Tidal disruption flare rates and demographics

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The promise of TDEs

... to map out the presence of otherwise unseen BHs

Can quiescent BHs coexist with surrounding dense star clusters?

estimated; the question then arises of whether the apparent quiescence of the nuclei of these galaxies is compatible with a massive hole’s presence. The answer depends on what happens to the debris from each disrupted star. How much is accreted or expelled? What is the associated luminosity or radiative efficiency? And how long does it take to digest or expel the debris from one star, in comparison with the interval between successive captures?

(Rees 1988)
Mapping out the presence of black holes

To use tidal disruption events as “signposts” to the presence of otherwise quiescent black holes, we need to know:

- What types of stars are disrupted? At what relative rates?
- How do these events fuel black hole accretion?
- Which accretion episodes power luminous flares?

These questions lie at the intersection of stellar dynamics, stellar evolution, hydrodynamics, and radiation transport.
a diversity of stars…

red giant

\[ R_* \sim 10^1 - 10^3 R_\odot \]

main sequence

\[ R_* \sim R_\odot \]

… and galaxies

white dwarf

\[ R_* \sim 10^{-2} R_\odot \]
Today’s talk

A. Galactic center dynamics feeds stars to tidal disruption
B. A diversity of stellar types
C. A diversity of galactic nuclei (& BHs)
D. Toward TDE population studies
galactic center dynamics
galactic center dynamics

loss cone:

\[ J_{lc} = \sqrt{2GM_{bh}r_T} \]
Over a “relaxation time” orbits change by order unity in energy and angular momentum.

The time for an orbit to experience $\Delta J \sim J_{lc}$,

$$t_{lc} \sim \frac{J_{lc}^2}{J_c^2} t_r \sim \frac{r_t}{a} t_r$$

Do orbits re-populate in one orbital period? Compare: $P_{\text{orb}}$, $t_{lc}$

⇒ Is the phase space repopulated?

Frank & Rees (1976), Lightman & Shapiro (1976), Magorrian & Tremaine (1999), Merritt (2013)
galactic center dynamics

Tidal disruption rate: integral of flux of stars over binding energy

\[ \text{Rate} \sim \int \frac{N_{lc}(\varepsilon)}{P_{\text{orb}}(\varepsilon)} \, d\varepsilon \]

\[ N_{lc}(\varepsilon) = N(\varepsilon) \frac{J_{lc}^2}{J_c^2} \]

Rate \sim \text{number density} \times \text{size of the loss cone}

\[ N_{lc}(\varepsilon) \sim N_{lc,\text{full}}(\varepsilon) \frac{P_{\text{orb}}}{t_{lc}} \]

Rate \sim \text{number density} \times \text{relaxation rate}

(note: dropping a logarithmic scaling…)

full LC

empty LC
galactic center dynamics

terms in rate expression:

stellar type:

size of loss cone

stellar density, distribution:

influence normalization & relaxation rate

\[ r_t \propto \rho_*^{-1/3} \]
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Main sequence TDEs

\[ \varepsilon F_{1c}(\varepsilon) \ [\text{yr}^{-1}] \]

\[ \Delta J \gg J_{1c} \quad \text{LC full} \]
\[ \Delta J \ll J_{1c} \quad \text{LC empty} \]

Integrated rate
\[ \sim 1 / 10,000 \ \text{yr per galaxy (OoM)} \]

Frank & Rees (1976), Lightman & Shapiro (1976), Magorrian & Tremaine (1999), Merritt (2013)

warning: cartoon!
Main sequence TDEs

One disruption per second in the observable universe!
Main sequence TDEs

mean binding energy $\sim 10^{-5} c^2$

max escape speed $\sim 10^4 \text{km/s}$

max binding energy $\sim 10^{-3} c^2$

$r_f = r_* \left( \frac{m_n}{m_*} \right)^{1/3}$

$\frac{dt}{dE}$

$\frac{dM}{dE}$

$t_{fb} \propto M_{bh}^{1/2} M_*^{-1} R_*^{3/2}$

$\dot{M} \propto \dot{M}_{\text{peak}} \left( \frac{t}{t_{fb}} \right)^{-5/3}$

BH-bound

ejected
Main sequence TDEs

• MS disruptions result in rapid, short accretion episodes

• ~50% of the mass returns to pericenter in the first 3 $t_{fb}$

(MacLeod+ 2013)
Giant star TDEs

\[ \varepsilon F_{1c}(\varepsilon) \, [\text{yr}^{-1}] \]

 tidal radius increases

\[ \Delta J \gg J_{1c} \]
LC full

\[ \Delta J \ll J_{1c} \]
LC empty

\[ \varepsilon \, [\text{erg}] \]
Giant star TDEs

\[ \varepsilon F_{1c}(\varepsilon) \text{ [yr}^{-1}] \]

... include a range of tidal radii and the fact that MS stars are more common:

\[ \Delta J \gg J_{1c} \]

LC full

\[ \Delta J \ll J_{1c} \]

LC empty

\[ \varepsilon \text{ [erg]} \]
Giant star TDEs

Giant stars always hold onto a portion of their envelope...

