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Research Paper

On isolated millisecond pulsars formed by the coalescence of neutron stars and massive white dwarfs

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Abstract

This paper uses population synthesis to investigate the possible origin of isolated millisecond pulsars as born from the coalescence of a neutron star and a white dwarf. Results show that the galactic birth rate of isolated millisecond pulsars is likely to lie between 5.8×10^{-5} yr^{-1} and 2.0×10^{-4} yr^{-1}, depending on critical variables, such as the stability of mass transfer via the Roche lobe and the value of kick velocity. In addition to this, this paper estimates that the solar mass of isolated millisecond pulsars can range from 1.5 and 2.0 M$_{\odot}$, making them more massive than other 'normal' pulsars. Finally, the majority of isolated millisecond pulsars in our simulations have spin periods ranging from several to 20 ms, which is consistent with previous observations.

Keywords: pulsars – general stars – neutron star – white dwarf

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1. Introduction

In 2017, GW170817, a gravitational wave produced by the merging of two neutron stars (NS), was observed by Advanced LIGO/Virgo (Abbott et al. 2017). Its transient counterparts were detected across almost the entire electromagnetic spectra (e.g., Abbott et al. 2017; Arcavi et al. 2017; Cowperthwaite et al. 2017), hence hailing the advent of a new era in multi-messenger astronomy.

Notably, only two seconds after the discovery of GW170817, a short γ-ray burst (GRB) was detected by both the *Fermi* and *INTEGRAL* space telescopes (Abbott et al. 2017). Traditionally, GRBs are divided into long GRBs and short GRBs. Long GRBs ($T_{90} \geq 2$ s) result from the death of massive stars and their accompanying supernovae. Short GRBs ($T_{90} \leq 2$ s), however, are a result of the merging of two compact objects (Paczynski 1986; Eichler et al. 1989; Piran 1992). Therefore, the discovery of a short GRB provides the tantalising prospect that GW170817 may have originated from a double NS merger. According to Abbott et al. (2017), the product of GW170817 was a compact object with a solar mass of 2.7 M$_{\odot}$. It is possible that this object may form a millisecond pulsar (MSP), a magnetar, in the future, or it may even rapidly collapse into a black hole (Dai & Lu 1998; Dai et al. 2006), but due to its sheer distance, there are no telescopes or astronomical equipment in the world capable of confirming its current state.

In 2006, Gehrels et al. (2006), Della Valle et al. (2006), and Gal-Yam et al. (2006) published the discovery of a special GRB: GRB060614. It was a long GRB ($\sim$100 s) and was not associated with any supernova (Gehrels et al. 2006; Della Valle et al. 2006; Gal-Yam et al. 2006). About this, King, Olsson, & Davies (2007) suggest that GRB060614 may have originated from the merging of an NS and a massive white dwarf (WD). Currently, a total of 10 GRBs have been observed as having GRB060614-esque properties (Ruffini et al. 2016).

What's more, the subset of NS + WD binaries, resulting from a merger, would be likely source for so-called 'calcium-rich gap' transients. These are a class of optical events characterised by subluminous type-I supernovae, such as SN 2005E (Perets et al. 2010; Kasliwal et al. 2012).

In theory, merging an NS and a massive WD could produce an isolated millisecond pulsar (IMSP) (van den Heuvel & Bonsema 1984). IMSPs are a special type of pulsar. According to data from Manchester et al. (2005), approximately 2 600 different pulsars have been observed, most of which are 'normal pulsars' with pulse periods of $P \sim 0.1$–10 s. However, there are roughly 325 other pulsars, which exhibit pulse periods of $\sim$1.4–20 ms (Pan, Wang, & Zhang 2013). These are so-called MSPs. The typical age (τ_c) of 'normal pulsars' is 10^7 yr, with a surface magnetic field strength (B) of 10^{12} G. For MSPs, however, these values are 10^9 yr and 10^8 G, respectively (Lorimer 2008). Generally, MSPs are thought to be NSs with a high rotation rate, being formed from the accreting matter of an NS and its companion star (see Alpar et al. 1982; Bhattacharya & van den Heuvel 1991).

