Probing the accretion induced collapse of white dwarfs in millisecond pulsars

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Abstract. This paper investigates the progenitors of Millisecond Pulsars (MSPs) with a distribution of long orbital periods (\(P_{\text{orb}} > 2\) d), to show the link between white dwarf (WD) binaries and long orbits for some binary MSPs through the Accretion Induced Collapse (AIC) of a WD. For this purpose, a model is presented to turn binary MSPs into wide binaries and highly circular orbits (\(e < 0.1\)) through the asymmetric kick imparted to the pulsar during the AIC process, which may indicate a sizeable kick velocity along the rotation of the proto-neutron star. The results show the effects of shock wave, binding energy, and mass loss (0.2\(M_\odot\)). The model shows the pulsar systems are relevant to AIC-candidates.

1. Introduction

A number of channels of Millisecond Pulsars (MSPs) formation have been discussed [1–3]. The Recycling process is usually considered as a standard model to produce MSPs. An old and quiescent Neutron Stars (NSs) is spun up to millisecond periods, through the accretion of matter from a companion when the system is in the low-mass X-ray binary (LMXB) phase of its evolution [4, 5]. Another often discussed theory involves the Accretion Induced Collapse (AIC) of an O-Ne-Mg white dwarf (WD) in binaries [6–10], which can indicate that (1) the WD is massive enough to be an O-Ne-Mg one, and thus in principle may be able to collapse to an NS (e.g. Cal 83 \(\sim 1.3M_\odot\) and RX J0648.04418 \(\sim 1.28M_\odot\)), and (2) the mass transfer rate is large enough to make the WD grow -by considering the critical value (\(\Delta M_{\text{crit}} \sim 0.1M_\odot - 0.2M_\odot\)) [11], because at low accretion rates Nova explosions and a WD will not grow. But to make a Type Ia SNe (a thermonuclear explosion of a CO WD that has grown to the Chandrasekhar limit), the WD needs to grow, so it needs a high accretion rate, such that steady nuclear burning on the surface ensues and the WD grows [12]. The time lines for the two routes of MSP evolutions, recycling and AIC, are depicted in figure 1.

2. Estimation of the new orbital period

The relation between the orbital eccentricity and the amount of mass \(\Delta M_{\text{SNe}}\) ejected in the SNe is

\[ e = \frac{\Delta M_{\text{SNe}}}{M_1 + M_2}, \tag{1} \]

where \(M_1\) and \(M_2\) are the masses of the first- and the second-born NSs.
Figure 1. The flow-chart illustrates various evolutionary scenarios for MSPs involving recycling and AIC.

According to the energy conservation law [13]

\[
\frac{GM}{R_{WD}} - \frac{GM}{L} = \frac{1}{2}[v_{\text{final}}^2 - v_{\text{initial}}^2],
\]

(2)

where \( G \) is the gravitational constant, \( M \) the mass companion, \( R_{WD} \) the WD radius, \( L \) the distance between the companions, \( v_{\text{initial}} \) the initial explosion velocity for the WD (it has been supposed that the \( v_{\text{initial}} \sim 0.1c \) [14], and \( v_{\text{final}} \) the velocity when the companion received the material on the surface; because the SNe ejecta may either directly strip material from the companion by direct transfer of momentum or evaporate the envelope through the conversion of the blast kinetic energy into internal heat [15]. It has been assumed that the amount of ejected mass during the explosion process by a WD is \( 0.1 M_\odot \).

\[
\Delta M_{\text{SNe}} = \frac{R^2}{L^2} \times 0.1 M_\odot.
\]

(3)

During the SNe, the WD will eject matter in every direction, so \( \Delta M_{\text{SNe}} \) is the amount of mass received by the companion (accreted material) and \( R \) is the radius of the companion. When \( L \gg R_{WD} \), after some calculations, equation (2) will be

\[
\frac{R_S c^2}{2R_{WD}} = 10^{-4} c^2,
\]

(4)

where \( R_S \) is Schwartchild radius.

