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F. A. Rasio and I. H. Stairs

The Galactic Formation Rate of Eccentric Neutron Star – White Dwarf Binaries

V. Kalogera, C. Kim

Northwestern University, Department of Physics and Astronomy, 2145 Sheridan Rd., Evanston, IL, 60201, USA

D. R. Lorimer

University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire, SK11 9DL, UK

M. Ihm, K. Belczynski

Northwestern University, Department of Physics and Astronomy, 2145 Sheridan Rd., Evanston, IL, 60201, USA

Abstract. In this paper we consider the population of eccentric binaries with a neutron star and a white dwarf that has been revealed in our Galaxy in recent years through binary pulsar observations. We apply our statistical analysis method (Kim, Kalogera, & Lorimer 2003) and calculate the Galactic formation rate of these binaries empirically. We then compare our results with rate predictions based on binary population synthesis from various research groups and for various ranges of model input parameters. For our reference model, we find the Galactic formation rate of these eccentric systems to be $\sim 7\ \mathrm{Myr}^{-1}$, about an order of magnitude smaller than results from binary evolution estimations. However, the empirical estimates are calculated with no correction for pulsar beaming, and therefore they should be taken as lower limits. Despite uncertainties that exceed an order of magnitude, there is significant overlap between the various rate estimates. This consistency lends confidence that our current understanding of the formation of these eccentric NS–WD binaries is reasonable.

1. Introduction

Binary pulsars with white dwarf companions (NS–WD binaries) in *eccentric* orbits have been revealed with binary pulsar and optical observations in recent years. This sub-population is considered to be rather special because, based on our standard understanding of binary evolution, NS–WD binaries are expected to be circular: a neutron star forms first from the original binary primary and the white dwarf formation follows mass transfer episodes that are expected to circularize the binary orbit. For a review of this scenario, see Lorimer (2001). The neutron star produced by this evolutionary path is expected to be 'recycled', i.e. spun-up by mass accretion from its companion. However, the existence of eccentric NS–WD binaries such as PSR B2303+46 (Stokes, Taylor, & Dewey

1985; van Kerkwijk & Kulkarni 1999) and PSR J1141−6545 (Kaspi et al. 2000; Bailes et al. 2003) implies that a different evolutionary path from the standard scenario is also be possible (Tutukov & Yungelson 1993; Portegies Zwart & Yungelson 1999; Tauris & Sennels 2000; Nelemans, Yungelson, & Portegies Zwart 2001; Brown et al. 2001; Davies, Ritter, & King 2002). The non-zero eccentricity of the binary orbit is introduced by a supernova (SN) explosion of the secondary companion that occurs after the original primary has already evolved into a white dwarf.

Our motivation for this study is to estimate the Galactic formation rate of eccentric binaries based on the observed pulsars. We apply our statistical analysis developed to estimate the Galactic double-neutron-star (DNS) merger rate (Kim, Kalogera, & Lorimer 2003) and derive a probability density function (PDF) of the Galactic formation rate for eccentric NS–WD binaries. This method provides us with rate estimates that are independent from those obtained using binary evolution calculations. We compare our empirical rate estimates to results from population synthesis calculations and conclude that, despite the large uncertainties, the results are indeed consistent.

2. Formation of Eccentric NS–WD Binaries

In our classical understanding of binary evolution, we expect that the formation process of NS–WD binaries in close orbits involves the circularization of the binary orbit, even for systems with massive white dwarfs: the neutron star forms first and possibly induces an eccentricity, but subsequent mass transfer from the white-dwarf progenitor is expected to circularize the orbit (Verbunt & Phinney 1995). Indeed PSR J0751+1807 (Lundgren, Zepka, & Cordes 1995; Nice, Splaver, & Stairs 2004) and PSR J1757−5322 (Edwards & Bailes 2001) have very small eccentricities ($e \leq 10^{-4}$). However, the discovery of the white dwarf companion to PSR B2303+46 (van Kerkwijk & Kulkarni 1999) led various groups to consider a different evolutionary path that could explain the observed eccentricity of $e = 0.658$ (Portegies Zwart & Yungelson 1999; Tauris & Sennels 2000; Nelemans, Yungelson, & Portegies Zwart 2001; Brown et al. 2001; Davies, Ritter, & King 2002).

