Helium white dwarf in PSR J0751+1807; too cool, in PSR J1012+5307; too hot?

Ene Ergma¹, Marek J. Sarna² and Jelena Gerškevitš–Antipova¹

¹ Physics Department, Tartu University, Ülikooli 18, EE2400 Tartu, Estonia
² N. Copernicus Astronomical Center, Polish Academy of Sciences, ul. Bartycka 18, 00–716 Warsaw, Poland.

Accepted: Received ; in original form 1999

ABSTRACT

We discuss the cooling history of the low–mass, helium core white dwarfs in short orbital period millisecond pulsars PSR J0751+1807 and PSR J1012+5307. The revised cooling age estimated by Alberts et al. agrees with the age estimation for PSR J1012+5307, removing the discrepancy between the spin–down age and the cooling age. However, if we accept this model then the helium white dwarf in the binary pulsar system PSR J0751+1807 must be much hotter than is observed. We propose that this discrepancy may be resolved if, after detachment of the secondary star from its Roche lobe in PSR J0751+1807, the star loses its hydrogen envelope due to pulsar irradiation. When hydrogen burning stops, the white dwarf will cool down much more quickly than in the case of a thick hydrogen envelope with a hydrogen burning shell. We discuss several possibilities to explain different cooling histories of white dwarfs in both systems.

Key words: binaries: close — binaries: general — stars: mass loss evolution — stars: millisecond binary pulsars — pulsars: individual: PSR J0751+1807 — pulsars: individual: PSR J1012+5307

1 INTRODUCTION

It is accepted that formation of a binary millisecond (or recycled) pulsar with a low–mass companion may be explained as the end–point of close binary evolution in which an old pulsar is spun–up by accretion from the red giant (secondary) (see Bhattacharaya & van den Heuvel 1991, for review). Once the secondary overflows its Roche lobe, it starts transferring mass and angular momentum to the neutron star. During the long term accretion phase the neutron star is generally assumed to be spun–up to the equilibrium period (P_eq). The equilibrium period can be written as (Bhattacharaya & van den Heuvel 1991):

\[ P_{eq} = 1.9 \text{ ms} B_9^{6/7} \left( \frac{M_{ns}}{1.4 M_\odot} \right)^{-5/7} \left( \frac{M}{M_{Edd}} \right)^{-3/7} R_6^{16/7} \]  

where \( B_9 = B/10^9 \text{ G}, R_6 = R_{ns}/10^6 \text{ cm} \) and \( M_{ns} \) are the magnetic field strength, radius and mass of the neutron star respectively and \( M_{Edd} \) is the Eddington mass accretion rate. After the whole envelope of the red giant has been transferred, the binary consists of a low–mass star with a helium core (progenitor of a low–mass helium white dwarf) and a fast rotating neutron star (millisecond pulsar). At this point the pulsar spin period starts to change due to magneto–dipole radiation, with a characteristic time \( t \) elapsed from this epoch

\[ t = \tau \times \left( \frac{2}{n - 1} \right) \left[ 1 - \left( \frac{P_0}{P} \right)^{n-1} \right] , \]  

where \( \tau = P/(2P) \), \( P_0 \) and \( P \) are the initial and current spin periods, and \( P \) is the spin period derivative. \( n \) is the braking index (=3) and if \( P_0 \ll P \) then \( t = \tau \). It is possible to estimate the age \( t \) from the cooling age of the white dwarf. The latter can be calculated from the observed parameters of the \( (T_{eff}, \log g) \). This gives a unique opportunity for determination of neutron star age which is independently of the spin–down theory of pulsars.

In this short note we shall discuss cooling properties of helium white dwarfs in short period binary systems with millisecond pulsars, PSR J0751+1807 and PSR J1012+5307.

