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Tidal disruption events in the multi-messenger astronomy era

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Summary. — In this paper we expose the physics of tidal disruption events and why they will play an important role in the field of multi-messenger astronomy.

1. – Introduction

We are currently living an astrophysical revolution. First of all, on 11th February 2016, there was the announcement of the first direct detection of gravitational waves (GWs), ripples in the fabric of space-time predicted by the theory of General Relativity (for historical details on GW prediction see [1] and [2]). This signal was emitted during the merger of two stellar black holes (BHs), that coalesced at 400 megaparsec (Mpc) from us, and it was revealed by the LIGO/Virgo Collaboration [3]. Then, around two years later, there was another thrilling discovery: for the first time a neutron star merger was seen both via GWs (GW 170817, see [4]) and electromagnetic (EM) radiation [5], the latter detected ∼2 seconds after the GW signal. This discovery has started a new thrilling era for High Energy Astrophysics.

In the upcoming years we expect more sources to be observed in both the domains. In fact, a new ground-based GW interferometer, KAGRA [6], will join LIGO [7] and Virgo [8] in the search of the GW sky. In addition, also a new generation of space-based interferometers, like the Laser Interferometer Space Antenna (LISA, [9]) and TianQin [10], is approaching. These instruments will work in a frequency interval lower than the one of current detectors, allowing us to expand the hunting of GW sources in the frequency window 10^{-4}–10 Hz. These instruments will work in synergy with new powerful telescopes such as Athena [11], Lynx [12], SKA [13] and CTA [14], that will rely on the information provided by the interferometers to know where in the sky to look for EM counterparts.

Between the sources that may play a crucial role in this field there are also tidal disruption events (TDEs). In the following, we describe the physics of TDEs, their gravitational emission and what we can learn from their future detection.

2. – Tidal disruption event physics

TDEs [15] are powerful astrophysical phenomena that occur when a star, orbiting around a super-massive BH (SMBH), is stripped away by the tides induced by the SMBH. Assuming that a star of mass m_* and radius r_* is on a Keplerian orbit with pericenter $r_{\rm p}$ around a SMBH $m_{\rm BH}$, the disruption requires

$$r_{\rm s} < r_{\rm p} < r_{\rm t}. \tag{1}$$

$r_{\rm s}$ is the Schwarzschild radius of the SMBH, below which the star is immediately swallowed, while $r_{\rm t}$ is the maximum distance to have the disruption, called tidal radius

$$r_{\rm t} \approx r_* \left(\frac{m_{\rm BH}}{m_*}\right)^{1/3}. \tag{2}$$

After the disruption around half of the stellar debris escapes on different hyperbolic orbits, while the other half circularizes around the SMBH and forms an accretion disc. These events are powerful electromagnetic sources, that produce luminous flares observed in different EM bands such as optical ([16] and references therein), X-ray ([17] and references therein) and radio ([18] and references therein). The lightcurve that characterized these events decreases with time as $t^{-5/3}$ [19], although some recent studies (see, *e.g.*, [20]) have stressed that deviations from this trend are expected in some specific bands.

TDEs not only are bright EM sources, but they also emit GWs. In particular, there are three GW emission phases during the event: i) while the star is approaching the pericenter and it gets stretched and compressed by the tides induced by the SMBH (see, *e.g.*, [21]), ii) while the star is disrupted at the pericenter (see, *e.g.*, [22]) and iii) when the stellar debris circularize (see, *e.g.*, [23,24]). All being equal, the gravitational wave burst produced at disruption is the strongest signal. In particular, if we consider a Sun-like star ($1M_\odot$ and $1R_\odot$) disrupted by a $10^6 M_\odot$ SMBH at a typical distance of 20 Mpc, we get the following (maximum) GW strain, h, and frequency f:

$$h \approx 10^{-22}, \tag{3a}$$

$$f \approx 10^{-4}\text{Hz}. \tag{3b}$$

Although f is within the interval where future space interferometers will operate, the strain is not very strong, thus it will be unlikely for LISA to detect single TDEs through GWs. For this reason, it is more interesting to investigate the gravitational signal produced not by an individual but by the entire cosmic population of TDEs, *i.e.*, their GW background.

3. – GW background from tidal disruptions: strategy and results

We have investigated the gravitational background from TDEs in [25] (refer to this paper for detailed explanations and calculations). In particular, we have considered two different contributions to this background: the one generated from the tidal destruction of main sequence (MS) stars by SMBHs and the one generated from the disruption of white dwarfs (WDs) by intermediate mass BHs (IMBHs). In the first scenario, we are working with *nuclear* TDEs, since we assume that these SMBHs, with masses from million to billion solar masses, reside in the cores of galaxies. Thus, a possible detection of this background signal could be used as a way to map the distribution of quiescent SMBHs through the universe, since different distributions would imply different background levels. In the second scenario instead, we are considering *globular* TDEs. As a matter of fact, when considering TDEs of WDs, SMBHs would have a mass so large that they would directly swallow the star. Thus, we study WDs disrupted by IMBHs in the range 10^3–$10^5 M_\odot$, and, for this kind of (so far hypothetical) BHs, the most likely environment are globular clusters (GCs). The detection of this signal would be first a powerful tool to collect information on the elusive population of IMBHs. Secondly, it would be a tentative of understanding which is the average occupation fraction of IMBHs in GCs.

For our analysis we have decided to compare these signals with the sensitivity curves of LISA and TianQin, but also of other space interferometers planned to work in a more distant future: the DECI-hertz interferometer Gravitational wave Observer (DECIGO, [26]), the Advanced Laser Interferometer Antenna (ALIA, [27, 28]) and the Big Bang Observer (BBO, [29]). We obtained two main results. First, the signal is proportional to the frequency as $f^{-1/2}$. This is a consequence of the impulsive nature of the GW emission associated to the disruption and it is a *distinctive* feature of the TDE background, different from the signal produced by other sources in the same frequency interval. Then, we have found that while the background from MS star is too low to be detected by any future planned instruments, the background from WDs disrupted by IMBHs could actually be a promising source for DECIGO and BBO, and in part even for ALIA. Thus, in the upcoming years, we can *actually* think to use the GW background from WDs tidally disrupted as a way to extract information on IMBHs.

4. – Conclusions

In conclusion, TDEs will provide some fascinating physics in the next future. As a matter of fact, they have already been observed through electromagnetic waves in different bands and we expect to see more of them with future powerful telescopes. At the same time, thanks to the space-based generation of gravitational interferometers, it could be possible to observe TDEs also through gravitational waves. These future discoveries might provide important clues on the existence of IMBHs, also expanding our knowledge regarding the distribution and abundance of GCs in the Universe.

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