In these modified scenarios, the original primary star, which is massive enough to form a white dwarf but not a neutron star, evolves first and transfers its mass to the secondary star. After the primary star loses its envelope it becomes a white dwarf, while the secondary continues its evolution but at a higher mass than its initial mass (high enough to form a neutron star) due to the mass transfer phase from the original primary. The primary eventually fills its Roche lobe and a common envelope phase ensues: the white dwarf and the helium core of the secondary spiral together as the common envelope of the two stars is ejected from the system. The outcome is a tight binary with a white dwarf and a helium star that is massive enough to explode in a supernova. This introduces an eccentricity to the orbit of the NS–WD binary that forms. Hence eccentric NS–WD binaries are formed because of two main facts relevant to the early evolution of the binary progenitor: (1) the initial binary components are both massive enough to form only a white dwarf, but still close to being massive

Table 1. Observational properties of eccentric NS–WD binaries. The columns indicate the pulsar name, spin period P, spin-down rate $\dot{P}$, orbital period P_b, the estimated mass of the WD companion m_c, orbital eccentricity e, characteristic age τ_c, time to reach the death line τ_d.

PSRs	P	$\dot{P}$	$P_{\rm b}$	$m_{\rm c}$	e	$\tau_{\rm c}$	$\tau_{\rm d}$
	(ms)	(s s^{-1})	(hr)	($M_\odot$)		(Myr)	(Gyr)
J1141−6545	393.9	4.29×10^{-15}	4.744	0.986	0.172	1.45	0.104
B2303+46	1066	5.69×10^{-16}	296.2	1.24	0.658	29.7	0.140

enough to form a neutron star; (2) the initial mass transfer phase from the primary to the secondary increases the mass of the secondary enough that it can now form a neutron star eventually, but only after the initial primary ends its evolution as a white dwarf.

3. Empirical NS–WD Formation Rate Estimates

In KKL, we introduced a statistical method to calculate a PDF of the rate estimates for Galactic close DNS systems. This method can be applied to any type of pulsar population of interest.

Here, we consider eccentric NS–WD binaries. In order to calculate their Galactic formation rate $\mathcal{R}_{\rm b}$, we need to estimate: (1) the number $N_{\rm tot}$ of Galactic pulsar populations with pulse and orbital characteristics *similar* to those in the observed sample of eccentric NS–WD (i.e. J1141−6545 or B2303+46); (2) the lifetime $\tau_{\rm life}$ of each observed system; (3) an upward correction factor $f_{\rm b}$ for pulsar beaming.

We calculate $N_{\rm tot}$ by modeling in detail the pulsar survey selection effects associated with the discovery of these systems for a number of parent pulsar population models described in KKL. The model assumptions for the pulsar luminosity function dominate the systematic uncertainties of our overall calculation.

For our reference model (model 6 in KKL), we obtain the most likely value of $N_{\rm tot}$ for PSRs J1141-6545 and B2303+46 to be $N_{1141}\simeq$370 and $N_{2303}\simeq$240, respectively.

The lifetime of the system is defined as $\tau_{\rm life}\equiv\tau_{\rm c}+\tau_{\rm d}$, where $\tau_{\rm c}$ is the characteristic age. $\tau_{\rm d}$ is the time which a pulsar will reach the "death line" (Ruderman & Sutherland 1975). We calculated $\tau_{\rm d}$ following (Chen & Ruderman 1993; eq. (9) in their paper). The calculated PDF of the formation rate is dominated by PSR J1141-6545-like population due to both the shorter lifetime and number abundance of this population (Fig. 1). The estimated formation rate for our reference model is $\mathcal{R}_{\rm b}= 6.8^{+5.6+13.7}_{-3.5-5.6}\,{\rm Myr}^{-1}$ at 68% and 95% confidence limits, respectively. The most likely values of $\mathcal{R}_{\rm b}$ lie in the range $0.5-16\,{\rm Myr}^{-1}$ for all the PSR population models we consider (see Table 2 for the rate estimates for a number of models with different pulsar luminosity functions). In the absence of observational constraints on the geometry of both pulsars, we decided to