2 OBSERVATIONAL DATA FOR MILLISECOND PULSARS

For both systems, the characteristic time \( t \) (eq (2)), to be compared with the cooling age of the white dwarf, is assumed to be equal to the spin–down age \( \tau \) of the neutron
star. This requires \( P_0 \sim P_{0i} \ll P \). The last restriction will be relaxed in the discussion section (par. 6).

2.1 PSR J0751+1807

This system consists of a 3.5 ms pulsar in a 6 h orbit with a \( \sim 0.15 \, M_\odot \) companion (Lundgren, Zepka & Cordes 1995). We estimate the magnetic field strength of neutron star from the relation

\[
B = 3 \times 10^{19} (P \dot{P})^{1/2}.
\]  

(3)

For the observed \( P \) and \( \dot{P} \) (\( 8 \times 10^{-21} \) s s\(^{-1} \)) we have \( B \sim 1.7 \times 10^8 \) G, and the spin–down age of the neutron star, \( \tau \sim 8 \) Gyr. For this age and \( M_{\text{red}} \sim 0.15 \, M_\odot \) a simple white dwarf cooling model by Mestel (1952) gives \( L \sim 10^{-4.3} \, L_\odot \). Lundgren et al. (1996) estimated a lower bound for the visual magnitude, \( m_v \geq 23.5 \), which requires \( T_{\text{eff}} < 9000 \) K and an age greater than \( 7.94 \times 10^8 \) years. From their data a main-sequence companion is ruled out down to an M5 star (\( M \sim 0.10 \, M_\odot \)), since such a star would have been detected at the distance of the pulsar. Therefore the pulsar companion in this system is clearly a white dwarf.

2.2 PSR J1012+5307

PSR J1012+5307 consists of a millisecond pulsar (with \( P = 5.256 \) ms) in a 14.52 h orbit with a \( \sim 0.15 \, M_\odot \) companion (\( M_{\text{red}} = 1.4 \, M_\odot \), \( i = 60^\circ \)). \( P = 1.46 \times 10^{-20} \) s s\(^{-1} \) leads to the spin–down age, \( \tau \sim 7.0 \) Gyr (Nicastro et al. 1995, Lorimer et al. 1995), and \( B \sim 2.6 \times 10^8 \) G. Van Kerwijk et al. (1996) and Callanan et al. (1998) estimated the mass of the helium white dwarf to be \( 0.16 \pm 0.02 \, M_\odot \). Taking the observationally determined gravity and effective temperature for the white dwarf, and adopting the cooling model of Iben & Tutukov (1986), the cooling age has been estimated as 0.3 Gyr (Lorimer et al. 1995). The discrepancy between these two age estimations is solved if, in the white dwarf cooling models, a thick hydrogen envelope with stationary hydrogen shell burning is taken into account (Alberts et al. 1996; Driebe et al. 1998), rising the cooling age to several Gyr.

3 THE EVOLUTIONARY CODE

The evolutionary sequences we have calculated consist of three main phases:

(i) detached evolution lasting until the companion fills its Roche lobe,

(ii) semi–detached evolution,

(iii) a cooling phase of the white dwarf (the final phase during which a system with a ms pulsar + low–mass helium white dwarf is left behind).

3.1 Detached phase

The duration of the detached phase is somewhat uncertain; it may be determined either by the nuclear time–scale or by the much shorter time–scale of the orbital angular momentum loss owing to the magnetized stellar wind.

3.2 Semi–detached phase

In our calculations we assume that the semi–detached evolution of a binary system is non–conservative, i.e. the total mass and angular momentum of the system are not conserved. The formalism which we have adopted is described in Muslimov & Sarna (1993). We introduce the parameter, \( f_1 \), characterizing the loss of mass from the binary system and defined by the relations,

\[
\dot{M} = \dot{M}_2 f_1 \quad \text{and} \quad \dot{M}_1 = -\dot{M}_2 (1 - f_1),
\]