For this reason, one might surmise that all MSPs evolved from binary systems. However, according to the Australia Telescope National Facility (ATNF) catalogue, approximately 1/3 of MSPs are isolated (Manchester et al. 2005). Their origins are highly debated, with different scholars proposing a variety of different possible scenarios.

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First, van den Heuvel & Bonsema (1984) proposed that IMSPs were a product of gravitational wave emissions after the merging of an NS and a massive WD. However, after the MSP PSR 1957+20 was discovered by Fruchter, Stinebring, & Taylor (1988), it was proposed that pulsar wind was the major cause of IMSP formation (Kluzniak et al. 1988). In other words, a low-mass helium WD (with a solar mass $\sim 0.02\ M_\odot$) would be left when the mass transfer results in a low-mass X-ray binary. Due to the high energetic radiation emitted from the MSP, the WD would then be completely ablated. This process was known as the Standard Model. However, Stappers et al. (1998) found that the timescale for ablation provided in the Standard Model was too long for an NS to evolve into an IMSP in Hubble time (see also Chen et al. 2013). Though the ~9-h orbit of PSR 1957+20 has a relatively short ablation timescale of merely 3×10^7 yr (Ryba & Taylor 1991), it is unlikely that this could truly be observed in such a short time phase.

Second, Bhattacharya & van den Heuvel (1991) proposed another possible evolutionary scenario. They believed that the MSPs formed from high-mass X-ray binaries can evolve into IMSPs when such binaries are disrupted by a core-collapse supernova from their companion stars. Although this scenario may be suitable for some IMSPs in these systems, it is unlikely to represent the most common formation models (Belczynski et al. 2010). Recently, a possible solution in the form of a triple-star formation model was discussed by Freire et al. (2011), based on ideas previously put forward by Eggleton & Verbunt (1986). In their model, the orbit of a triple star system expands when materials transfer from the donor star to the NS. Subsequently, the accreting NS will then evolve into an MSP. If the triple star system becomes dynamically unstable, then it is possible for the MSP to be ejected, hence forming an IMSP. Portegies Zwart et al. (2011), however, contradict this model, stating that these phenomena in fact contribute very little to the formation of IMSPs.

As can be seen from the discussion above, none of the three scenarios above have been able to provide a definitive explanation for the origin of IMSPs. In the first model, Nelemans, Yungelson, & Portegies Zwart (2001) estimate that there are, theoretically, $\sim 2.2 \times 10^6$ NS + WD binaries in the Galaxy and the merger rate of these systems ranges from about $1.0 \times 10^{-6}\ \mathrm{yr}^{-1}$ (Cooray 2004) to $1.4 \times 10^{-4}\ \mathrm{yr}^{-1}$ (Nelemans et al. 2001). Similarly, Thompson, Kistler, & Stanek (2009), with 95% confidence, state that the lowest galactic merger rate for NS + WD systems is $2.5 \times 10^{-5}\ \mathrm{yr}^{-1}$.

This paper builds on the previous research mentioned above, undertaking its own investigation into the possibility of forming IMSPs via the merging of NSs and WDs. Section 2 below presents both the authors' assumptions and details on the modelling algorithms. This is then followed by a set of results in Section 3 and final conclusions in Section 4.

2. Models

In this paper, the authors draw on the rapid binary star evolution (BSE) code, as expounded in Hurley, Pols, & Tout (2000), Hurley, Tout, & Pols (2002), and updated by Kiel & Hurley (2006). Unless specifically mentioned, our default input parameters are also based on those found in the above literature.

2.1. Kick velocity

During its formation, non-spherical symmetry of an NS creates additional 'kick' velocity. The physical origin of this non-spherical symmetry, however, remains somewhat enigmatic. In 1975, Katz (1975) suggested that these kicks may have a dichotomous nature, which was later confirmed by Hartman et al. (1997) and Pfahl, Rappaport, & Podsiadlowski (2002). Despite this, kick velocity cannot be easily controlled during observation, due to its numerous and complicated selection effects.

