Direct formation of millisecond pulsars from rotationally delayed accretion-induced collapse of massive white dwarfs

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ABSTRACT
Millisecond pulsars (MSPs) are believed to be old neutron stars, formed via Type Ib/c core-collapse supernovae, which have subsequently been spun up to high rotation rates via accretion from a companion star in a highly circularized low-mass X-ray binary. The recent discoveries of Galactic field binary MSPs in eccentric orbits, and mass functions compatible with that expected for helium white dwarf companions, PSR J2234+06 and PSR J1946+3417, therefore challenge this picture. Here, we present a hypothesis for producing this new class of systems, where the MSPs are formed directly from a rotationally delayed accretion-induced collapse of a super-Chandrasekhar mass white dwarf. We compute the orbital properties of the MSPs formed in such events and demonstrate that our hypothesis can reproduce the observed eccentricities, masses and orbital periods of the white dwarfs, as well as forecasting the pulsar masses and velocities. Finally, we compare this hypothesis to a triple-star scenario.

Key words: stars: neutron – pulsars: general – stars: rotation – supernovae: general – white dwarfs – X-rays: binaries.

1 INTRODUCTION

Almost since the discovery of PSR B1937+21, the first millisecond pulsar (MSP; Backer et al. 1982), it has been suggested that these objects are old neutron stars spun up to high spin frequencies of several hundred Hz via accretion of mass and angular momentum from a companion star (Alpar et al. 1982; Bhattacharya & van den Heuvel 1991). In this so-called recycling phase, the system is first observable as a low-mass X-ray binary (LMXB, e.g. Bildsten et al. 1997), later as an accreting X-ray MSP (Wijnands & van der Klis 1998), or even as an MSP in the transition phase between an accretion powered MSP and a rotation powered radio MSP (Archibald et al. 2009; Tauris 2012; Papitto et al. 2013).

An inevitable consequence of a long phase (107–108 yr) of recycling in an LMXB, where tidal forces operate, is that it should leave a fossil record of a highly circular system (Phinney & Kulkarni 1994). And indeed, until recently, all of the more than 100 observed, fully recycled MSPs (here defined as pulsars with spin periods less than 20 ms), in binaries with helium white dwarf (He WD) companions and located outside of globular clusters, have very small eccentricities in the range \( e \approx 10^{-7} \)–10−3 (ATNF Pulsar Catalogue; Manchester et al. 2005). Pulsar systems in globular clusters, on the other hand, often have their orbits perturbed after the recycling phase terminates because of their location in a dense environment (Rasio & Heggie 1995; Heggie & Rasio 1996). Until the start of 2013, the only known fully recycled MSP with a high eccentricity, and located in the Galactic field, was PSR J1903+0327 (\( e \approx 0.44 \); Champion et al. 2008). This MSP has a G-type main-sequence companion star and is thought to have originated from a hierarchical triple system that ejected one of its members (Freire et al. 2011; Portegies Zwart et al. 2011; Pijloof, Caputo & Portegies Zwart 2012).

1.1 Discovery of MSPs in eccentric orbits
Recently, Deneva et al. (2013) presented the discovery of PSR J2234+06 and soon afterwards Barr et al. (2013) announced the discovery of PSR J1946+3417. PSR J2234+06 and PSR J1946+3417 are of special interest because they resemble each other and share very unusual properties. Both of these Galactic field pulsars (see Table 1) have a spin period, \( P \approx 3 \) ms, an orbital period, \( P_{\text{orb}} \approx 30 \) d and a companion mass, \( M_2 \approx 0.24 \) M⊙. All these values are within typical ranges expected for MSPs with He WD companions. However, both of these MSP binaries are also eccentric, \( e \approx 0.13 \), which is unusual and unexpected from current formation theories of MSPs, as explained above. Therefore, it is clear that these system must have a formation history which is different from the ‘normal’ MSP-WD systems in the Galactic field.

We notice that the two median expectations for the companion masses of PSR J2234+06 and PSR J1946+3417 are very similar to each other and fairly close to the values expected from the correlation between WD mass and orbital period for post-LMXB systems (e.g. Tauris & Savonije 1999); if the unknown orbital inclination...
angle and the slight widening of the orbit from the event that imparted the eccentricity is accounted for, see Section 3. This provides confidence that the current companions are indeed He WDs which have lost their hydrogen envelopes via stable Roche lobe overflow (RLO). Optical detections would confirm this.

