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Neutron Star Merger Afterglows: Population Prospects for the Gravitational Wave Era

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Following the historical observation of GW170817 and its electromagnetic follow-up, new neutron star merger afterglows are expected to be observed as counterparts to gravitational wave signals during the next science runs of the gravitational interferometer network. The diversity of the observed population of afterglows of these future events is subject to various factors, which are (i) intrinsic, such as the energy of the ejecta, (ii) environmental, such as the ambient medium density or (iii) observational, such as the viewing angle and distance of the source. Through prescribing a population of mergers and modelling their afterglows, we study the diversity of those events to be observed jointly in gravitational waves and electromagnetic bands. In the future, observables of detected events such as viewing angle, distance, afterglow peak flux or proper motion will form distributions which together with predictions from our study will provide insight on neutron star mergers and their environments.

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1. Introduction

On August 17^{th} 2017, historical observations of the merger of a binary neutron star (BNS) were made. These were triggered by the detection by the interferometers of the LIGO-Virgo Collaboration (LVC) of the gravitational wave (GW) signal from the inspiral phase of the merger (1). These GW were followed by three electromagnetic counterparts: (i) a short and hard gamma ray burst (GRB) (2; 3), (ii) a thermal reddening emission, fainting on the scale of tens of days, known as a kilonova (KN) (e.g. 4; 5), and a multi-wavelength (radio to X-ray) long-lived emission known as the afterglow (AG) (6; 7; 8). These observations were historical in many regards. First of all, they confirmed BNS mergers as the progenitors of short GRBs, as hypothesized early in the history of GRB science (9) and indirectly confirmed since then. Secondly, they inaugurated the era of multi-messenger astronomy with GW, and exposed the latter as an invaluable tool to study BNS mergers and short GRBs. Lastly, this single event had enormous repercussions in numerous branches of physics and astrophysics. To state only the most noteworthy of these, this event allowed to further more test general relativity, to constrain the equation of state of hyperdense matter, to make a stand-alone measurement of the Hubble constant and to assess the locus of r-process nucleosynthesis.

The AG and KN provided a wealth of information on this event: its sub-arcsecond localization, external medium density, the kinetic energy of the ultrarelativistic jet which was produced in the merger, the viewing angle, etc. A breakthrough observation was the very long base interferometry imaging of the remnant through the radio AG (10; 11), which confirmed the emergence of the jet and somewhat constrained its geometry and our viewing conditions.

On April 1^{st} 2019 the LVC has begun the third GW observing run (O3). It will run for a year with the two LIGO and the Virgo interferometers all with enhanced sensitivities with respect to O2. We thus expect more GW from BNS mergers, and KN and AG counterparts. Given the 170817 event and our knowledge of BNS mergers from short GRB science, what AG and KN should we expect in this new O3 run? What will these future events' AGs look like? How will they help us to study the evolution and environment of BNSs? What will they teach us more on GRBs and their dissipation mechanisms?

We address these questions with the approach of a population study.

2. From the intrinsic population to multi-messenger events

2.1 Multi-messenger detection criteria

We model the GW, radio AG and KN emissions of individual events using a synthesis of prior knowledge on GRB afterglows and observations from 170817. These three signals depend on the event's intrinsic parameters such as the jet's kinetic energy and opening angle, on external parameters such as the density of the host medium, and finally on our observing conditions such as the luminosity distance to the merger and the viewing angle (from our line-of-sight to the jet axis). For the AG, we suppose that the jet's contribution to the flux dominates the contribution of an eventual lateral structure at the peak of the AG, when the signal is most likely to be observed.

We prescribe initial distribution on all of these parameters thanks to prior knowledge from GRB science and observations of the 170817 event. These make up an intrinsic population of mergers which occur in the local Universe with a rate of $\sim 1540^{+3200}_{-1220}$ Gpc^{-3}yr^{-1}, as inferred by the LVC during the O1 and O2 runs (1). The GW, AG and KN of these events are not all detectable because of detector limitations. For the GW, this is described by the interferometer's horizon, for the AG by the radio array limiting sensitivity (at 3 GHz in our case) and for the KN by the depth of the visible-IR follow-up searches. Applying these detection criteria for the detection of the GW, the AG and the KN allows us to determine those events detectable[1] in these messengers. Since the follow-up of these events is triggered by the GW, we select the events observable in GW *and* through their AG and KN. These constitute a population of jointly detectable events which we will study here.

As the detectors improve, this population will change, and we may thus make prospects for the expected detectable population in different multi-messenger detector configurations.

