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Neutrinos in neutron star mergers: Nucleosynthesis and kilonova

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Summary. — The recent detection of gravitational waves and electromagnetic signals from the merger of a binary neutron star has confirmed our basic understanding of how this catastrophic events occur. The detected kilonova signal is compatible with the radioactive decay of heavy nuclei synthesized via the rapid neutron capture process. However, the presence of an early blue component, in addition to a later redder emission, points to a non-trivial and non-homogeneous angular distribution of the properties of the ejecta powering the kilonova. Detailed, anisotropic modeling of the kilonova emission, largely based on the results of simulations of matter ejection from a binary merger including neutrinos, is able to explain the observed emission. This confirms the central role of weak interactions in determining the composition and ultimately the opacity of the expanding ejecta.

1. – Introduction

Binary neutron star (BNS) mergers are cosmic laboratories for fundamental physics. All four fundamental interactions play a key role in shaping the many observables that qualify these events as a prototype case for multimessenger astrophysics. Multidimensional, multiphysics, and multiscale numerical models are necessary tools to predict and to interpret the associated observables. Results of many years of research were remarkably confirmed by the combined detection of gravitational waves (GWs) and electromagnetic (EM) radiation from the first event compatible with a BNS merger, as reported by the Ligo and Virgo Scientific Collaboration and by several groups of astronomers all over the world [1, 2]. In fact, the gravitational wave event denoted GW170817 was immediately followed by a gamma-ray burst (GRB) and a peculiar transient, called *kilonova* (KN, or *macronova*). This KN emission appeared initially as a UV/optical bright transient, before reddening on a time scale of a few days. These detections confirmed that compact binary mergers are one of the sites for the production of the heaviest elements via the rapid neutron capture process (r-process), occurring in the relatively small amount of matter ejected in the merger. Indeed, the radioactive decay of the freshly synthesized r-process nuclei powers the KN emission while the ejecta expands into the interstellar medium, becoming progressively more transparent. r-process nucleosynthesis occurs when the time scale for neutron captures is much smaller than that of β-decays. A significant excess of neutrons over protons in decompressed NS matter is a sufficient condition for the r-process to occur. However, its extent depends dramatically on the neutron richness, parametrized by the electron fraction, Y_e: matter with $Y_e \lesssim 0.25$ produces all nuclei above the second r-process peak, including lanthanides, while matter with $Y_e \gtrsim 0.25$ synthesizes nuclei between the first and second r-process peak (*e.g.*, [3]). The presence of lanthanides is crucial in shaping the KN emission, since open electron f-shells increase the atomic opacity of photons by more than two orders of magnitudes, compared with Fe-group nuclei, delaying the escape of diffusing photons from the expanding ejecta and lowering the photospheric temperature. The bulk of cold NS matter in ν-less weak equilibrium has $Y_e \lesssim 0.10$. However, as a consequence of the merger, the conversion of kinetic energy in internal energy increases the matter temperature (up to a few tens of MeV) and boosts neutrino production and absorption. The copious emission of neutrinos of all flavors from the possibly unstable central massive NS and from the disk ($\sim$0.1 $M_\odot$) powers a luminosity of $\sim 10^{53}\,\mathrm{erg\ s^{-1}}$, with typical neutrino energies of 10–15 MeV. Charged current reactions involving electron (anti)neutrinos convert neutrons into protons and vice versa, determining Y_e of the ejecta. Thus, in addition to being one of the possible central engines for GRBs or undergoing peculiar flavor transformations (*e.g.*, [4,5]), neutrinos and weak reactions are crucial in BNS mergers to predict the composition of the ejecta and the properties of the EM transients.

2. – Anisotropic matter ejection in binary neutron star mergers

State-of-the-art simulations of the merger and post-merger have revealed that matter ejection happens through different channels (*e.g.*, [6-10]). Each channel is characterized by a different ejection mechanism, providing the expanding matter with qualitatively different properties and a certain degree of anisotropy. Tidal interactions and shock waves eject matter within a few ms (dynamical ejecta). Matter ($\sim 10^{-3}$–$10^{-2} M_\odot$) is preferentially expelled on the equatorial plane, even if shock expansion and neutrino irradiation determine the ejection at all latitudes, with typical velocities $v \sim 0.2$–$0.3\,$c. Simulations including neutrino absorption show that ν_e captures drive Y_e above 0.25 for latitudes above $\sim 45°$. On time scales of a few tens of ms, neutrino re-absorption inside the remnant expands the disk and ultimately drives an outflow known as ν-driven wind, mainly at high polar latitudes. Depending on the neutrino luminosity and massive NS lifetime, neutrinos can unbind up to a few percent of the disk. Velocities in the wind are $\sim$0.1 c, while the interaction with neutrinos drives $0.3 \lesssim Y_e \lesssim 0.4$ (fig. 1, left panel). Finally, on the longer viscous time scale, the outer edge of the disk expands due to viscosity and cools. Nuclear recombination of free baryons into nuclei releases an amount of energy ($\sim$8 MeV per baryon) large enough to unbind a significant fraction of the disk (up to 30%) with typical velocities $\lesssim$0.1 c. Detailed simulations including neutrino emission showed that Y_e in the viscous ejecta presents a broad distribution, $0.1 \lesssim Y_e \lesssim 0.45$, rather uniform in its angular distribution, with a peak around 0.25. Matter ejected in the polar direction with $Y_e \gtrsim 0.25$ is expected not to produce lanthanides and to have a photon opacity of $\sim 1\,\mathrm{cm^2\ g^{-1}}$, while the equatorial component is usually significantly enriched in those elements, which increase the photon opacity up to $\gtrsim 10\,\mathrm{cm^2 g^{-1}}$. The broad

