How to interpret observations of neutron-star mergers?

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Abstract. The recent first multi-messenger observation of a neutron-star merger, GW170817 and its electromagnetic counterparts, has sparked tremendous excitement particularly because long-standing questions related to heavy-element nucleosynthesis and the nuclear equation of state could finally be tested with unprecedented capabilities. This proceedings article briefly reviews the main observation channels of neutron-star mergers and how those can be used to obtain insight about questions related to nucleosynthesis and the nuclear equation of state.

1. Introduction

The main astrophysical site(s) of the rapid neutron-capture process has (have) long remained elusive, and ever since the idea of neutron-star (NS) mergers as sources of r-process elements was pointed out for the first time [1], this idea has been investigated by researchers from various fields with intense interdisciplinary efforts. The first multi-messenger observation of a NS merger, GW170817 (e.g. [2]), was exceptionally fascinating, because it suggested that huge amounts of r-process elements were ejected. Additionally, GW170817 and similar upcoming events offer unique possibilities to constrain the still mysterious nuclear equation of state (EOS). With currently available detectors, a neutron star merger is visible in gravitational waves (GW) and in various frequency bands of electromagnetic radiation. In the following we will briefly overview the observable signals and how those can be used to infer information about r-process nucleosynthesis and the nuclear equation of state. Where applicable, we will comment on what has been learned in the specific case of GW170817.

2. Gravitational waves

The GW signal in most cases will be the first and shortest signal observed. The LIGO-VIRGO network starts seeing GWs about tens of milliseconds before the merger [2], i.e. during the inspiral when the GW amplitude is highest. From the inspiral GW signal the total mass of the
binary, $M_1 + M_2$, can be determined rather accurately, while the extracted mass ratio, $M_1/M_2$, typically contains larger uncertainties [2]. The inspiral signal is sensitive to the EOS specific tidal deformability [3] and its detection therefore allows to constrain the radius, $R_{\text{NS}}$, of a cold, non-rotating neutron star. In the case of GW170817, the inspiral signal constrains the radius to lie within about $10 \text{ km} \lesssim R_{\text{NS}} \lesssim 13.5 \text{ km}$ [3]. If the merger remnant does not form a black hole (BH) immediately after the merger, the newly formed NS-remnant is subject to strong oscillations that give rise to an additional post-merger GW signal, which carries invaluable information about the nuclear EOS [4, 5, 6, 7]. Probably the most useful information comes from the peak frequency that is associated with the quadrupole fluid oscillation mode. Due to its tight correlation with characteristic EOS properties [5, 6] it will be possible to assign (with some finite uncertainty of course) a point in the desired mass-radius relationship of cold neutron stars for each event that provides the peak frequency. Last but not least, the post-merger GW signal could possibly shed light on whether a transition of baryonic matter to quark matter takes place right at or shortly after the merger [8]. In the case of GW170817 no post-merger GW signal could be identified, but the prospects for future detections are optimistic [7].

3. Kilonovae

It was realized a few years ago [9] that ejecta from NS mergers produce an observable electromagnetic transient in the optical and near-infrared bands, a so-called kilonova (or macronova), which is powered by radioactive decay and heating of freshly synthesized r-process material. The kilonova emission is an important complimentary counterpart to the GW signal that allows to measure the masses and composition of r-processed material. In practice, however, the seemingly straightforward task of interpreting the observed kilonova lightcurve amounts to a challenging endeavor, because complex modeling techniques, each containing significant limitations and uncertainties, are required in order to infer the amount, velocity, and composition of the ejected material from observed lightcurves: 1) Computationally expensive first-principle hydrodynamical simulations of the merger and its remnant need to be performed that provide accurate predictions for the ejecta masses and the local fraction of electrons ($Y_e$, equal to the number of protons per nucleon) in the ejecta. 2) Nuclear physics models need to be elaborated and nucleosynthesis calculations be prepared that reliably predict the nuclear abundances and radioactive heating rates from a given hydrodynamical ejecta configuration (e.g. [10]). 3) Sophisticated atomic-shell calculations and photon radiative transfer simulations need to be conducted in order to finally obtain a lightcurve and spectra from 1) and 2). The main source of photon opacity in r-process material is due to lanthanides and actinides, because these elements provide a large number of possible line transitions between excited electron states [11, 12].

An additional level of complexity is given by the circumstance that a NS merger does not just release a single ejecta component with homogeneous $Y_e$ isotropically into all directions, but instead it expels multiple components with broad distributions in $Y_e$ and with anisotropic viewing-angle dependence. The following rough (and possibly not exhaustive) classification of ejecta components can be made:

The initial portion of ejecta, launched during the most dynamical phase of the merger (up until about 10 ms after the collision) is called prompt or dynamical ejecta. Within this ejecta component one can further distinguish between [13, 14, 15, 16] a) tidal ejecta, which are ripped off the outer tips of the disrupting neutron stars due to tidal forces and expand mostly into equatorial directions, and b) shock-heated ejecta, which are pushed onwards predominantly towards the poles by pressure forces because of the violent shock that emerges when both stars collide. Because the tidal ejecta are launched very quickly without experiencing significant neutrino emission or absorption, their $Y_e$ remains low (recall that without neutrino interactions the original very low value of $Y_e$ would just be retained). Hence, many neutrons are available for the r-process and large amounts of lanthanides are produced, which for the kilonova means
that the opacities are high and that photons are released with low spectral temperatures corresponding to red colors. The shock-heated ejecta, on the other hand, experience many neutrino interactions in the course of being pushed outward by the collision shock because of the much higher temperatures and the enhanced irradiation by neutrinos. This drives \( Y_e \) to higher values, reduces the amount of lanthanides in the ejecta and correspondingly the opacities, and would most likely lead to a blue-ish kilonova.

