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Wide binary pulsars from electron-capture supernovae

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ABSTRACT

Neutron stars receive velocity kicks at birth in supernovae. Those formed in electron-capture supernovae from superasymptotic giant branch stars – the lowest mass stars to end their lives in supernovae – may receive significantly lower kicks than typical neutron stars. Given that many massive stars are members of wide binaries, this suggests the existence of a population of low-mass ($1.25 < M_{\rm psr}/{\rm M}_{\odot} < 1.3$), wide ($P_{\rm orb} \gtrsim 10^4$ d), eccentric ($e \sim 0.7$), unrecycled ($P_{\rm spin} \sim 1$ s) binary pulsars. The formation rate of such binaries is sensitive to the mass range of (effectively) single stars leading to electron capture supernovae, the amount of mass lost prior to the supernova, and the magnitude of any natal kick imparted on the neutron star. We estimate that one such binary pulsar should be observable in the Milky Way for every 10 000 isolated pulsars, assuming that the width of the mass range of single stars leading to electron-capture supernovae is $\lesssim 0.2\,{\rm M}_{\odot}$, and that neutron stars formed in electron-capture supernovae receive typical kicks less than $10\,{\rm km\,s^{-1}}$. We have searched the catalogue of observed binary pulsars, but find no convincing candidates that could be formed through this channel, consistent with this low predicted rate. Future observations with the Square Kilometre Array may detect this rare sub-class of binary pulsar and provide strong constraints on the properties of electron-capture supernovae and their progenitors.

Key words: stars: neutron – pulsars: general – supernovae: general.

1 INTRODUCTION

Stars with initial masses $\lesssim 8\,{\rm M}_{\odot}$ end their lives as white dwarfs, while more massive stars undergo core-collapse supernovae and form neutron stars or black holes (Woosley, Heger & Weaver 2002; Doherty et al. 2017). Superasymptotic giant branch (SAGB; Garcia-Berro & Iben 1994; Doherty et al. 2017) stars[1] on the boundary between these two regimes are thought to result in electron-capture supernovae (ECSNe; Miyaji et al. 1980; Nomoto 1984, 1987) leading to the formation of a neutron star. The mass range of single stars expected to undergo ECSNe is narrow and roughly in the range 8–$10\,{\rm M}_{\odot}$, although the exact mass range is very uncertain and depends on the details of the models (e.g. Poelarends et al. 2008; Doherty et al. 2015, 2017; Jones et al. 2016; Leung, Nomoto & Suzuki 2020). The mass range for ECSNe may be wider in interacting binaries (e.g. Podsiadlowski et al. 2004; Doherty et al. 2017; Poelarends et al. 2017; Siess & Lebreuilly 2018), which may result in the majority of ECSNe occurring in binary systems. Whether ECSNe occur in single stars at all is an open question (e.g. Willcox et al. 2021).

ECSNe are expected to have low luminosities compared to other classes of supernovae, and be observed as Type IIp or IIn supernovae (e.g. Tominaga, Blinnikov & Nomoto 2013; Moriya et al. 2014; Hiramatsu et al. 2021). No observed supernovae have been conclusively associated with an ECSN, but SN2018zd may be the best candidate to date (Hiramatsu et al. 2021). Other candidates include the supernova that formed the Crab nebula/pulsar (e.g. Nomoto et al. 1982; Smith 2013; Moriya et al. 2014), though see Gessner & Janka (2018).

Numerical simulations succeed in realizing ECSNe from first principles (e.g. Dessart et al. 2006; Kitaura, Janka & Hillebrandt 2006). Recently, Gessner & Janka (2018) performed hydrodynamical simulations of ECSNe and found that the remnant neutron stars receive a kick of only a few ${\rm km\,s^{-1}}$ at most. The small kicks arise from the rapid explosion, which does not allow time for substantial asymmetries to develop. Kicks this small are much lower than the typical velocities of a few hundred ${\rm km\,s^{-1}}$ inferred for neutron stars from the proper motions of isolated Galactic pulsars (e.g. Lyne & Lorimer 1994; Hobbs et al. 2005; Verbunt, Igoshev & Cator 2017). For this reason, ECSNe play an important role in the formation of double neutron star binaries (e.g. Vigna-Gómez et al. 2018; Giacobbo & Mapelli 2019), the retention of neutron stars in globular clusters (Pfahl, Rappaport & Podsiadlowski 2002a), the population of wide neutron star high-mass X-ray binaries (Pfahl et al. 2002b; Podsiadlowski et al. 2004; Knigge, Coe & Podsiadlowski 2011) and the mass distribution of neutron stars in binaries (Schwab, Podsiadlowski & Rappaport 2010; Ozel et al. 2012).