Typically, the distribution of the kick velocity is a Maxwellian with a dispersion (σ_k) of

$$P(\nu_k) = \sqrt{\frac{2}{\pi}}\frac{\nu_k^2}{\sigma_k^3}e^{-\nu_k^2/2\sigma_k^2}. \tag{1}$$

In Hansen & Phinney (1997), analysis of the proper motion of approximately 100 pulsars found σ_k to be equal to 190 km s^{-1}. Hobbs et al. (2005), however, examined the proper motion of 233 pulsars and found that the kick velocity could be described by a single Maxwellian with $\sigma_k = 265$ km s^{-1}. In the present investigation, we apply different velocity dispersions in different cases.

2.2. Evolution of NS + WD binary systems

NSs and WDs are both stellar remnants. Once binary systems are formed from them, there can often be disastrous consequences. In NS + WD systems, gravitational wave radiation can cause the orbital angular momentum (J_{orb}) to decay. Faulkner (1971) noted that the decay ratio of J_{orb} was the following formula, where c is the speed of light and a is the separation of the binary system:

$$\frac{\dot{J}_{GB}}{J_{orb}} = -\frac{32G^3}{5c^5}\frac{M_{NS}M_{WD}M}{a^4}. \tag{2}$$

As the orbital period shrinks, the WD fills its Roche lobe and begins to act as a donor, transferring its mass to the NS. This mass transfer can be either dynamically stable or unstable—at this point, either outcome is possible. Based on an investigation into stable mass transfer, using polytropic models, Hjellming & Webbink (1987) and Hurley et al. (2002) concluded that if the mass ratio of the components ($q = M_{donor}/M_{gainer}$) is larger than a certain value, q_c, at the onset of Roche lobe overflow, then the mass transfer will be dynamically unstable. Otherwise, the mass transfer will be stable. According to Hurley et al. (2002), the value of q_c, in an NS + WD binary system is 0.628. However, based on the isotropic re-emission mechanism,[a] van Haaften et al. (2012) put forward even stricter criteria for mass transfers in an NS + WD system to be stable, i.e. the critical mass of the WD (M_{WD}^c) donor must be 0.37 $M_\odot$. Recent scholarship into the angular momentum of material lost in disc winds, such as Bobrick, Davies, & Church (2017), has found that the M_{WD}^c may also be equal to 0.2 $M_\odot$, significantly lower than previously thought. If the mass transfer does, for some reason, become dynamically unstable, then the WD will be tidally disrupted by the NS, which, in turn, may lead to a merger and a gravitational wave event (Paschalidis et al. 2009; van den Heuvel & Bonsema 1984). However, according to Margalit & Metzger (2016), in most circumstances, the mass accreted by an NS is insufficient to induce a gravitational collapse. It is often capable, however, of simply increasing the rotational velocity of the NS by several milliseconds. For this reason, it is critically important to consider the parameters of dynamically unstable mass transfer in our investigative models.

[a]By assuming that the accreting limit of the gainer precisely equals Eddington limit, the additional transferred matter is unbound to the binary system and its gravitational energy is released (Soberman, Phinney, & van den Heuvel 1997; Tauris & Savonije 1999).

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Table 1. Parameters of the population models for NS + WD binaries

Case	q_c or M^c_{WD}	σ_k (km s^{-1})
Case 1	$q_c = 0.628$	190
Case 2	$M^c_{WD} = 0.37$	190
Case 3	$M^c_{WD} = 0.2$	190
Case 4	$q_c = 0.628$	265
Case 5	$M^c_{WD} = 0.37$	265
Case 6	$M^c_{WD} = 0.2$	265

In order to discuss the effect of q_c on the formation of IMSPs, the authors calculated a total six possible cases, each of which contain different combinations of mass and kick velocity values, such as those mentioned above (see Table 1).

2.3. Post-merger NS

As mentioned above, this paper is built on the assumption that the merging of an NS and a WD can produce an IMSP. After a merge, Metzger (2012) estimated that about 20–50% of the WD's matter is accreted by the NS and then the remainder is ejected as energy, released by both gravity and nuclear reactions during the tidal disruption of the WD. Here, we assume that the post-merger mass of the NS is equal to $M_{NS} + 0.5M_{WD}$.

