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*Letter to the Editor*

# The binary pulsar PSRJ 2145−0750: a system originating from a low or intermediate mass X-ray binary with a donor star on the asymptotic giant branch?

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**Abstract.** It is shown that the 6.84-day orbital period and relatively high companion mass of the 16.1ms period binary pulsar PSRJ 2145-0750 find a consistent explanation if the progenitor-system consisted of a donor star in the mass range $1-6\,M_\odot$ with an orbital period such that this star overflowed its Roche-lobe on the Asymptotic Giant Branch (AGB). The present system then resulted after a phase of Common Envelope (CE) evolution. Initial donor masses in the range $2.4-6\,M_\odot$ are possible only if, in addition to the orbital gravitational binding energy, other energy sources are available for expelling the envelope. The post-CE remnants of donors in the mass range $4-6\,M_\odot$ overflow their Roche lobes and continue to transfer mass at a near or super Eddington rate for of order $10^6$ yrs. This provides a simple way to explain the rapid spin and weak magnetic field of PSRJ 2145-0750.

**Key words:** binary pulsars–pulsar individual–stars evolution–close binaries– x-ray stars

## 1. Introduction

The 16ms binary pulsar PSRJ 2145-0750 has a circular orbit with a period of 6.839 days (Bailes et al. 1994). In this respect it resembles binary millisecond pulsars in the Galactic disk such as PSR 1855+09 ($P_b$ = 12.33$^d$, P = 5.4ms) and J 0437-4715 ($P_b$ = 5.74$^d$, P = 5.75ms).

However, two differences with the latter type of systems are:

1. The companion of PSRJ 2145-0750 has a mass $> 0.43\,M_\odot$, and probably $> 0.51\,M_\odot$ (50% probability), whereas the companions in the eight millisecond pulsar binaries with $P_b < 12.5$d have $M_c \lesssim 0.26\,M_\odot$. (The latter companions are helium white dwarfs and the evolution of these systems is well understood, cf. Verbunt 1990, 1993).
2. The spin period of PSRJ 2145-0750 is 16ms, i.e. considerably longer than those of the last-mentioned eight systems, which have an average <P> = 3.8ms, the longest period among them being 7.5ms.

We argue here that these differences are due to a different evolutionary history, and that PSRJ 2145-0750 originated from a wide binary system that went through a stage of CE-evolution. A similar suggestion was recently made by Phinney and Kulkarni (1994), who proposed that the evolutionary history of PSRJ 2145-0750 was similar to that of PSR 0655+64, and that these systems started out with companions considerably more massive than $2\,M_\odot$ ($\geq 5\,M_\odot$ in the case of PSR 0655+64, cf. Van den Heuvel and Taam 1984). We show here, however, that for PSRJ 2145-0750 also original companions less massive than $2\,M_\odot$ are possible and that, in fact, the entire mass range $1-6\,M_\odot$ is probably allowed.

## 2. Some Evolutionary Considerations

Helium white dwarfs cannot have masses $\gtrsim 0.45\,M_\odot$ (cf. Kippenhahn and Weigert 1990), which is the limiting mass for helium ignition by a flash. Since the companion of PSRJ 2145-0750 has almost certainly a mass larger than this value, it most likely is a CO white dwarf. It must be a white dwarf, since the ultra-short pulse period and the weak B-field of PSRJ 2145-0750 clearly indicate that it is a recycled pulsar (see e.g. Bhattacharya and Van den Heuvel 1991; Bhattacharya 1992; Verbunt 1993). Hence, its companion must now be at the endpoint of its nuclear evolution; the circular orbit rules out the possibility that it is a neutron star.

There are, basically, two ways to produce a CO-white dwarf:

1. From a normal hydrogen-rich star, when this star has passed through the phase of core-helium burning and is on the AGB,

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burning helium and hydrogen in shells around its degenerate CO-core.