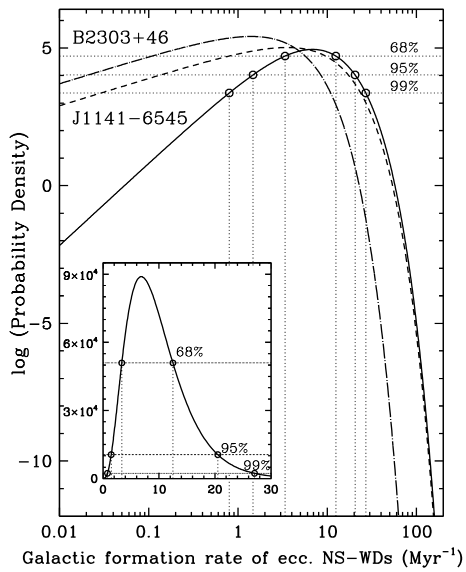

Figure 1. The PDF of Galactic formation rate estimates for eccentric NS–WD binaries (solid line) for our reference model. Dashed and dot-dashed lines represent the individual PDFs of the formation rates for sub-population of binaries similar to either PSR B2303+46 or J1141−6545. No corrections for pulsar beaming have been applied.

not include any such upward correction for pulsar-beaming. Therefore, our estimated rates should be considered as lower limits. We can also compare these estimates with those for the Galactic DNS rate. The most likely values of DNS rates are found in the range $4-224$ Myr^{-1} for the models considered with pulsar beaming correction. (see Kim et al., in this volume; Kalogera et al. 2004). Since the beaming correction factor for young pulsars is presumably larger than those for recycled pulsars, the true Galactic formation rate for eccentric NS–WD binaries is expected to be comparable to that of DNS systems.

Population synthesis calculations have been widely used to study the formation of various types of compact object binaries including eccentric NS–WD binaries. The range of details in the evolutionary calculations as well as the extent (if any) of the parameter studies vary significantly. In this section we summarize the main results from theoretical studies in literature and compare them to the empirical rates derived in the previous section.

Portegies Zwart & Yungelson (1999) obtained a formation rate for eccentric NS–WD binaries comparable, but somewhat larger than that of DNS systems ($\mathcal{R}_{\rm b}$=44 and 34 Myr^{-1} for eccentric NS–WD and DNS systems respectively). Tauris & Sennels (2000) presented similar results ($\mathcal{R}_{\rm b}\sim$ 57 Myr^{-1}) and concluded that the formation rate of eccentric NS–WD binaries is ∼18 times higher than that of DNS systems. Davies, Ritter, & King (2002) estimated the Galactic formation rate of systems like J1141−6545 or B2303+46. They obtained formation rates in the wide range of $\sim 10^{-5}-10^{-3}$ yr^{-1} when considering both J1141−6545−like and B2303+46−like systems with different evolutionary his-

Table 2. The estimated Galactic formation rate and the most likely value of $N_{\rm tot}$ of eccentric NS–WD binaries for models with different pulsar luminosity functions. The model number is the same as in KKL. We show the most likely value of $R_{\rm b}$ at 68% and 95% confidence limits.

Model	$R_{\rm b}$	(Myr^{-1})		N_{1141}	N_{2303}
	peak	68%	95%		
1	2.1	$^{+1.7}_{-1.0}$	$^{+4.0}_{-1.6}$	110	70
6	6.8	$^{+5.6}_{-3.5}$	$^{+13.7}_{-5.4}$	370	240
9	0.7	$^{+0.6}_{-0.4}$	$^{+1.4}_{-0.6}$	40	30
10	2.6	$^{+2.1}_{-1.3}$	$^{+5.1}_{-2.0}$	140	90
12	1.0	$^{+0.8}_{-0.5}$	$^{+1.9}_{-0.8}$	50	40
14	0.5	$^{+0.4}_{-0.2}$	$^{+0.8}_{-0.4}$	20	20
15	15.7	$^{+13.1}_{-8.1}$	$^{+31.9}_{-12.4}$	870	530
17	3.9	$^{+3.3}_{-2.0}$	$^{+8.1}_{-3.1}$	220	130
19	1.1	$^{+0.9}_{-0.6}$	$^{+2.3}_{-0.9}$	60	40
20	8.3	$^{+7.2}_{-4.3}$	$^{+17.7}_{-6.6}$	490	260