After merging, the spin (P_s) of the NS is also affected by its surrounding matter. There is a great deal of scholarship on the interaction between rotating magnetised NSs and their surrounding matter (e.g. Pringle & Rees, 1972; Illarionov & Sunyaev, 1975; Lipunov, Börner, & Wadhwa, 1992; Lovelace, Romanova, & Bisnovatyi-Kogan, 1999). In these works, the value of P_s chiefly depends on both the NS' mass accretion rate and also its magnetic field. What's more, during the merging process, the mass accretion rate ($\sim 10^{-2}$ $M_\odot$ yr^{-1}) is significantly higher than the Eddington accretion rate (Metzger 2012). Lipunov (1982) investigated magnetised NSs with a super-Eddington rate of accretion, giving the NS' equilibrium spin period as

$$P_s^{eq} = 1.76 \times 10^{-1} \mu_{30}^{2/3} M_{NS}^{-2/3} \text{s}. \quad (3)$$

In the above, $\mu_{30} = \mu/(10^{30}\ \text{G cm}^3)$, where $\mu = B_{NS} R_{NS}^3/2$ denotes the magnetic dipole momentum, B_{NS} is the magnetic field, and R_{NS} is the radius of the NS. In this particular case, the $R_{NS} = 10^6$ cm. After the merger, the spin then decreases due to a brake in the current (Beskin 1993). Hence, the evolution of spin can be given approximately as

$$\frac{dP_s}{dt} = \frac{10^{-39} B_{NS}^2}{P_s}. \quad (4)$$

The evolution of NS' magnetic fields is still unknown. Using their death and spin-increase line as evidence, Urpin & Konenkov (1997) calculated a decrease in an NS' magnetic field strength as it evolved into an MSP. Their calculation was as follows:

$$B(t) = B_0 \left(\frac{t_0}{t_0 + t}\right)^\beta. \quad (5)$$

In the above, B_0, t_0, and t, respectively, denote the initial field strength, the time-scale of decay, and the age of the NS. β is a free parameter. Based on figures from the ATNF, pulsars which age less than 10^5 yr have magnetic fields of between roughly 10^{12} and 10^{13} G, averaging out at approximately 8×10^{12} G. Hence, this work takes the value of B_0 as 8×10^{12} G and t_0 as 10^5 yr. In the majority of cases, the time it takes for an NS to form and then merge with its companion star may range from around 10^6–10^8 yr. For this reason, the authors follow in the footsteps of Urpin & Konenkov (1997), taking β as 1.0. Whilst merging, the magnetic field of the NS may either increase via a so-called winding-up process (Ohlmann et al. 2016) or decrease due to an enhanced Ohmic dissipation of accreted matter. However, to the authors' knowledge, there are currently no models available to simulate this event. For this reason, the models used in this paper assume that magnetic fields do not change during the merging process.

3. Results

In order to understand more about the birth rate of IMSPs and their physical properties, the authors use population synthesis to simulate the evolution of 10^7 binary systems.

The cases considered in the present study show a similarity to those in Lü, Yungelson, & Han (2006), Lü et al. (2008, 2009, 2012), and Lü, Zhu, & Podsiadlowski (2013). Notably, the authors use a simple approximation to the initial mass function (IMF), based on Miller & Scalo (1979). The primary mass is then generated using the formula suggested by Eggleton, Fitchett, & Tout (1989). The distribution of separations is given by $\log a = 5X + 1$, where X is a random variable between 0 and 1 and a is orbital separation in units of $R_\odot$. In our models, all binaries have initial circular orbits and the metallicity Z is set to 0.02 for PopulationI stars.

Furthermore, in the case of a constant star formation rate, the authors assume that one binary, with a primary body more massive than 0.8 $M_\odot$, is formed annually in the Galaxy (Yungelson, Tutukov, & Livio 1993; Han, Podsiadlowski, & Eggleton 1995; Yisikandeer et al. 2016).