2. In a helium star of mass $\lesssim 2.0\,M_\odot$ (cf. Habets 1985, 1986), during helium shell burning.

The latter model is, however, ruled out for the origin of PSRJ 2145-0750 for the following reasons. Systems consisting of a helium star and a neutron star are already the result of CE-evolution. For helium stars $\leq 2.0\,M_\odot$ this first CE-evolution always produces orbital periods $\lesssim 1$ day. This is due to the fact that to produce a helium star, the CE-phase should start prior to helium ignition, which implies a rather short initial orbital period. This, in combination with the fact that much orbital energy is required to eject the massive hydrogen-rich envelopes of their progenitors, leads always to post-CE orbital periods < 1 day. The subsequent CE-evolution and/or mass transfer from the helium star to the neutron star is unable to substantially increase this period, as one can easily verify. Therefore, only the first possibility remains for the origin of PSRJ 2145-0750. The present orbital period of the system shows that if one starts with a companion on the AGB, the system must have undergone a deep phase of CE-evolution.

## 3. The Relation between Initial and Final Orbits

To calculate the ratio of final and initial orbital radius $(a_2/a_1)$ in the case of CE-evolution, we use the formalism of Webbink (1984, 1992):

$$a_2/a_1 = \frac{M_2 \cdot M_{1f}}{M_{1f} + M_{1e}} \cdot \frac{1}{(M_2 + 2M_{1e}/\eta\lambda r_l)} \tag{1}$$

where $M_2$ is the mass of the neutron star, $M_{1f}$ the mass of the remaining core of the AGB-star, $M_{1e}$ the hydrogen-envelope mass of this star (which is lost), $\lambda$ a parameter that depends on the density distribution of the star, $r_l$ is the ratio of Roche-lobe radius to orbital radius before spiral-in, and $\eta$ is the 'efficiency' factor of CE-evolution. Both $\lambda$ and $r_l$ are of order 0.5.

The value of $\eta$ is more difficult to establish. If the only energy source available for the expulsion of the envelope is the drop in orbital gravitational binding energy of the binary during spiral-in, $\eta$ will always be $\leq 1$. It is, however, possible that other energy sources are available in the envelope, such as recombination energy of ions and molecules, accretion energy onto the neutron star, etcetera (cf. Iben and Livio 1993). In that case $\eta$ may become larger than unity. We will consider these two cases separately, and discuss now the possible range in $\eta$ values.

The change in orbital radius $(a_2/a_1)$ is sometimes expressed differently from Eq. 1, e.g. in the work of Iben and Tutukov (1984, 1985, 1993). These authors use an efficiency factor $\alpha_{CE}$ of CE-evolution, defined for example in Eq. 17 of Iben and Livio (1993). The relation between $\eta$ and $\alpha_{CE}$ is that for companions in the mass range $2 - 5\,M_\odot$ to obtain the same change in orbital radius, $\eta$ should be roughly four times larger than $\alpha_{CE}$. So on theoretical grounds, when no other energy sources are available in the envelope, one expects $\alpha_{CE}$ to be $\leq 0.25$, which is indeed confirmed by 2-D and 3-D numerical simulations of CE-evolution, which yield $\alpha_{CE} \simeq 0.15$ (cf. Terman et al. 1994), and $\eta$ values 0.3 to 0.6 (Taam and Bodenheimer 1989, 1992).

One way to attempt to determine $\alpha_{CE}$ is from observations, as was done by De Kool (1990) and Yungelson et al. (1993) by studying the distribution of orbital periods (and other parameters) of double nuclei of planetary nebulae (PNN). By comparing the observed distribution with distribution resulting from numerical simuations, they find that $\alpha_{CE}$ in the range $0.1 - 1.0$ gives the best fit. This would imply $\eta$ values up to about 4, which is not unreasonable since many PNN may have resulted from AGB stars, which may have had additional energy sources in their envelopes. In view of the above we will consider two possible values of $\eta$, $\eta = 1$ and 4, and study what conditions these $\eta$ values impose on the initial system parameters of PSRJ 2145-0750.