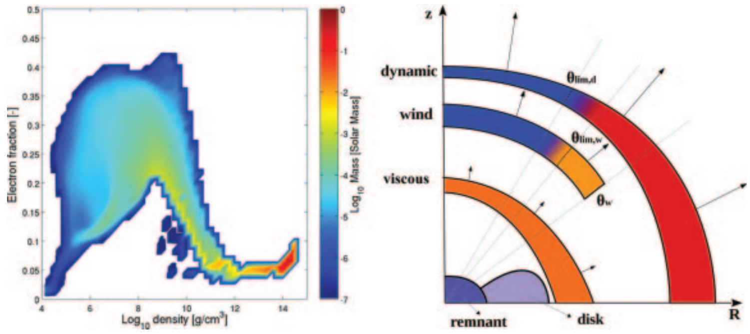

Fig. 1. – Left: color-coded histogram of the density and electron fraction distribution in the remnant of a BNS merger under the influence of neutrino irradiation [6]. Right: sketch of the multicomponent, anisotropic model used in [11]. Blue/orange/red regions correspond to low-/intermediate-/high-opacity ejecta.

distribution of Y_e in the viscous ejecta is expected to produce an intermediate amount of lanthanides, as well as an intermediate opacity.

3. – Anisotropic, multicomponent kilonova model

Recently we have explored if AT2017gfo light curves could be explained in terms of the properties of the ejecta [11]. We have set up a multicomponent, anisotropic KN model, where the polar angle is discretized in different slices and the matter properties have an explicit dependence on the polar angle (fig. 1, right panel). Within each slice, the semi-analytical model presented in [12, 13] is adopted. In addition, we considered variations in the nuclear heating rate due to different nuclear compositions, time-dependent thermalization efficiency, and the effect of irradiation of inner on outer photospheres. The computational efficiency of our scheme has allowed a broad parameter exploration and a fit of the synthetic light curves against the observed ones. We found that a total ejecta of 0.03–0.06 $M_\odot$ is required to explain the data. Moreover, the explicit dependence on the polar angle gave a constraint on the relative inclination between the merger axis and the light of sight of 30°, compatible with measurements derived from GW and GRB afterglow observations. Finally, we found that the presence of fast expanding, low-opacity (*i.e.*, lanthanide-poor) ejecta at high latitude is required to fit the data. This result is a possible direct evidence of the role of neutrinos in setting the properties of the ejecta and in shaping the KN emission properties.

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REFERENCES

[1] Abbott B. P. *et al.*, *Phys. Rev. Lett.*, **119** (2017) 161101.
[2] Abbott B. P. *et al.*, *Astrophys. J.*, **848** (2017) L12; L13.
[3] Martin D. *et al.*, *Class. Quantum Grav.*, **35** (2018) 3.
[4] Perego A. *et al.*, *J. Phys. G*, **44** (2017) 084007.
[5] Frensel M. *et al.*, *Phys. Rev.*, **95** (2017) 023011.

[6] Perego A. *et al.*, *Mon. Not. R. Astron. Soc.*, **443** (2014) 4.
[7] Just O. *et al.*, *Mon. Not. R. Astron. Soc.*, **448** (2015) 1.
[8] Sekiguchi Y. *et al.*, *Phys. Rev. D*, **91** (2015) 064059.
[9] Radice D. *et al.*, *Mon. Not. R. Astron. Soc.*, **460** (2016) 3.
[10] Siegel D. and Metzger B. D., *Phys Rev. Lett.*, **119** (2017) 23.
[11] Perego A. *et al.*, *Astrophys. J.*, **850** (2017) L37.
[12] Grossman D. *et al.*, *Mon. Not. R. Astron. Soc.*, **439** (2014) 757.
[13] Martin D. *et al.*, *Astrophys. J.*, **813** (2015) 2.