3.1. NS + WD binaries

There are three possible evolutionary pathways for NS + WD binaries. Firstly, the WD is unable to fill its Roche lobe, due to its long orbital period within Hubble time. Secondly, the WD can fill its Roche lobe and its matter can undergo a stable transfer to the NS, hence evolving into an ultra-compact X-ray binary. Thirdly, the WD successfully fills its Roche lobe and the merging process begins. It is the latter of the three pathways that is the focus of this investigation.

According to ATNF, there are a total of 147 binaries, composed of one pulsar and one WD (Manchester et al. 2005). Figure 1 gives a comparison of WD masses and orbital periods between the NS + WD binaries in our simulation and those from ATNF. On average, our results tend to show overall larger masses than those observed in other systems, where figures are usually recorded as around 0.2–0.3 $M_\odot$. For example, there were even systems in which the mass of the WD is between 0.4 and 0.8 $M_\odot$. Since these WDs have smaller radii, they will never fill their Roche lobes in Hubble time. In fact, the majority of NSs recorded in these systems appear to have already passed their deadline, hence should no longer be observed as pulsars.

If the WDs in NS + WD binaries fill their Roche lobes within Hubble time, then mass transfer shall inevitably occur. Once mass transfer begins, if $q < q_c$ or $M_{WD} < M^c_{WD}$, then it will be dynamically stable and the original binaries will, in turn, evolve into new ultra-compact X-ray binaries. At present, there are a total of 30 known ultra-compact X-ray binaries and formation candidates in the Galaxy (Liu, van Paradijs, & van den Heuvel 2007; Nelemans & Jonker 2010). The evolution of such ultra-compact X-ray binaries has been investigated by previous researchers, such

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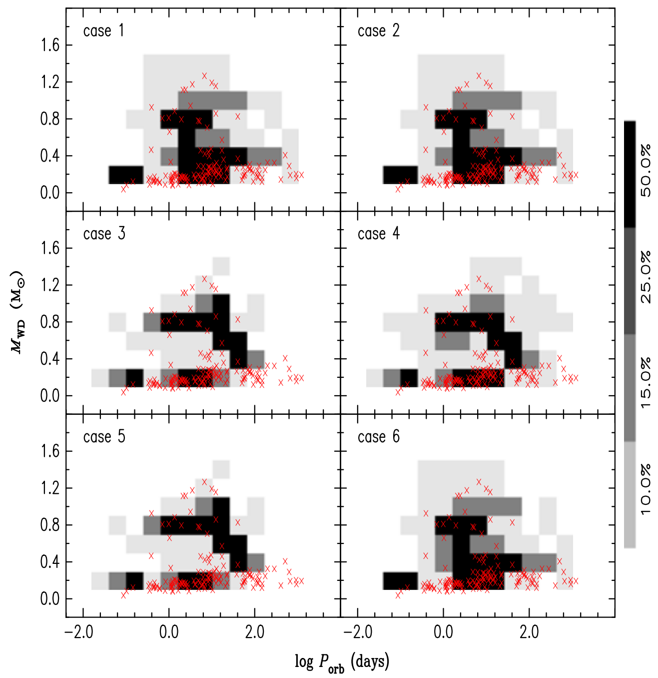

Figure 1. Grey-scale maps of WD masses and orbital periods in NS + WD binaries. The red multiplication sign (×) represents observational values for the binaries composed of a pulsar and a WD. The observational data comes from the ATNF, as cited in Manchester et al. (2005).