It has been assumed that the explosion to be instantaneous (short duration) like in very close binaries [13], in the range of LMXBs, Cataclysmic Variable-type binaries (CVs) and close double pulsars, such as the PSR 1913+16, J0737- 3039AB and the close WD-pulsar system PSR 0655+64 [12]. Hence \( v_{\text{final}} \approx v_{\text{initial}} \approx 0.1c \)

\[
v_k = \frac{\Delta M v_{\text{final}}}{M} = \frac{R^2}{L^2} (M/0.1 M_\odot)^{-1} \cdot v_{\text{final}},
\]

(5)

where \( v_k \) is the kick velocity of the companion. It should be noticed that if the angular momentum of the accreted material equals the orbital angular momentum, due to the instability in the accretion shock around a proto-NS. This would enhance the possibility for the companion to be kicked away [16]. An assumption here is that a more energetic explosion would be able to impart a greater initial angular velocity onto the proto-NS than a lesser explosion, and the result is typically an eccentric orbit with an orbital period of a days. The escape velocity for the companion in the gravitational field of the WD is

\[
v = \sqrt{\frac{2GM_{WD}}{L}} \approx \sqrt{\frac{R_S}{L}} c.
\]

(6)
Hence, this is the largest kick velocity that a system can attain after a symmetric SNe explosion in case of $v_k \gg v$. Now let us define the $\eta$ parameter as the ratio between two velocities

$$\eta = \frac{v}{v_k} \sim 10^{-2} \left( \frac{R}{L} \right)^2 \left( \frac{L}{R_S} \right)^{1/2} \left( \frac{M}{M_\odot} \right)^{-1}. \quad (7)$$

Assuming canonical values for $L \sim 3 \times 10^{10}$ cm, $R \sim 10^9$ cm and $R_S = 3 \times 10^5$ cm, $\eta \sim (\frac{M}{M_\odot})^{-1} = 1$. The energy difference between the initial and final positions of the companion in the explosion is

$$\frac{GM_{WD}}{2L} - \frac{GM_{WD}}{2L_1} = \frac{1}{2} v^2. \quad (8)$$

Then by substituting $R_S$, equation (6) and (7) into equation (8),

$$\frac{R_S}{2L} - \frac{R_S}{2L_1} = \frac{v^2}{c^2} \rightarrow \frac{v_k^2}{2c^2} - \frac{v^2}{c^2} = \frac{R_S}{L} \left[ 1/2 - \eta^2 \right], \quad (9)$$

where $P_{orb} \propto L^{3/2}$, then

$$L_1 = \frac{L}{1 - 2\eta^2} \Rightarrow \frac{P_{orb1}}{P_{orb}} = [1 - 2\eta^2]^{-3/2}, \quad (10)$$

where $L_1$ is the new distance after the explosion and $P_{orb1}$ is the new orbital period corresponding to $L_1$. Figure 2 demonstrates that $P_{orb1}$ will be evolved and kicked up to relatively long orbital period. (i.e. PSR J0900-31, $P_{orb} = 18.7$ d, $e = 1.03 \times 10^{-5}$ and PSR J1600-30, $P_{orb} = 14.35$ d, and $e = 1.74 \times 10^{-4}$). The above described model could actually be used for wide and circular binary MSPs, since the AIC process in a close binary will not induce a sizeable kick velocity to the thus formed NS [17]. In our binary MSPs, we have taken the latest observational results from the ATNF pulsar catalog [18], and it has been found that $\sim 67\%$ (73 out of 323) of all MSPs could be formed through the AIC process.

3. Summary and Conclusions

The dynamical instability occurs in binary systems through the AIC, is driven by dissipative processes such as kicks, mass lose and shock wave. These effects may have acquired enough energy to the companion star and then can account for the differences in their distributions. Consequently, the AIC decreases the mass of the NS and increases the orbital period leading to orbit circularization. It turns out that the contribution of AIC process which potentially presents in the binary pulsars, is about $\sim 67\%$ after the final substantial orbital eccentricities. In addition, in some cases the kick is sufficient to disrupt the system, producing a population of isolated MSPs.

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Figure 2. The $P_{\text{orb}}/P_{\text{orb}}$ and $L_1/L$ as a function of $\eta$.

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