MICRO-TIDAL DISRUPTION EVENTS BY STELLAR COMPACT OBJECTS AND THE PRODUCTION OF ULTRA-LONG GRBs

Hagai B. Perets[1], Zhuo Li[2], James C. Lombardi, Jr.[3], and Stephen R. Milcarek, Jr.[3]

[1] Physics Department, Technion—Israel Institute of Technology, Israel
[2] Department of Astronomy and Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing, China
[3] Department of Physics, Allegheny College, Meadville, PA 16335, USA

ABSTRACT

We explore full/partial tidal disruption events (TDEs) of stars/planets by *stellar* compact objects (black holes (BHs) or neutron stars (NSs)), which we term micro-TDEs. Disruption of a star/planet with mass $M_\star$ may lead to the formation of a debris disk around the BH/NS. Efficient accretion of a fraction ($f_{acc} = 0.1$ of the debris may then give rise to bright, energetic, long (10^3–10^4 s), X-ray/gamma-ray flares, with total energies of up to $(f_{acc}/0.1) \times 10^{52} (M_\star/0.6\,M_\odot)$ erg, possibly resembling ultra-long gamma-ray bursts (GRBs)/X-ray flashes (XRFs). The energy of such flares depends on the poorly constrained accretion processes. Significantly fainter flares might be produced if most of the disk mass is blown away through strong outflows. We suggest three dynamical origins for such disruptions. In the first, a star/planet is tidally disrupted following a close random encounter with a BH/NS in a dense cluster. We estimate the BH (NS) micro-TDE rates from this scenario to be a few $\times 10^{-6}$ (a few $\times 10^{-7}$) yr^{-1} per Milky Way galaxy. Another scenario involves the interaction of wide companions due to perturbations by stars in the field, likely producing comparable but lower rates. Finally, a third scenario involves a BH/NS that gains a natal velocity kick at birth, leading to a close encounter with a binary companion and the tidal disruption of that companion. Such events could be associated with a supernova, or even with a preceding GRB/XRF event, and would likely occur hours to days after the prompt explosion; the rates of such events could be larger than those obtained from the other scenarios, depending on the preceding complex binary stellar evolution.

Key words: gamma-ray burst: general – gamma rays: stars – stars: black holes – stars: neutron – X-rays: binaries

1. INTRODUCTION

The disruption of stars by massive black holes (MBHs) has been studied extensively over the last few decades, and in particular following the observational detection of candidate tidal disruption events (TDEs; see Komossa 2015 for a review). However, stars (and sub-stellar objects such as planets/brown dwarfs) can also be tidally disrupted by stellar compact objects (COs), such as stellar black holes (BHs), neutron stars (NSs), and white dwarfs (in this paper we focus on the former two; white dwarfs (WDs) will be discussed elsewhere), with typical masses a factor of 10^{-6} smaller than the masses of TDE-producing MBHs. These "micro"-TDEs (μTDEs) result from close encounters between a star and CO. The importance of such close encounters was first emphasized in the context of the tidal capture mechanism suggested by Fabian et al. (1975) to explain the formation of close compact binaries (and thus the formation of cataclysmic and X-ray binaries), and was later invoked to explain non-standard formation and evolution of exotic stars such as blue stragglers, Thorne–Zytkow objects (Thorne & Zytkow 1977), and a variety of close binary systems (see Shara 1999 for a short review).

Encounters of COs can be categorized into several possible scenarios: physical collisions, tidal disruptions, tidal captures, and tidal encounters. These scenarios correspond respectively to the progressively larger distance of the closest approach of the CO trajectory to the star. Here we study the case of tidal disruptions, whereas other cases of physical collisions or alternatively more distant tidal encounters of COs with stars have been studied by others (Fabian et al. 1975; Thorne & Zytkow 1977; Fryer & Woosley 1998; Hansen & Murali 1998;

Fryer et al. 1999; Alexander & Kumar 2001; Zhang & Fryer 2001; Broderick 2005).

Three distance scales are important for describing the encounters: the distance of closest approach R_p, the radius $R_\star$ of the star, and the radius of tidal disruption

$$R_t \simeq R_\star \left(\frac{M_\bullet}{M_\star}\right)^{1/3},$$

where $M_\bullet$ and $M_\star$ are the masses of the CO and the stellar (or planetary) object, respectively.

In close (non-collisional) encounters the tidal forces can be sufficiently strong to completely or partially disrupt the star, in which case a fraction of the stellar mass may fall back, self-interact, and eventually be accreted onto the CO. Although the possibility of tidal disruption of stars by stellar COs in close encounters was suggested by many, the observational signature of μTDEs, their frequency, and their consequences have been little explored. In this paper we discuss this possibility and suggest that μTDEs can result in highly energetic flares, possibly similar to gamma-ray bursts (GRBs) or X-ray flashes (XRFs), but much longer ($>$ a few $\times 10^3$ s) and fainter than most of them. We find that the timescale of these flares is a few tens of minutes to hours, potentially related to the recently observed class of ultra-long GRBs (Greiner et al. 2015; Levan 2015). An alternative scenario in which the debris forms an extended long-lived disk around the CO, producing an X-ray source very similar to an X-ray binary, is not discussed here; we refer to Krolik (1984) for an in-depth study of this possibility (first discussed by Hills 1976a), which may occur independently of the early accretion flare on which we focus in this work.

The paper is organized as follows. We first discuss the properties of μTDEs in Section 2, and provide a basic estimate of their rates in Section 3. We then discuss the observational implications for such transient events as well as their remnants and summarize.

