GW190425 IS INCONSISTENT WITH BEING A BINARY NEUTRON STAR BORN FROM A FAST MERGING CHANNEL

Mohammadtaher Safarzadeh\textsuperscript{1}, Enrico Ramirez-Ruiz\textsuperscript{1,2}, Edo Berger\textsuperscript{3}

\textsuperscript{1}Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA, mmsafarz@ucsc.edu
\textsuperscript{2}Niels Bohr Institute, University of Copenhagen, Blegdamsvej 17, 2100 Copenhagen, Denmark
\textsuperscript{3}Center for Astrophysics \vert Harvard \& Smithsonian, 60 Garden Street, Cambridge, MA

ABSTRACT

The LIGO/Virgo Scientific Collaboration (LSC) recently announced the detection of a compact object binary merger, GW190425, with a total mass of $3.4_{-0.1}^{+0.3}$ $M_\odot$, and individual component masses in range of about 1.1 to 2.5 $M_\odot$. If the constituent compact objects are neutron stars, then the total mass is five standard deviations higher than the mean of $2.66 \pm 0.12$ $M_\odot$ for Galactic binary neutron stars. The non-detection of such massive BNS systems in the Galaxy indicates a potential bias against their detection, which can arise if such massive BNS systems are born with short orbital periods and hence inspiral times of $\sim 10$ Myr. However, we show that the reported merger rate, $R_{GW190425} = 460_{-290}^{+1050}$ yr$^{-1}$ Gpc$^{-3}$, requires extremely high formation efficiency for such systems of $\lambda_{\text{BNS}} = 2 \times 10^{-3} - 5 \times 10^{-3}$ $M_\odot^{-1}$, orders of magnitude larger than the formation efficiency of fast merging BNS systems from population synthesis models, $\lambda_{\text{BNS}} \approx (2 - 5) \times 10^{-6} M_\odot^{-1}$. Moreover, the comparable merger rates inferred from GW190425 and GW170817 is problematic for two reasons: (i) more massive systems are expected to have a lower formation rate, and (ii) fast merging channels should constitute $\lesssim 10\%$ of the total BNS systems if case BB unstable mass transfer is permitted to take place as a formation pathway. We argue that to account for the high merger rate of GW190425 as a BNS system requires: (i) a change in our understanding NS formation in supernova explosions, or (ii): that more massive NSs need to be preferentially born with weaker magnetic fields so that they would be undetectable in the radio surveys. Whether such an explanation is plausible would require detailed modeling of BNS population with careful treatment of their magnetic fields evolution.

1. INTRODUCTION

Recently, the LSC announced the detection of a compact object merger with total mass of $3.4_{-0.1}^{+0.3}$ $M_\odot$, dubbed GW190425 (Abbott et al. 2020). The merger’s total mass lies in the range that each component can be consistent with being a neutron star. Prior to this detection all the known binary neutron star (BNS) systems in the Galaxy occupied a very narrow range in mass, with total mass of $\approx 2.66 \pm 0.12 M_\odot$ (Farrow et al. 2019), and the BNS system GW170817 with total mass of $\approx 2.74_{-0.01}^{+0.04} M_\odot$ fell within this mass distribution as well (Abbott et al. 2017).

If GW190425 is a BNS system, it is critical to explain why such massive BNS system have not been observed in the Galaxy to date. One possible solution is the presence of bias against detecting such system. The bias can arise if such massive binaries are preferentially formed from a channel that the BNS has very short periods with inspiral phase below 10 Myr. This will subsequently lead to severe Doppler smearing (Cameron et al. 2018) rendering their detection challenging. But does such channel exist in nature?

