Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
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Let there be light: Illuminating kilonovae with the radiative transfer code `POSSIS`

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Abstract. The detection of an electromagnetic counterpart to the gravitational-wave source GW 170817 marked year zero of the multi-messenger gravitational-wave era. This event was generated by the merger of two neutron stars and gave rise to an electromagnetic transient, dubbed a “kilonova”. In this proceeding article, I will show how radiative transfer simulations can illuminate neutron star mergers and provide a connection between numerical models and observational data. I will present viewing-angle dependent kilonova predictions made with the Monte Carlo radiative transfer code `POSSIS` and show how these can be used to interpret data, place constraints on models and guide future follow-up campaigns of gravitational-wave triggers.

Keywords. methods: numerical, stars: neutron, gravitational waves, polarization

1. Introduction

On August 17, 2017, a transient event was identified as the electromagnetic counterpart of the gravitational wave source GW 170817 detected by the LIGO/Virgo interferometers (Abbott et al. 2017a). The event was intensively followed by all the main ground-based and space-borne facilities across the entire electromagnetic spectrum (Abbott et al. 2017b). Generated by the merger of two neutron stars, this single event ushered in the era of multi-messenger gravitational-wave astronomy and provided a smoking gun for historically debated conjectures on e.g. the origin of “short Gamma-Ray Bursts” (Troja et al. 2017) and “r-process” elements in the Universe (Watson et al. 2019). The radioactive decay of r-process nuclei synthesised during the merger powers the so-called “kilonova” (KN), an optical-infrared thermal emission that was predicted more than 20 years ago (Li & Paczyński 1998) and spectacularly observed in connection to GW 170817. In the five years following this historical event, no further KN has been identified neither in follow-up searches during the third LIGO-Virgo-KAGRA (LVK) observing run (O3) nor serendipitously in off-line searches (see the contribution by I. Andreoni in this issue).

The current understanding of the KN in GW 170817 requires the presence of (at least) two ejecta components with different compositions: a first component characterized by relatively low opacities from light “r-process” nuclei ($Z < 57$) and powering a so-called “blue KN” in the first $\sim$ day after the merger, and a second component characterized by higher opacities from heavier “r-process” nuclei ($Z \geq 57$), including lanthanides and actinides) powering a so-called “red KN” at later times. Ejecta with different compositions are also predicted from numerical-relativity (NR) simulations of neutron star mergers (see Nakar 2020 for a recent review). Broadly speaking, material ejected on dynamical timescales retains the low electron fractions (high neutronizations) of the parent neutron star(s) and can produce heavy r-process nuclei including lanthanides and actinides. In contrast, higher electron fractions and thus production of lighter r-process

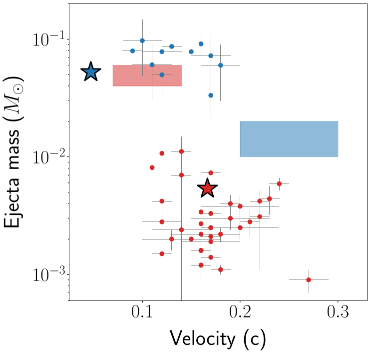

Figure 1. Figure adapted from Nedora et al. (2021). Ejecta masses and velocities inferred for GW 170187 (rectangles and stars) compared to values predicted in a grid of NR simulations from Nedora et al. (2021, filled circles). The range of values inferred for the "blue KN" (blue rectangle) and "red KN" (red rectangle) in GW 170817 are inconsistent with NR simulations, with the former being too fast to originate from a disk-wind (blue circles, assuming 30% of the disk is ejected) and the latter too massive to stem from dynamical ejecta (red circles). The best-fit to GW 1701817 from a 2D KN grid produced with `POSSIS` is found for ejecta masses of $0.052\,M_\odot$ in the disk-wind (blue star) and $0.005\,M_\odot$ in the dynamical ejecta (red star), values that are consistent with predictions from NR simulations.

elements are expected from a post-merger disk wind. Despite this possible connection, however, properties inferred for the KN in 2017 do not match those expected from NR simulations (see Fig. 1), with the blue KN being too fast to originate from a post-merger disk-wind and the red KN too massive to stem from a dynamical-ejecta component.

Properties of the blue and red KN in GW 170817 were extracted using one-dimensional and/or semi-analytical models (e.g. Kasen et al. 2017; Perego et al. 2017; Tanaka et al. 2017; Villar et al. 2017). These models overlook the asymmetric nature of neutron star mergers and/or are unable to predict the viewing-angle dependence of the signal. The different ejecta components predicted in NR simulations are either not modelled or treated independently and summed, overlooking the expected reprocessing of radiation by different components (Kawaguchi et al. 2018). More accurate predictions are expected from 3D Monte Carlo radiative transfer simulations, where multiple components with various geometries can be easily modelled and the interplay between different components is naturally incorporated by tracking Monte Carlo photons. In this proceeding article, I will highlight some of the results obtained using `POSSIS`, a 3D Monte Carlo radiative transfer code that can be used to predict viewing-angle dependent KN observables (spectra, light curves and polarization) for multi-dimensional models. We refer the reader to Bulla (2019) for more details about the code.

