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Development of Phenomenological Gravitational Wave Signals from Rotating Core-Collapse Supernovae in a Multi-Messenger Environment

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My Master's thesis is focused on the reconstruction of Gravitational Wave (GW) signals from Core-Collapse Supernovae (CCSNe) by mean of the *ccphen* code written by Prof. Pablo Cerda-Duran. In particular, type II SNe are the candidates for this work, since we haven't so far a complete theoretical model to predict the waveforms of these events. We have already detected binary mergers of two Neutron Stars (NS-NS), two Black Holes (BH-BH) or a mix of these (NS-BH), but we haven't an exhaustive representative of star collapse. Thus the main goal of my project is to reconstruct with the aforementioned C\Python hybrid code the waveforms of these sources.

What produces GW signals is the asymmetric breakdown of the star (otherwise the quadrupole moments are identically zero), that possesses some features. The shock-wave starts with the bounce of the in-falling matter over the incompressible nucleus made up by degenerate neutrons (NSs or BHs depending on the mass of the progenitor). The *Bounce phase* is the beginning of the simulations (on the x-axis there is the time after the bounce). This phase at first glance differs accordingly to the Equation of State (EoS) of the progenitor star and the magnitude of the rotation (actually only fast rotating progenitors show this signal). Nevertheless we can adopt the *Master Template* to normalize the strain amplitude h_n (the one linked to the relative deformations of the interferometer's arms) of the n-th waveform with the difference between the maximum and minimum of the GW Δh_n (also considering the distance to the source D). In this way, averaging all the waveforms, we obtain a template that is now the same for any EoS we use (with its own variance).

Some models show also the *Prompt convection*, which lasts for $50 - 100\,\mathrm{ms}$ at about $100\,\mathrm{Hz}$. The magnitude of this component is uncertain and is strongly correlated with the details of numerical simulations.

The key component of the signal is due to the *g-modes* of the Proto-Neutron Star (PNS), well recognizable by the arch-like shape of its spectrogram. Its onset is immediately after the bounce or with some delay (of the order of $200\,\mathrm{ms}$) at a frequency of $100\,\mathrm{Hz}$ and its duration is till the ignition of the explosion. In this context minor modes arise, the so-called *SASI modes* (Standing Accretion Shock Instability), whose duration is comparable to the *g-modes*, but with lower frequencies (albeit it starts at $100\,\mathrm{Hz}$) according to a linear trend. These components are simulated distinguishing the case of rotating and non-rotating PNSs. We initiate with the non-rotating case. We perform a decomposition in spin-weighted spherical harmonics (because of the tensorial nature of the GW) so to have the l, m components of h ($l = 2$ for the quadrupole moments, the dominant ones as of the strain, and $m = -l, \ldots, l$). This is the simplest case of GW emission. Introducing angular velocity we have a splitting of the curves in the spectrogram depending on the value of m (for fixed, constant rotation). In this case we have to do a reference system change, from the co-rotating one (same formulation as before, since in the reference of the star everything is still if we exclude deformations caused by the rotation) to the laboratory system from which we see the star spinning. So we express the strain amplitude of one system in term of the other and quantify the signal. At the very end we introduce deformations in the form of perturbations of the spherically symmetric background density with the deformation vector that is purely radial (given the symmetries of the source).

The final stage of the Supernova is the actual explosion that leaves a low frequency signal below $\sim 10\,\mathrm{Hz}$. What causes the revival of the outburst (stopped by the external layers of the star) are supposedly the neutrinos produced by electron captures by protons. Neutrinos are the particles that trigger the runaway explosion and are the key ingredients in many theoretical models of CCSNe.

This kind of sources are therefore a good probe for multi-messenger observations, since we can theoretically detect both GWs and neutrinos, having a full insight of CCSNe. Modelling this phenomena with theoretical waveforms could solve some questions about GW emission and neutrino-driven mechanisms of these objects, also giving a wider knowledge of General Relativity processes.

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