BNS systems are thought to form through two distinct channels: Field formation (Tauris et al. 2017; Chruslinska et al. 2018) and dynamical assembly (Ramirez-Ruiz et al. 2015), which is highly sub-dominant compared to field formation channel (Ye et al. 2020). The field formation scenario predicts a delay time distribution that follows a power law (Dominik et al. 2012). However, a sub-population of fast-merging systems can exist if unstable case BB mass transfer takes place in a common envelope between a He Hertzsprung gap (HG) star and a NS (Ivanova et al. 2003; Dewi & Pols 2003) depending on the component masses and orbital period. The outcome of such unstable Case BB mass transfer is uncertain; these systems enter into Roche Lobe Overflow as a He HG stars, and as such, the donor stars in these systems lack clear core-envelope boundaries. Recent work by Vigna-Gómez et al. (2018) does not rule out an unstable Case BB phase accounting for the Galactic BNS population, while a stable case BB is favored over.

In this Letter we show that assuming GW190425 is a massive BNS system, the reported merger rate from LIGO/Virgo data is in tension with the expected merger rate of BNS systems born from fast-merging channels. In §2 we estimate the merger rate of systems similar to GW190425 assuming they arise from a fast-merging channel. In §3 we discuss the formation efficiency of such systems from population synthesis analysis. In §4 we ar-
guez that if GW190425 is a BNS system, its high merger rate would imply massive NSs are born with similar rate to their lower mass counterparts, and their magnetic fields should be suppressed. We summarize the results in §5.

2. FORMATION RATE GW190425 TYPE SYSTEM AS FAST MERGING BNS SYSTEMS

If such systems are the product of fast-merging channels, the estimate of their merger rate is simplified as the delay time distribution is short enough that it can be ignored (Safarzadeh et al. 2019a). The star formation rate of the universe can be parameterized as a function redshift as (Madau & Dickinson 2014):

\[ \psi(z) = 0.015 \frac{(1+z)^{2.7}}{1 + ((1+z)/2.9)^{3.6}} \frac{M_\odot}{\text{yr}^{-1} \text{Mpc}^{-3}}. \]

(1)

We combine this with the analytic expressions for metallicity evolution used from Eldridge et al. (2019). Here, the fractional mass density of star formation at and below metallicity mass fraction of \( Z \) is given by:

\[ \Psi \left( z, \frac{Z}{Z_\odot} \right) = \psi(z) \frac{\hat{F}(0.84, (Z/Z_\odot)^2 10^{0.3z})}{\Gamma(0.84)}, \]

(2)

where \( \hat{F} \) and \( \Gamma \) are the incomplete and complete Gamma functions.

The merger rate of such massive BNS systems is therefore given by:

\[ R_{\text{GW190425}} = \lambda_{\text{BNS}} \Psi \left( 0, \frac{Z}{Z_\odot} \right) \times 10^9 \text{ yr}^{-1} \text{ Gpc}^{-3}, \]

(3)

where \( \lambda_{\text{BNS}} \) indicates the number of such systems born per unit solar mass of stars.

The reported value of \( R_{\text{GW190425}} = 460^{+1050}_{-390} \text{yr}^{-1} \text{Gpc}^{-3} \) (Abbott et al. 2020) translates into a range of \( \lambda_{\text{BNS}} \approx 2.3 \times 10^{-4} - 5 \times 10^{-3} \) if we assume that the progenitors of such systems have metallicities of \( \lesssim 0.1 Z_\odot \) to have a total mass about the reported value (Giacobbo & Mapelli 2018) due to fallback mechanism and electron capture supernovae. If we treat the assumption that low metallicity is needed to produce such systems (i.e., that the efficiency of massive BNS formation from case BB unstable mass transfer is insensitive to progenitor metallicity) we find \( \lambda_{\text{BNS}} = 7.5 \times 10^{-6} - 1.6 \times 10^{-4} \).