tories. Finally, Nelemans, Yungelson, & Portegies Zwart (2001) derived 240 Myr^{-1} for the formation rate of all types of NS–WD binaries, which is comparable to other studies. We consider this rate to be an upper limit of eccentric NS–WD (shown as an open square with a downward arrow in Fig. 2).

In addition to the above results from then literature, we have performed population synthesis calculations using the `StarTrack` population synthesis code (Belczynski, Kalogera, & Bulik 2002; Belczynski et al. 2004). We have explored a selection of models (more than any of the other studies) that promise to give us the widest variations of rate estimates. We derive a range $\sim 30 - 100$ Myr^{-1} (using an absolute normalization of models based on empirical supernova rate estimates for our Galaxy; Cappellaro, Evans, & Turatto 1999).

The different results from various population studies are mainly attributed to varying assumptions about the initial mass function, the initial mass-transfer process, the assumed star-formation or supernova rate used as a normalization factor, the initial binary fraction, and NS kicks. We also note that the lifetime of the system is a free parameter in the theoretical rate estimation, which is attributed to at least an order of magnitude of the uncertainty in the calculation.

4. Comparison with Rates from Binary Evolution

In Figure 2, we overlap the empirical formation rate estimates for eccentric NS–WD binaries (filled circles with error bars labeled by KKL) with previous studies (open squares and a thick solid line labeled by N01: Nelemans, Yungelson, & Portegies Zwart 2001; TS00: Tauris & Sennels 2000; PZY99: Portegies Zwart & Yungelson 1999; and D02: Davies, Ritter, & King 2002), as well as results from `StarTrack` (thin solid lines with filled triangles). It is encouraging that the overall rate estimates from different methods appear to be consistent with one

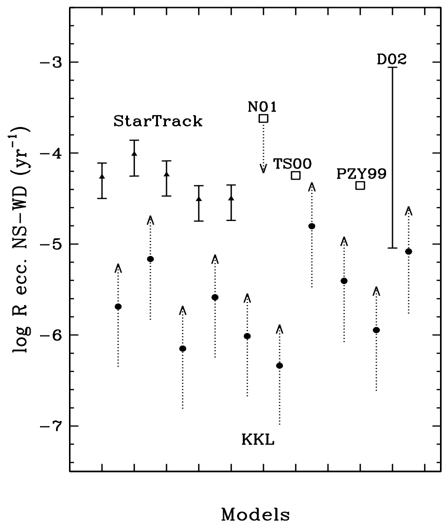

Figure 2. Comparison between the empirical and theoretical rate estimates. Error bars with filled triangles indicate results from `StarTrack`, open squares and a solid line are adapted from the literature, and filled circles with error bars are obtained in this work (see text for details).

another. If we consider the most likely values of the empirical rate estimates (filled circles), they are somewhat smaller than the theoretical values. However, within a 95% confidence interval, the empirical and theoretical estimates become comparable. We also emphasize that the upward correction for pulsar beaming has not been applied, and therefore the empirical rate estimates should be considered as lower limits.

In conclusion, we find that our empirical estimates for the Galactic formation rate of eccentric NS–WD binaries are overall consistent with the estimates derived from binary population synthesis models. Despite the large uncertainties we consider this consistency as evidence that our current theoretical understanding for the formation of eccentric NS–WD is reasonable. However, the extent of the range covered by the empirical estimates and the population synthesis studies that attempt at least a minimal parameter study (e.g., Davies, Ritter, & King 2002, and our results from `StarTrack`) indicates once again the necessity for careful parameter studies of rate calculations. It also indicates that the empirical rates could in principle be used to constrain binary evolution calculations.

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