The origin of GW170817

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Abstract The first double neutron star merger was observed by LIGO/Virgo collaboration on August 17, 2017 (GW170817). The possible formation scenarios include isolated (classical) binary evolution, dynamical formation in globular, or nuclear clusters, and other more exotic scenarios like the involvement of quark stars. Here we present the recent simulated results aimed at formation of a binary compact object with a special attention put to GW170817 progenitors. All tested formation scenarios give merger rates far below the observational estimated ones. The highest merger rate is predicted for isolated binary evolution which is still 2 orders of magnitude too small. The scenario involving quark stars shows even worse comparison, but may potentially explain other observational features of GW170817. The results tell us that one of the options is possible: either the only observation is just a statistical coincidence, our understanding of stellar and binary physics is incomplete, or we are missing some important non-canonical formation scenario.

Keywords: Stars: massive, Neutron-star physics, Quark-star physics, Gravitational waves

1. Introduction

Recently, several double compact object mergers have been observed by LIGO-Virgo collaboration (Abbott et al. 2017). Among them there is only one merger of two neutron stars, GW170817 (Abbott et al. 2018), the rest being double black hole mergers. Up to now, none mixed mergers (a neutron star with a black hole) have been observed.

Double neutron star mergers potentially have much more progenitors, because neutron stars typically originate from lighter stars, which are more abundant on the zero-age main-sequence. However, double black hole mergers give much more significant signal and, as a result, were statistically predicted to be observed more frequently (Belczynski et. all 2016). Except GW170817, the locations of mergers are not known precisely.

Although black holes detected in the Milky Way have mass in the range ～5-15 solar masses, these detected in merging double compact objects have masses between 7 and 50 times higher than the Sun (only 25% of them have masses below 15 solar masses). This contrast motivated a search for different formation scenarios of black holes in the merging double compact objects, than these found for galactic black holes, which are predominantly components of low-mass X-ray binaries. For example, it was suggested that compact objects in these systems may originate from primordial black holes (e.g. Hawking 1971), or populations III stars (e.g. Madau & Rees 2001). Double neutron star mergers, although being a minority among detected gravitational wave sources, are much better for analysis, because such problems are omitted (all neutron stars have very similar masses between 1-2 solar masses, Lattimer 2012). Additionally, the double neutron star merger produces simultaneously electromagnetic radiation, which allows for multi-messenger observations (e.g. Abbott et al 2017b, Evans et al. 2017).

2. Merger rate estimations for GW170817

GW170817 (also known as GRB170817, or AT2017gfo) is the first observed merger of double neutron stars (Abbott et al. 2017). The parameters estimated on the base of its gravitational wave emission are the chirp mass ($M_{chirp} = 1.188 M_{Sun}$) and mass ratio ($q = M_2/M_1 > 0.7$). It is localized on the outskirts of the old elliptical galaxy NGC 4993. The galaxy probably had an episode of star formation 3-7 Gyr ago (Troja et al. 2017). Belczynski at al. (2018) assumed the metallicity to be sub-solar ($Z = 50\% Z_{Sun}$).

Three main formation scenarios are considered in the context of double neutron star mergers. The first one is the isolated (classical) binary evolution (e.g. Lipunov et al. 1997, Belczynski et al. 2016, Stevenson et al. 2017), which occurs in the galactic disks where interactions between stars are rare (however see Klencki et al. 2017). Various models were calculated and compared in the contact of double neutron star merger by Chruslinska et al. (2018). Other scenario predicts a formation of merging double neutron stars in globular clusters (e.g. Portegies Zwart et al. 2004, Askar et al. 2017). Stars and binaries in such environment experience many interactions during which binaries are formed, altered, or destroyed. Neutron stars before the merger might have been a part of a few tens of significant interaction before the close double neutron star was formed. A very similar is a situation in nuclear clusters where dynamical interaction may lead to formation of GW170817 progenitors (e.g. Arca-Sedda et al. 2017).

Belczynski et al. (2018) performed a comparison between merger rate estimations based on these main formation channels and the merger rate obtained from the observation of GW170817. Specifically, they performed simulations of isolated binary evolution using the population synthesis code Startrack (Belczynski 2002, 2008) and simulations of a dynamical formation of double neutron star merger progenitors using Monte Carlo code MOCCA (Giersz et al. 2013, Hypki & Giersz 2013) for globular and nuclear clusters.

The models tend to provide rates which are significantly lower than predicted from observations (see Table 1). Therefore, Belczynski et al. (2018) in their study used combinations of parameters which maximize the rates in particular channels using earlier works of Chruslinska et al. (2018) and Askar et al. (2017). Please note, that not the same parameters give highest rates in different formation channels.