(4)

where \( \dot{M} \) is the mass–loss rate from the system, \( \dot{M}_2 \) is the rate of mass–loss from the secondary star, and \( \dot{M}_1 \) is the accretion rate onto the neutron star (primary). The matter leaving the system will remove angular momentum according to the formula

\[
\dot{J} = f_2 \frac{M_1 M}{M_2 M} \, \dot{M} \, \tau_{\text{eff}} \, \text{yr}^{-1},
\]

(5)

where \( \dot{M} = M_1 + M_2 \), \( M_1 \) and \( M_2 \) are the masses of the neutron star and secondary star respectively. Here we have introduced an additional parameter, \( f_2 \), which describes the efficiency of the orbital angular momentum loss from the system due to a stellar wind (Tout & Hall 1991). In our calculations we assume \( f_1=1 \) and \( f_2=1 \).

We also assume that the secondary star, possessing a convective envelope, experiences magnetic braking (Mestel 1968; Mestel & Spruit 1987; Muslimov & Sarna 1995), and as a consequence of this, the system loses its orbital angular momentum. For magnetic stellar wind we used the formula for the orbital angular momentum loss

\[
\dot{J} = -3 \times 10^{-7} \frac{M_1^2 R_2^2}{M_2 M a^2} \, \frac{\tau_{\text{eff}}}{\tau_{\text{MSW}}} \, \text{yr}^{-1},
\]

(6)

where \( a \) and \( R_2 \) are the separation of the components and the radius of the secondary star in solar units.

In the semi–detached phase we have also included the effect of illumination of the secondary star by the millisecond pulsar. In our calculations we assume that the atmosphere of the secondary star is heated by the hard (X–ray and \( \gamma \)-ray) radiation from the pulsar (Muslimov & Sarna 1993). The effective temperature, \( T_{\text{eff}} \), of the companion during the illumination stage is determined from the relation

\[
L_{\text{in}} + P_{\text{dir}} = 4 \pi \sigma R_2^2 T_{\text{eff}}^4.
\]

(7)

where \( L_{\text{in}} \) is the intrinsic luminosity corresponding to the radiation flux coming from the stellar interior, \( \sigma \) is the Stefan–Boltzmann constant and \( R_2 \) is the radius of the secondary. \( P_{\text{dir}} \) is the millisecond pulsar radiation that heats the photosphere, given by

\[
P_{\text{dir}} = f_3 \left( \frac{R_2}{2a} \right)^2 \frac{L_{\text{rot}}}{\tau_{\text{eff}}},
\]

(8)

where \( L_{\text{rot}} \) is “rotational luminosity” of the neutron star due to magneto–dipole radiation (plus a wind of relativistic particles)

\[
L_{\text{rot}} = \frac{2}{3} \rho_0^2 B^2 R_\text{n}^6 \left( \frac{2\pi}{P} \right)^4
\]

(9)

in the above formula \( R_\text{n} \) is the neutron star radius, \( f_3 \) is a factor introduced to account for the efficiency of transformation of the irradiation flux into thermal energy (in our
3.3 Cooling phase

For systems in the white dwarf cooling phase, we take into account two processes:

(i) the loss of orbital angular momentum due to the emission of gravitational radiation (Landau & Lifshitz 1971),

(ii) an irradiation induced stellar wind, with corresponding loss of orbital angular momentum estimated as

\[ \dot{J}_{\text{wind}} = \frac{q}{1 + q} \frac{M_{\text{wind}}}{M_2}, \]

where \( q \) is the mass ratio \( q = M_1/M_2 \) and \( \dot{M}_{\text{wind}} \) is a mass loss of an irradiation induced stellar wind defined by the simple van den Heuvel & van Paradijs (1988) model

\[ \dot{M}_{\text{wind}} = f \frac{R_2}{GM_2} \left( \frac{R_2}{2a} \right)^2 \frac{2 R_2^6}{3 c^3} B^2 \left( \frac{2 \pi}{P} \right)^4, \]

where \( f \) is efficiency factor (from 0 to 1) and \( a \) is the separation between the stars in solar units. In our calculations we assume three values of \( f \): 0, 0.1 and 0.5 (very efficient irradiation).