Given that many massive stars are members of wide, non-interacting binaries (e.g. Moe & Di Stefano 2017), a population of neutron stars receiving (very) low kicks during ECSNe would lead to the prediction of wide, eccentric, unrecycled binary pulsars, which

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[1]Recently O'Grady et al. (2020) reported the observation of ∼10 SAGB star candidates in the Magellanic Clouds.

would not be predicted if ECSNe lead to large kicks (and thus disrupt wide binaries). Observations of wide binary pulsars (or the lack of these systems) could therefore be a powerful test of whether ECSNe can occur in effectively single stars. This could provide insights into ECSNe and their progenitors.

In this paper, we develop a simple model for the formation of low-mass ($M_{\rm psr} \sim 1.3\,{\rm M}_{\odot}$), wide ($P_{\rm orb} > 10^4$ d), eccentric ($e > 0.5$), unrecycled ($P_{\rm spin} \sim 1$ s) binary pulsars in the Galactic field formed by ECSNe. We describe our model in Section 2.1, and present results of a FIDUCIAL model in Section 2.2. We test the sensitivity of our predictions to model uncertainties in Section 2.3. We estimate the number of wide binary pulsars observable in the Milky Way in Section 2.4, finding that roughly one wide binary pulsar should be observable for every 10 000 isolated pulsars, assuming that the mass range of (effectively) single stars that lead to ECSNe is $<0.2\,{\rm M}_{\odot}$ (Willcox et al. 2021). In Section 3, we search for candidate wide binary pulsars in the observed pulsar population. We find no candidates that are well explained by our model, consistent with our estimated rates; the observation of these systems is hampered by the lack of sensitivity of pulsar observations to orbital periods much longer than the observing baseline of a few decades. We argue that a few (two to three) apparently isolated observed pulsars could actually be in wide binaries. We conclude in Section 4.

2 ELECTRON CAPTURE SUPERNOVAE IN A POPULATION OF MASSIVE, WIDE BINARY STARS

2.1 Method and fiducial assumptions

We model a population of wide, massive, non-interacting binary stars at solar metallicity, appropriate for pulsars formed recently in the Milky Way. A large fraction of intermediate/massive stars are known to be part of binaries (e.g. Sana et al. 2012; Moe & Di Stefano 2017). We are interested in the evolution of single $\sim 8\,{\rm M}_{\odot}$ SAGB stars at solar metallicity, which may end their lives in ECSNe and produce observable pulsars in the Milky Way. Given the uncertainties in the masses of SAGB stars which undergo ECSNe (Doherty et al. 2017), we assume[2] that all primaries (initially the most massive star in the binary) have a mass of $8\,{\rm M}_{\odot}$, as appropriate for solar metallicity SAGB stars. We do not model binaries with primary stars with initial masses greater than $8\,{\rm M}_{\odot}$, as we assume that these will have already evolved and undergone core-collapse supernovae, receiving high kicks of order a few hundred km s^{-1}, resulting in the disruption of the binary (see e.g. Vigna-Gómez et al. 2018; Renzo et al. 2019).

We sample the remaining properties of each binary from statistical distributions based on observations of massive, wide binaries. We denote our default set of assumptions our FIDUCIAL model. We examine the predictions of this model in Section 2.2, and consider some alternate assumptions in Section 2.3.

We determine the mass of the secondary star by drawing the mass ratio of the binary $q = m_2/m_1$ from a power-law distribution with a slope of -2 for mass ratios $q > 0.1$, favouring typical mass ratios of around $q = 0.2$, based on observations of massive, wide binaries (Abt, Gomez & Levy 1990; Sana et al. 2014; Aldoretta et al. 2015; Moe & Di Stefano 2017).