## 4. Limits to the Initial System Configuration

### 4.1. The case $\eta = 1$

We will assume that $M_c = M_{1f} = 0.6\,M_\odot$, which is the most commonly found mass of CO-white dwarfs (Weidemann 1990). For $M_2$ we assume 1.4 $M_\odot$. Then, for any given value of $M_{1e}$ one finds with equation (1) the minimum orbital radius $a_1$ before spiral-in, by using the present orbital radius $a_2 = 0.09\,AU$. For example, assuming an initial companion mass $M_1 = 1.4\,M_\odot$, one has $M_{1e} = 0.8\,M_\odot$ and one finds that $a_1$ should have been > $1.15\,AU \simeq 260 R_\odot$. One finds that a $1.4\,M_\odot$ star with a CO-core at this orbital separation overflowing its Roche-lobe, is on the AGB.If $\eta$ is somewhat smaller than unity, the required $a_1$-value and stellar radius required for overflowing its Roche lobe is, of course, even larger. Hence, the spiral-in model with an $1.4\,M_\odot$ AGB-companion provides a viable scenario for obtaining the present orbit and companion mass of PSRJ 2145-0750.

It is easy to show that the same holds for slightly more massive companions, up to about $2.4\,M_\odot$. For $M_1 > 2.4\,M_\odot$ and $\eta = 1$ the minimum orbital radius $a_1$ required to obtain the present orbital radius $a_2$, becomes larger than the largest radius possible for an AGB-star of that mass. Thus, for $\eta \leq 1$ the CE-model cannot work for $M_1 > 2.4\,M_\odot$. On the other hand, even for AGB-companions in the mass range $1.0 - 1.4\,M_\odot$, CE-evolution and spiral-in may still have occurred with a $1.4\,M_\odot$ neutron star, since with a fully convective envelope, CE- evolution occurs even for mass ratios $M_1/M_2$ as low as 0.5 (Hjellming 1989). The entire mass range $1.0 - 2.4\,M_\odot$ is therefore allowed for the companion, for $\eta \leq 1$. The resulting white dwarfs in all these cases have masses of about $0.6\,M_\odot$.

As the entire CE-phase and loss of the envelope on the AGB lasted less than $\sim 10^3$ yrs (cf. Terman et al. 1994), the accretion of $\geq 0.01\,M_\odot$ required to spin the neutron star up to $P = 16$ms must have occurred prior to the CE-phase (unless one would assume that highly super-Eddington accretion can take place during a CE-phase, as argued by Chevalier (1993). With companions $\leq 2.4\,M_\odot$ it is most likely, that this spin-up occurred due to wind accretion during the long-lasting phase as a normal red giant, prior to the AGB-phase. For stars of $1\,M_\odot$ and $2\,M_\odot$ the duration of the brightest part of the normal giant (H-shell burning) phase is about $2.10^7$ yrs. During this phase the luminosity is typically $\sim 500\,L_\odot$ and $R \sim 10^2\,R_\odot$, which leads, with the formula of Kudritzki and Reimers (1978) to a stellar wind mass loss rate $\dot{M}_w \simeq 1,2 \times 10^{-8}\,M_\odot/yr$, at a velocity of order $90 km/s$.

As the orbital separation before spiral-in was $\sim$ 1.2 AU, one then calculates that the fraction of the wind mass loss captured by a neutron star of $1.4\,M_\odot$ is about $\dot{M}_a \simeq 0.02\dot{M}_w \simeq 2.5 \times 10^{-10}\,M_\odot/yr$. In $2.10^7$ yrs the amount captured is about $0.005\,M_\odot$. Later, after the helium flash, during double shell burning, a similar amount can be captured, such that in total $\sim 0.01\,M_\odot$ can be accreted. This is just sufficient to spin the neutron star up to its required 16ms-period. Also, at the above accretion rate, the shortest possible spin-period that can be reached (the so-called equilibrium period) is