2. THE TIDAL DISRUPTION AND ACCRETION

Tidal disruption of stars was discussed in the context of binary formation through tidal capture (Hills & Day 1976; Hills 1976b). In this context the radius of tidal disruption was important as the closest distance at which stars can be captured, but the tidal disruption itself was only briefly mentioned. Tidal disruptions of stars by WDs and NSs were simulated by Ruffert (1992) and Lee et al. (1996), respectively, but the observational signatures from the subsequent accretion of debris were not explored. Tidal disruption of a star by an MBH and its observational signature was discussed by many authors (Lacy et al. 1982; Rees 1988; Evans & Kochanek 1989; Cannizzo et al. 1990; Laguna et al. 1993; Loeb & Ulmer 1997; Ulmer et al. 1998; Kim et al. 1999; Ulmer 1999; Ayal et al. 2000; Bogdanović et al. 2004) and possibly observed in recent years (Li et al. 2002; Gezari et al. 2006; Lu et al. 2006; van Velzen et al. 2011; see Komossa 2015 for a recent review). We follow a similar analysis used for this scenario, and complement it using results from hydrodynamical simulations of μTDEs. These are used to calculate the relevant parameters for the disruption of stars by *stellar* COs.

As a star is ripped apart by the tidal forces of a CO, the debris is thrown in a fan-like fashion into high-eccentricity orbits with a large range of periods, covering a range of specific energy

$$\Delta E \sim \frac{GM_\bullet R_*}{R_p^2}$$

where R_* is the radius of the star and R_p is the pericenter of the orbit (Lacy et al. 1982). For cases in which the star is completely disrupted, simulations show that the mass distribution of the out-thrown debris is nearly constant as a function of the energy (Ulmer 1999). A large fraction of the debris would later be flung out and become unbound (Ayal et al. 2000). The gravitational energy dissipated in this stage is possibly emitted as a long and very faint flare, with energetics much smaller than those expected from the later accretion phase, which is the main focus of this study.

The returning debris streams self-interact and a large fraction of the bound material becomes unbound, whereas the rest circularizes and forms a torus (e.g., see simulations of a disruption by a WD by Ruffert 1992) at a radius of about $r_c = 2R_p$. In the next stage, after circularization, the torus formed from the fallback material is then accreted by the CO (Evans & Kochanek 1989; Kochanek 1994; Ayal et al. 2000; Li et al. 2002), possibly producing a flare. In the following we discuss the observational signature (timescales, energetics) of such flares. We note that Lu et al. (2008) have discussed a related scenario and explored the accretion stage in a tidal disruption by an intermediate-mass BH; they suggest that this scenario leads to jet formation, producing a GRB with no associated supernova.

2.1. Timescales

2.1.1. Fallback Time

In the following we consider two cases: disruption with a low mass ratio with a high mass ratio. In the former, the mass of the disrupted star/planet is assumed to be negligible compared with the CO mass, and the CO can be assumed to be stationary at the center of mass of the system. Such a case corresponds to the tidal disruptions of planets or low-mass stars by stellar COs. However, when the mass of the disrupted object is relatively large (a tenth to a few tenths of the CO mass), the CO can no longer be assumed to be stationary or to reside at the center of mass of the system. The first scenario, with a low mass ratio, has been discussed extensively in the literature in the context of widely studied TDEs by MBHs; although different in scale the results should also apply to the μTDE case of low mass ratio; we briefly review the results obtained for that case. The scenario with a high mass ratio has been little studied and we therefore run hydrodynamical simulations of such tidal disruptions to characterize some of their basic properties.

Tidal disruptions with low mass ratio. In the first stage following the disruption, the bound fraction of the debris, $f_{\rm fall}$, falls back and returns to the pericenter. The first bound material returns after a time

$$t_{\min} = \frac{2\pi R_p^3}{(GM_\bullet)^{1/2}(2R_\star)^{3/2}}$$
$$\approx 3.52 \times 10^5 \left(\frac{R_p}{2.15R_\odot}\right)^3 \left(\frac{R_\star}{0.1R_\odot}\right)^{-3/2} \left(\frac{M_\bullet}{10M_\odot}\right)^{-1/2} {\rm s},$$

$$(1)$$

where the normalization was done for a Jupiter-like planet with radius $R_\star = 0.1R_\odot$ disrupted by a BH with a typical mass of $10\,M_\odot$ at a closest approach of $R_p = R_t = 2.15\,R_\odot$. Assuming a flat distribution of debris energies, the return rate of the bound material to pericenter at late times (Rees 1988; Phinney 1989; Ulmer 1999) is

$$\dot{M} \sim \frac{1}{3}\frac{M_\star}{t_{\min}}\left(\frac{t}{t_{\min}}\right)^{-5/3},$$

$$(2)$$

where the peak return rate occurs at about $t \sim 1.5t_{\min}$ (Evans & Kochanek 1989) and half of the mass of the fallback debris returns by about $t \sim 6t_{\min}$. Indeed, such behavior is seen in our hydrodynamical simulations of a BH tidally disrupting a Jupiter-mass planet (see Figure 1). Note, however, that simulations by Ayal et al. (2000) show that a large fraction of the returned debris later becomes unbound. They find the total accreted mass of debris to be four times smaller than found earlier, with an approximately constant accretion rate. Nevertheless, this does not make a significant change to the overall derived timescale. We also mention the work by Coughlin & Begelman (2014), who take a somewhat different approach and suggest the formation of an extended jet-producing envelope.