The binary orbital periods are drawn from a distribution which is flat in the log between 10^4 d (assumed to be the minimum orbital period of non-interacting binaries) and 10^7 d (Öpik 1924; Abt 1983; Sana et al. 2012; Moe & Di Stefano 2017). Wide binaries have low binding energies, and may be disrupted by flyby encounters with passing stars in the Galactic field (e.g. Yabushita 1966; Weinberg, Shapiro & Wasserman 1987). As discussed by Igoshev & Perets (2019), the typical lifetimes (before being disrupted this way) of the massive, wide binaries we consider here are longer than the $\sim$50–200 Myr the binary needs to survive to produce an observable binary pulsar (see Section 2.2). Observations suggest that most massive wide binaries are eccentric (e.g. Moe & Di Stefano 2017). In our FIDUCIAL model we assume that the initial eccentricities of wide binaries are drawn from a UNIFORM distribution between 0 and 1. We assume that the supernova occurs at a random time in the binary orbit.

The pre-supernova masses of SAGB stars are uncertain (Doherty et al. 2017). For our FIDUCIAL model, we assume that SAGB stars lose no mass during their pre-supernova evolution (this is the NO MASS LOSS model from Section 2.3). This is approximately what occurs for stars in this mass range using the default mass-loss rate prescriptions in the binary population synthesis code COMPAS (Stevenson et al. 2017; Vigna-Gómez et al. 2018) that we use for estimating formation rates in Section 2.4. This implies that SAGB stars eject a large amount of mass during the supernova, which translates to a large mass-loss kick (Blaauw 1961). Detailed SAGB models suggest that the envelope of these stars may be lost prior to the supernova through a brief phase with high wind mass-loss rates and thermal pulses (Doherty et al. 2017). We therefore consider alternate assumptions regarding the pre-supernova mass-loss of SAGB stars in Section 2.3.

We assume that all ECSNe give rise to neutron star natal kicks of the same magnitude. In our FIDUCIAL model, we assume that the magnitude of this kick is 10 km s^{-1}, and we examine this in more detail in Section 2.3. In reality, the natal kick will likely depend in detail on the properties of the progenitors. However, to our knowledge, no such detailed prescription for ECSN kicks exists at present. Our simple model is intended to allow us to easily understand the impact that natal kicks have on the binary.[3] We make the standard assumption that the distribution of kick directions is isotropic (e.g. Tauris et al. 2017). We determine the post-supernova orbital parameters following Kalogera (1996).

ECSNe are formed from the lowest mass stars to go supernova, with core masses around the Chandrasekhar mass. The gravitational mass of the remnant neutron star is less than its baryonic mass by around 10 per cent, with the exact mass difference depending on the unknown neutron star equation of state. We assume that the baryonic mass of all neutron stars formed through ECSNe is $1.36\,{\rm M}_{\odot}$ (e.g. Takahashi, Yoshida & Umeda 2013; Gessner & Janka 2018); for our assumed relation between the baryonic and remnant masses (Timmes, Woosley & Weaver 1996), this results in gravitational masses of $1.26\,{\rm M}_{\odot}$.

2.2 Fiducial model predictions

To elucidate the main predictions of this model, we first consider the results of the FIDUCIAL model described above. We examine the robustness of these results to various assumptions in Section 2.3.

We show the orbital periods and eccentricities of wide binary pulsars following the ECSN in Fig. 1. We see that essentially all eccentricities are possible, although higher eccentricities are preferred; the median eccentricity in this model is around 0.7. Around 10 per cent of binaries that remain bound are in high enough eccentricity orbits after the supernova that their periapsis separation

[2] We have checked that the exact mass assumed does not impact our conclusions.

[3] We expect that our results would be qualitatively similar if a narrow distribution of kick velocities was used.