2. Extracting ejecta parameters from GW 170817

In Dietrich et al. (2020), we simulated a KN grid with `POSSIS` assuming axial symmetry and the combination of a dynamical-ejecta component at high velocities with a disk-wind component at lower velocities. Four free parameters were varied: the dynamical-ejecta mass $m_{\rm ej,dyn}$, the disk-wind mass $m_{\rm ej,wind}$, the half-opening angle Φ of the dynamical-ejecta lanthanide-rich region, and the viewing angle $\theta_{\rm obs}$ (see their figure S5 for the specific ejecta structure). The grid includes a total of 1540 models. As shown in Fig. 1, the best-fit to the KN in GW 170817 is found for $m_{\rm ej,dyn} = 0.005\,M_\odot$ (red star) and $m_{\rm ej,wind} = 0.052\,M_\odot$ (blue star), values that are consistent with those predicted by NR simulations from Nedora et al. (2021, blue and red circles). We note that velocity structures in this grid are fixed with corresponding average velocities

$\bar{v}_{\rm ej,dyn} = 0.17c$ and $\bar{v}_{\rm ej,wind} = 0.05c$. Fig. 1 shows how ejecta parameters extracted from fitting GW 170817 with multi-dimensional radiative transfer simulations are consistent with those expected from NR simulations, thus solving the tension found using more simplistic (one-dimensional and/or semi-analytical) KN models (see blue and red rectangles in Fig. 1 and discussion in Section 1). This highlights the importance of modelling multiple ejecta components with appropriate morphologies and accounting for the interplay between them, aspects that are naturally incorporated in multi-dimensional radiative transfer simulations (Kawaguchi et al. 2018, Kawaguchi et al. 2020).

3. KN detectability

The lack of KN detections during O3 showed the community how lucky an event GW 170817 was. Its sky localization was small, it was relatively nearby and viewed from an angle close to the jet axis, making the intrinsically faint-and-fast KN easier to identify. In contrast, O3 events deemed to involve at least one neutron star were characterized typically by much larger localization area and found at larger distances, making the discovery of the associated electromagnetic counterpart and KN significantly more challenging (see Coughlin 2020 for a review of the follow-up searches in O3). In Sagués Carracedo et al. (2021), we explored how survey strategies can be optimized in the future to maximize KN detections. Specifically, we used a KN grid simulated with `POSSIS` and study the detectability of such KNe at different distances and as seen from different viewing angles. We found that detecting KNe at distances of ~ 200 Mpc (5 times larger than for GW 170817 and typical for O3 events) requires survey depths of 23 mag and is facilitated by adopting red filters (e.g. with *gri* rather *gr*-only observations).

4. KN polarization

The main sources of opacity in KNe at near-ultraviolet/optical/near-infrared wavelengths are electron (Thomson) scattering and bound-bound opacities (Tanaka et al. 2020). The former can linearly polarize radiation, while the latter is thought to depolarize it. For ejecta that are spherically symmetric (or circular in projection), each polarizing contribution is canceled by one 90 degree away and no polarization signal is expected. The ejecta of neutron star mergers, however, are predicted to have multiple components with different properties (e.g. masses, compositions) and geometries, breaking the spherical symmetry and polarizing the KN signal. In Bulla et al. (2019) and Bulla et al. (2021), we showed for the first time that the KN signal from binary neutron star and neutron-star black-hole mergers can be polarized up to a few percent levels in the optical/near-infrared range and at early times (~ 1 d), rapidly decreasing thereafter. In particular, the detection of a polarization signal in future KNe would be a smoking gun for lanthanide-poor compositions in at least some part of the ejecta since electron scattering is subdominant in regions of the ejecta where lanthanides and heavy r-process elements are produced. Moreover, the strong viewing-angle dependence of the KN polarization signal could be used in the future to constrain the inclination of the merging system.

5. Improving on H_0 with KNe

The simultaneous detection of gravitational waves and light in GW 170817 led to independent measurements of the distance and redshift of the source, thus providing a direct and model-independent estimate of the local expansion of the Universe (Hubble constant H_0, Abbott et al. 2017c). Using gravitational waves as “standard sirens” (Holz & Hughes 2005), this approach holds promise to arbitrate the existing tension in H_0 measurements between the Early (Planck Collaboration et al. 2020) and the Late (Riess et al. 2021) Universe. However, a well-known degeneracy in the gravitational-wave signal between distance and inclination angle translates into large uncertainties on H_0, even when an electromagnetic counterpart is identified (Abbott et al. 2017c). Fortunately not only the gravitational-wave signal but also the KN signal is strongly viewing-angle dependent. This enables to pin down the system inclination from the KN, helping relieve the degeneracy and thus improving on H_0. In Dhawan et al. (2020), we constrained the viewing angle of GW 170817 by fitting the observations with a KN grid simulated with `POSSIS`. As a result, the constrain on the viewing angle led to an improvement of 24% on H_0. A similar approach was used by Coughlin et al. (2020) to improve on H_0 using the KN in GW 170817 and four candidate KNe from historical short Gamma-Ray Bursts.

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