Partial tidal disruptions with high mass ratio. The $t^{-5/3}$ infall rate back to the CO discussed above corresponds to the case of complete or nearly complete tidal disruption of a low-mass object (compared with the disrupting CO). If the object is completely disrupted then there is nothing special about the
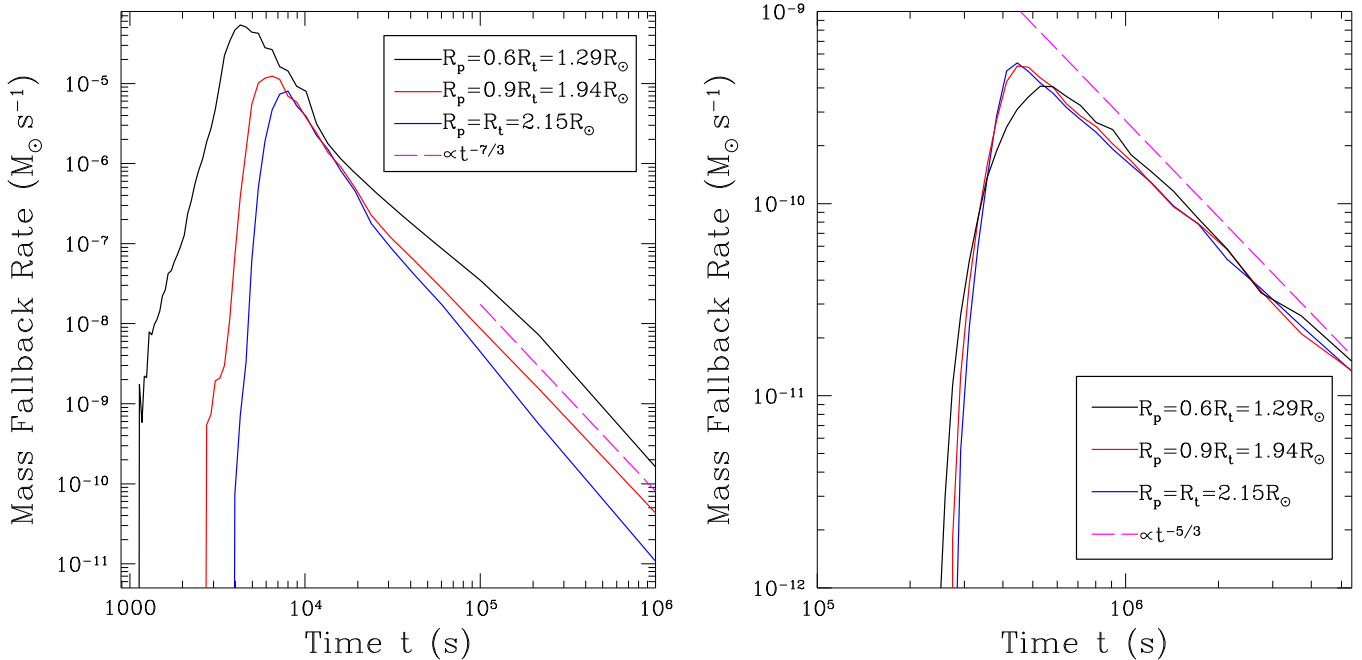
Figure 1. The return rate of debris from a main-sequence Sun-like star (left panel) and from a Jupiter-like planet (right panel) due to tidal disruption by a black hole of $10 M_\odot$. Solid curves show simulation results for a parabolic orbit with a closest approach of $0.6 R_t$ (black), $0.9 R_t$ (red), and $1 R_t$ (blue), where the tidal radius $R_t = 2.15 R_\odot$. Dashed magenta lines show the approximate return rate at late times, which is seen to scale approximately as $t^{-7/3}$ for the partially disrupted Sun-like star and as $t^{-5/3}$ for the nearly completed disrupted Jupiter-like planet.

debris field near gas that is marginally bound to the black hole, and the classic $t^{-5/3}$ behavior follows. The results change somewhat when the object is only partially disrupted, as can happen more frequently in cases of high mass ratio or when the object has a dense core. The surviving remnant affects the distribution of gas marginally bound to the black hole, and a fallback rate steeper than $t^{-5/3}$ results; see, e.g., MacLeod et al. (2012) for simulations of partial disruptions of giant stars by a supermassive black hole, and discussion of these issues by Guillochon & Ramirez-Ruiz (2013) and Hayasaki et al. (2013).

To study partial tidal disruptions in cases of high mass ratio, we have carried a set of hydrodynamical simulations using the *StarSmasher* code. *StarSmasher* is a smoothed particle hydrodynamics (SPH) code that evolved from *StarCrash* (Faber et al. 2010), which itself has its origins in the SPH code of Rasio (1991). The primary enhancement of *StarSmasher* over its predecessors is that it incorporates equations of motion derived from a variational principle to ensure accurate evolution of energy and entropy (Gaburov et al. 2010). In addition, gravitational forces between particles are calculated by direct summation on NVIDIA graphics cards.

We consider the tidal disruption of a solar-mass star or a Jupiter-like planet, modeled with 395,000 particles, by a $10 M_\odot$ BH point particle. A wider range of parameter space for tidal disruptions will be discussed in more detail elsewhere. The solar-mass star is evolved with the TWIN stellar evolution code to an age of 4590 Myr to give a radius $\sim 1 R_\odot$; the hydrodynamical simulations employ an equation of state (EOS) consisting of ideal-gas and radiation-pressure components. The Jupiter-like planet is modeled as an $n = 1$ polytrope of mass $10^{-3} M_\odot$ and radius $0.1 R_\odot$, with a $\Gamma = 2$ EOS. We consider both parabolic and hyperbolic encounters (but we discuss only the former cases here, more relevant for the expected relative velocities), and study cases of different closest approach $R_p = 0.6$, 0.9, and $1 R_t$ (that is, $R_p = 1.29 R_\odot$,

Table 1
The Fraction of Bound Fallback Material

| | R_p ($R_\odot$) | Mass Fraction | | |
		Bound	Unbound	Left in Star/Planet
Sun-like star	1.29	0.2	0.1	0.7
	1.94	0.06	0.02	0.92
	2.15	0.04	0.01	0.95
Jupiter-like planet	1.29	0.49	0.49	0.02
	1.94	0.49	0.49	0.02
	2.15	0.49	049	0.02

Note. The mass fractions are the fractions of bound fallback material and the return rate obtained from hydrodynamical simulations (using the *StarSmasher* code) of tidal disruptions of a solar-mass star and a Jupiter-mass planet by a $10 M_\odot$ BH.