$$P_{eq} = 2.4\mathrm{ms}\,M^{-5/7}\,B_9{}^{6/7}\,(\dot{M}_a/\dot{M}_{Edd}) \quad (2)$$

where $B_9$ is the surface dipole magnetic field strength in units of $10^9$ G, and $\dot{M}_{Edd}$ is the maximum possible accretion rate: $1.4 \times 10^{-8}\,M_\odot/yr$. Indeed the shortest spin period that can be reached for $B_9 = 1$ and $\dot{M} = 2.5^{-10}\,M_\odot/yr$ is slighly below 16ms. We thus conclude that for $\eta = 1$ the bulk of the spin-up in PSRJ 2145-0750 must have taken place in the various giant phases of the donor star, prior to spiral-in.

**Table 1.** Initial orbital radius $a_1$ and initial Roche-lobe radius $R_{L1}$ of PSRJ 2145-0750 for the case $\eta$=4 for four different initial donor masses, $M_1$. The two listed values of the final donor mass $M_{1f}$ are: immediately after spiral-in and the final white dwarf mass (according to Iben and Tutukov 1993). Further explanations in the text.

| $M_1$ ($M_\odot$) | $M_{1f}$ ($M_\odot$) | $a_1$ ($R_\odot$) | $R_{L1}$ ($R_\odot$) | $R_{EAGB}$ ($R_\odot$) $R_{TP-AGB1}$ $R_{TP-AGB2}$ |
|---|---|---|---|---|
| 3 | 0.56 → 0.555 | 470 | 210 | 24 |
| | | | | 260 |
| | | | | 420 |
| 4 | 0.76 → 0.74 | 585 | 275 | 40 |
| | | | | 330 |
| | | | | 520 |
| 5 | 0.99 → 0.82 | 830 | 410 | 60 |
| | | | | 430 |
| | | | | 600 |
| 6 | 1.31 → 0.86 | 760 | 390 | 100 |
| | | | | 570 |
| | | | | 630 |

### 4.2. The Case $\eta = 4$

Here three-quarters of the energy required to expell the envelope comes from non-orbital energy sources, such that now heavier envelopes can be expelled. Iben and Tutukov (1993) give the masses of the post CE-remnants of AGB-stars of 3, 4, 5 and $6\,M_\odot$, for final Roche-lobe radii of $0.5\,R_\odot$ and $5\,R_\odot$. As the latter value is closest to what is required for PSRJ 2145-0750, we adopted here the corresponding remnant masses, which are listed in Table 1. These masses determine the masses of the expelled envelopes. Therefore, with Eq. 1 and $\eta = 4$ one can calculate for each of these four initial donor masses the resulting $(a_1/a_2)$ values, and, with $a_2$=0.09 AU, one then finds the corresponding $a_1$ values, which are listed in the table. The table lists also the corresponding Roche-lobe radii of the donors prior to spiral-in, as well as the radii of the stars on the onset of the AGB-phase ($R_{EAGB}$), at the onset of the Thermal Pulsing AGB ($R_{TP-AGB1}$) and at the end of the Thermal Pulsing AGB ($R_{TP-AGB2}$).

If the Roche-lobe radii are larger than the last-mentioned radius, the progenitor system is not possible. The table shows, that with $\eta = 4$ original donors in the mass range $3 - 6\,M_\odot$ are possible. (A rough estimate shows that even donor masses as high as $7\,M_\odot$ cannot be excluded.)

A very important point, noted by Iben and Tutukov (1993) is that for original donor masses $4 - 6\,M_\odot$, the remnant stars, of mass $M_{1f}$, after spiral-in fill their Roche-lobes and continue to transfer mass to their companions, at a high rate, in the range $10^{-8}\,M_\odot/yr$ to $10^{-6}\,M_\odot/yr$, for about $10^6$ yrs.

