Neutron Star Mergers at the Dawn of Multimessenger Astrophysics
massive binaries, accretion disks and phase transitions
(extended abstract)

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1 Multimessenger astrophysics

Multimessenger astrophysics represents a new paradigm in our understanding of the universe, transcending traditional observational boundaries by combining information from various cosmic messengers. This interdisciplinary field integrates data from electromagnetic signals, gravitational waves, and high-energy particles, enabling a more comprehensive exploration of the cosmos.

The detections of gravitational waves (GWs) originating from black hole (Abbott et al., 2016) and neutron star mergers by the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Virgo interferometer have provided novel insights and validated several key predictions of Einstein's theory of general relativity. Complementing these GW observatories, space-based telescopes like the Chandra X-ray Observatory and the Fermi Gamma-ray Space Telescope, have enabled the precise localization and characterization of the electromagnetic counterparts associated with GW events.

One of the most notable events in multimessenger astrophysics is the merger of two neutron stars, which was first detected in 2017 through the simultaneous observation of GWs and electromagnetic radiation across the entire spectrum, from gamma-rays to radio waves (Abbott et al., 2017). This groundbreaking discovery provided many insights on different physical phenomena, from the properties of matter at very high densities (Raaijmakers et al., 2020) to the origin of heavy elements (Nedora et al., 2021).

2 Binary neutron star merger

Binary neutron star (BNS) systems typically form from massive binary progenitor stars, which, in the final state of their evolution, can collapse to a neutron star (NS) (Belczynski et al., 2018). The binary system loses angular momentum via gravitational emission, decreasing the orbital separation. As the NSs approach each other, tidal interactions become significant. Tidal forces deform the NSs, leading to dissipation of orbital energy and further shrinking of the orbit. Ultimately, the BNS merge into a single, more massive object. This process is accompanied by a violent release of energy in the form of GWs and ejection of matter, leaving a compact object surrounded by an accretion disc (Bernuzzi, 2020; Radice et al., 2020).

Accretion discs formed in BNS mergers are the engine responsible for many relevant physical processes. It is commonly retained that gamma-ray bursts are triggered by the rapid accretion of the disc into the black hole (BH) (Berger, 2014). A relevant portion of the disc (up to $30 - 50\%$ of the initial torus mass, see e.g. Fahlman & Fernández, 2022) is instead ejected by multiple mechanisms: redistribution of the angular momentum, thermal effects (Metzger et al., 2010), neutrino winds (Perego et al., 2014), magnetic stresses (De Villiers et al., 2005). By rapid neutron capture process (Lippuner & Roberts, 2015), the ejected matter is responsible for the nucleosynthesis of heavy elements. The radioactive decay of these unstable isotopes produce an electromagnetic transient referred as kilonova (Li & Paczynski, 1998).

3 Numerical simulations

The merger and post-merger dynamics in BNS is highly non-linear and complex, involving many areas of physics. Just to list some, nuclear physics is required to describe the matter in the high-density and moderate-temperatures regime reached during the merger; general relativity (GR) is essential for the description of the space-time and to model the GWs emission; neutrino radiation has strong impact on the energy dissipation as well as on the matter composition and ejection (Perego et al., 2014).

In this complex scenario, numerical relativity simulations of BNS mergers are the main tool used to link models to observations. The effects of different physical inputs can be simulated and then compared to the observations.

The numerical methods employed in this thesis are implemented in the general framework provided by the `Einstein toolkit` (Löffler et al., 2012). They featured a finite-difference scheme to discretize the Einstein's equations, while the general relativistic hydrodynamics is handled via the finite-volume high-resolution shock-capturing code `WhiskyTHC` (Radice & Rezzolla, 2012; Radice et al., 2014, 2018a). The NS matter is described as a fluid made by neutrons, protons, nuclei, electrons, positrons, and photons, assuming nuclear statistical equilibrium. All the simulations described in this thesis employ the same `Leakage` + `M0` scheme to evolve the changes in composition and energy due to the neutrino interactions (Galeazzi et al., 2013; Radice et al., 2018b).

4 Thesis resume

In this thesis we mainly focus on the study of the BNS merger GW190425 detected by the Ligo and Virgo interferometers on the 25th of April, 2019, on the characterization of the accretion discs formed from the merger of a binary system composed by two NSs and on the effects of a hadron to quark phase transition that can occurs during such mergers.