$1.94 R_\odot$, and $2.15 R_\odot$). Runs with larger closest approach ($R_p \sim 4 R_\odot$) resulted in only a negligible fraction of the stellar (or planetary) mass falling back onto the BH. None of our runs implements radiative cooling. As can be seen in Table 1, our simulations results in a *partial* disruption, leaving behind the denser core of the star, which is not disrupted. We did not follow the long-term stellar evolution of such disruption remnants, which could be of interest in itself.

In order to estimate the fallback rate, we use the so-called freezing model as in MacLeod et al. (2012):

$$\frac{dM}{dt} = \frac{dM}{dE}\frac{dE}{dt} = \frac{1}{3}(2\pi G M_\bullet)^{2/3}\frac{dM}{dE}t^{-5/3}.$$

Here Kepler's third law has been used to relate the specific binding energy $E = G M_\bullet/(2a)$, where a is the semimajor axis of a parcel of debris, to the time t for that material to return to periapsis. This approximation neglects the influence of the

Table 2
The Rates of μTDEs from Various Potential Channels

Formation Channel	μTDE Rate (yr^{-1} per MW galaxy)	
	BH	NS
Encounters in dense clusters	2.8×10^{-6}	4.8×10^{-7}
Natal kicks	1.4×10^{-6}	3.4×10^{-7}
Perturbed wide binaries	10^{-7}	...

Note. Note that the rate from the scenario of natal kicks corresponds only to binaries with separations >10 AU. The rates for the channel of perturbed wide binaries correspond to the scenario of high rates obtained by Michaely & Perets (2016), for direct-collapse BHs with no natal kicks (reproducing the formation rate of LMXBs in the Galaxy); therefore this channel and the scenario of natal kicks are mutually exclusive.

remnant star, if it exists, on the fallback time. Note that the canonical $t^{-5/3}$ behavior of dM/dt follows from having a flat distribution of dM/dE versus E. More generally, dM/dE depends on the strength of the tidal interaction as well as the density profile of objects being disrupted. Objects that are completely or nearly disrupted tend to give relatively flat dM/dE at small E and therefore $dM/dt \sim t^{-5/3}$ at late times. In contrast, objects that are only partially disrupted yield a fallback rate dM/dt that drops off more quickly with time.

The actual distribution of dM/dE from our simulations is determined by sorting the mass of unbound particles into bins of E. For each unbound SPH particle, we calculate E as the sum of its specific kinetic energy (relative to the black hole) and its specific gravitational potential energy due to all mass in the system. For our Jupiter-like planetary disruptions (with $R_* \ll R_p \sim R_t$), unbound gas forms a long stream with one end that reaches back to the black hole only once the planet (or what remains of it) has retreated well outside the tidal radius. Since the tidal disruption plays out fully before the return of the gas to the black hole, it is sufficient to determine the distribution of dM/dE from a single snapshot of the simulation, taken shortly before the first stripped material returns.

In the disruption of our Sun-like stars (with $R_* \sim R_p \sim R_t$), stripped material from the star encircles the black hole and collides with other infalling material before the tidal disruption has fully completed, and it is consequently not possible to use a single snapshot to determine the fallback mass rate over all times. We therefore use a sequence of snapshots when binning particles by their specific energy in these cases. The first snapshot is taken about 10^3 s after the periapse passage: all particles that can be identified as being bound to the black hole are included in this binning, although these particles may have their bin locations adjusted while we step through about an additional five future snapshots spaced over about five dynamical timescales. As new particle are identified as being bound to the black hole, they are included in the binning. If in a later snapshot a previously binned particle has not yet reached 20% of its expected fallback time t, then it is instead rebinned according to its binding energy E calculated from that later snapshot. This procedure avoids issues associated with particles that have encircled the black hole colliding with infalling material.

As can be seen in Figure 1 the return rate of the most bound material happens on timescales comparable with scaling for the case of low mass ratio (Equation (1)), but the profile of the return rate is steeper, approximately $\sim t^{-7/3}$, with only a weak dependence on the pericenter separation R_p for the cases considered. We also note that in these simulations the fraction of material bound to the black hole after the disruption is of the order of 0.04 for a closest approach at the tidal radius ($R_p = 2.15 R_\odot$), whereas impacts at deeper penetrations result in higher fractions (0.06 and 0.2 for $R_p = 1.94\,R_\odot$ and $R_p = 1.29\,R_\odot$, respectively); for the following we adopt $f_{\mathrm{fall}} = 0.1$ as a typical value.

2.1.2. Accretion Time

After circularization the bound debris from the tidal disruption forms a torus or disk around the CO (for example, see Ruffert 1992) at a radius of $r_c \simeq 2R_p$. The accretion timescale for this disk, assuming it is thick (with the ratio of disk scale height to its radius, h, of the order of 1), is of the order of the viscous time

$$
\begin{aligned}
t_{\mathrm{acc}} &\approx \frac{t_{\mathrm{kep}}(2R_p)}{\alpha 2\pi h^2} \\
&\approx 4.5 \times 10^4 \, h^{-2} \left(\frac{\alpha}{0.1} \right)^{-1} \left(\frac{R_p}{2.15 R_\odot} \right)^{3/2} \left(\frac{M_\bullet}{10 M_\odot} \right)^{-1/2} \mathrm{s}
\end{aligned}
\tag{3}
$$

where $t_{\mathrm{kep}}(r)$ is the Keplerian orbital period at orbital radius r and α is the viscosity constant. The value of α is unknown, and we normalize it with the commonly used value $\alpha = 0.1$.