### 1.2 A triple-system formation scenario?

By analogy with PSR J1903+0327, one could advance the hypothesis that both PSRs J2234+06 and J1946+3417 originated as hierarchical triple systems, which evolved into a neutron star orbited by two F/G-type dwarfs. Because of the widening of the inner orbit during the subsequent neutron star accretion in the LMXB phase, the systems later became dynamically unstable (e.g. Mikkola 2008) and one of the components was eventually ejected. The only difference being that it was the donor star (the WD progenitor) in the inner binary which was ejected in the case of PSR J1903+0327 (Freire et al. 2011; Portegies Zwart et al. 2011; Pijlou et al. 2012), whereas it would have been the outer tertiary star in the cases of PSR J2234+06 and PSR J1946+3417. In a triple system, the Kozai process (Kozai 1962) may lead to large cyclic variations in the inner orbital eccentricity prior to ejection of the tertiary star (e.g. Mardling & Aarseth 2001). Hence, one may expect a wide range of eccentricities of the surviving MSP-WD binaries. Whether or not triple-star evolution, or formation and ejection of a binary system from a dense cluster, is plausible for the relatively small eccentricities (e ≈ 0.13) observed in PSRs J2234+06 and J1946+3417 (compared to e = 0.44 for PSR J1903+0327) requires detailed modelling beyond the scope of this Letter.

Here, we advocate for another solution. In Section 2, we present a hypothesis of a new direct formation channel of MSPs which can exactly explain both the unusual properties and the similarities of the recently discovered MSPs. In Section 3, we present simulations and make further falsifiable predictions about these systems which can be tested in the near future. In Section 4, we discuss future perspectives and we summarize our conclusions in Section 5.

### 2 DIRECT FORMATION OF MSPs VIA DELAYED AIC

Besides from formation via core-collapse supernovae (SNe), it has been suggested for many years that neutron stars may also be produced from accretion-induced collapse (AIC) of a massive oxygen–neon–magnesium white dwarf (ONeMg WD) in a close binary (Nomoto et al. 1979; Taam & van den Heuvel 1986). The properties of such neutron stars are unknown. It has been suggested that AIC events cannot produce MSPs directly since r-mode instabilities would spin down any young, hot MSP on a very short time-scale (Andersson, Kokkotas & Schutz 1999). However, if the scenario described here is confirmed by further observations, then the role of r-mode instabilities has to be revised.

In the following, we rely on the results of the recent modelling by Tauris et al. (2013). They investigated a scenario where MSPs are produced indirectly via AIC, i.e. the AIC leaves behind a normal neutron star which is subsequently recycled to become an MSP, once the mass-transfer resumes after the donor star refills its Roche lobe and continues LMXB evolution until the end. Their main result is that as a consequence of the fine-tuned mass-transfer rate necessary to make the WD grow in mass, the resultant MSPs created via the AIC channel preferentially form with 10 < P_\text{orb} < 60 d, clustering more at P_\text{orb} ≈ 20–40 d. Furthermore, the modelling of these systems produced He WD companions with masses, M_\text{WD} ≳ 0.24–0.31 M_\odot. These values are interesting since they match exactly the observed values of P_\text{orb} and M_\text{WD} for the newly discovered MSPs in eccentric orbits (Table 1). However, in the Tauris et al. (2013) scenario of indirect formation of MSPs, continued post-AIC mass transfer leads to highly circularized systems. Therefore, that scenario cannot explain the newly discovered MSPs with e ≲ 0.1.

### 2.1 Rotationally delayed accretion-induced collapse (RD-AIC)

In case a mass-gaining WD is spun up to rapid rotation via near-Keplerian disc accretion (Langer et al. 2000), it can avoid AIC (Yoon & Langer 2004, 2005) and evolve further to super-Chandrasekhar mass values via continuous accretion (cf. fig. 7 in Tauris et al. 2013, for the possible growth up to ≳ 2 M_\odot).

Here, we propose a scenario, where accretion leads to the formation of a super-Chandrasekhar mass ONeMg WD which initially avoids AIC as a result of rapid rotation. Only after the accretion has terminated, and the WD loses sufficient spin angular momentum (see below), does it undergo AIC to directly produce an MSP. We shall refer to this event as rotationally delayed accretion-induced collapse (RD-AIC), see Fig. 1.