The results of Belczynski et al. (2018) are presented in Table 1. Estimations based on observations (LIGO/Virgo; 90% credibility; Abbott at al. 2017) are provided for comparison. Three synthetic models refer to isolated (classical) evolution, dynamical formation in globular clusters, and dynamical formation in nuclear clusters. Estimations marked as pessimistic, realistic, and optimistic depict the lower, average and upper estimates for LIGO/Virgo results. For synthetic models these columns refer to estimates calculated for a burst star formation 10 Gyr ago (pessimistic), 5 Gyr ago (realistic), and 1 Gyr ago (optimistic).

Table1. *Local double neutron star merger rates [yr* $^{-1}$*] (within D=100 Mpc*^{3}*) after Belczynski et al. (2018)*

Model	pessimistic	realistic	optimistic
LIGO/Virgo	0.3	1.5	4.7
classical binaries	8×10^{-3}	1×10^{-2}	5×10^{-2}
globular clusters	2×10^{-5}	5×10^{-5}	2×10^{-4}
nuclear clusters	7×10^{-6}	1×10^{-5}	1×10^{-4}

Although simulations of double neutron stars show good agreement with Galactic populations of binary pulsars, or rates of gamma ray bursts (Chruslinska et al. 2017), the merger rates of double neutron stars are far below the estimates based on the observation of GW170817. The comparison shows (Table 1) that isolated evolution provides merger rates that are closest to the LIGO/Virgo rates, but still about 2 orders of magnitude smaller. Interestingly, isolated binary evolution correctly predicts merger rates of double black holes (e.g. Belczynski et al. 2016).

We note that all observations are subject to uncertainties due to beaming, unknown emission mechanisms, and low statistics, which may, potentially, change the comparison in favor of the simulations. Additionally, it is possible that NGC 4993 experienced a recent star formation episode (300-400 Myr ago; Palmese et al. 2017). If true, it will significantly increase synthetic merger rates, because double compact objects merge more effectively in young stellar environments.

3. Quark stars merger

The existence of stars built partially or totally from deconfined quarks was predicted theoretically. The former are called twin-stars (e.g. Alford et al. 2013), whereas the latter are possible in the context of the so-called two-families scenario (e.g. Drago et al. 2014, Wiktorowicz et al. 2017). The two-families scenario shows a promising framework to explain all phenomena connected with the GW170817 event (De Pietri et al. in prep).

In order to obtain predictions for the merger rates within the two-families scenario, it was assumed that the transition from a hadronic star to a quark star occurs at a conversion mass of $M_{max}^{H} = 1.5 - 1.6 M_{Sun}$ (Wiktorowicz et al. 2017). The results from simulations (De Pietri et al. in prep) show the prevalence of mixed mergers (hadronic star with a quark star) for low mass ration (but within observational estimated range for GW170817: $0.7 < q < 0.85$). The merger rate is $2 \times 10^{-4} yr^{-1}$ in the volume limited by a sphere with a radius of 100 Mpc (for a comparison with Belczynski et al. 2018). Although higher than estimates of merger rates for two hadronic stars or two quark stars, this estimate is more than 4 orders of magnitude below the merger rates estimated on the base of the observations of GW170817. We note that for higher mass ratios ($q > 0.85$) two hadrons stars give higher merger rates (up to 6.4×10^{-3} than a mixed merger, or double quark star merger.

4. Conclusions

All tested formation scenarios give merger rates far below the observationally estimated rate for the GW170817 event. Among tested model, the most promising is the isolated (classical) binary evolution in the field, which, nevertheless, gives merger rates about 100 times smaller than inferred from LIGO observations.

If GW170817 is not just a statistical coincidence and next observational runs will confirm the actual merger rate estimates, we will know that our understanding of stellar physics in at least one of the main formation channels is incomplete, or some of the exotic or currently unknown scenarios give much higher merger rates of double neutron stars.

An example of such a less canonical scenario is a merger of a star built of hadrons with a star composed of quarks. We showed that for merger similar to GW170817 and with low mass ratios ($0.7 < q < 0.85$) the merger rate of such mixed mergers is higher than for neutron stars. Nonetheless, the merger rate (about$10^{-4} yr^{-1}$ within a distance of 100 Mpc) is still much smaller than these inferred from observations (a few per year within a distance of 100 Mpc).

Acknowledgments

The work was partly supported by the President's International Fellowship Initiative (PIFI) of the Chinese Academy of Sciences under grant no.2018PM0017 and by the Strategic Priority Research Program of the Chinese Academy of Science Multi-waveband Gravitational Wave Universe (Grant No. XDB23040000).

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