(MacLeod+ 2012)
Giant star TDEs

Giants are vulnerable to TD

\[ r_t \propto M_*^{-1/3} R_* \]

mass is spread over longer timescales

\[ t_{fb} \propto M_*^{-1} R_*^{3/2} \]

But they are relatively rare

\[ \Gamma_{TD} \propto r_t^{1/4} \]

(MacLeod+ 2013)
Giant star TDEs

- MS and giant star tidal disruptions make similar contributions at low Eddington ratios.

(MacLeod+ 2013)
White dwarf TDEs

\[ \varepsilon F_{1c}(\varepsilon) \, [\text{yr}^{-1}] \]

\[ \Delta J \gg J_{1c} \]

LC full

\[ \Delta J \ll J_{1c} \]

WD

LC empty

(MacLeod+ 2014)
Horizon radius versus tidal disruption radius

- MS stars are directly consumed above $\sim 10^8$ solar masses
- WDs above $\sim 10^5$ solar masses

\[ r_t = \left( \frac{M_{bh}}{M_*} \right)^{1/3} R_* \]

\[ r_s = \frac{2GM_{bh}}{c^2} \]
The role of stellar structure in TDE outcomes

white dwarf disruption fuel accretion at ~million times Eddington

jet production & beamed emission

t_{peak} \sim \text{hours}

(see also: Rosswog, Luminet, Haas, Cheng, Clausen, Krolik, Piran, Zalamea)
The role of stellar structure in TDE outcomes

Multi-wavelength signatures of WD disruption

Figure 1. This diagram depicts the observed multiband light curve of a hypothetical deep-passing WD tidal disruption by a $M_{10^3} M_\odot$. We have assumed that a jet is launched carrying kinetic energy of $610^{51} \text{erg}$ from the disruption of a $M_{0.2}$ WD, or $2 \times 10^{51} \text{erg}$. Line styles denote different viewing angles with respect to this jet axis. Dotted-dashed lines are along the jet axis, while solid lines denote an off-axis perspective. Colors show different wavelengths of emission from X-ray to 1 GHz radio. For a viewer along the jet axis, a luminous jet may precede an optical-wavelength thermonuclear transient. The thermonuclear transient significantly outshines both jet afterglow and disk thermal emission at optical wavelengths. For off-axis events detected in the optical, accompanying X-ray emission from the accretion disk along with a radio afterglow complete the multi-wavelength picture and significantly distinguish these thermonuclear transients from other SNe.

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(MacLeod+ 2016)
star + BH combinations yield TDFs

Which object + BH combinations are most likely to produce luminous flares?

- a given combination produces a flare with a certain luminosity, duration, wavelength

For example:

if we imagine that to produce a luminous flare we require

\[ r_s < r_t < 10r_s \]
A. Galactic center dynamics feeds stars to tidal disruption
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D. Toward TDE population studies
A diversity of galactic nuclei

(Arcavi+ 2014, French+ 2016, ... )
A diversity of galactic nuclei

Tidal disruption rate: integral of flux of stars over binding energy

\[ \text{Rate} \sim \int \frac{N_{lc}(\varepsilon)}{P_{\text{orb}}(\varepsilon)} \, d\varepsilon \]

- full LC: \( N_{lc}(\varepsilon) = N(\varepsilon) \frac{J_{lc}^2}{J_c^2} \)

- empty LC: \( N_{lc}(\varepsilon) \sim N_{lc,\text{full}}(\varepsilon) \frac{P_{\text{orb}}}{t_{lc}} \)

Rate \sim \text{number density} \times \text{size of the loss cone}

Rate \sim \text{number density} \times \text{relaxation rate}
A diversity of galactic nuclei

<table>
<thead>
<tr>
<th>TDE Host</th>
<th>Half-light Surface Brightness</th>
<th>Sersic Index</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASASSN-14ae</td>
<td>2''</td>
<td>2.61</td>
</tr>
<tr>
<td>ASASSN-14li</td>
<td>2''</td>
<td>4.91</td>
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<tr>
<td>PTF-09ge</td>
<td>2''</td>
<td>4.03</td>
</tr>
<tr>
<td>RBS 1032</td>
<td>2''</td>
<td>2.24</td>
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<tr>
<td>SDSS J1323</td>
<td>2''</td>
<td>5.03</td>
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<tr>
<td>ASASSN-14ae</td>
<td>2''</td>
<td>1.4</td>
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<td>RBS 1032</td>
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<td>1.51</td>
</tr>
<tr>
<td>SDSS J1323</td>
<td>2''</td>
<td>1.67</td>
</tr>
</tbody>
</table>