It is important to notice that under the new hypothesis presented here, accretion ceases completely before AIC occurs. At that stage, the detached system consists of two WDs: a low-mass He WD (the
2.1.1 Observational and theoretical support for RD-AIC

Observations of binaries confirm that accreting WDs rotate much faster than isolated ones (Sion 1999); in one case, HD 49798/RX J0648, there is even evidence for a WD rotating with a spin period of only \( P_{\text{WD}} = 13.2 \) s (Mereghetti et al. 2011), corresponding to \( \sim 50 \) per cent of its critical (break-up) rotation frequency. The observational evidence for such fast rotation supports the increase of the mass stability limit above the standard value for non-rotating WDs (1.37 \( M_\odot \)), as required by our scenario. An analogous idea of rotationally delayed Type Ia supernova (SN Ia) explosions has been proposed by Justham (2011) and Di Stefano, Voss & Claeys (2004) for massive CO WDs.

For WDs with rigid body rotation, the resulting super-Chandrasekhar masses are in the range 1.37–1.48 \( M_\odot \) (Yoon & Langer 2004, and references therein). For differentially rotating WDs, the stability limit may in principle reach \( \sim 4.0 \) \( M_\odot \), although it is quite possible that efficient transport of angular momentum by magnetic torques and/or baroclinic instabilities acts to ensure rigid rotation (Piro 2008). On the other hand, recent observations of exceptionally luminous SNe Ia (e.g. Howell et al. 2006; Scalzo et al. 2010) suggest that their WD progenitors had a mass of \( \sim 2.0–2.5 \) \( M_\odot \). If the critical rotation frequency is obtained during accretion, then further mass accumulation is prohibited, unless angular momentum is transported from the WD back to the disc by viscous effects (Popham & Narayan 1991; Saio & Nomoto 2004).

The final fate of super-Chandrasekhar ONeMg WDs depends on whether or not the effects of electron captures dominate over nuclear burning (Nomoto et al. 1979; Nomoto & Kondo 1991). The onset of electron captures on \( ^{24}\text{Mg} \) and \( ^{20}\text{Ne} \) occurs at a density of \( \rho \approx 4 \times 10^4 \text{ g cm}^{-3} \), whereas the density for the ignition of explosive nuclear burning (oxygen deflagration) depends on the central temperature. Therefore, after accretion has terminated, the final fate of a super-Chandrasekhar WD depends on the competition between its cooling rate and its loss of angular momentum, as demonstrated in detail by Yoon & Langer (2004, 2005). If the WD interior has crystalized by the time its spin angular momentum decreases below the critical level (corresponding to \( J_{\text{crit}} \approx 0.4 \times 10^{30} \text{ erg s} \), for a 1.48 \( M_\odot \) WD), it undergoes RD-AIC.

Yoon & Langer (2004, 2005) discussed the loss of WD spin angular momentum due to gravitational wave emission caused by so-called CFS instabilities to non-axisymmetric perturbations. In their second paper, these authors investigated 2D models and found that only r-mode instabilities (Andersson 1998) are relevant for accreting WDs, whereas bar-mode instabilities (Chandrasekhar 1970; Friedman & Schutz 1978) are irrelevant because the ratio of rotational to potential energy cannot reach the critical limit of \( T/W = 0.14 \) (corresponding to \( J = 4 \times 10^{30} \text{ erg s} \)). The estimated time-scale of removing (or redistributing) angular momentum has been estimated to be in the range \( 10^5–10^9 \) yr, depending on \( T/W \) and the degree of differential rotation of the WD (Lindblom 1999; Yoon & Langer 2004, 2005). However, recent work by Ilk& Soker (2012) questions the efficiency of r-mode instabilities, and hence, they advocate for a very long delay time-scale >1 Gyr. This would give the super-Chandrasekhar mass WD plenty of time to cool down, crystallize and undergo RD-AIC, thus favouring our scenario.

![Figure 2](https://academic.oup.com/mnrasl/article-abstract/438/1/L86/1008436)

To summarize, we postulate that MSPs can be formed directly (without any need for further spin-up from a companion star) in an RD-AIC event that happens up to \( \sim 1 \) Gyr after termination of the mass-transfer phase.

In Fig. 2, we show an evolutionary track of a rapidly spinning WD undergoing RD-AIC (see fig. 11 in Yoon & Langer 2005, for more detailed tracks). The WD is assumed to be non-spinning initially and has a mass of 1.2 \( M_\odot \) prior to accretion from its companion star. We assumed rigid rotation and efficient angular momentum accretion at the Keplerian disc value. The r-mode instabilities (giving rise to loss of rotational energy via gravitational waves) were calculated during accretion following Lindblom (1999). If the time-scale of loss of spin angular momentum, from the termination of the accretion phase until the WD has a spin angular momentum, \( J < J_{\text{crit}} \), is sufficiently long (\( \sim 10^9 \) yr), then the result is an AIC event (Yoon & Langer 2005).