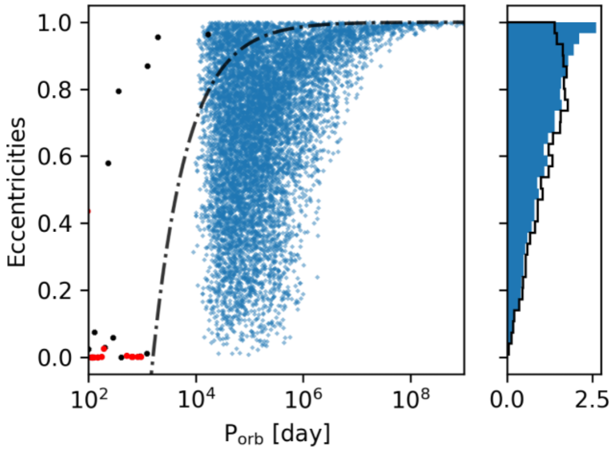

Figure 1. *Left-hand panel:* Orbital periods ($P_{\rm orb}$) and eccentricities of wide binaries after an ECSN in our FIDUCIAL model (blue points; see Section 2.1 for details). The black dot–dashed line shows the eccentricities above which a binary would interact at periastron for a giant ($m_2 = 4\,{\rm M}_\odot$, $1\,000\,{\rm R}_\odot$) companion as a function of orbital period. The black points show the orbital periods and eccentricities of known binary pulsars (Manchester et al. 2005). Recycled pulsars are shown in red. Uncertainties for the observed systems are typically much smaller than the size of the points. *Right-hand panel:* Normalized probability distribution of the eccentricities of wide binary pulsars. The solid black line shows the distribution after removing those binaries that would interact at periastron, as discussed in Section 2.2.

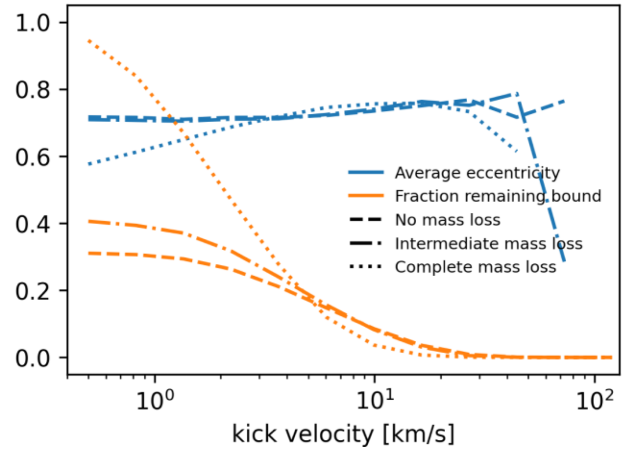

Figure 2. Fraction of wide binaries ($P_{\rm orb} > 10^4$ d, $m_1 = 8\,{\rm M}_\odot$) which remain bound after an ECSN (orange) and their average post-supernova eccentricity (blue), as a function of the kick velocity imparted to neutron stars in ECSNe. The different line styles show different assumptions about the amount of mass SAGB stars lose *prior* to the supernova (see Section 2.3). The NO MASS LOSS model is shown with a dashed line, the INTERMEDIATE MASS LOSS model is shown with a dot–dashed line, and the COMPLETE MASS LOSS model is shown with the dotted line. This figure shows results from the UNIFORM eccentricity model.

would be equal to the radius of a low-mass giant companion ($R = 1000\,{\rm R}_\odot$), potentially leading to mass transfer or a binary merger once the companion evolves. All other binaries do not interact, and therefore we expect the pulsar to be unrecycled and have typical properties of unrecycled pulsars, with a spin period $P_{\rm spin} \sim 0.1$–1 s and a spin-down rate of $10^{-17} < \dot{P} < 10^{-13}$ (e.g. Boyles et al. 2011), unless ECSNe preferentially produce pulsars with particular rotational characteristics or luminosities. With the exception of the binaries with the highest eccentricities (which may result in mergers in any case), these binaries are sufficiently wide that gravitational radiation and tidal effects are not expected to significantly affect the binary orbit after the supernova on time-scales when the pulsar is observable,[4] and thus we neglect modelling these. We therefore expect that the properties of observable systems should be very similar to their post-supernova orbital properties. We find that, because of the low kicks associated with ECSNe, these wide binary pulsars have low typical systemic velocities of $\lesssim 10\,{\rm km\,s^{-1}}$.

The lifetime of an $8\,{\rm M}_\odot$ star is ∼40 Myr (Pols et al. 1998; Hurley, Pols & Tout 2000). Assuming a pulsar lifetime of 10 Myr (100 Myr; see above), this in turn implies that only companions more massive than $7\,{\rm M}_\odot$ ($4\,{\rm M}_\odot$) can have evolved to massive ($M > 1\,{\rm M}_\odot$) oxygen–neon white dwarfs while a pulsar is still visible. Lower mass stars will still be unevolved main-sequence stars. In our FIDUCIAL model, we find that only 2 per cent (10 per cent) of these systems should have massive oxygen–neon white dwarf companions with $M_{\rm WD} \sim 1\,{\rm M}_\odot$, while the rest should have low-mass $M < 7\,{\rm M}_\odot$ ($4\,{\rm M}_\odot$) main-sequence companions. The median companion mass ($\sim 2.8\,{\rm M}_\odot$) arises from a competition between the initial distribution of binary mass ratios (which favours low-mass companions) and the supernova dynamics (binaries with a more massive companion are more likely to survive the supernova).