2.2 The kinetic energy distribution

As an illustration of the choice of a parameter distribution for the intrinsic population of mergers, the jet kinetic energy distribution is directly deduced from prior work on the luminosity function of short GRBs. This is a fundamental quantity of GRB science and has been constrained from observations by various authors (e.g. 12; 13; 14). For a given GRB, the kinetic energy available to the jet for the AG is the energy which remains after dissipation in gamma-rays. Starting from a short GRB luminosity function, and supposing a typical duration of 0.2 s and gamma-ray efficiency of 20%, we obtain a distribution for the kinetic energy of the merger jets. Using the short GRB luminosity function of (12), we obtain the distribution of Fig. 1.

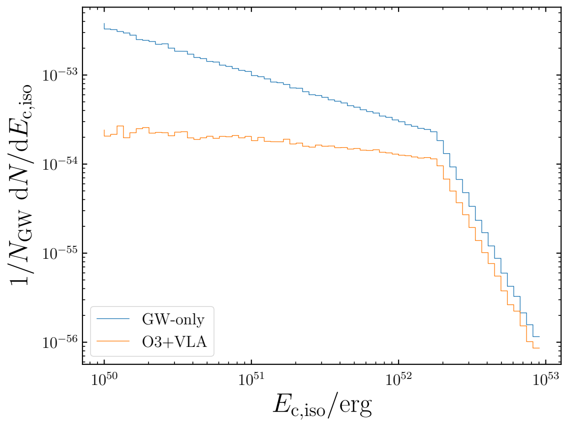

Figure 1: Distribution of the kinetic energies of the jets produced in the BNS mergers, for the intrinsic (blue) and jointly detectable (orange) populations. The distribution for the intrinsic population is normalized, and that for the observable population is scaled to the $\sim$ 35% of GW-detected events to produce a detectable radio AG.

The selection by radio detection favors the higher-energy jets, and this is reflected in the kinetic energy distribution of the detectable population.

3. Results

3.1 Joint event rates

Using our population model, we can predict the rates of jointly detectable events. Assuming a limiting radio sensitivity of at the level of the Very Large Array (10 μJy) and a GW horizon at the O3 level ($\sim$ 250 Mpc), we predict that $10-30$% of GW-detected events should have a

[1] Note that we say *detectable* and not *detected*, for reasons which will be made clear later.

detectable radio AG. This depends on the population model, and the observation of many events should be considered as a further constraint on the jet kinetic energy function, and thus on the short GRB luminosity function. In this case, the one-year O3 run should produce $\sim$ 9 BNS GW events (15), of which $1-3$ should have a detectable AG. As the horizons increase, these numbers are increased, and the design-level interferometers (horizon of $\sim$ 450 Mpc) coupled to the Square Kilometer Array of the late 2020s (sensitivity of $\sim$ 1 μJy) should produce $\sim$ 20 BNS GW triggers per year of operation (15), of which $2-6$ with a detectable radio AG.

From the point of view of the KN, we detail in Sec. 3.4 that our population study shows that even for the large horizons of the design interferometers, the magnitudes of the KN will remain accessible to the typical follow-up instruments. There remains nonetheless the question of whether these will be detected. This is a pivotal question because the detection, follow-up and astrophysical treatment of the AG requires the pin-pointing of the source, and thus to find and detect the KN within the GW-inferred sky-map of the signal. We will come back to this later.

3.2 On the viewing angle of future events

The radio detection strongly biases the observed population towards smaller viewing angles. Nonetheless, the configuration of the O3 run should provide events with a mean viewing angle over 20°, the value assumed by GRB170817.

These events should show long increasing phases of their light-curves, thus allowing a detailed study of the jet structure. This could possibly give insight on the dissipation mechanisms at play in the lateral structure of the jet, which may have produced the thermal tail observed in GRB170817A (2) and found in archival studies of short GRBs (16).

Also, we predict that about 10% of the joint events to come should be seen on-axis (our line-of-sight within the jet), likely resulting in a GRB counterparts. We note that our figure is consistent with rates of GW-GRB associations found by others with a different approach (17).

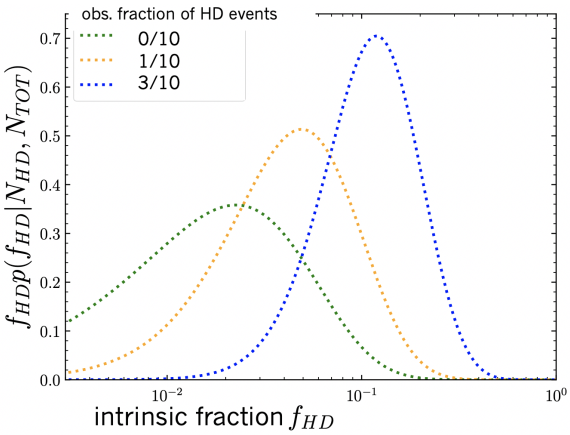

Figure 2: Posterior probability distribution of the intrinsic fraction of high-density (1 cm^{-3}) mergers obtained after having observed 0 (green), 1 (orange) or 3 (blue) of these among a total of 10 events, the others being at low density (10^{-3} cm^{-3}).

