TDEs: Tidal Disruption Events... or Totally Different Explanation[1]?

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[*Warning: These notes focus on deriving appropriate scalings; constant factors of order unity are not traced in a self-consistent manner.*]

[1] Alternative backronym coined by Sterl Phinney

1. Debris stream orbits

A self-gravitating object of mass m and size r (be it a star or a binary) will be tidally disrupted or separated by a massive body (e.g., a massive black hole) of size M at the tidal disruption radius $R_{\rm TD}$ at which the tidal force from the massive body exceeds the object's gravity:

$$\frac{Gm}{r^2} \lesssim \frac{GM}{R_{\rm TD}^2} - \frac{GM}{(R_{\rm TD}+r)^2} \sim \frac{GMr}{R_{\rm TD}^3}, \tag{1}$$

i.e.,

$$R_{\rm TD} = \left(\frac{M}{m}\right)^{1/3} r \approx 0.5 \left(\frac{M}{10^6 M_\odot}\right)^{1/3} \left(\frac{m}{M_\odot}\right)^{-1/3} \left(\frac{r}{R_\odot}\right) \mathrm{AU}. \tag{2}$$

Consider an object which approaches the massive body on a parabolic orbit with periapsis equal to $R_{\rm TD}$. The most bound material from the disrupted object will have specific energy

$$-\frac{GM}{R_{\rm TD}-r} - \left(-\frac{GM}{R_{\rm TD}}\right) \approx -\frac{GMr}{R_{\rm TD}^2} = -\frac{GM}{2a},$$

where a is the semimajor axis of the orbit of this most bound material:

$$a_{\rm mb} \sim \frac{R_{\rm TD}^2}{r} \left(\frac{M}{m}\right)^{2/3} r \sim \left(\frac{M}{m}\right)^{1/3} R_{\rm TD} \approx 50 \left(\frac{M}{10^6 M_\odot}\right)^{2/3} \left(\frac{m}{M_\odot}\right)^{-2/3} \left(\frac{r}{R_\odot}\right) \mathrm{AU}. \tag{3}$$

Since this most-bound material has a periapsis at $R_{\rm TD}$ and an apoapsis at $\approx 2a$, it will have an eccentricity of order

$$1 - e \sim \left(\frac{m}{M}\right)^{1/3} \approx 0.01 \left(\frac{M}{10^6 M_\odot}\right)^{-1/3} \left(\frac{m}{M_\odot}\right)^{1/3}, \tag{4}$$

i.e., $e_{\rm mb} \approx 0.99$ for our fiducial values. The orbital period of the most-bound ejecta is

$$P_{\rm mb} = 2\pi \frac{a_{\rm mb}^{3/2}}{(GM)^{1/2}} \approx 4\,\mathrm{months} \left(\frac{M}{10^6 M_\odot}\right)^{1/2} \left(\frac{m}{M_\odot}\right)^{-1} \left(\frac{r}{R_\odot}\right)^{3/2}. \tag{5}$$

The mass return rate peaks on timescales of order $P_{\rm mb}$. A non-negligible fraction of the disrupted star's mass returns on these timescales (perhaps $\approx 0.1m$, of the $0.5m$ total bound mass). Thus, the peak mass return rate is

$$\dot{m} \sim 0.1\frac{m}{P_{\rm mb}} \approx 0.3\frac{M_\odot}{\rm year}\left(\frac{M}{10^6 M_\odot}\right)^{-1/2}\left(\frac{m}{M_\odot}\right)^2\left(\frac{r}{R_\odot}\right)^{-3/2}. \tag{6}$$

At very late times, the mass return rate is (Rees, 1998)

$$\dot{m} = \frac{dm}{dE}\frac{dE}{dP} \propto t^{-5/3}. \tag{7}$$

This is because most material is marginally bound, so dm/dE for the marginally bound material is a constant, while $E \propto a^{-1} \propto P^{-2/3}$.

2. Accretion luminosity

Assuming a radiative efficiency of 10%, if this material were immediately accreted through a think disk, this would correspond to a peak luminosity of

$$L \sim 0.1\dot{m}c^2 \approx 0.03\frac{M_\odot c^2}{\rm year}\left(\frac{M}{10^6 M_\odot}\right)^{-1/2}\left(\frac{m}{M_\odot}\right)^2\left(\frac{r}{R_\odot}\right)^{-3/2}. \tag{8}$$

Note that this exceeds the Eddington luminosity of

$$L_{\rm Edd} \approx 10^{-3}\frac{M_\odot c^2}{\rm year}\left(\frac{M}{10^6 M_\odot}\right). \tag{9}$$

In fact, observed TDEs are underluminous; this is one of the open questions of TDEs.

3. Challenges with the disk accretion model

Of course, there is no reason to assume that accretion will happen immediately. Direct accretion from streams with a closest approach of ~ 100 Schwarzschild radii at periapsis and an eccentricity of ~ 0.99 is impossible. Energy and angular momentum must first be dissipated, presumably in stream-stream collisions. The key questions to answer are:

1. Would the timescales associated with TDEs and used to interpret them, including $P_{\rm mb}$ and the famous $\dot{m} \propto t^{-5/3}$ late-time mass return rate, be affected by the delays to bring in the material, circularise it, and accrete it, as well as by possible photon diffusion delays through optically thick material?

2. Could those stream-stream collisions be directly responsible for the observed emission (perhaps with accretion occurring much later, and not directly observationally associated with the TDE)?

4. Stream-stream collisions

Suppose that streams collide near periapsis only because of periapsis precession (by $\sim \frac{GM}{c^2 R_{\rm TD}} \approx 0.02$ rad in the absence of massive body spin). Periapsis velocity... Relative velocity... Energy liberation... Typical temperature – X-rays! Peak luminosity of $\approx 3 \times 10^{-6} \frac{M_\odot c^2}{\rm year}$ – too low?

Optical thickness. Depends on configuration of material. Spread uniformly over $R_{\rm TD}$ – then diffusion time is 100 years. Spread over tube of cross-section radius r – then diffusion time of order 1 month.