Accretion induced collapse of white dwarfs in binary systems and their observational properties

D T Wickramasinghe\textsuperscript{1}, Jarrod R Hurley\textsuperscript{2}, Lilia Ferrario\textsuperscript{1},
Christopher A Tout\textsuperscript{3} and Paul D Kiel\textsuperscript{2}

\textsuperscript{1} Mathematical Sciences Institute, The Australian National University, Canberra, Australia
\textsuperscript{2} Centre for Astrophysics and Supercomputing, Swinburne University of Technology, P.O. Box 218, VIC 3122, Australia
\textsuperscript{3} Institute of Astronomy, Cambridge, UK

E-mail: jhurley@swin.edu.au

Abstract. Neutron stars can form through core collapse (CC) following a supernova explosion of a massive star, or from a white dwarf that first forms in a binary system and then collapses into a neutron star via accretion induced collapse (AIC). So far, there have been no unambiguous identifications of AIC neutron stars in our Galaxy, although it has been suspected that they may exist among the population of binary millisecond pulsars (BMSPs). We summarise results of new calculations on the expected birth rates of binary systems with AIC neutron stars and discuss the predicted orbital period of systems with He, CO and O-Ne-Mg white dwarfs and main sequence companions. We argue that AIC systems may make an important contribution to the observed population of BMSPs.

1. Introduction

The BMSPs have neutron stars with magnetic fields of $10^8 - 10^9$ G, much smaller than the fields of $10^{11} - 10^{13}$ G found in the bulk of isolated radio pulsars. The origin of the low fields has been the subject of much debate.

One view is that the neutron stars in the BMSPs have formed from the core collapse (CC) of a massive star with fields of $\sim 10^{11} - 10^{13}$ G that are essentially of crustal origin. The crustal field decays by 5 orders of magnitude in response to accretion (Konar and Bhattacharya 1997), and the neutron star spins-up maintaining spin equilibrium with the inner edge of the disc which recedes towards the neutron star. During these phases, the system is seen as a low mass or an intermediate mass X-ray binary (LMXB/IMXB). At the end of the accretion disc phase, the rapidly spinning and low field neutron star emits radio emission and is seen as a BMSPS.

Another often discussed channel for the production of BMSPs involves the accretion induced collapse (AIC) of a white dwarf (Michel 1987). Here, during the course of mass transfer, a white dwarf reaches the Chandrasekhar limit, and collapses to form a neutron star (Bhattacharya and Van den Heuvel 1991). An AIC is the expected outcome of thermal time scale mass transfer in a binary system with orbital periods ($P_{\text{orb}}$) of a few days if accretion occurs onto an O-Ne-Mg white dwarf (e.g. Ivanova and Taam 2004).

In the AIC scenario, we may expect the magnetic field distribution of the BMSPs to reflect in some way the magnetic field distribution of their progenitor white dwarfs. Here, the results of recent studies of the magnetic field distribution in white dwarfs may be relevant. There is now
good evidence that the white dwarf field distribution is bi-modal with a high field component (HFMWD: \( B \sim 10^6 - 10^9 \) G) that peaks at \( 3 \times 10^7 \) G comprising some \( 12 - 15\% \) of the white dwarf population, and a low field component (LFMWD: \( B \sim 10^3 - 10^5 \) G) that extends down to at least the current limit of detectability (\( \sim 10^4 \) G) comprising \( \sim 15\% \) of the white dwarf population (Jordan et al. 2007). The implication for the AIC scenario is that magnetic white dwarfs that are massive enough to undergo collapse by mass accretion could potentially lead to a group of rapidly spinning neutron stars with fields amplified to neutron star values.

The role played by accretion in modifying field strength and structure is still under debate. The competition between the advection of the field due to accretion of un-magnetised material, and the decay of the field due to Ohmic dissipation has been discussed by many investigators both in the context of neutron stars (Bisnovatyi-Kogan and Komberg 1974; Urpin and Geppert 1995; Cumming, Zweibel and Bilsden 2001), and white dwarfs (Cumming 2002) on the assumption of spherical accretion. The complications introduced by non-spherical accretion have been discussed more recently by Zhang and Kojima (2006) and Payne and Melatos (2007).

In the field evolutionary scenario discussed by Cumming (2002) for the magnetic cataclysmic variables, the fields in intermediate polars are screened during the accretion disc phase, and re-emerge to pre-screened AM Her type fields when accretion ceases in the period gap. The field decay is minimal. In the CC scenario for the BMSPs the fields in the neutron stars are assumed to decay by five orders of magnitude, and reach an asymptotic value as the current carrying regions in the crust are pushed towards regions of higher conductivity by the accretion flow (Konar and Bhattacharya 1997). In the AIC scenario, a decay of the field may or may not be necessary depending on whether the white dwarf that collapses belongs to the high field or low field group of magnetic white dwarfs.

In this paper, we present a comparative study of the population properties of binary systems that contain neutron stars that form from CC and AIC extending previous similar studies that have focussed exclusively on the CC route. We show that the different routes predict different relative populations of neutron stars with main sequence, He, CO, O Ne Mg white dwarfs, different orbital period distributions, and total birth rates which can potentially be used to distinguish between the different scenarios. We show that it may be possible to have a scenario in which the bulk of the observed BMSPs come form the accretion induced collapse of white dwarfs with different implications for field evolution and decay in accreting compact stars.