After the dynamical merger phase the remnant settles into an axisymmetric configuration that continues to generate ejecta up until about 10 s after the merger. Two main types of post-merger (or secular or remnant) ejecta are [17, 18, 19, 20, 21, 22] c) neutrino-driven winds, which move outward as a result of heating from neutrino absorption typically towards polar directions, and d) viscous ejecta, which arise on grounds of dissipation and angular momentum transport connected to magnetohydrodynamical turbulence. Based on long-term evolution models including neutrinos available so far [17, 21] neutrino-driven (viscous) winds typically have values of \( Y_e \gtrsim 0.3 \) (\( Y_e \lesssim 0.3 \)), such that the corresponding kilonovae would be rather blue (red).

The sensitive dependence of kilonova properties on \( Y_e \) attained during and after the merger calls for a careful treatment of neutrinos in numerical simulations. However, since solving the 6-dimensional Boltzmann equation for neutrinos is too expensive for long-term simulations, various approximative methods are currently being employed throughout the literature (e.g. [23, 24, 25, 16]), i.e. essentially all provided numbers for \( Y_e \) of the ejecta carry more or less substantial uncertainties associated with the respective transport approximation. Future developments of more advanced neutrino schemes as well as cross-comparisons between each other and with observations will have to clarify, what level of accuracy is needed in order to reliably extract ejecta properties from observed kilonova lightcurves.

The kilonova accompanying GW170817 is best explained using at least two components, a red and a blue component [2, 26]. Although the mass and composition of the ejecta associated with each component are still beset with considerable uncertainties (for the aforementioned reasons) the multi-component kilonova already strongly suggests that NS mergers indeed are significant sources of r-process elements. Moreover, the observation impressively confirms theoretical models that predicted multiple ejecta components and that emphasized the important role of neutrino interactions (e.g. [27, 17, 19, 28]).

Even though a post-merger GW signal could not be detected and therefore no definitive statement can be made, the bright kilonova and correspondingly large ejecta masses strongly suggest that a NS-remnant survived at least for tens of milliseconds after the merger [13, 29]. This assumption allows to formulate additional constraints for the nuclear EOS, because only sufficiently stiff EOSs can support a NS-remnant for a given total binary mass. In [30] the empirical relation found in [13] was used to constrain the NS radius from below, giving \( R_{NS} \gtrsim 10.7 \) km. The method in [30] can also be employed in future events where a prompt collapse can be identified to formulate upper (instead of lower) limits on \( R_{NS} \). Other, partially related constraints have also been formulated by other authors with similar results (e.g. [31]).

4. Gamma-ray burst and electromagnetic spindown emission
Another class of electromagnetic transients can be produced by a NS merger if an ultra-relativistic jet is launched from the central object. NS mergers have long been hypothesized to be sources of such jets in order to explain short gamma-ray bursts (sGRBs). One may wonder if the jet could have a significant impact on the ejecta and therefore the kilonova lightcurve. Since the jet is most likely launched after the release of the dynamical ejecta (and possibly additional ejecta from a NS-remnant) it has to punch through the previously ejected outflow components on its way towards the observer [32, 33]. In doing so, it pushes ejecta material aside, which gets shocked and forms a so-called cocoon. The impact of shock-heating, cocoon formation,
Figure 1. Snapshots of hydrodynamical simulations of a post-merger BH-torus system surrounded by previously ejected dynamical and neutrino-driven wind ejecta without (left) and with (right) a central jet engine. The jet drills a hole through the ejecta cloud and deposits part of its energy in the form of a shock-heated cocoon.

and spatial redistribution of merger ejecta on the nucleosynthesis yields and on the observable kilonova and gamma-ray signal is currently being investigated using neutrino-hydrodynamical models (see Fig. 1 for snapshots of preliminary models with and without a jet). In the case of GW170817 a jet has been observed but with unusually low gamma-ray luminosity, probably because the jet was seen off-axis such that the ultra-relativistic core of the jet was not visible to us [2].

Another potentially quite energetic observable electromagnetic transient could be produced by a long-lived NS-remnant, which owing to its high rotation rates and strong magnetization could radiate a significant fraction of its initial rotation energy on a timescale of seconds to thousands of seconds. The result that no signature of such spindown emission has been seen in the course of GW170817 can be interpreted as evidence for the collapse of the NS-remnant. Based on this interpretation the authors of [34, 35] formulated an upper limit for the maximum mass of a cold, non-rotating NS, $M_{\text{max}} \lesssim 2.17 M_{\odot}$.

5. Conclusions
Multi-messenger observations of neutron-star mergers have recently become possible. GW170817 has already impressively confirmed that NS-mergers can be significant r-process sources, and it allowed to formulate and apply new constraints on the nuclear EOS. Hopefully soon we will witness many more observations that in combination with improved theoretical models will help researchers to finally uncover the remaining mysteries associated with NS mergers, r-process nucleosynthesis, and the nuclear EOS.

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