We therefore expect the formation of an accretion disk during the few thousand seconds after the tidal disruption (Equation (1)), for the assumed parameters. This might be observable in the timescale for the rise of the flare. Later on the debris material will be accreted on timescales of a few 10^4–10^5 s onto the CO (Equation (3)), whereas additional fallback material is expected to accrete continuously onto the CO at a rate that decays as a power law (Equation (2) or somewhat steeper for disruption with a high mass ratio). The exact timescale for the formation of the accretion disk is therefore less important as the evolution is dominated by the longer accretion timescales. We do note, however, that for the longer-term evolution as well as in the case of the disruption of larger, evolved star (e.g., red giant), occurring at a much larger radius, the accretion rate will be dominated by the fallback time rather than the accretion timescale. It was suggested that such a scenario may explain the origin of some X-ray binaries (J. Steiner & J. Guillochon 2015, private communication; see also Hills 1976a and Krolik 1984 for long-lived X-ray sources formed by tidal capture).

2.2. Flare Energy

The flare energy corresponds to the accreted mass $E_f = \eta f_{\mathrm{acc}} M_\star c^2$, with η the efficiency of transferring the rest mass to radiation energy in the accretion process, and f_{acc} the fraction of the star's mass that is accreted.

These processes of accretion and flaring (e.g., through production of a jet) are still poorly understood, and the amount of accreted mass is strongly dependent on the accretion scenario. Taking two very different scenarios, we try to give some possible lower and upper estimates of the radiated energy released in this stage. We stress that the current lack of knowledge of these accretion processes makes more accurate calculations suggestive at most.

If a fraction ζ of the circularized debris is accreted by the CO, that is $f_{acc} = \zeta f_{fall}$, then

$$E_f = 1.1 \times 10^{52} \, (f_{fall}/0.1)(\zeta/1)(\eta/0.1)(M_\star/0.6 M_\odot) \text{ erg},$$

which is somewhat lower than but still comparable with (especially for the disruption of higher-mass stars) the isotropic equivalent energy of ultra-long GRBs. The true energy released in observed GRBs should be reduced to $E\Omega/4\pi$, with Ω the unknown solid angle of the GRB jet. The derived μTDE energy could therefore be larger than required for a GRB by orders of magnitude, if $\Omega \ll 1$, and therefore even much lower f_{acc} could be sufficient. Such hyper-accretion rates of $\dot{M}_{acc} \sim 10^{10} \dot{M}_{Edd}$ are very similar to that of an accreting CO in a common envelope with a massive star, which has been studied both analytically (Chevalier 1993; Brown et al. 2000 and references within) and in simulations (e.g., Armitage & Livio 2000 and references within). Such accretion disks may be dominated by advection and quite possibly give rise to strong outflows and jets (see Narayan & Quataert 2005 for a short review).

Narayan et al. (2001) suggest a convection-dominated accretion flow model to describe an accretion scenario, in which case only a small fraction of the material is accreted, with a strong dependence on the outer radius of the accretion disk and an appropriate decrease in the flare energy. In this model, the accreted mass fraction is

$$f_{acc} \sim 14.1 f_{fall} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{R_{out}}{r_s}\right)^{-1}$$

$$\approx 1.4 \times 10^{-4} f_{fall} \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{R_p}{2.15 R_\odot}\right)^{-1} \left(\frac{M_\bullet}{10 M_\odot}\right),$$

where we have set $R_{out} \approx 2 R_p$ for the outer radius of the accretion disk and where r_s is the Schwarzschild radius of the CO. In fact, a non-negligible fraction of the energy released may not even be emitted but rather advected to the CO, at least in the case of a BH accretor, which would make even this estimate only an approximate upper limit for the flare energy in this case.

We conclude that the estimates for the energy emitted in the accretion flare could vary by orders of magnitudes. If most of the tidal debris mass is accreted to the CO, and the energy is emitted efficiently, then such accretion flares may be as energetic as GRBs or XRFs and should be observable from extragalactic distances, though they would be much fainter than typical GRBs/XRFs due to their much longer duration. Such flares could have XRF- or GRB-like characteristics but would not necessarily be associated with a supernova. Indeed, Lu et al. (2008) have suggested such a related scenario for GRB 060614 where no associated supernova was observed. They suggested a scenario of a jet formation process, which could produce such a GRB following the tidal disruption of a solar-mass star by an intermediate-mass black hole. Alternatively, as different accretion scenarios suggest, large outflows from the accretion disk may allow only a small fraction of the tidal debris to be accreted, in which case much fainter flares will be produced.

3. μTDE RATES

For a μTDE to occur we require a star/planet to pass by a CO at a distance of no more than the radius of tidal disruption.

In the following we consider four possible scenarios in which such close encounters can happen, and assess the μTDE rates and the expected typical environment in which they occur in each of these cases. These scenarios include: (1) a CO has a random close encounter with another star/planet in a dense stellar cluster; (2) a CO in a binary/planetary system is kicked (e.g., through a NS/BH natal kick) and encounters its close binary/planetary companion; (3) very wide binaries in the field are led into highly eccentric orbits due to multiple scattering with field stars, resulting in a close encounter.

Another possibility of encounter is through the secular evolution of a CO-hosting quasi-stable triple system (Antonini & Perets 2012) leading to close encounters (similar to the WD–WD collisions suggested by Katz & Dong 2012). However, the uncertainties involved in this scenario, and in particular the fraction of progenitor triple systems, are large, and the discussion of this scenario is beyond the scope of this work.