3 PROPERTIES OF THE RD-AIC EVENTS AND RESULTANT MSP-WD SYSTEMS

The implosion of a WD with a radius of about 3000 km and an assumed surface magnetic flux density, \( B \sim 10^8 \) G (e.g. Jordan et al. 2007) into a neutron star with a radius of \( \sim 10 \) km should produce, by conservation of magnetic flux, an MSP surface B-field of \( 10^9 \) G \( \times (3000/10)^2 \times 10^6 \) G. The resultant neutron star must have a spin-rate below the break-up limit and for a typical MSP spin period of a few ms, it is expected that it must lose spin angular momentum during the AIC, possibly by ejection of a few 0.01 \( M_\odot \) of baryonic matter in a circumstellar disc. According to modelling by Dessart et al. (2006), Kitaura, Janka & Hillebrandt (2006), Metzger, Piro & Quataert (2009), Darbha et al. (2010), up to a few 0.01 \( M_\odot \) of material is ejected in the AIC event, possibly leading to synthesis of \( ^{56}\text{Ni} \) in the disc which may result in a radioactively powered, short-lived SN-like transient (that peaks within \( \lesssim 1 \) d and with a bolometric luminosity \( \sim 10^{41} \text{ erg s}^{-1} \)).
The RD-AIC hypothesis makes several very precise, easily falsifiable predictions:

(i) As already mentioned, the He WD companions in our RD-AIC scenario are expected to have masses in the range $M_2 \simeq 0.24$–0.31 $M_\odot$ (up to 0.35 $M_\odot$ for low-metallicity WD progenitors) and orbital periods of 10–60 d. In rare cases, we expect WD masses up to $\sim 0.41 M_\odot$, if the donor star had a zero-age main sequence (ZAMS) mass $> 2.3 M_\odot$ (Tauris et al. 2013).

(ii) The binding energy of a neutron star can be expressed as: $E_b \simeq 0.084 (M_{\text{NS}}/M_\odot)^2 M_\odot c^2$ (Lattimer & Yahil 1989), where $M_{\text{NS}}$ is its gravitational mass. The collapse of super- Chandrasekhar mass WDs of $1.37$–$1.48 M_\odot$ (for rigid rotation) therefore leads to MSPs with gravitational masses of $1.22$–$1.31 M_\odot$, if we assume that $0.02 M_\odot$ of baryonic material is lost during the AIC.

(iii) The sudden release of gravitational binding energy (and mass ejection into a disc) increases the orbital period and imposes an eccentricity to the system given by (Bhattacharya & van den Heuvel 1991) $\epsilon = \Delta M/(M_{\text{NS}} + M_2)$, if the AIC is symmetric and no kick is imparted to the newborn MSP (see below). Here, we assume that the pre-AIC binary orbit is circular, which is a good assumption for LMXBs were tidal torques circularize the system on a short time-scale. For the ranges of $M_{\text{NS}}$ and $M_2$ given above, this leads to a remarkable narrow range of post-AIC eccentricities: $0.09$–$0.12$. (The exact values depend on the still unknown equation of state of neutron stars.) This result is in excellent agreement with the systems presented in Table 1, cf. Section 3.1 for a discussion.

(iv) The momentum kick imparted to a newborn neutron star via an AIC event is expected to be small. This follows from detailed simulations of AIC events which imply explosion energies significantly smaller than those inferred for standard iron-core collapse SNe (Dessart et al. 2006; Kitaura et al. 2006), and also because of the small ejecta mass and the short time-scale of the event (compared to the time-scales of the non-radial hydrodynamic instabilities producing large kicks), e.g. Podsiadlowski et al. (2004); Janka (2012). Our hypothesis therefore predicts that eccentric binary MSPs with He WDs will have small peculiar space velocities.

3.1 Simulations of the $(P_{\text{orb}}, \epsilon)$ plane

The spread of eccentricities and orbital periods of the resultant systems formed via RD-AIC is extremely sensitive to any kick given to the MSP during the AIC event. In Fig. 3, we demonstrate this by showing a Monte Carlo simulation of the expected eccentricities and orbital periods using the range of pre-AIC parameters given above and adding small kick velocities of $w \leq 10 \text{ km s}^{-1}$. The dynamical effects were calculated following the formulae of Hills (1983). The properties of systems undergoing RD-AIC events are seen to be surprisingly similar to the characteristics of the recently discovered MSPs in eccentric orbits (Table 1).

