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Gravitational wave signals from binary-single black hole encounters in star clusters

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Star clusters are the main dynamical formation channel for binary black holes (BBHs). In these dense environments, BBH mergers are driven by gravitational wave emission and binary-single encounters with other objects in the cluster. This work is focused on the gravitational wave (GW) signals emitted by close encounters between a BBH and an isolated black hole, highlighting the various outcomes that can arise from these interactions. To estimate the GW spectrum of these signals, numerical simulations are performed using the N-body code ARWV, with stellar mass black holes serving as input masses. Our study considers the potential for these burst signals to fall within the sensitivity band of current and future ground-based detectors, depending on the parameters involved.

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1. Introduction

The gravitational wave (GW) community is currently working on the future third generation GW detectors, namely Einstein Telescope (ET) [1] and Cosmic Explorer [2], after the successful observation runs of Advanced Virgo [3] and Advanced LIGO [4]. The increased sensitivity of these future ground-based detectors will result in hundreds of thousands of GW events rather than the actual tens of events recorded annually [5]. Furthermore, other instrumental innovations - such as the space-based detector LISA [6], the pulsar timing arrays [7] and decihertz Moon-based GW detectors [8] - will result in a coverage of the GW spectrum ranging from nanohertz to kilohertz.

This broadened frequency range will enable investigations into GW emissions from non conventional sources. Among these sources are hyperbolic encounters between compact objects, black holes (BHs) in particular. The recent detection of GW190521, the most massive BH merger detected so far, has raised interest in such encounters. In fact, some follow-up studies [9, 10] suggest that this merger could be the result of a dynamical interaction between unbound stellar-mass BHs, providing indirect evidence of dynamical interactions in star clusters. Nevertheless, at the moment we are still not able to discriminate whether the detected binaries are in an isolated or in a dynamical environment, and new evidence is needed to fill this gap.

Many studies have explored two-body hyperbolic encounters both from the analytical [11, 12] and from the numerical [13, 14] point of view. Many population models in star clusters have been developed as well ([15] and references therein), shedding light on cluster dynamics. In [16] we carried out experiments bridging these two perspectives, incorporating a population model to simulate realistic encounters between three BHs, in a binary-single configuration, acting as a source of GWs; we provided a realistic estimate of the detectability of gravitational radiation from single-binary hyperbolic flyby in nuclear star clusters (NSC) and the rate of these events.

Here, we aim to provide a description of these encounters, investigating their detectability by the ET detector.

2. Astrophysical Background

For the purpose of this study, we focus on NSCs since they are the most massive type of clusters. As a consequence, they have a very high escape velocity and can retain BHs that experience a kick during formation, after a supernova explosion, or after encounters and mergers. Furthermore, in star clusters, due to the high density of objects, BBHs become harder not only by the emission of GWs but also by close encounters with other bodies in the environment [17].

In this context, we consider binary-single interactions when the three interacting bodies are BHs. The outcome of such BBH-BH encounters is typically a flyby where the binary and the intruder object interact on an hyperbolic orbit. Depending on the geometrical parameters involved, the intruder can also remain trapped with the binary in an unstable triple system that breaks when one of the three objects acquires enough velocity to escape. If the binding energy of the binary is higher than the average kinetic energy of the stars in the cluster, the velocity of the intruder after the encounter is greater than the one with which it approached the binary, as a consequence of the conservation of energy, and the binary tightens [17].

Using these properties, in [16] we conducted a study on the detectability of GW signals from binary-single hyperbolic encounters. We used stellar-mass BH as input masses and considered hard binaries in an environment that is the core of an NSC. We also found that the size of the core strongly impacts the rate of binary-single encounters in NSCs. Up to redshift $z = 3.5$, the rate is within the range $[0.006 - 0.345]\ \mathrm{yr}^{-1}\ \mathrm{Gpc}^{-3}$ where the lower and upper limits are given considering a core radii of 0.1 pc and 1 pc, respectively.

In agreement with the presence of these sources in NSC cores, we built the distribution of the parameters involved. After considering a set of hyperbolic binary-single simulations, generated by considering parameter values taken from their distributions, we inferred that the majority of GW signals produced by hyperbolic encounters are in the frequency band of LISA; no signals were in the ground-based interferometers' frequency band. Despite this, we found a relationship between the characteristic frequency of the signals with both the semi-major axis of the binary and the impact parameter with which the intruder approaches.

3. Methods

In this study, we aim at simulating numerically BBH-BH encounters that generate GW signals observable by ET. According to what we derived in [16], we tuned the initial conditions to reach amplitude and frequencies that fall into the ET detection band, yet consistent with the presence of the interacting bodies in a NSC.

Table 1: Initial parameter values that we slightly change to simulate the 21 binary-single encounters. From the left side of the table are reported: the two masses of the binary, the mass of the intruder, the semi-major axis and the eccentricity of the binary, relative velocity and impact parameter with which the intruder approaches the binary. We consider all three BH spinless.

m_1 [$M_\odot$]	m_2 [$M_\odot$]	m_3 [$M_\odot$]	a [AU]	ecc	v [km/s]	b [AU]	spins
30.0	25.0	10.0	8e-05	0.0	50.0	0.005	0

We perform 21 simulations of binary-single encounters through the N-body code `ARWV` [18–20]. Starting from a common set of initial conditions (Table 1), we slightly change the parameter values to understand how small changes affect the outcome of the simulation. Due to the small values of the semi-major axis of the binary and the impact parameter of the intruder, selected to fall into the ET detection band, none of the simulations outputs a flyby (i.e. hyperbolic encounters). In all the simulations the intruder remains bound with the bodies of binary for a few orbits before leaving the system (i.e. resonant encounter) or it remains bound to the newborn BH coming from the merger of the binary during the three-body interaction. A second-generation binary can be also formed by the original binary in which one of the two components merged with the intruder. In some simulations, we recorded two consecutive mergers in less than an hour.

