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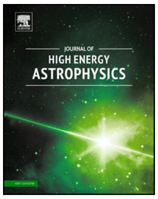

Review

Recent developments in the theory of tidal disruption events

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ABSTRACT

In this paper we will review some recent developments in the theory of Tidal Disruption Events (TDE). In particular, we discuss how recent work has led to a reconsideration of the time evolution of the debris of the disrupted star, which in turn determines the lightcurve of the event. We discuss the efforts being currently made to understand how an accretion disc forms around these objects. Finally, we discuss whether we can expect these systems to undergo rigid precession as a consequence of the Lense–Thirring torques produced by a spinning black hole.

1. Introduction

Tidal disruption events (TDE) occur when a star passes too close to a compact object, such as a supermassive black hole (SMBH), that the tidal field of the compact object is able to overcome the stellar self-gravity and tear the star apart. The basic theory of tidal disruption events has been developed in the late '70s and throughout the '80s (Lacy et al., 1982; Rees, 1988; Phinney, 1989; Evans and Kochanek, 1989).

For many years, the general picture was that such events would result in a strong flare from the center of a (possibly quiescent) galaxy, with moderately super-Eddington luminosities and a spectrum peaking in the UV-soft X-ray bands. Indeed, many TDE candidates have been discovered by X-ray (Komossa and Bade, 1999; Esquej et al., 2008; Cappelluti et al., 2009; Halpern et al., 2004) and UV (Gezari et al., 2008, 2009, 2012) surveys. The launch of Swift has modified our understanding and interpretation of these events in a drastic way. Indeed, Swift has led to the discovery of two new TDE (Bloom et al., 2011; Burrows et al., 2011; Zauderer et al., 2011; Cenko et al., 2012) characterized by the emission of a relativistic jet pointing in our direction, thus demonstrating that even such short-lived events can be associated with the formation of jets. We refer the reader to Komossa (2015, in this issue) for a thorough review of the observational status regarding TDE.

These discoveries have prompted a new generation of theoretical studies, aimed on the one hand at investigating more in detail the hydrodynamics associated with TDE (Lodato et al., 2009; Guillochon and Ramirez-Ruiz, 2013; Hayasaki et al., 2013; Shiokawa et al., 2015; Cheng and Bogdanović, 2014), its emission properties (Strubbe and Quataert, 2009; Lodato and Rossi, 2011; Guillochon et al., 2014), possible influence of general relativistic effects (Kesden, 2012b, 2012a; Stone and Loeb, 2012), and obviously the appearance and development of jets (Giannios and Metzger, 2011; Piran et al., 2015).

In this paper, we will briefly discuss some recent results concerning three different aspects of the theory of tidal disruption events: (i) the hydrodynamics of the disruption process, (ii) the appearance of optical and UV lightcurves and (iii) the possibility of observing Lense–Thirring precession in such events.

2. The hydrodynamics of tidal disruption events

As mentioned above, the basic theory developed in the '80s still provides a good zero-th order approach to the problem. A star of mass M_* and radius R_* is tidally disrupted if it approaches a black hole of mass $M_{\rm BH}$ closer than the tidal radius $R_{\rm t}$:

$$R_{\rm t} = \left(\frac{M_{\rm BH}}{M_*}\right)^{1/3} R_* \approx 23 R_{\rm S} M_6^{-2/3}, \qquad (1)$$

where $R_{\rm S}$ is the Schwarzschild radius of the black hole, $M_6 = M_{\rm BH}/10^6 M_\odot$ and the last equality assumes a solar type star. One can see that TDEs occur very close to the event horizon, so that relativistic effects might play an important role in their dynamics. One should also note that if the SMBH is more massive than $\approx 10^8 M_\odot$ the tidal radius lies within the event horizon and no TDE can occur (note that the inclusion of relativistic effects increases this limit to $\approx 10^9 M_\odot$, Kesden, 2012b). One can also define the

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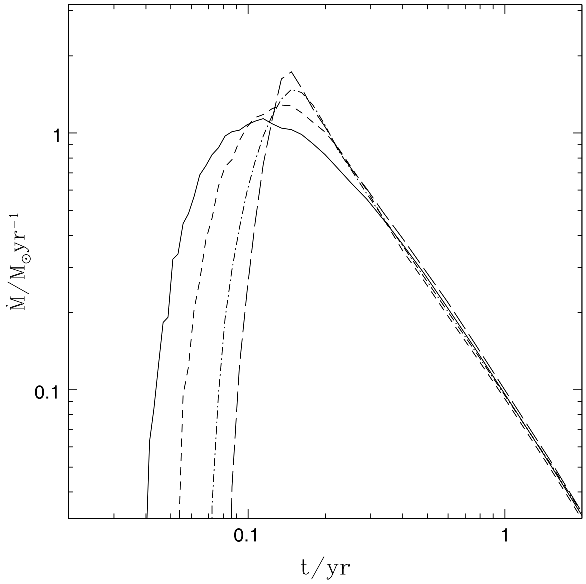

Fig. 1. Evolution of the accretion rate onto a $10^6 M_\odot$ SMBH following the disruption of stars with different internal structure, parameterized as polytropes with different indices γ. From left to right: $\gamma = 1.4, 1.5, 5/3, 1.8$.
From Lodato et al. (2009).