3.3 Insight on fast-merging binaries

Another bright insight of this population study is on the evolution of BNSs. Those which have a high eccentricity after the second supernova or an efficient common envelope phase merge after only a short inspiral time. Many studies have found evidence for a excess of such binaries in the population (e.g. 18; 19; 20; 21). Such fast-merging binaries are likely to merge in higher density environments, because their kicks have a shorter time to take them from their high-density formation loci to rarefied environments.

Mergers in high densities produce brighter AGs because of the strong dependence of the peak flux to the medium density ($F_p \propto n^{4/5}$). This entails that if there is indeed a population of high-density mergers, they should be over-represented in the observed population with respect to their intrinsic fraction. Thus, only a small number of joint events is needed to obtain tight constraints on the intrinsic population of these fast-merging binaries. This is illustrated in Fig. 2, which shows that an 1-σ uncertainty of $\sim$ 0.3 dex can be obtained on the intrinsic fraction of high-density mergers after observing only 3 high-density mergers among 10 joint events.

3.4 A word on kilonovae and on detecting the detectable

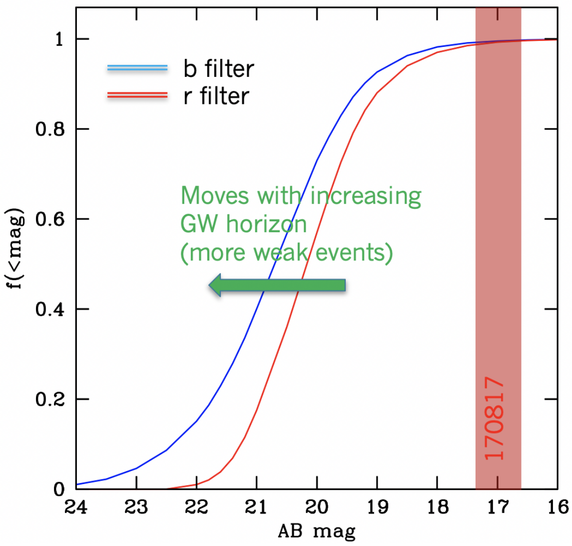

Figure 3: Cumulative distribution of the expected magnitudes of the KN signals counterparts to GW triggers in the O3 run, in the b (blue) and r (red) band. The discovery magnitude of KN170817 is indicated for comparison.

The observations of the KN of 170817 (4) and prior theoretical considerations (e.g. 22) led to the idea that the outflows from the merger producing the KN emission were of two kinds, with different origins, physical characteristics and Vis.-IR signatures. One is rather polar, and its origin is not clear. Its electron fraction is high, leading to a low lanthanide enrichment, a low opacity and thus a blue color. The other is equatorial, composed of tidal ejections before the merger and dynamical ejections upon merger, and rather electron-poor. Its opacity is greater, and has a red, slower-evolving emission.

In consequence, the visible-IR signal from the KN also depends on the viewing angle to the system. Using the same approach as for the AG with a simple model for this angular dependence, one may determine the distribution of the magnitudes to expect for the KN as counterparts to GW in the O3 run and beyond. This is illustrated in Fig. 3 for the O3 configuration in b and r bands. As announced earlier, the magnitudes we expect are in range of the follow-up instruments, up to design-level GW horizons.

Nonetheless, the detection of the KN may reveal challenging for two reasons. The first is the typical volume to explore during the O3 run to find the KN. Indeed, the proximity of GW170817 ($\sim$ 40 Mpc) allowed for a small GW-inferred localization map ($\sim$ 30 deg^2), and the prompt localization of the KN at a magnitude of $\sim$ 17 in NGC4993. As the horizon increases, and assuming a constant relative uncertainty $\Delta D/D \sim 25\%$ on the GW-inferred distance and the median localization prospects for the O3 run (15), one finds that the volume (and thus the number of galaxies) to explore in search of the KN will be 100 times larger than in the case of GW170817. This can be a severe limitation to the pin-pointing of the event, and thus to the AG detection.

The second challenging aspect is the contrast of the KN signal with respect to the host galaxy. The KN is a point source inside the extended emission of the host galaxy, and the distance to the object plays strongly against its detection.

4. Conclusions

In conclusion, regardless of the evolution of gravitational wave and radio detectors, mutli-wavelength afterglows and kilonovae will remain instrumental in the study of double neutron star mergers, as revelators of both their evolution and merging phenomenon. They will bring precious insight provided the sources may be accurately localized in the sky, which may reveal challenging as of the present gravitational wave observing run.

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