We compute the wave amplitude using the coordinates of the position and velocity of the bodies that the ARWV simulations return to us in output. We choose the plus polarization as the GW amplitude of our signals.

In order to study the detectability of these events by ET, we simulate ET detector noise by generating Gaussian white noise colored with the detector's design sensitivity curve [21] in which we inject our signals. We use the Welch method to obtain the amplitude spectral density of the noise. The signal injections are carried out using the Python packages `gwpy` [22, 23] and `pycbc` [24].

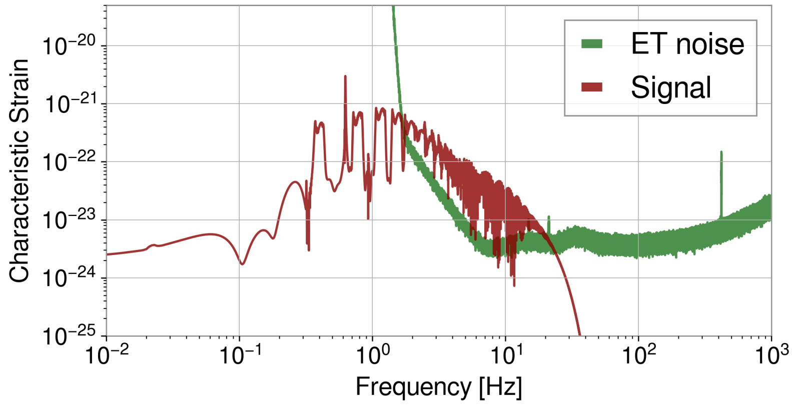

Figure 1: Characteristic strain (red) of our simulated gravitational signal and the strain amplitude of the ET simulated noise (green). The signal presents as initial conditions of the parameters the value reported in 1.

4. Results

We compute the characteristic strain for the entire set of simulations. In Fig. 1 is reported the characteristic strain of one of the simulated signals, compared with the strain amplitude of ET noise. The initial conditions of this simulation are listed in Table 1. After the first encounter, the intruder remains bound to the binary making two other close encounters before leaving the system. The spike at around 0.6 Hz in Fig. 1 is due to the accumulated signal from the initial binary before the first encounter. The signal-to-noise ratio SNR computed as the area between the characteristic strain and the characteristic noise strain for this source at 230 Mpc is 51.4.

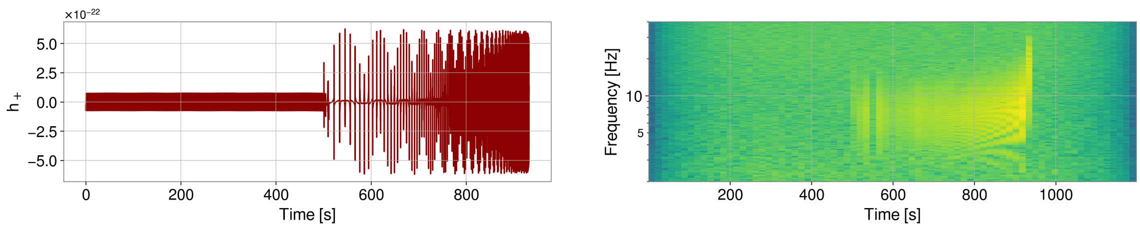

Figure 2: Time series of the simulated signal (left) and spectrogram (right). The spectrograms is of the data containing the noise and the signal are tapered and bandpassed, then normalized by the median of the frequency bins.

The right panel in Fig. 2 shows the spectrogram of the data containing the GW signal injected in simulated ET noise sampled at 4096 Hz. We taper and bandpass the data between 2 Hz and 30 Hz and then apply the Welch method using 16 s long segments with an 8 s overlap to compute the spectra. We then normalize each frequency bin by its median to highlight the time variation.

The simulation of Fig. 2 has the initial values of Tab 1 but the impact parameters here is 6×10^{-3} AU. After two encounters at around 500 s and a third one at 510 s the intruder merged with the less massive object of the binary and the resulting BH formed a second-generation binary with the other object of the binary. This new binary is very eccentric and starts the inspiral phase until the merger, visible in the spectrogram in Fig 2. This evidence is repeated across many other simulations; from the spectrograms we see that, for sources at 230 Mpc, the bursts due to the encounters are clearly visible. The presence of these bursts prior to the merger constitutes our core finding. The GWs signals that we observe with LIGO-Virgo are mergers of compact objects that inspiral until the merger; our results suggest that it would be interesting to inspect the data looking for signs of a burst before the merger, just as we saw it happening in our simulations. If this burst is revealed, and its sky location is compatible with that of the merger, it would imply the presence of that binary in a dynamical environment.

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PoS(EPS-HEP2023)073

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