[4]The typical lifetime of an unrecycled pulsar is only 10–100 Myr (e.g. Lynch et al. 2012; Chattopadhyay et al. 2021).

2.3 Variations from fiducial assumptions

Our model (described in Section 2.1) necessarily makes a number of simplifying assumptions. One of the key uncertainties is the pre-supernova (envelope) mass of SAGB star progenitors of ECSNe (Poelarends et al. 2008). Large pre-supernova masses will lead to large amounts of mass ejected during the supernova, leading to large mass-loss kicks (Blaauw 1961). In order to investigate the impact, we use three simple models. The name of each model refers to the amount of mass-loss the SAGB stars experience *prior* to the ECSN. In the NO MASS LOSS model we assume that the stars do not lose any mass through stellar winds prior to the supernova explosion. This is approximately what currently happens in binary population synthesis codes like COMPAS (Stevenson et al. 2017, 2019; Vigna-Gómez et al. 2018). Here, we do not intend this model to be realistic, but to demonstrate the extreme case. At the other extreme is the COMPLETE MASS LOSS MODEL where we assume that the pre-supernova mass is equal to the baryonic mass of the remnant neutron star, $1.36\,{\rm M}_\odot$ (Vigna-Gómez et al. 2018). This model is motivated by detailed SAGB models that show that these stars have high mass-loss rates of order $10^{-4}\,{\rm M}_\odot\,{\rm yr}^{-1}$ during the final stages of their lives (see Doherty et al. 2017, for a review). However, we again expect that this model is too extreme. In between these two extremes, in the INTERMEDIATE MASS LOSS model we assume that the star experiences some mass-loss and then ejects $M_{\rm ej} = 5\,{\rm M}_\odot$ of mass during the supernova, based on models for the expected ejecta mass for ECSNe, along with that inferred from the Crab nebula (Fesen, Shull & Hurford 1997; Tominaga et al. 2013; Hiramatsu et al. 2021). For models that include pre-supernova mass-loss we assume Jean's mode mass-loss, which leads to widening of the binary by a factor of a few. We neglect wind mass transfer, which may be important even in wide binaries due to the slow wind speeds of SAGB stars (e.g. Höfner & Olofsson 2018; Saladino et al. 2018). We show the fraction of wide binaries that remain bound after the ECSN, and the average eccentricity of the remaining bound binaries for each of these models in Fig. 2.

The magnitude of kicks that neutron stars formed in ECSNe receive is another key uncertainty (Gessner & Janka 2018). In Fig. 2, we vary the kicks in the range 0.5–120 $\mathrm{km\,s^{-1}}$. In all cases we assume that all ECSNe lead to the same kick magnitude. We find that for kicks less than 5 $\mathrm{km\,s^{-1}}$ (Gessner & Janka 2018) at least 20 per cent of wide binaries would be expected to survive the supernova. If ECSNe impart no kicks, around 30 per cent of binaries remain bound in the NO MASS LOSS model, while this fraction is close to 100 per cent for the COMPLETE MASS LOSS model. Kicks $\gtrsim$10 $\mathrm{km\,s^{-1}}$ start to disrupt a large fraction (>90 per cent) of wide binaries in all models, with essentially all binaries disrupted by kicks >100 $\mathrm{km\,s^{-1}}$ (where the fraction remaining bound is $<10^{-4}$). To summarize, this suggests that, given our current understanding of kicks from ECSNe (Gessner & Janka 2018), a significant fraction of wide binaries should survive, and a sizable population of wide binary pulsars should exist.

We also show in Fig. 2 how the median eccentricity of the wide binaries that remain bound varies with the kick velocity. All models lead to an average post-supernova eccentricity of $e \sim 0.7$ regardless of the mass-loss model or the magnitude of natal kicks. We also find that our models with higher kicks than our FIDUCIAL model result in slightly higher typical companion masses (since only stars with comparable mass companions survive the supernova).