4 FUTURE PERSPECTIVES AND TESTS

If the WD companions happen to be bright, then a study of their spectral lines will yield the mass ratio of the binary components, $q$. Furthermore, given the eccentric orbits of these MSPs, we will certainly be able to measure the rate of advance of periastron ($\dot{\omega}$) for these systems. If the radius of the companion is small compared to the size of the orbit (which is the case for a WD), then $\dot{\omega}$ is solely due to the effects of general relativity and can be used to estimate the total mass of the system (Weisberg & Taylor 1981). The combination of $\dot{\omega}$ and $q$ would be enough to determine the masses of the components. Another possible solution is the measurement of the Shapiro delay for these systems. Even a relatively low-precision measurement of $\dot{\omega}_1$ (Freire & Wex 2010) can, when combined with the measurement of $\dot{\omega}_2$, yield very precise component masses, as in the cases of PSR J1903+0327 (Freire et al. 2011) and PSR J1807$-$2500B (Lynch et al. 2012). These mass measurements are very important for testing the RD-AIC hypothesis, which predicts MSP masses between $1.22$ and $1.31 M_\odot$. Measuring a higher MSP mass would, if not falsifying our hypothesis, require differential rotation of the progenitor WD, which may be a problem with respect to the need of a long delay time-scale (Iklov & Sokol 2012).

The unusual MSPs discussed in this Letter were discovered in recent pulsar surveys (e.g. Cordes et al. 2006; Barr et al. 2013; Deneva et al. 2013) with high time and frequency resolution that have greatly increased the number of known MSPs, revealing new rare pulsar populations. If on-going and future surveys detect many eccentric MSPs with WD companions with $\epsilon \sim 0.1$ and $P_{\text{orb}} = 10$–60 d, this would not only support our RD-AIC hypothesis; it would also imply that AIC events do not produce kicks (or at least $w \leq 5 \text{ km s}^{-1}$, cf. Fig. 3) and that WDs rotate rigidly. Furthermore, it would imply that $r$-mode instabilities do not necessarily slow down young, hot MSPs, as previously suggested (Andersson et al. 1999).

Note, there may also be eccentric MSPs with WDs formed via the triple scenario outlined in Section 1.2, which will have a much wider distribution in the $(P_{\text{orb}}, \epsilon)$ plane and possibly more massive companions. Detection of an MSP with a main-sequence companion and $\epsilon \sim 0.1$ would support a triple-star scenario for the formation of MSPs with $\epsilon \sim 0.1$, and thus significantly weaken the need for our RD-AIC hypothesis.

Population synthesis investigations of MSP formation via AIC have been performed by Hurley et al. (2010) and Chen et al. (2011). The former study concluded that, in general, the AIC channel to
MSP formation is important. The latter study investigated direct MSP formation via AIC and concluded that the probability of forming eccentric MSPs can be ruled out (even using high kicks they could not produce eccentric MSPs with $P_{\text{orb}} \geq 20\,\text{d}$), in contradiction with the new discoveries, cf. Table 1. We recommend new population synthesis modelling using our RD-AIC scenario in order to probe more carefully the expected number of such eccentric MSP systems to be detected, and for the statistics of their resulting parameter space. Ideally, the triple-system scenario should be modelled for comparison as well.

Finally, it should be investigated under which circumstances a binary evolves via RD-AIC or follows the Tauris et al. (2013) path. The latter was calculated using a point mass accreting WD which did not allow for detailed spin angular momentum modelling. For the resulting MSPs with He WD companions, the values of $P_{\text{orb}}$ and $M_2$ are expected to be roughly similar. The RD-AIC scenario, however, produces eccentric systems.

5 SUMMARY

The common scenario for the formation of MSPs via recycling in LMXBs is well established with plenty of observational evidence, as discussed in Section 1. The RD-AIC hypothesis presented in this Letter provides an additional formation channel of MSPs that makes very specific predictions about future discoveries and the existence of a separate population of eccentric MSPs. If this hypothesis is confirmed by future observations, it would also have interesting consequences for better understanding the direct AIC channel to produce MSPs, i.e. with respect to WD progenitor masses, (absence of) momentum kicks in AIC and possibly even constraining neutron star equations-of-state given that the post-AIC eccentricities depend on the released gravitational binding energy.

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