3.4 The code

The models of the stars filling their Roche lobes were computed using a standard stellar evolution code based on the Henyey-type code of Paczyński (1970), which has been adapted to low–mass stars. Convection is treated with the mixing-length algorithm proposed by Paczyński (1969). We solve the problem of radiative transport by employing the opacity tables of Iglesias & Rogers (1996). Where the Iglesias & Rogers (1996) tables are incomplete, we switch to opacity tables of Heubner et al. (1977). For temperatures less than 6000 K we use opacities calculated by Alexander & Ferguson (1994) and Alexander (private communication). Finally, we assume a Population I chemical composition for the secondary (\( X=0.7 \), \( Z=0.02 \)).

4 EVOLUTIONARY CONSIDERATIONS

To produce short orbital period systems composed of a low–mass helium white dwarf and a millisecond pulsar, it is necessary that the low–mass secondary (red giant) fills its Roche lobe below the so called bifurcation period, and above the boundary period (Ergma & Sarna 1996, Ergma, Sarna & Antipova 1998). Ergma et al. (1998) and recent calculations by Sarna, Ergma & Antipova (2000) have shown that after detachment of the secondary star from its Roche lobe, a rather thick hydrogen layer is left on the top of the helium core. This thick hydrogen layer will greatly influence the cooling history of the very low–mass helium white dwarf (\( < 0.25 \, M_\odot \)).

Alberts et al. (1996) were the first to argue that because white dwarfs with \( M_{\text{wd}} < 0.2 \, M_\odot \) do not show thermal flashes (as found by Webbink, 1975), the amount of hydrogen in the envelopes must remain high, resulting in a much longer phase of significant hydrogen burning. Thus cooling times for these objects are considerably extended. This removes the discrepancy between the cooling and spin–down ages for the millisecond binary systems PSR J1012+5307 (Alberts et al. 1996, Driebe et al. 1998, Sarna et al. 1999, 2000).

But now the question arises for the PSR J0751+1807. The evolutionary history for both pulsar systems are very similar, as argued by Ergma & Sarna (1996). This means that in PSR J0751+1807 the helium white dwarf must also be in the stable, long–lasting hydrogen–burning phase, which leads to long cooling times. However, observations show that the white dwarf in this system is undetectable, and really very old.

To solve this discrepancy, we propose that irradiation of the secondary star by the millisecond pulsar PSR J0751+1807 causes mass loss after detachment from the Roche lobe. After detachment the star with a hydrogen burning shell evolves from the red giant region towards higher effective temperatures. If we accept the simple irradiation driven mass loss model proposed by van den Heuvel & van Paradijs (1988), then using eq. 11, for \( R_2 = 0.56 \, R_\odot \) (see point 2 on Fig. 1), \( a = 2 \, R_\odot \), \( M_2 = 0.15 \, M_\odot \), \( R_{\text{as}} = 10 \, \text{km} \) and \( f = 0.1 \) (efficiency factor), we have \( \dot{M}_{\text{wind}} \sim 4 \times 10^{-10} \, M_\odot \, \text{yr}^{-1} \). Since the evolutionary timescale to evolve is rather long (at least several hundred million years), about 0.01 \( M_\odot \) of the hydrogen envelope will be lost. As a result, the hydrogen burning shell will switch off, and the white dwarf may cool down very quickly.

5 SIMPLE COOLING MODEL FOR THE WHITE DWARF IN PSR J0751+1807

To illustrate how the mass loss due to irradiation will influence the cooling evolution of the pre–white dwarf (after detachment from Roche lobe), we computed the evolutionary sequence for a system of \( 1.5 + 1.4 \, M_\odot \), with \( P_{\text{orb,i}} \) (RLOF)=1.07 d (RLOF – Roche lobe overflow) and \( Z=0.02 \) (Fig. 1). After detachment from the Roche lobe, mass loss at a rate estimated from eq. 11 has been included (Fig. 2).