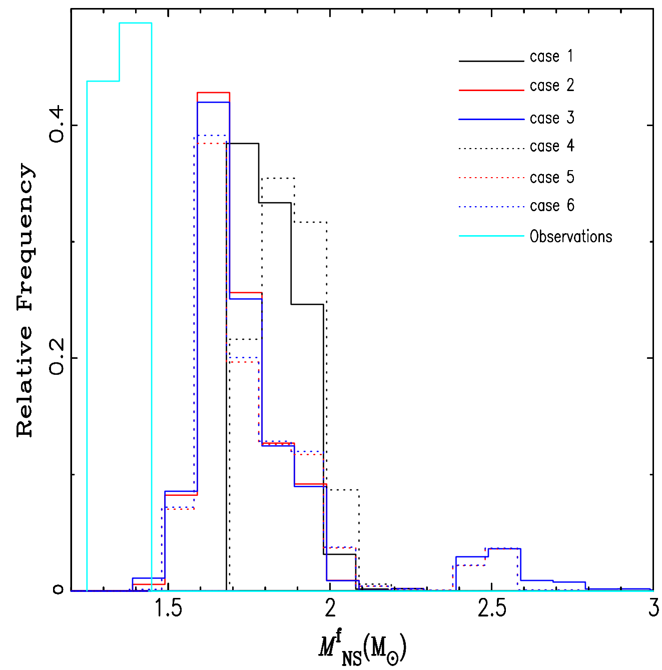

Figure 2. The mass distribution of IMSPs in the paper's investigative models. The observational data consist of currently known normal stars' pulsar masses, which are taken from https://stellarcollapse.org/nsmasses (Lattimer 2012).

as Yungelson (2008), van Haaften et al. (2012), and Lü et al. (2017). Contrastingly, if $q > q_c$ or $M_{WD} > M^c_{WD}$, then a dynamical mass transfer will occur stably and the NS and WD will begin to merge into an IMSP.

3.2. IMSP population

In our investigative models, an IMSP's mass equals $M_{NS} + 0.5M_{WD}$. Figure 2 uses a chart to illustrate the distribution of IMSP mass in our models. From the chart, one can see that when $q_c = 0.628$, the solar mass of the IMSP ranges from 1.7 to 2.0 $M_\odot$, whereas the mass of other models lies between 1.5 and 1.7 $M_\odot$. This shows that IMSPs are generally more massive than normal pulsars, which themselves have a total mass of around 1.4 $M_\odot$. Unfortunately, academia has not yet been able to provide any accurate measurements for the exact mass of an IMSP. What's more, the highest left peak in Figure 2 reaches approximately 2.5 $M_\odot$. This highlights the possibility that the progenitors of NSs may have had a higher initial mass and shorter initial period, causing NSs to gain a total solar mass of approximately >2.0 $M_\odot$ during their pre-merging period.

In addition to mass, spin periods are also one of the most important physical parameters of an IMSP. Figure 3 presents spin distributions for the IMSPs recorded in the present study. In general, the data correlates with previous observations, but some peaks in our model seem to show a somewhat slower spin than those observed in previous studies. This leads one to surmise that the widely accepted figures for the magnetic field of a post-merger NS could possibly be an overestimation. Nevertheless, the magnetic field of an NS is notoriously hard to determine. Furthermore, researchers have not yet reached a common understanding on the decay of an accreting NS' magnetic field. One possibility was proposed by Bisnovatyi-Kogan & Komberg (1974), who, through the examination of original magnetic fields, concluded that the decay of an NS may be caused by its accreted matter.

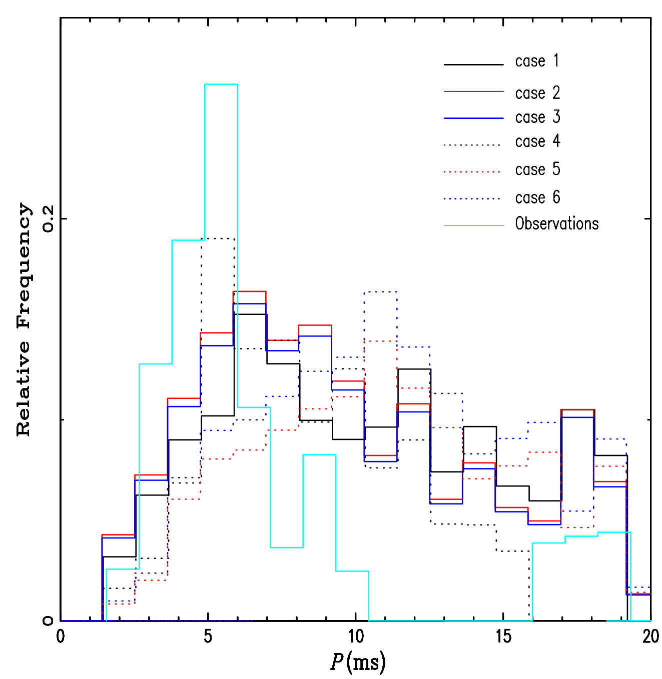

Figure 3. The distributions of spin periods for IMSPs in different models. The data included comes from the ATNF, as cited in Manchester et al. (2005).