3.1. μTDEs from Stellar Encounters in Dense Stellar Clusters

There are several scenarios in which a close encounter between a CO and a star/planet could occur. An isolated CO may interact directly with a star or a binary in a two- or three-body encounter, respectively. Similarly a CO in a binary system may interact with another star or a binary system in three- or four-body interactions, with encounters between higher multiplicities possible. The dominant type of encounter would depend on the environment and the multiplicity of the systems (Leigh & Sills 2011, and references therein). In the following we estimate the μTDE rate from such random encounters; these rates are summarized in Table 2.

3.1.1. Two-body Interactions

The encounter rates between stars have been studied by many (see, e.g., Di Stefano & Rappaport 1992 for very similar calculations). Here we give the rates of encounters leading to a TDE, i.e., where the closest approach of a star/planet to a given CO is smaller that the tidal radius. Such encounter rates are dominated by the contribution from the densest stellar systems, such as globular clusters (GCs) and galactic nuclei.

Consider a CO of mass M_{co} in the core of a cluster containing N_* single stars (for a discussion of binaries, see below). A tidal disruption will take place if the distance of closest approach between this CO and a star is less than the tidal radius R_t. If each ordinary star had a mass M_*, the tidal disruption rate from the one CO would be

$$\dot{p}_{co}(R_t, \sigma) = 2\pi G(M_{co} + M_*) N_* R_t \sigma^{-1} V_c^{-1}$$

where σ is the relative velocity dispersion and the core volume V_c can be written in terms of the core radius R_c of the GC as $V_c = 4\pi R_c^3/3$. Here we are assuming that the collision cross section is dominated by gravitational focusing. The total disruption rate in a single GC is then

$$\Gamma_{co} \approx \dot{p}_{co} N_{co} \approx \dot{p}_{co} n_0 f_{co} V_c,$$

where N_{co} is the total number of COs in the GC core, n_0 is the number density of stars in the core, and f_{co} is the fraction of COs in the stellar population (see Di Stefano & Rappaport 1992).

Typical GC cores have densities of $n_0 \simeq 10^5 \text{ pc}^{-3}$, and a typical core radius $R_c = 1$ pc (Pryor & Meylan 1993; Gnedin & Ostriker 1997). Typical velocity dispersions in GC cores are

roughly $\sigma \simeq 20$ km s^{-1} (see, e.g., Di Stefano & Rappaport 1992). The fraction of COs in the stellar population is taken to be $f_{NS} = 0.017$ and $f_{BH} = 0.012$ (taking a Salpeter mass function between 0.6 and 120 $M_\odot$; NSs are assumed to originate from stars of mass between 8 and 15 $M_\odot$ and BHs are assumed to originate from stars more massive than 15 $M_\odot$); however, due to NS natal kicks and binary heating of BHs in a cluster, only a fraction of these COs are retained in the cluster. We assume a retention fraction of 0.05, following Pfahl et al. (2002), and we take typical masses of a neutron star and black hole to be 1.4 $M_\odot$ and 10 $M_\odot$, respectively. For COs of 1–10 $M_\odot$, the tidal radius falls approximately in the range $R_\odot \lesssim r_t \lesssim 2\,R_\odot$ for stars (and also for Jupiter-like planets, whereas terrestrial planets are disrupted only at distances about half of this because of their higher average densities). Using these typical values, we calculate the rates of disruption of stars by COs. We find $\Gamma_{NS} = 3.2 \times 10^{-9}$ yr^{-1} and $\Gamma_{BH} = 1.8 \times 10^{-8}$ yr^{-1}. These rates are consistent with more detailed cluster simulations where physical collisions were considered (e.g., Ivanova et al. 2008). Although the population of BHs is smaller than that of NSs, their larger mass makes the encounter cross section much larger, thus enhancing the rate of close encounters. For the ∼150 GCs observed in the Milky Way (MW) galaxy we finally get the tidal disruption rates per MW-like galaxy to be $\Gamma_{NS}^{gal} = 4.8 \times 10^{-7} (f_{NS}/0.017)(f_{ret}/0.05)$ yr^{-1} and $\Gamma_{BH}^{gal} = 2.8 \times 10^{-6}$ $(f_{BH}/0.012)(f_{ret}/0.05)$ yr^{-1}. We point out that many galaxies contain much larger number of GCs, and thus these estimates are only lower limits.

The rates of μTDEs of planets depend on the unknown fraction of free-floating planets in GCs; for a ratio of free-floating planets to stars, $f_{ffp\text{-}star}$, of one (one free-floating planet per star) the rate should be slightly lower (due to the smaller combined mass), but comparable to that of stellar disruptions, and the rate should scale linearly with $f_{ffp\text{-}star}$.

3.1.2. Three- and Four-body Interactions

Interactions between three and four (or more) bodies are much more complicated, as they may involve resonant encounters in which the stars can pass by each other several times. These could show chaotic behavior in which the stars may pass each other at almost any arbitrary distance (see, e.g., Valtonen & Karttunen 2006, and references within). Such behavior can much enhance the possibility of very close passages followed by tidal disruptions. Calculation of these rates requires better knowledge of the characteristics and distributions of binaries and compact binaries in clusters, and a detailed treatment that is beyond the scope of this work. However, from comparison with the somewhat similar scenario of stellar collisions and tidal captures (Krolik et al. 1984; Fregeau et al. 2004; Leigh & Sills 2011), in which such encounters were found to make an important contribution, we note that our results thus give only a lower limit on the tidal disruption rates, which could be higher by a factor of a few as a result of these few-body encounters.

3.2. μTDEs from Natal Kicks of COs

In the previous section we considered random encounters between a star and an unrelated CO. Such an encounter can happen with a non-negligible rate only in dense stellar clusters. A very different scenario for encounters may arise in systems containing NSs or BHs with a stellar or sub-stellar companion. In such systems the two companions may interact closely following the natal kick imparted to the NS/BH at birth.