The mass loss phase leads to a change of the orbital angular momentum, which leads to significant changes in the orbital period evolution (Fig.3). Figure 4 shows the evolution of the visual magnitude (\( m_V \)) of the progenitor of the white dwarf during the cooling phase, with wind mass loss included.

In the H–R diagram (Fig. 1) the evolution of this system is presented with and without mass loss. The decrease of the mass of the hydrogen envelope leads to a significant decrease of the hydrogen shell burning efficiency. Therefore, if compared to the evolution of a white dwarf with stationary hydrogen shell burning, the cooling time is decreased. For example, when log \( L/L_\odot \approx -2.0 \), the cooling age without mass loss is \( 8.4 \times 10^9 \, \text{yrs} \), with moderate mass loss (\( f=0.1 \)) is \( 5.07 \times 10^9 \, \text{yrs} \), and with very efficient mass loss (\( f=0.5 \)) is \( 2.17 \times 10^9 \, \text{yrs} \). Due to angular momentum loss by the irradiation induced wind, the orbital period and separation of the system (after detachment of the secondary from the Roche lobe) initially increases (Fig. 3). Because of this increase in the separation, and shrinking of the white dwarf (see eq. 11)
Figure 1. HR diagram with evolutionary tracks of a 1.5 \( M_\odot \) star with 1.4 \( M_\odot \) neutron star. Different phases of evolution are: detached evolution before filling the Roche lobe (0–1), semi-detached evolution (1–2), and detached evolution during the cooling of a white dwarf (2–3). Phase (2–3) is plotted for three different cases; normal cooling (thick solid line), cooling with irradiation induced wind \((f=0.1)\) (thick dashed line) and very efficient irradiation induced wind \((f=0.5)\) (thick dash–dotted line). The thin solid line shows the ZAMS as calculated using our code.

Figure 2. The dependence of the mass loss rate as a function of time in two different phases of evolution: semi-detached evolution (phase 1–2) – solid line and cooling with irradiation induced wind. For the wind phase we show two different efficiencies of the wind: \( f=0.1 \) (dashed line) and \( f=0.5 \) (dash–dotted line).

Figure 3. Evolution of the orbital period during the cooling phase for the three cases considered. The meaning of the lines is the same as for Fig. 1. The thin dashed line shows location, at which the surface effective temperature of the white dwarf is equal to 9000 K.

Figure 4 gives the limit for acceptable \( m_V \) from theoretical cooling tracks. We can exclude normal cooling (with shell hydrogen burning) due to a too low \( m_V \). Two other cases of cooling with irradiation induced wind give the right range of visual magnitude. For the upper limit of pulsar age (spin–down age \( \sim 8 \) Gyrs) \( m_V \) and \( T_{\text{eff}} \) are (22.4, 7200K) for \( f=0.1 \) and (24.7, 4700K) for \( f=0.5 \).

One can ask why we do not observe circumbinary material inside PSR J0751+1807, as we do in PSR 1957+20 or PSR 1744–24A (Lyne 1995). We propose that after having lost most of its hydrogen envelope (during the high mass loss phase), the star hydrogen burning stops and relaxes to a low–mass helium white dwarf. Irradiation of the white dwarf by the pulsar may be significant, but it does not lead to change in the internal structure of the envelope (as it does for a low–mass star with a convective envelope and shell nuclear burning). Therefore, no hot extended envelope is created and no mass loss induced.