penetration factor $\beta = R_\mathrm{t}/R_\mathrm{p}$, where R_p is the pericenter of the orbit of the star (usually assumed to be parabolic). The simple theory by Rees (1988) is based on the assumption that the bound debris of the disrupted star follow Keplerian orbits with different periods depending on their depth within the black hole's potential well and fall back to pericenter at a rate:

$$\dot{M}_\mathrm{fb} = \frac{M_*}{3t_\mathrm{min}}\left(\frac{t}{t_\mathrm{min}}\right)^{-5/3}, \tag{2}$$

where

$$t_\mathrm{min} = \frac{\pi}{2^{1/2}}\left(\frac{R_\mathrm{t}}{R_*}\right)^{3/2}\sqrt{\frac{R_\mathrm{t}^3}{GM_\mathrm{BH}}} \approx 41 M_6^{1/2}\mathrm{d}. \tag{3}$$

The above formula for t_min assumes that the spread of mechanical energies in the debris is essentially determined by the relative width into the BH potential well at the tidal radius (Sari et al., 2010; Guillochon and Ramirez-Ruiz, 2013; Stone et al., 2013). In this case, the peak accretion rate is predicted to be significantly above the Eddington level, by up to two orders of magnitude for a $10^6 M_\odot$ black hole, while in the case of a more massive black hole, the peak rate is only moderately super-Eddington, and becomes sub-Eddington for $M_\mathrm{BH} \gtrsim 3 \times 10^7 M_\odot$.

A major recent development of the theory has been the realization (Lodato et al., 2009) that such fallback rate is only appropriate at late times, while the early evolution of the system, and thus the early rise of the corresponding lightcurve depends on the structure of the disrupted star. In particular, Lodato et al. (2009) demonstrated both analytically and numerically that more compressible stars are characterized by a more gentle rise to the peak accretion rate, while more incompressible stars show a sudden rise, followed almost immediately by a $t^{-5/3}$ decline (see Fig. 1).

A similar conclusion has also been obtained by Guillochon and Ramirez-Ruiz (2013), who reproduce the numerical simulations of Lodato et al. (2009) and also extend their analysis to cases with lower β, that is to partial tidal disruptions. In the case of partial disruptions Guillochon and Ramirez-Ruiz (2013) compute the amount of mass that can be stripped by the black hole and show that the fallback rate at late times becomes much steeper than the canonical $t^{-5/3}$ because of the progressive lack of material with small mechanical energy (which for partial disruptions is retained by the star). Note that such partial TDEs might have been observed in some cases (Campana et al., 2015) and might contribute to low-level accretion in quiescent galaxies (MacLeod et al., 2013).

3. Disc formation

The focus of recent investigations into the hydrodynamics of TDE has shifted progressively to the problem of the formation of an accretion disc after the return to pericenter of the debris. This issue has been discussed using simple 1D diffusion models for the disc by Cannizzo et al. (1990), and more recently by Shen and Matzner (2014). The first paper to investigate numerically this issue has been the one by Hayasaki et al. (2013). These authors consider the fate of a star in a bound eccentric orbit, with a pericenter distance equal to 1/5 of the tidal radius (thus a very penetrating event). They consider both the case of a purely Keplerian potential and the case where relativistic precession of the orbits is included. The conclusion is that relativistic precession is essential to lead to the formation of the accretion disc.

The issue has been then further discussed by Bonnerot et al. (2015). They perform an extensive analysis, through high-resolution SPH simulations, exploring the parameter range in terms of orbital eccentricity of the star, penetration factor, and gas cooling properties. In particular, they consider $\beta = 5$ (for comparison to Hayasaki et al., 2013) and $\beta = 1$, moderately eccentric orbits (with eccentricity $e = 0.8$ and 0.95) and two extreme assumptions of isothermal and adiabatic evolution of the gas, to mimic the case where cooling is efficient or not, respectively.

Such simulations are computationally highly challenging, especially as the eccentricity of the orbit is increased, so that most investigations have either considered the limit of a moderate-low eccentricity (Hayasaki et al., 2013; Bonnerot et al., 2015) or the limit of a smaller mass ratio between the black hole and the disrupted star (Shiokawa et al., 2015).

Figs. 2 and 3 visually describe some of the results by Bonnerot et al. (2015). Fig. 2 refers to the case where the gas evolves isothermally. The lower panel shows the evolution in a purely Keplerian potential, while the upper panel refers to the relativistic potential. The images are snapshots of the projected gas density at the times shown, in units of the period of the disrupted star, that in this case has an eccentricity $e = 0.8$ and a penetration factor $\beta = 5$. Only in the latter case, a thin disc forms due to orbit crossing of the debris. It lies at the circularization radius (indicated by a dashed circle on the last snapshot). Fig. 3 refers to the adiabatic case for the same stellar orbital parameters and the relativistic potential. Also in this case, a disc forms. However, since the gas is adiabatic, it puffs up and settles down in a toroidal configuration which is still centrifugally supported in its inner part and located between the circularization radius and the semi-major axis of the star (indicated by dashed and dotted circles respectively on the last snapshot).

A more quantitative description of the evolution of the debris is shown in Fig. 4, which shows the time evolution of the average orbital energy of the debris relative to the expected circularization energy, in the various simulations. The upper panel refers to the isothermal cases in the Keplerian (dashed line) and relativistic potential (solid line). The lower panel shows a comparison between simulations with different orbits of the incoming star: the solid line refers to an eccentricity of $e = 0.8$ and a penetration factor $\beta = 5$, the dashed line refers to an eccentricity of $e = 0.8$ and a penetration factor $\beta = 1$ and the long-dashed line refers to an eccentricity of $e = 0.95$ and a penetration factor $\beta = 5$. It can be seen that circularization occurs faster (that is, it occurs on a smaller number of dynamical times) as the orbit becomes more eccentric and as the penetration factor increases.