Massive, wide binaries are observed to generally have eccentric orbits (Malkov et al. 2012; Moe & Di Stefano 2017). In addition to our FIDUCIAL model where the initial eccentricities of binaries are drawn from an UNIFORM distribution, we have also tested the impact of assuming that binaries initially have CIRCULAR orbits, or eccentricities drawn from a THERMAL distribution ($p(e) \propto e$). Eccentric binaries survive symmetric supernovae (i.e. with no natal kicks) more often than a circular binary of the same mass and orbital period due to the lower orbital velocity at, and greater time spent near, apoapsis. The fraction of binaries which survive a symmetric supernova increases from around 20 per cent for the CIRCULAR model to 50 per cent in the THERMAL model. The initial eccentricity distribution is unimportant for natal kicks $\gtrsim$10 $\mathrm{km\,s^{-1}}$.

Overall, with our three different assumptions regarding pre-supernova mass-loss from SAGB stars, and three eccentricity distributions for massive binaries, we have simulated nine different models with different assumptions. For each model we used 12 different values for the kick velocity of neutron stars in the range 0.5–120 $\mathrm{km\,s^{-1}}$, resulting in a total of 108 models.

2.4 Estimate of the formation rate of wide binary pulsars

ECSNe are rare events, constituting a few per cent of the core-collapse supernova rate (Poelarends et al. 2008; Doherty et al. 2017; Jones et al. 2019; Hiramatsu et al. 2021). The rate of ECSNe in wide binaries is sensitive to the mass range of (effectively) single stars that lead to ECSNe. Willcox et al. (2021) recently showed that the width of this mass range cannot be greater than 0.2 $\mathrm{M_{\odot}}$ in order to not overproduce low-velocity pulsars compared to observations (e.g. Verbunt et al. 2017; Igoshev 2020).[5] Using the population synthesis models from Willcox et al. (2021), we have calculated the formation rate of wide binaries in which the primary star is expected to undergo an ECSN i.e. the fraction of all binaries that are born in the parameter space described in Section 2.1. We compare this to the number of isolated pulsars (which we assume have similar radio lifetimes, luminosities, beaming fractions etc.) produced in the same model. We find that one of these wide binaries is formed for every 100 isolated pulsars formed in our population synthesis models. A significant fraction of wide binaries are disrupted by the supernova in all of our models (cf. Fig. 2), with typically ∼10 per cent surviving the supernova. We therefore find one wide binary that remains bound following the ECSN (hereafter wide binary pulsars) is formed for every ∼1000 isolated pulsars, leading to the possibility that ∼3 of the ∼3000 observed isolated pulsars may have wide binary companions. Wide binary pulsars may be misclassified as isolated pulsars due to their long orbital periods compared to the typical durations that pulsars have been observed (decades at most). Here, we assume that binaries with orbital periods greater than 100 yr would be misclassified as isolated pulsars (Willcox et al. 2021). In our models, we find that ∼ 1–10 per cent of these wide binary pulsars have orbital periods shorter than 100 yr, with larger kicks generating a higher fraction. Putting this all together, we estimate that one wide binary pulsar formed through an ECSN will be observed for every 10 000 isolated pulsars. This is consistent with the current lack of observations of such systems (see Section 3), but raises the possibility of observing these systems with future pulsar surveys such as the Square Kilometre Array (SKA) that will expand the number of known pulsars to >10 000 (e.g. Keane et al. 2015). Given that ECSNe make up only a small fraction of all supernovae, it is also worth considering whether a small fraction of neutron stars formed from more massive stars in more common core-collapse supernovae can also produce wide binary pulsars. According to our models, for typical kicks greater than 100 $\mathrm{km\,s^{-1}}$ (Hobbs et al. 2005; Verbunt et al. 2017), less than 1 in 10^4 binaries survive the supernova (cf. Fig. 2). This indicates that the dominant formation channel for wide binary pulsars will be through neutron stars formed with low kicks in ECSNe. We emphasize that the rate estimates above are sensitive to several uncertain model assumptions (cf. Section 2.3).