2. Models and Results
We have carried out a population synthesis study that allows for the formation of neutron stars by both the core collapse (CC) and the accretion induced collapse (AIC) routes. The model is based on the the rapid binary star evolution (BSE) code constructed by Hurley et al. (2002). The model allows for tidal interactions (circularization and synchroniztion), supernova kicks, angular momentum loss by gravitational radiation and magnetic braking, mass transfer on nuclear, thermal and dynamical timescales and via winds and covers all aspects of the evolution of stars from the main-sequence up to and including the remnant stages. The details of our calculations will be presented elsewhere (Hurley et al. 2009). Here, we present results for our standard model which has small kicks for AIC neutron stars (dispersion of 20 km s\(^{-1}\)), imposes the Eddington limit for accretion, and uses the reduced helium star wind from Kiel and Hurley (2006).

The evolution of CC systems has been discussed by Podsiadlowski, Rappaport and Pfahl (2002). The period evolution bifurcates into two branches at an orbital period of \( \sim 1 \) d (the bifurcation period). If the secondary star is less massive than \( \sim 2 M_\odot \), the system evolves towards shorter orbital periods after the bifurcation period driven by magnetic braking and gravitational radiation. On the other hand, systems with more massive secondaries evolve to longer orbital periods driven by thermal time scale evolution. The systems in the former group
Table 1. Birth rates of the different types of binary system.

|       | BMSP          | BMSP(observable) | LMXB (observable) |
|-------|---------------|------------------|-------------------|
| AIC NS|               |                  |                   |
| all   | 3.5548E-04    | 1.4757E-04       | 2.3968E-04        |
| MS    | 9.7418E-07    | 0.0000E+00       | 9.7418E-07        |
| WD    | 2.0631E-04    | 1.4399E-04       | 6.2320E-05        |
| CC NS |               |                  |                   |
| all   | 5.2864E-05    | 1.2813E-05       | 5.2864E-05        |
| MS    | 8.8235E-06    | 0.0000E+00       | 8.8235E-06        |
| WD    | 2.2716E-05    | 1.1884E-05       | 2.2716E-05        |

have short periods and low mass He WD, CO WD or O-Ne-Mg WD companions at the end of their orbital evolution. Those in the latter group have long orbital periods at the end of their evolution and have He WD companions.

In the AIC route, the primary star is less massive and therefore first evolves into a white dwarf and then subsequently collapses into a neutron star due to accretion. The orbital evolution bifurcates into two routes as with the CC route so both routes predict binary systems of the same type, but with different orbital period distributions and in different proportions. The model also predicts a significant class of extremely short period ($P_{orb} \sim 2 \times 10^{-4} - 10^{-2}$ days binaries with low mass He WD, CO WD and O-Ne-Mg WD companions). These are systems that have been through two phases of common envelope evolution (see Hurley et al. 2009).

We show in Figure 1 the period distributions predicted by our calculations of systems that result from the CC and AIC routes that are detached and observable as BMSPs. Both routes predict a broad peak centered at $P_{orb} \sim 10$ d roughly as observed. These are systems that have evolved towards longer periods and with He WD companions. The secondary peak at $P_{orb} \sim 100$ d is only weakly present in the AIC route and even less so in the CC route. A similar discrepancy was found by Podsiadlowski et al. (2002). This suggests inadequacies in current treatments of binary stellar evolution that determine the bifurcation period. The birth rates of the different types of binary system arising from the two routes are summarised in Table 1, where we have also given the rates of systems potentially observable as BMSPs. The AIC route has a birth rate that is $\sim 10$ times higher for systems with WD companions suggesting that this route makes the dominant contribution to the observed BMSP population. On the other hand, the birth rate of systems with MS companions is significantly higher for the CC route compared to the AIC route. The CC route is therefore likely to be the major contributor to LMXBs.

3. Discussion and Conclusions
We have explored the possibility that neutron stars that result from the accretion induced collapse (AIC) of a white dwarf may play a role in explaining the BMSPs. Our calculations have shown that both the CC and AIC routes result in populations of binary systems that can be identified with LMXB/IMXBs while transferring matter, and BMSPs at the end of an accretion phase. Furthermore, both routes predict binary systems with MS, He WD, CO WD, O-Ne-Mg WD companions, albeit in different relative proportions.

If we focus on BMSPs with WD companions, which is the dominant group in the observed sample, our results indicate birth rates that are $\sim 10$ times higher for BMSPs that come from the AIC route. On the other hand, if we focus on LMXBs with main sequence companions, we find birth rates that are 10 times larger for the CC route. Both routes make a contribution to the observed population of ultra compact LMXBs.

For BMSPs that come from the AIC route, the fields would primarily be a consequence of the white dwarf ancestry of the neutron star. The field in such a neutron star at birth is
essentially the field that would have resided in the core of the white dwarf that is compressed by the collapse. White dwarfs massive enough for AIC in the low and high field groups will lead to neutron stars with fields of $10^8 - 10^{10}$ G and $10^{10} - 10^{15}$ G respectively. Depending on which group dominates, field decay may or may not be necessary to explain the origin of the BMSPs.

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