Perseus in Sicily: From Black Hole to Cluster Outskirts
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On the likelihood of Gravitational Wave emission during the Tidal Disruption of stars by Super Massive Black Holes

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Abstract. Tidal Disruption Events (TDEs) are a common feature between Active and Quiescent Galactic Nuclei; the study of these events is a very useful tool to probe phenomena that relate to the formation of an accretion disc or a jet. Also, the accretion rate at the beginning of the tidal flare is expected to be significantly super-Eddington and might result in high energy emission (in soft X-rays but sometimes up to the gamma regime, as in the the case of Swift J1644, see Komossa, 2015). These events may even play an important role in the newborn field of the Multimessenger Astronomy. This work is set within this context. Indeed, it is a study of generation of Gravitational Waves (GWs) from the hot accreting torus resulting after a TDE. Since the torus has only formed recently, magnetic fields are not expected to be strong enough, so that the torus is likely to be unstable to the Papaloizou-Pringle Instability (PPI), producing a strongly varying mass quadrupole. Here, the study of the evolution of such tori is developed, using both analytical calculation and a Smoothed Particle Hydrodynamics simulation (SPH). In particular the goal of this work is to determine the GW waveform and to compute the characteristic strain of these GWs in order to see if they are detectable by the Laser Interferometer Space Antenna (LISA).

Keywords. gravitational waves, black hole physics, accretion, accretion disks

1. Introduction

TDEs are known to be important sources of electromagnetic radiation; in addition, they could also be sources of gravitational radiation. As a matter of fact, during these events huge masses are involved, which undergo very high accelerations as they move close to the event horizon of a Supermassive Black Hole (SMBH). This work aims at studying the GW emission of a hot, thick accretion disc, resulting after a TDE, which is unstable with respect to the PPI. The work is divided in four parts: 1) an analytical study of the system, in order to see if these waves are detectable by LISA; 2) a numerical study of the system, starting from a simulation made by Nealon *et al.*, 2017, with PHANTOM, a Smoothed Particle Hydrodynamics and Magnetohydrodynamics code; 3) the study of the waveforms; 4) an extension of all the previous calculation in the case of rotating Black Holes.

2. Analytical estimates

In this first part we assume that the TDE occurs in the Virgo Cluster, at a distance of 16 Mpc. Results can be easily rescaled to other distances, since the strain scales

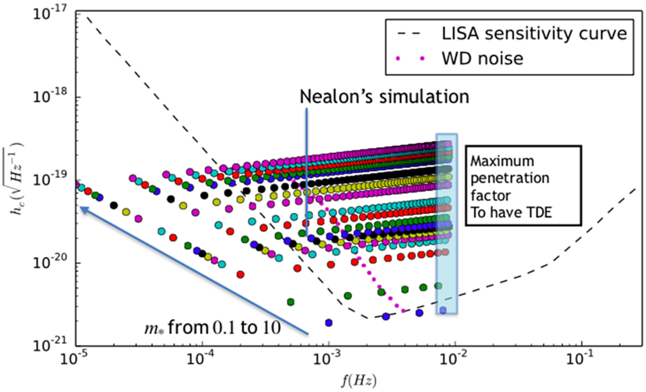

Figure 1. The plot shows the trend of h_c with respect to f, for Main Sequence Stars. The BH mass is $M_6 = 1$. The penetration factor β varies between $\beta_{min} = 1$ and $\beta_{max} = R_t/R_S$.

inversely with distance. In particular, we perform a study of the parameters of the system, considering different masses of the central Black Hole (BH), different types of stars that could be tidally disrupted and different closest approach between the star and the BH. We provide an analytical calculation of the magnitude of the gravitational wave strain tensor, using the approximated formula (e.g. see Thorne, 1998),

$$h \approx \frac{1}{r} \frac{4GE_{\rm kin}}{c^4}, \tag{2.1}$$

where h is the magnitude of the stress tensor which stands for the amplitude of the ripple in the fabric of space-time, G is the gravitational constant, c is the speed of light, $E_{\rm kin}$ is the kinetic energy and r is the distance of the source. The main goal of this study is to see if the characteristic strain, that is $h_c \doteq h\sqrt{f^{-1}}$, where f is the GW frequency, that we assume to be of the order of the Keplerian frequency at the circularization radius of the debris (see Bonnerot *et al.*, 2016), is above the LISA sensitivity curve.

3. Results

One important parameter for the study of this problem is the penetration factor $\beta = R_t/R_p$, where R_t is the tidal radius of the star, i.e. the maximum distance for the star to be disrupted by the BH and R_p is the pericentre of the stellar orbit before disruption. This factor varies between 1 (when $R_p = R_t$), and a maximum value, when R_p is equal to the Schwarzschild radius of the BH. We found that these waves may be detected by LISA, if discs resulting by Main Sequence (MS) and Red Giant (RG) stars are considered. In particular figure 1 shows the gravitational signal for MS stars; a BH of mass $M_6 = 1$ (that is $M_{\rm BH} = 10^6 M_\odot$) is considered. Each color represents a particular value of the stellar mass, which varies from $0.1M_\odot$ to $10M_\odot$. The factor β grows from left to right. It can be seen that, while β increasing, the gravitational signal is above the LISA sensitivity curve. We obtained a similar plot also for RG stars (not shown here). We expect that our analytical results overestimate the GW signal, because we suppose a 100% density perturbation. Thus, after our analytical study, we began a numerical study of the system based on the simulation by Nealon *et al.*, 2017, where they considered $M_{\rm disc} = 1M_\odot$, $\beta = 5$ and $M_6 = 1$; we rescaled their data to different values of the parameters involved. From this numerical study we estimate that the signal is two order of magnitude lower, but it is still in part above the LISA sensitivity curve, especially for the most penetrating events.

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