NSs and BHs are usually born following a violent supernova (SN) explosion or through the coalescence of two COs (WD+WD, WD+NS, NS+NS). NSs, and possibly BHs, are thought to be born from these supernova explosions with high velocities of tens to hundreds of kilometers per second (so-called natal kicks; see, e.g., Pfahl et al. 2002 for a review and references). The comparison between the observed high velocities of pulsars and the measured low velocities of their progenitor stars is a strong indication of such kicks. BH formation may also involve an intermediate stage of collapse into a NS, suggesting that BHs may acquire similarly high-momentum kicks, leading to kick velocities that are lower than those of typical NS natal kicks, due to the higher mass of BHs: $v_{kick}^{BH} = (M_{NS}/M_{BH})v_{kick}^{NS}$. BHs formed through coalescence of COs might also acquire such high velocities (Rosswog et al. 2000).

Following these high-velocity kicks most binary systems would break up, ejecting the newly formed NS/BH and leaving behind their now isolated companions. However, in some systems the kick imparted to the newly formed NS/BH will give rise to a close-approach trajectory near the stellar/planetary companion (see, e.g., Leonard et al. 1994; Broderick 2005). If the encounter is sufficiently close, the companion might be disrupted. The total rates of μTDEs from such a scenario depend on many uncertain parameters such as the fraction and distribution of semimajor axes of such binary systems and the distribution of the velocity kicks; a detailed population synthesis model to better evaluate the μTDE rates from this scenario will be discussed elsewhere. In the following we provide an order-of-magnitude estimate.

If the natal kick imparted to the CO after SN explosion is randomly oriented and the kick velocity is larger than the Keplerian velocity of the binary (i.e., the interaction is dominated by the natal kick velocity), the probability of tidal disruption is the angular phase space covered by the stellar companion target; i.e., the disruption probability is of the order of $\sigma_t/4\pi a^2$, where $\sigma_t = \pi R_t^2(1 + 2GM_{bin}/R_t v^2)$ is the cross section for such a close encounter (including the gravitational focusing term), v is the relative velocity, and a is the binary separation just after the SN. The probability for such events is therefore a decreasing function of the binary separation.

Binaries with a massive primary ($>8\,M_\odot$ progenitors of NSs or BHs) and separations smaller than ∼10 AU will interact through a common envelope. Let us first consider only binaries with larger separations. Moe (2015 and private communication; see also Sana et al. 2012) finds that ∼80% of all massive stars have a binary companion with separation in the range 0.3–20 AU, distributed in a log-uniform way. We therefore obtain that ∼0.3 of all massive stars have non-strongly interacting binary companions in the separation range 10 AU < r < 20 AU. Given the dependence of the disruption probability on the binary separation, the rate of μTDEs will be dominated by binaries in this range, and we neglect the additional smaller contribution from wider binaries (only ≲20% of all massive stars have binary companions with $a > 20$ AU). The disruption probability is therefore of the

order of

$$p \sim \left(\frac{\sigma_t}{4\pi a^2}\right) \simeq \left(\frac{r_t^2}{a^2}\right)\left(\frac{GM_{\rm bin}}{2r_t v_{\rm kick}^2}\right)$$

$$\simeq 5 \times 10^{-6}\left(\frac{M_\bullet/10M_\odot}{M_\star/M_\odot}\right)^{1/3}\left(\frac{R_\star}{R_\odot}\right)$$

$$\times \left(\frac{(M_\bullet + M_\star)/11M_\odot}{(v_{\rm kick}/190\ {\rm km\ s^{-1}})^2}\right)\left(\frac{15\ {\rm AU}}{a}\right)^2.$$

The core-collapse SN rate in the Galaxy is $\sim 2.8 \pm 0.6$ per century (Li et al. 2011). Therefore, assuming a binary fraction of 0.3 in the relevant separation range and $v_{\rm kick}^{\rm NS} \sim 190$ km s^{-1}, and 2/3 of these SNe producing a NS while the rest produce a BH, we obtain a μTDE rate of $\sim 3.4 \times 10^{-7}$ yr^{-1} per MW galaxy for NSs, while the more massive BHs (with hence a smaller kick velocity) provide a rate of $\sim 1.4 \times 10^{-6}$ yr^{-1} per MW galaxy.

Interacting binaries that evolve through mass transfer may go through a common envelope and either merge or give rise to a compact binary with a short period, prior to the SN explosion. In such compact binaries the orbital Keplerian velocity is high and could be comparable with or much higher than the kick velocity, such that the conditions for a close approach following the natal kick need to be fine-tuned (Troja et al. 2010). Troja et al. (2010) studied in detail the possibility of a collision between two COs in a close binary following a SN kick, obtaining collision probabilities of the order of 10^{-8}–10^{-7}. The cross section for a tidal encounter with a star is much higher than the cross section for a collision (by a factor of the tidal radius to the CO radius in the gravitational focusing regime), suggesting this channel as a potentially promising channel for μTDEs, with a probability of tidal disruption of the order of 10^{-4}–10^{-3}. Nevertheless, the formation rate of such short-period binaries just prior to the SN explosion depends strongly on binary stellar evolution that is not well understood, and in particular on the common-envelope phase. We do note that X-ray binaries evolve through a short-period binary phase, and that their formation efficiency is low (the formation rate of X-ray binaries is of the order $\sim 3 \times 10^{-7}$ yr^{-1} per MW galaxy), suggesting that this channel might not be very efficient.

3.3. μTDEs from Perturbed Wide Binaries in the Field

Michaely & Perets (2016) suggest that low-mass X-ray binaries (LMXBs) might form in the field through close interactions between a CO and a wide binary companion induced by perturbations from field stars (following Kaib & Raymond 2014, who discussed a similar scenario for the collsion of two main-sequence stars). Such a process leads to processes similar to tidal capture, and may therefore produce tidal disruption events at similar rates. Michaely & Perets consider various scenarios; the most efficient scenarios can reproduce the population of LMXBs in the Galaxy. If we assume that this is indeed the main channel for LMXB formation (especially BH-LMXBs) we should expect a similar rate of μTDEs from the same scenario, namely of the order of a few times 10^{-7} yr^{-1} per MW galaxy.