© 0000 RAS, MNRAS 000, 000–000
case, at the end of the accretion phase, field decay takes place (see Bhattacharya & Srinivasan 1995 for review). In this ages of PSR J1012+5307 Burderi et al. (1996) have accepted explain the discrepancy between the cooling and spin–down  low–mass helium white dwarfs (\(M < 0.2 M_\odot\)) in which almost all residual hydrogen is lost in a few thermal flashes (via Roche–lobe overflow) occurs between 0.183–0.213 \(M_\odot\), which well agrees with the cooling scenario proposed by Burderi et al. (1998).

Therefore we may accept that PSR J1012+5307 is in a long term hydrogen shell burning stage and this may be the reason why the white dwarf is too hot (accepting that spin–down age of 7 Gyr, which value could be even larger if the pulsar has a significant transverse velocity (Hansen & Phinney 1998), is almost equal to the cooling age). For PSR J0751+1807 the irradiation driven mass loss reduces the hydrogen envelope mass, the hydrogen burning decreases and the white dwarf is quickly cooled.

Taking into account the effect of illumination, \(P_{eq}\) is \(\sim 1.6 \times 10^{-3}\) s (Ergma & Sarna 1996). Therefore, if the pulsar in PSR J1012+5307 has been spun up to \(P_{eq}\), it also has suffered irradiation driven mass loss. If we do not include illumination then \(P_{eq}\) is longer, since at the beginning of RLOF mass transfer is proceeding on the thermal time–scale at a rather high mass accretion rate, and the neutron star spins–up to millisecond periods. After about 0.2 \(M_\odot\) have been lost, the mass transfer rate decreases and the neutron star enters a “propeller phase” during which the fast rotating neutron star will slow down. To avoid irradiation–driven mass loss from this system the external irradiation flux must be less than critical flux \(\sim 1.6 \times 10^{12}\) erg s\(^{-1}\) cm\(^{-2}\) (Podsiadlowski 1991). Let us estimate the value of the initial pulsar period \(P_0\) to allow such a flux. Simple estimates show that \(P_0\) must be longer than \(3.85 \times 10^{-3}\) s, and the time elapsed from detachment of the Roche lobe is \(\sim 3.2 \times 10^3\) yrs. If \(P_0 > 3.85 \times 10^{-3}\) s then there is no irradiation driven mass loss and the hydrogen burning is stationary, prolonging the cooling time. Since both systems are in many parameters very similar to each other, only the white dwarf cooling time–scale is very different and there must be something which leads to the different cooling histories for the helium white dwarfs in these systems. Different irradiation fluxes \(F_\gamma \propto (J1012+5307) \approx 10 \times F_\gamma \propto (J0751+1807)\) may explain the discrepancy.

We would like to point to an important issue neglected in many papers. Usually the comparison with observed system is made for one or several parameters (for example the cooling age of the white dwarf, \(T_{eff}\) and so on) but not with all available data. For binary systems we must build a self–consistent picture with the right orbital parameters (which may be a very hard task, as in the case of the two systems discussed here), masses (if known) and cooling parameters of the white dwarf.

The effect of irradiation on the secular evolution of binaries containing a millisecond pulsar has been discussed in a recent review paper by D’Antona (1996). She has pointed out that one needs to distinguish the two main effects of irradiation with following terms; i) illumination: structural changes in the whole stellar structure due to irradiation, which may cause the secondary to fill its Roche lobe again, ii) evaporation: direct driving of mass loss from the secondary. Both cases give the same final result – the decrease of the mass of the hydrogen envelope.

We propose that for PSR J0751+1807 the irradiation by the pulsar causes irradiation–driven mass loss from secondary, resulting in exhaustion of the hydrogen envelope.

\[\text{Helium white dwarf} \]
and as a consequence of this, a hydrogen shell burning stops. The irradiation–driven wind influences also the cooling phase, decreasing the cooling time–scale by a factor 1.7–4 (depending on how efficient this process is).

For the PSR J1012+5307 system the irradiative flux may be too small to cause significant mass loss, and hydrogen shell burning will be maintained for a long enough time to keep the white dwarf hot.