3 SEARCH FOR CANDIDATE BINARY PULSARS FORMED BY ECSNE

Despite the low expected observation rate of wide binary pulsars (Section 2.4), we have examined the pulsar catalogue to see if any known binary pulsars are consistent with having formed in this way. We do not find any compelling candidates, in agreement with our estimated formation rates. We show the orbital periods and eccentricities of observed wide (P_{orb} > 100 d) binary pulsars in Fig. 1, taken from version 1.65 of the ATNF catalogue (Manchester et al. 2005), accessed using PSRQPY (Pitkin 2018). The widest observed binary pulsar PSR J1024−0719 (not shown in Fig. 1 due to the large uncertainties in its parameters) has an orbital period of 2000–20 000 yr (Bassa et al. 2016; Kaplan et al. 2016). PSR J1024−0719 is a 5 ms pulsar (Bailes et al. 1997), and thus has likely been recycled; its formation likely involves stellar dynamics (and hence it is not formed through the channel we propose here), and it may originate from a triple or a globular cluster (Bassa et al. 2016; Kaplan et al. 2016). Other than PSR J1024−0719, the upper limit of orbital periods of known binary pulsars is around 10^4 d (cf. Fig. 1, see also Igoshev & Perets 2019), with a preference for high eccentricities.

Many of the known wide binary pulsars are consistent with formation channels involving episodes of prior mass transfer, unlike the formation channel we consider here. For example, PSR J0823+0159 (B0820+02; Manchester et al. 1980; Hobbs et al. 2004; Xue et al. 2017) is a 0.8 s pulsar in a wide (>1200 d) binary with a low eccentricity (e = 0.01) and a 0.6 $\mathrm{M_{\odot}}$ white dwarf companion (Kulkarni 1986; Koester, Chanmugam & Reimers 1992; Koester &

[5]This also agrees with recent constraints on the width of the ECSN mass range from s-process element abundances in ultra faint dwarf galaxies (Hirai, Wanajo & Saitoh 2019; Tarumi et al. 2021)

Reimers 2000). Tauris, Langer & Kramer (2012) propose that PSR B0820+02 formed from a wide low-mass X-ray binary. In addition, several candidates have massive B/Be star companions; these are not compatible with our model since it predicts low-mass main-sequence companions. One example of such a system is PSR J1740−3052 (Stairs et al. 2001), a young 570 ms pulsar in a 230 d, $e = 0.57$ binary orbit with a massive ($M > 11\,M_\odot$) B star companion (Bassa et al. 2011). Similarly, PSR J0045−27319 is a young binary pulsar with a 0.926 s spin period, in a 54 d orbit with an eccentricity of $e = 0.8$ whose companion is also a B star of $\sim$10 $M_\odot$ (Kaspi et al. 1994; Bell et al. 1995). PSR J1638−4725 (Lorimer et al. 2006) is a binary pulsar with an orbital period of 1941 d and a high eccentricity $e > 0.95$. It has a companion mass of $\sim$8 $M_\odot$, which is likely again too massive to be explained by our model. PSR B1259−63 (PSR J1302−6350, Johnston et al. 1992, 1994) is a 47 ms pulsar with an orbital period of 1237 d, an eccentricity of $\sim$0.9. PSR B1259−63 again has a massive ($M \sim 10\,M_\odot$) Be star companion, SS 2883. In this case both the spin period of the pulsar (indicating recycling) and the companion mass make it incompatible with our model. PSR J2032+4127 is a 143 ms pulsar in a wide (20–30 yr) binary with a highly eccentric ($e > 0.8$) orbit (Lyne et al. 2015). It too has a massive Be star companion ($\sim$15 $M_\odot$). Another binary pulsar of interest is the recently discovered PSR J1954+2529 (Parent et al. 2022), which is a 0.93 s non-recycled pulsar in a wide (82.7 d), eccentric ($e = 0.114$) orbit with a low-mass companion. The relatively close orbit of this binary (compared to the systems we have focused on in this paper) again suggests that this binary may have experienced a phase of mass transfer prior to the formation of the pulsar. Since the primary has already formed a neutron star in these systems, it seems likely that they have undergone binary interactions in which some mass from the primary was transferred to the secondary prior to the supernova, particularly in the binaries hosting Be stars (e.g. Vinciguerra et al. 2020).

There is also an observed population of wide, unrecycled (young) binary pulsars known in globular clusters, which have been associated with ECSNe (Lyne, Manchester & D'Amico 1996; Boyles et al. 2011; Lynch et al. 2012). However, the formation of these binaries likely involved dynamical interactions, rather than the isolated binary evolution channel we discuss here, so we do not examine them further here.