4.1 Numerical simulations and analysis of the BNS merger GW190425

GW190425 was the second GW signal compatible with a BNS merger detected by the Advanced LIGO and Advanced Virgo detectors. Since no electromagnetic counterpart was identified, whether the associated kilonova was too dim or the localisation area too broad is still an open question. We simulate 28 BNS mergers with the chirp mass of GW190425 and mass ratio $1 \leq q \leq 1.67$, using numerical-relativity simulations with finite-temperature, composition dependent equation of state (EOS) and neutrino radiation. The energy emitted in GWs is $\lesssim 0.083\ \mathrm{M}_{\odot}c^2$ with peak luminosity of $1.1 - 2.4 \times\ 10^{58}/(1+q)^2 \mathrm{erg\ s}^{-1}$. Dynamical ejecta and disc mass range between $5 \times\ 10^{-6} - 10^{-3}$ and $10^{-5} - 0.1\ \ \mathrm{M}_{\odot}$, respectively. Asymmetric mergers, especially with stiff EOSs, unbind more matter and form heavier discs compared to equal mass binaries. The angular momentum of the disc is 8 - 10 $\mathrm{M}_{\odot}\ GM_{\mathrm{disc}}/c$ over three orders of magnitude in M_{disc}. While the nucleosynthesis shows no peculiarity, the simulated kilonovae are relatively dim compared with GW170817. For distances compatible with GW190425, AB magnitudes are always dimmer than ~ 20 mag for the B, r and K bands, with brighter kilonovae associated to more asymmetric binaries and stiffer EOSs. We suggest that, even assuming a good coverage of GW190425's sky location, the kilonova could hardly have been detected by present wide-field surveys and no firm constraints on the binary parameters or EOS can be argued from the lack of the detection.

4.2 Accretion disks in binary neutron star mergers

Accretion discs formed in BNS mergers are the engine responsible for many relevant physical processes. Numerical simulations of accretion discs have been used to investigate the outcome of such processes, but the initial configuration of the disc lack of an unique analytical description and some assumptions are still needed. In this work I analyze in detail the properties of accretion discs from 44 BNS merger simulations, with the aim of furnishing reliable initial conditions and a comprehensive characterization of the accretion discs. I found that the discs are usually thick, with an aspect ratio decreasing with the mass ratio of the binary from ~ 0.7 to 0.3. Despite the disc sample spans a broad range in mass and angular momentum, their ratio is independent on the EOS and on the mass ratio of the binary. I have found that this can be traced back to the rotational profile of the disc, characterized by a constant specific angular momentum of $3 - 5 \times 10^{16}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$. The entropy per baryon and the electron fraction depend on the mass ratio of the binary. For small mass ratio ($q \lesssim 1.3$) they follow a sigmoidal distribution with the density, for which I provide a detailed description and a fit. The disc properties discussed in this work can be used as a robust set of initial conditions for future long-term simulations of accretion discs from BNS mergers, posing the basis for a progress in the quantitative study of the outflow properties.

4.3 Effects of first order QCD phase transitions in BNS mergers

Quantum chromodynamics (QCD) is the theory describing the strong interaction of quarks and gluons. At low energies quarks and gluons are bound together forming hadrons and mesons. Increasing the energy scale, the interaction becomes asymptotically weaker carrying to a new state of matter made of a deconfined plasma of quark and gluons called quark-gluon plasma (QGP). QGP has been observed experimentally for the first time in the late 1980s at the CERN and in BNL, probing the transition in the high temperature and low density regime. Despite many efforts, the nature of the phase transition (PT) at high densities and relatively low temperatures remains mainly unknown. This is the regime reached in BNS mergers, where the central density can be few times the nuclear saturation density $\rho_0 \sim 2.8 \times 10^{14}$ g cm^{-3}. BNS mergers are fruitful laboratory for high density physics. Indeed, the EOS of nuclear matter is linked to the properties of the GWs emitted during the inspiral, merger and post-merger phases. Since the properties of the PT to quark matter are highly uncertain, different constructions have been used to simulate its appearance and its effects during the merger of binary neutron stars. In this work, I present an ongoing project aimed at comparing different first-order PT constructions within a consistent simulation setup. The purpose is to clearly asses the systematic behind the PT model.

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