ACKNOWLEDGEMENTS

We would like to thank Prof. M. Różycka for help in improving the form and text of the paper. We would like to thank referee Dr. F. D’Antona for constructive comments. This work was supported in part by the Polish National Committee for Scientific Research under grant 2-P03D-005-16 and 2-P03D-014-07, and by the Estonian SF grant 4338.

REFERENCES

Alberts F., Savonije G. J., van den Heuvel E. P. J., Pols O. R., 1996, Nature, 380, 676
Alexander D. R., Ferguson J. W., 1994, ApJ, 437, 879
Bhattacharya D., van den Heuvel E. P. J., 1991, Physics Rep., 203, N1, 2
Bhattacharya D., Srinivasan G., 1995, in Lewin W.H.G., van Paradijs J., van den Heuvel E.P.J., eds. “X-ray Binaries”, Cambridge Univ. Press, Cambridge p. 495
Burderi L., King A. R., Wynn G.A., 1996, MNRAS, 283, L63
Burderi L., King A. R., Wynn G. A., 1998, MNRAS, 300, 1130
Callanan P. J., Garnavich P. M., Koester D., 1998, MNRAS, 298, 207
D’Antona F., 1996, in “Evolutionary Processes in Binaries” eds. by R. A. M. J. Wijers, M. B. Davies, Ch. Tout, p. 267
Driebe T., Schönberner D., Blöcker T., Herwig F., 1998, A&A, 339, 123
Ergma E., Sarna M. J., 1996, MNRAS, 280, 1000
Ergma E., Sarna M. J., Antipova J., 1998, MNRAS, 300, 352
Huebner W. F., Merts A. L., Magee N. H. Jr., Argo M. F., 1977, Astrophys. Opacity Library, Los Alamos Scientific Lab. Report No. LA–6760–M
Iben I., Tutukov A. V., 1986, ApJ, 311, 742
Iglesias C. A., Rogers F. J., 1996, ApJ, 464, 943
Landau L. D., Lifshitz E. M., 1971, Classical theory of fields. Pergamon Press, Oxford
Lorimer D. R., Festin L., Lyne A. G., Nicastro L., 1995, Nature, 376, 393
Lundgren S. C., Zepka A. F., Cordes J. M., 1995, ApJ, 453, 419
Lundgren S. C., Cordes J. M., Foster R. S., Wolszczan A., Camilo F., 1996, ApJ, 458, L33
Lyne A. G., 1995, in The Lives of the Neutron stars, eds. M. A. Alpar, U. Liziloglu, J. van Paradijs, p. 213
Mestel L., 1952, MNRAS, 112, 583
Mestel L., 1968, MNRAS, 138, 359
Mestel L., Spruit H. C., 1987, MNRAS, 226, 57
Muslimov A. G., Sarna M. J., 1993, MNRAS, 262, 164
Muslimov A. G., Sarna M. J., 1995, ApJ, 448, 289
Nicastro L., Lyne A. G., Lorimer D. R., Harrison P. A., Bailes M., Skidmore B. D., 1995, MNRAS, 273, L68
Paczyński B., 1969, Acta Astron., 19, 1
Paczyński B., 1970, Acta Astron., 20, 47
Podsiadlowski Ph., 1991, Nature, 350, 136
Sarna M. J., Antipova J. Ergma E., 1999, in Proceedings of the 11th European Workshop on White dwarfs, ASP, Vol.169,400

Sarna M. J., Ergma, E., Gerškevitš–Antipova J., 2000, MNRAS, in press
Tout C. A., Hall D. S., 1991, MNRAS, 253, 9
van den Heuvel E. P. J., van Paradijs J., 1988, Nature, 334, 227
van Kerkwijk M. H., Bergeron P., Kulkarni S. R., 1996, ApJ, 467, L41
Webbink R. F., 1975, MNRAS, 171, 555