3. FORMATION RATE OF FAST-MERGING BNS SYSTEMS IN POPULATION SYNTHESIS MODELS

In Safarzadeh et al. (2019b) we analyzed formation models of BNSs from StarTrack (Belczynski et al. 2002, 2006, 2008) population synthesis code to search for fast merging channels. Three key parameters, and therefore 8 different models were analyzed. The first parameter concerns with the behavior of binaries when a star enters into a common envelope (CE) with a Hertzsprung gap (HG) donor star; during a CE, a NS enters the envelope of its companion, exchanging orbital energy to unbind the donor’s envelope (Fragos et al. 2019) and accrete only modest amounts (\( \lesssim 0.1 M_\odot \)) of envelope material in the process (MacLeod & Ramirez-Ruiz 2015). For giant stars, with a clear core-envelope boundary, the end result of this process (so long as there is enough orbital energy available to keep the system from merging) is a closely bound binary comprised of the accretor star and the giant star’s core. However, HG stars lack well-defined cores, and studies are inconclusive as to whether binaries entering into a CE during this phase can survive without merging (Deloye & Taam 2010).

Two different sub models, A and B have been analyzed, which treat differently CE event with HG donor stars. Submodel A treats HG stars such that a core could be distinguished from an envelope in their evolutionary phase, hence a successful CE ejection is possible, while submodel B assumes any system entering into a CE with a HG donor will merge. As a second parameter, the kick velocity received by a NS at birth is varied. Our standard model adopts natal kicks randomly drawn from a Maxwellian distribution with \( \sigma = 265 \text{ km s}^{-1} \), based on the observed velocities of single Galactic pulsars (Hobbs et al. 2005), and we explore the models that adopt \( \sigma = 135 \text{ km s}^{-1} \). Finally, we test models with two different metallicities: \( Z = Z_\odot \) and \( Z = 0.1Z_\odot \).

In submodel A, case BB unstable mass transfer make up a population of fast merging channel BNSs. In submodel B, the fast merging channel comes from BNSs on highly eccentric orbits due to natal kicks in favorable directions. The summary of the analysis is presented in Figure 1.

The formation rate of fast-merging BNS systems is about \( 2 - 5 \times 10^{-8} M_\odot \) yr\(^{-1} \) for submodel A where the range spans the uncertainty to the metallicity and natal kick assumptions. For submodel B the formation efficiency is about \( 3 \times 10^{-8} - 5 \times 10^{-7} \). Such small formation channels are inconsistent with the required large formation efficiency of \( \lambda_{\text{BNS}} = 2.3 \times 10^{-4} - 5 \times 10^{-3} \) inferred from GW190425 if this system is a BNS system formed through a fast-merging channel at low metallicities. Even if we treat the metallicity as a parameter with unknown impact, the absolute minimum efficiency of \( \lambda_{\text{BNS}} = 7.5 \times 10^{-6} \) is still in tension with the efficiency range in population synthesis models of \( \lambda_{\text{BNS}} = 2 - 5 \times 10^{-6} M_\odot \).

4. NEUTRON STARS WITH WEAK MAGNETIC FIELDS AS A POSSIBLE SOLUTION

Despite their different total masses, the reported merger rate from LSC, \( R_{\text{GW190425}} = 460^{+1050}_{-390} \text{yr}^{-1} \text{Gpc}^{-3} \), \( R_{\text{GW170817}} = 760^{+1340}_{-480} \text{yr}^{-1} \text{Gpc}^{-3} \), are similar. In a recent study Sukhbold et al. (2016) showed that a small percentage (\( \lesssim 10\% \)) of stars with mass between 18 \(- 120 M_\odot \) can make NSs with mass greater than 1.6 \( M_\odot \), while NSs with mass consistent with the observed galactic population could form from stars with mass between 10 \(- 18 M_\odot \). Assuming a Salpeter initial mass function following \( dN/dM \propto M^{-2.7} \), the relative expected formation rate of GW190425 to GW170817 type systems should be at least (conservatively) less than 10\%. Therefore, on the face value, such high merger rate for such a
massive BNS system calls to radical change in our understanding of supernova explosion and fall-back physics. If we assume our understanding of supernova fall back mechanism is not complete, and prone to large corrections (e.g., Schröder et al. 2018), and therefore assume the formation rate of massive neutron stars could be comparable to their less massive systems, we should ask the question of why such massive systems have not been observed in radio surveys so far. If this is the case, we suggest that such systems could have a second type of bias: they might be born with buried magnetic fields due to a mass accretion phase in their binary evolution process.