In conclusion, we do not find any observed binary pulsars that are well explained by our model. This is likely either due to radio pulsar observations not being sensitive to orbital periods significantly greater than the observing duration, leading to wide binary pulsars being misclassified as isolated pulsars (Bassa et al. 2016; Kaplan et al. 2016), or because wide binary pulsars do not exist, either because the mass range of single SAGB stars leading to ECSNe is very narrow (cf. Willcox et al. 2021), or because ECSNe lead to natal kicks $\gtrsim$10 km s^{-1} (cf. Fig. 2). These lead to the observed pulsar population being too small to observe these rare wide binary pulsars. Future radio observations with MeerKAT (Bailes et al. 2020) and the SKA (Keane et al. 2015) will expand the known pulsar population, hopefully observing these systems. It may also be possible to use *Gaia* to observe wide, low-mass main-sequence star companions to young pulsars (e.g. Igoshev & Perets 2019; Antoniadis 2021).

4 SUMMARY AND CONCLUSION

Both theoretical and observational evidence point to neutron stars formed in ECSNe receiving low kicks at birth (Pfahl et al. 2002b; Gessner & Janka 2018). We argue that if ECSNe occur in a population of wide, non-interacting binaries, low kicks predicts the existence of low-mass ($1.2 < M_{\rm psr}/M_\odot < 1.3$), wide ($P_{\rm orb} > 10^4$ d), eccentric ($e \sim 0.7$), unrecycled ($P_{\rm spin} \sim 1$ s) binary pulsars in the Galactic field. These binary pulsars typically have low-mass main-sequence companions (Section 2.2). Our model shows that at least 20 per cent of wide binaries are expected to survive an ECSN (cf. Fig. 2), if natal kicks are $\lesssim$5 km s^{-1}. The exact fraction depends on the pre-supernova masses of SAGB stars, and the natal kicks imparted to neutron stars (cf. Fig. 2, Section 2.3).

We searched the catalogue of observed binary radio pulsars for systems with characteristics matching those described above (Section 3). We did not find any candidates which are well explained by this model. Using binary population synthesis models (Willcox et al. 2021) we have estimated the formation rate of these wide binary pulsars, finding that roughly one binary should be observable for every 10 000 isolated pulsars. This is consistent with the lack of detection of such a system in the current population of observed pulsars, but raises the possibility of observing them in the future with the SKA. Our low predicted observed rate is a result of a narrow mass range of single star ECSN progenitors (Willcox et al. 2021), combined with the fact that pulsar observations are not sensitive to orbital periods longer than a few 10^4 d. The observation of a wide binary pulsar could provide evidence that ECSNe can occur for effectively single stars.

Key uncertainties remain in the modelling of ECSNe. These uncertainties include the mass range of progenitors which are expected to undergo ECSNe, what their pre-supernova masses are (for single stars when their envelopes are not stripped through binary interactions), and what magnitude kicks neutron stars receive in ECSNe. If the mass range of (single) SAGB stars leading to ECSNe is narrow, they will be inherently rare (or possibly even non existent), while ECSNe kicks larger than predicted by recent models (Gessner & Janka 2018) would disrupt most wide binaries (cf. Fig. 2). We have assumed that all ECSNe form neutron stars, while some may lead to thermonuclear explosions or white dwarf formation (e.g. Jones et al. 2016, 2019; Tauris & Janka 2019; Leung et al. 2020). Our discussion has focused on ECSNe, but the lowest mass iron core-collapse supernovae may also produce neutron stars with low kicks (e.g. Müller et al. 2019; Stockinger et al. 2020).

In this paper, we have focused on the formation of wide binary pulsars from wide, non-interacting binaries, since these would provide a clean probe of SAGB star evolution and ECSNe without any complications from binary interactions. ECSNe are likely more common in close, interacting binaries (e.g. Vigna-Gómez et al. 2018; Vinciguerra et al. 2020; Willcox et al. 2021). Since a sizeable fraction of massive stars are in triples (Moe & Di Stefano 2017), these may also provide important contributions to the formation of wide binary pulsars through distinct evolutionary channels (see e.g. Bassa et al. 2016; Hamers & Thompson 2019). Improved theoretical modelling of SAGB stars will aid in solidifying the theoretical predictions for populations of binary pulsars, while observing a large population of binary pulsars will place ever greater observational constraints on the evolution of these stars.

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DATA AVAILABILITY

The results of this work are available from the authors at reasonable request. This paper used results from the binary population synthesis code COMPAS (v02.19.02) as presented in Willcox et al. (2021). The latest version of COMPAS is publicly available at www.github.com/TeamCOMPAS/COMPAS.

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