These remnants consist of a degenerate CO-core and a thick helium envelope, and are burning helium at the bottom of this envelope. During this helium shell burning phase the envelope slowly expands giving rise to the mass transfer. The remnants of the $5\,M_\odot$ and $6\,M_\odot$ stars transfer mass at a rate $\sim 10^{-6}\,M_\odot/yr$ for about $(1-2)\mathrm{x}10^5$ yrs, while their mass transfer rate for the entire duration of the transfer ($1.5\mathrm{x}10^6$ yrs and $8\mathrm{x}10^5$ yrs, respectively) is $\geq 3.10^{-8}\,M_\odot/yr$ and $\geq 10^{-7}\,M_\odot/yr$, respectively. For the $4\,M_\odot$ remnant it is $\approx 10^{-8}\,M_\odot/yr$ for $1.4\mathrm{x}10^6$ yrs.

It is important to note that the transferred matter is helium, such that the maximum possible accretion rate (Eddington limit) is twice that for hydrogen, i.e. $\sim 3\mathrm{x}10^{-8}\,M_\odot/yr$. Thus, from the remnants of the $5\,M_\odot$ and $6\,M_\odot$ stars the neutron star may have accreted $\sim 0.045\,M_\odot$ and $0.024\,M_\odot$, respectively, and in the $4\,M_\odot$ case $0.014\,M_\odot$. These amounts, transferred by Roche-lobe overflow, are more than sufficient to spin the neutron star up to $\leq$ 16ms and will also make the magnetic fields decay to a low value (cf. Taam and Van den Heuvel 1986). Since after the mass transfer phase the companion contracts to become a white dwarf, a system with a rapidly spinning pulsar will stay behind.

## 5. Discussion and Conclusions

We conclude that
1. If $\eta \leq 1$ (no energy sources other than orbital are available for expelling the envelope of the donor) the donor star prior to spiral-in was an AGB star of mass $\leq 2.4\,M_\odot$. The bulk of the spin-up of the neutron star, as well as its field decay, must in this case have taken place by stellar wind accretion during various giant phases of the companion, prior to spiral-in. The estimated cumulative amount of accretion in this case was just sufficient

($\sim 0.01\,M_\odot$ to spin the neutron star up to its present spin period, and the accretion rate was low, $\lesssim 2.5 \times 10^{-10}\,M_\odot/yr$.
2. If other energy sources for expelling the envelope are available, i.e. $\eta$ considerably larger than unity, initial companions in the mass range $2.4 - 6\,M_\odot$ are also possible. Also here the CE-phase started when the companion was on the (probably early) AGB-phase. For initial donors of $4 - 6\,M_\odot$ the post-CE remnant continued to transfer helium by Roche-lobe overflow for of order $10^6$ yrs at near- or super-Eddington rates, amply sufficient (cumulative $0.014 - 0.045\,M_\odot$) to spin the neutron star up to its present spin period, and decrease the strength of its magnetic field.

It has not escaped our attention that if the initial donor had been slightly more massive (i.e. $8 - 12\,M_\odot$) a similar type of evolution would have taken place, though the mass of the CO-core would have been sufficiently massive to collapse to a neutron star. As in this case the mass of CO-core and its helium mantle were $\gtrsim 2\,M_\odot$ a second phase of orbital shrinking would have occurred, presumably followed by the same type of helium transfer to the neutron star, for of order $10^5$ yrs or longer. This will have decreased its magnetic field and will have spun-up its rotation to a short period. We suggest that this prolonged post-CE mass transfer stage is the cause of the abnormally weak B-fields and rapid spin also of the Hulse-Taylor and Wolszczan pulsars.

Recently, a system closely resembling PSRJ 2145-0750 was discovered by Fernando Camilo at Princeton. This new system, PSRJ 1023+10, has P=16.45ms, $P_{orb}$=7.8 days, a circular orbit and a companion of mass $\geq 0.72\,M_\odot$ (most likely a value $0.87\,M_\odot$). Its evolutionary history must have been very similar to that of PSRJ 2145-0750, with an initial donor in the mass range $4 - 6\,M_\odot$ or even slighly higher.

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