The surface magnetic field strength of millisecond pulsars (MSPs) is found to be about 4 orders of magnitude lower than that of garden variety radio pulsars (with a spin of $\approx 0.5$ s and $B \approx 10^{12}$ G). One of the proposed mechanisms is burial of the surface magnetic field under matter accreted from a companion (Romani 1990; Cumming et al. 2001; Melatos & Phinney 2001; Choudhuri & Konar 2002; Payne & Melatos 2004) where accretion of about $10^{-5} M_\odot$ of material onto the surface of a NS can significantly reduce its dipole moment.

Except for PSR J0737-3039 which is a double pulsar, all the other binary neutron stars have one of the NSs as pulsar. If GW190425 represent a case in which both NSs have their magnetic fields buried, and therefore not detectable as pulsars, this would indicate that there has to be an evolutionary phase in which both of the NSs go through a phase of mass accretion such that their recycled mass increase together with diminishing their magnetic fields. In the case of GW170817, a binary hosting a low-luminosity pulsar provides a concordant Milky Way analog progenitor model (Ramirez-Ruiz et al. 2019).

5. SUMMARY & DISCUSSION

The LSC recently announced the detection of compact object binary merger, GW190425, with total mass of $3.4^{+0.3}_{-0.1} M_\odot$. This system lies five standard deviations away from the known Galactic population of binary neutron stars (BNSs) with mean total mass of $2.66^{+0.12}_{-0.15} M_\odot$. The comparable merger rate of this system to GW170817 raises several issues that we attempted to elucidate in this Letter.

The LSC suggest that such massive system were not detected in previous radio surveys because we would be biased against observing such systems if they are born from a far-merging channel. Assuming such system are born from from a fast-merging channel, namely in a case BB unstable mass transfer, would indicate that the delay time of such system is extremely short (less than 10 Myr). In order to be consistent with the reported merger rate of GW190425 from LIGO O3 data ($\mathcal{R}_{GW190425} = 460_{-290}^{+1050} \text{yr}^{-1} \text{Gpc}^{-3}$), one concludes that the efficiency of formation of fast merging BNS systems should be between $\lambda_{\text{BNS}} \approx 2 \times 10^{-4} - 5 \times 10^{-3} M_\odot^{-1}$ depending of what we assuming as the maximum allowable metallicity of their progenitor stars. However, this is in strong tension with the production efficiency of fast merging BNS systems from population synthesis models ($\lambda_{\text{BNS}} \approx 2 - 5 \times 10^{-6} M_\odot^{-1}$).

Moreover, the comparable merger rate challenges our understanding of supernova explosion in massive stars as more massive NSs are born from heavier progenitors such that the relative formation rate of massive to normal BNS systems should be at least suppressed by an order of magnitude.

Regardless of the issues above, if we assume our understanding of the supernova and fall back physics is subject to drastic modifications, we suggest that the only way to reconcile the observed rate with the lack of previous detection of such systems in radio surveys is if these systems have suppressed magnetic dipole moment.

Figure 1. The inferred formation efficiency of massive BNS systems if GW190425 represents such a system (blue shaded region) and formed from a fast-merging channel in the field. The x-axis shows maximum metallicity below which such a formation channel could be active. The black and red shaded regions represent the fast merging channel efficiency from population synthesis models. Two different sub models, A and B have been analyzed which treat the common envelope event with HG donor stars differently. In submodel A, the fast merging BNS population comes from systems experiencing case BB unstable mass transfer (MT). In submodel B, the fast merging channels are highly eccentric BNSs. The uncertainty in each bands comes from different assumptions regarding the natal kicks of the neutron stars at birth and the metallicity dependence of efficiency of the CE phase. The large formation efficiency required to account for GW190425 as a BNS system born out of a fast merging channel is inconsistent with the formation efficiencies expected in the population synthesis models (Dominik et al. 2012).
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