TDE hosts have relatively:
- High bulge/total ratios
- High Sersic indices
A diversity of galactic nuclei

Rate \propto \sum_{M_*}^{1} \sigma^{-1}

\beta = -1.1 \pm 0.7

\alpha = 0.9 \pm 0.2

(Graur+ 2017)
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Toward TDE population studies

Emission from TDEs is multiwavelength, multicomponent (thermal, beamed), considering events by “category” is becoming possible:

See also Hung+ 2017 (opt/uv), Auchettl+ 2017 (x-ray), and Alexander+ 2017 (radio).
Toward TDE population studies

As we push toward understanding emission mechanisms and the production of TDFs from TDEs, we additionally need to consider the way these events propagate into survey detections.

![Graph showing observed optical/UV TDFs](image-url)
Toward TDE population studies

As we push toward understanding emission mechanisms and the production of TDFs from TDEs, we additionally need to consider the way these events propagate into survey detections.

For every bright event there are many fainter flares:

- Less accreted mass?
- Lower radiative efficiency?
- Different stellar dynamics (e.g. impact parameter)?

(van Velzen 2017)
Toward TDE population studies

As we push toward understanding emission mechanisms and the production of TDFs from TDEs, we additionally need to consider the way these events propagate into survey detections.

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**Fig. 5.** — Cumulative distribution of host galaxy stellar mass and black hole mass. We show the observed distribution, compared to the distribution for two different mock TDF samples. The black solid line is our fiducial TDF model, using Eq. 9 to account for the suppression of the TDF rate due to the capture of stars by black holes. The dashed line shows the distribution that is obtained if the event rate is independent of mass. This second scenario clearly is inconsistent with the observations as it predicts too many flares from high-mass host galaxies.

**Fig. 6.** — Identical to Fig. 5, but showing three models for the event rate and luminosity function (see Table 4). We see that both the AGN flare scenario and SNe that trace the star formation rate (SFR) or galaxy mass are inconsistent with the observed distributions. While a SNe model with a rate that is independent of galaxy properties is consistent with the observed mass distribution, this scenario is not consistent with the observed distribution of the Eddington ratio (Fig. 7).

For each of these samples, we compute the p-value for rejecting the null-hypothesis. The distribution of the resulting p-values follows a log-normal distribution with a standard deviation of only 0.2 dex. We can thus conclude that Poisson fluctuation in the number of detected TDF candidates will not lead to a false detection of horizon suppression (a 9-fluctuation of $N_{\text{TDF}}$ is required to reach $p > 0.1$).

The simulated distributions of galaxy mass and black hole mass for the other three scenarios that we consider (see Table 4) are shown in Figure 6.

### DISCUSSION

**3.1. TDFs are not due to stellar explosions**

We find that our fiducial TDF model correctly reproduces the distribution of host galaxy total stellar mass, host galaxy black holes mass, and Eddington ratio (see Fig. 5 and Fig. 7). From Fig. 6, we conclude that if the observed TDFs are due to a hypothetical new class of nuclear SNe, the rate of these events needs to be independent of host galaxy mass or star formation rate. This requirement could be considered unlikely, because the rate of most types of known SNe either scales with the host galaxy surface brightness, or is limited to a particular subset of galaxies (e.g., Fruchter et al. 2006). Direct evidence against the possibility that observed optical TDF candidates are a new class of SNe is the observed distribution of the Eddington ratio. The Eddington limit for photons does not apply to stellar explosions, but for each simulated SNe we can still compute the Eddington ratio based on the central black hole mass of its host galaxy. If the flare rate is independent of galaxy properties and not constrained by the Eddington limit, more than half of the observed optical TDF candidates should have super-Eddington luminosities (Fig. 7). The luminosity of candidate TDFs, however, is observed to be capped near the Eddington luminosity. The probability that a flux-limited SNe sample would produce this skewed distribution of $f_{\text{Edd}}$ is small (KS test yields $p = 6 \times 10^{-4}$). We find the same result if we use a Gaussian distribution (Eq. 4) to draw with the luminosity of the simulated SNe.

**3.2. TDFs are unlikely due to AGN**

An instability in an AGN accretion disk could lead to a rapid increase of the accretion rate and may therefore contribute to TDFs. As we push toward understanding emission mechanisms and the production of TDFs from TDEs, we additionally need to consider the way these events propagate into survey detections. (van Velzen 2017)
Conclusion

- A *diversity* of stellar types interact with and are disrupted by massive black holes.

- Accretion episodes range from *hours to years*, *single or repeating* depending on stellar type and orbital dynamics.

- Different transients selectively illuminate black holes of various mass, and galactic nuclei of particular properties.

LSST: 100-1000 events per year. It is critical to address these questions now!
Conclusions

Thank you!

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