+1)^2}{h^2} - \left( \frac{1}{h^2} + \frac{1}{r^2} \right) \left( 1 - \frac{r_S}{r} \right) \right]^{-1/2} \frac{dr}{r^2}
\]

\[
\Delta \phi_{N} = 2 \int_{r_-}^{r_+} \left[ \frac{E - U(r)}{h^2/2} - \frac{1}{r^2} \right]^{-1/2} \frac{dr}{r^2}
\]

\( r_+ \) : Apocenter distance  
\( r_- \) : Pericenter distance  
\( r_S \) : Schwarzschild radius  
\( E \) : Specific energy  
\( h \) : Specific angular momentum

Error rate increases as \( e \) is lower and \( \beta \) is higher
Summary & Discussion

1. GR precession (perihelion shift) plays an important role in accretion disk formation via circularization of stellar debris from stars on moderately eccentric orbits.  
   【Energy dissipation rate ($\varepsilon_{\text{end}}-\varepsilon_{\text{ini}}/\varepsilon_{\text{ini}}$): 0.4% for Newtonian case, more than 100% for GR case】

2. Angular momentum is conserved from pre-tidal disruption to post-tidal disruption via debris circularization

3. For spin effect of Kerr black hole case, pseudo-Newtonian potential is not available. We need to incorporate Post-Newtonian expansion formula into the SPH code.
Thank you for your attention