4. DISCUSSION AND SUMMARY

In this paper we have explored the partial and full tidal disruptions of stellar and sub-stellar objects by stellar COs.

Such disruptions may result in energetic flares of long duration (tens of minutes to hours) following the accretion of the tidal debris onto the CO. The flare energy is highly dependent on the poorly understood accretion process, and could vary by orders of magnitude. If most of the tidal debris mass is accreted to the CO, and the energy is emitted efficiently, the accretion flares may be as energetic as GRBs or XRFs and should be observable from extragalactic distances, probably with GRB/XRF-like characteristics but with much longer timescales (10^3–10^4 s, and hence fainter), possibly decaying in a power-law fashion. Such flares are also not necessarily associated with a supernova (where GRB 060614 may serve as a possible candidate; see Lu et al. 2008 for a similar suggestion). Alternatively, large outflows may allow only a small fraction of the tidal debris to be accreted, in which case much fainter flares, with total energies smaller by orders of magnitude, may arise.

Our main focus was on disruptions by BHs. Though many similar aspects are expected to characterize disruptions by NSs and WDs, the latter have a physical surface and the accreted material may interact with the surface, possibly producing violent events such as X-ray bursts (NSs) and novae (WDs). Moreover, the accretion of material through TDEs may affect the evolution of such COs and their spin, in cases where a significant amount of material is accreted. This work focuses on the accretion event itself, but future follow-up work should address the long-term implications and observational signatures from μTDEs, which are beyond the scope of our current discussion.

On the longer timescales debris from a μTDE may continue to fall back slowly, possibly forming a long-lived accretion disk (e.g., especially if the disrupted star is an evolved star) that could power an X-ray binary-like object, though with only an accretion disk and not an actual stellar companion (J. Steiner & J. Guillochon 2015, private communication; see also Hills 1976a; Krolik 1984 for a consideration of long-lived X-ray sources formed by tidal capture). In an alternative scenario the debris that falls back on the CO gives rise to a gaseous envelope around the CO, possibly forming a Thorne–Zytkow object; however, this requires the fallback of the disrupted star to be very large (Thorne & Zytkow 1977), likely arising only from a direct collision rather than a tidal disruption.

Flares following close encounters in dense stellar systems are likely to occur mainly in dense systems such as globular clusters, galactic nuclei, or massive young clusters, and may thus be observable in both early- and late-type galaxies, with total μTDE rates of 10^{-7}–10^{-6} yr^{-1} per MW galaxy; comparable rates might also be obtained through tidal disruptions occurring in perturbed wide (>1000 AU) binaries in the field. Flares following a kick of the CO into a stellar/sub-stellar companion are likely to be associated with a SN and would occur in star-forming regions, typically months after the SN. Such μTDEs can also occur at rates comparable with the other scenarios, but are rare compared to the rate of core-collapse SNe, i.e., they occur once for every $\sim 10^5$ core-collapse SNe. We do caution, however, that the latter rate may be underestimated since it does not include the potential contribution from kicks in short-period planetary systems or binaries (possibly evolved through a common-envelope phase prior to the SN); μTDEs in the latter systems may occur hours to days after the explosion (i.e., during the early stages of the

SN rise). The ultra-long GRB 111209A has been observed to be associated with a very luminous SN (Greiner et al. 2015). The delay between the SN and the GRB in this case was at most a few days, and therefore a μTDE interpretation for this event indeed requires a compact, likely post-common-envelope binary. We should stress that μTDEs are super-Eddington events, and the radiation process likely arises from a jet. In this case the *observed* rates should be reduced compared with our calculations by a beaming factor, while the apparent luminosities we describe should be enhanced by the same factor.

We note that XRFs mentioned are typically those observed by the *Swift* mission following GRBs, following gamma-ray triggers. They typically last longer than GRBs, 10^4–10^5 s. Though the timescale of such events is comparable to that for μTDEs, our scenarios are not likely to be related to them or to explain such events. Rather we suggest a scenario where the *initial* prompt event occurs on long timescales and is not triggered by a prompt GRB.

The possible cases where μTDEs could be related to prompt GRBs are those in which a GRB results in the formation of a CO, which is then kicked and disrupts a companion. In this respect, we can mention the very long flare (a few $\times$ 10^4 s) observed in GRB 050724 a few hours after the prompt emission, which could possibly be explained by a μTDE. Interestingly, this would come into accord with a scenario suggested by MacFadyen et al. (2005) for this GRB. They try to explain a shorter late flare in this same event by shock heating from the prompt GRB explosion on a companion, which they suggest exists for this GRB progenitor. Taking into account the appropriate velocities possible for a kick, the timescale for both events (the shock heating and the tidal disruption) would correspond to the same distance between the binary members. However, the relevant timescales as well as other flares observed in this event make other scenarios equally, if not more, plausible than a disruption event.

The late flare (16 days after the GRB) in the case of GRB 050709 (Fox et al. 2005) is also noteworthy. The very long delay between the flares could potentially be explained by a μTDE event, e.g., produced following a natal kick during the formation of a BH from the merger of two NSs, which then disrupts a wider companion. Such a scenario might be fine-tuned, but currently no other scenario for this extremely late flare has been suggested.

Finally, the recently discovered sample of ultra-long GRBs could potentially be explained as μTDEs. Such a scenario would naturally explain their very long timescales compared with regular long GRBs, and would suggest the possible existence of events on a yet longer timescale, albeit fainter.

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