3.3. Merger rate

Using the method of population synthesis, the present study estimates that the merger rate of NS + WD binaries lies between 5.8×10^{-5} yr^{-1} (case 4) and 2.0×10^{-4} yr^{-1} (case 3). From case 1 to case 3, the numbers of NS + WD binaries also increased from 666 to 1981, thanks to differing critical values. In other words,

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one can conclude that the smaller the critical mass of a WD, the more IMSPs will be formed. In addition to this, comparing case 1 with case 4, case 2 with case 5, and case 3 with case 6 suggests that the higher the kick velocity is, the less IMSPs are formed. This is because the nascent NS' kick velocity plays a determining role in whether the binary can continue to survive or whether, if the kick velocity is too high, it will be disrupted by a supernova explosion.

Furthermore, the authors of the present survey also consider NS + WD mergers as a potential progenitor of calcium-rich supernovae. According to Kennicutt (1998), the Milky Way took 0–10 $M_\odot$ yr^{-1} to form. If one takes the median of this range, then that makes 5 $M_\odot$ yr^{-1} the rate of star formation. Kasliwal et al. (2012), however, put forward a possible a lower limit for calcium-rich gap events of 7×10^{-7} Mpc^{-3} yr^{-1}.

To calculate the total star production rate, one can use the following formula from Strolger et al. (2004):

$$\mathrm{SFR} = 10^9 a(t^b e^{-\frac{t}{c}} + d e^{\frac{d(t-t_0)}{c}})\, \mathrm{M_\odot\ yr^{-1}\ Gpc^{-3}}. \quad (6)$$

Therein, t denotes the age of the Universe in Gyr and t_0 is the current age of the Universe. If one follows through with Strolger et al.'s (2004) method and takes t_0 to be 13.47 Gyr, and the parameters $a = 0.021$, $b = 2.12$, $c = 1.69$, and $d = 0.207$, then one can infer that the rate of Ca-rich gap transients in the Galaxy is roughly 5×10^{-4} yr^{-1}. This result is relatively close to our simulation-base estimations.

In general, our results are consistent with Nelemans et al. (2001). The merger rate of NS + WD binaries is approximately 3–10 times that of double NS systems (Portegies Zwart & Yungelson 1999). Although gravitational waves are released during the merging of an NS and a WD, they can hardly be detected, due to their relatively low amplitude and frequency. It is their electro-magnetic counterparts that should be observed, as they eject significantly more observable matter. As for whether GRBs, such as GRB060614, originate from the merger of an NS and a WD binary, this hypothesis is certainly possible, but many more multi-band observations are still needed until we get a more defined and clear-cut answer.

4. Conclusion

In this paper, the authors investigated the merging of NS and WDs as the possible origin of IMSP. This paper not only estimated that IMSPs' galactic birth rate is between approximately 5.8×10^{-5} yr^{-1} and 2.0×10^{-4} yr^{-1}, depending on variables such as stable mass transfer via the Roche lobe and kick velocity, but also predicted that the solar mass of IMSPs lies between 1.5 and 2.0 $M_\odot$, which makes them more massive than normal pulsars. What's more, most of the IMSPs in our simulations have a spin period of several to 20 ms, which is consistent with previous observations.

If it is true that the majority of IMSPs originate from the merging of NSs and WDs, then this event may trigger a GRB060614-esque reaction and produce gravitational waves. If it be possible to detect these in the future, then our field will be one step closer to a fuller understanding of GRBs and gravitational waves.

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