The evolution of helium white dwarfs
Applications for millisecond pulsars

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Introduction

Low-mass white dwarfs with helium cores (He-WDs) are known to result from mass loss and/or exchange events in binary systems where the donor is a low mass star evolving along the red giant branch. Therefore, He-WDs are common components in binary systems with either two white dwarfs or systems with a white dwarf and a millisecond pulsar (MSP).

If the cooling behaviour of He-WDs is known from theoretical studies (see Kippenhahn *et al.* 1968, Iben & Tutukov 1986, Alberts et al. 1996, Benvenuto & Althaus 1998, Hansen & Phinney 1998a,b, Driebe et al 1998, Sarna et al. 1998) the ages of MSP systems can be calculated independently of the pulsar properties provided the He-WD mass is known from spectroscopy. The white dwarf cooling age can than be compared with the pulsar's spin-down age as it has recently been done for the system PSR J1012+5307 (Nicastro et al. 1995) by Hansen & Phinney (1998b), Driebe et al. (1998) and Sarna et al. (1998) using the spectroscopic data of van Kerkwijk et al. (1996) and Callanan et al. (1998).

Method and calculations

Driebe et al. (1998) investigated the evolution of He-WDs in the mass range $0.18 < M/\mathrm{M}_\odot < 0.45$. using the code of Blöcker (1995). The evolution of a $1\,\mathrm{M}_\odot$-model was calculated up to the tip of the red giant branch (RGB). High mass loss terminated the RGB evolution at appropriate positions depending on the desired final white dwarf mass. When the model started to leave the RGB, mass loss was virtually switched off and the models evolve towards the white dwarf cooling branch (see Fig. 1). The applied procedure mimicks the mass transfer in binary systems.

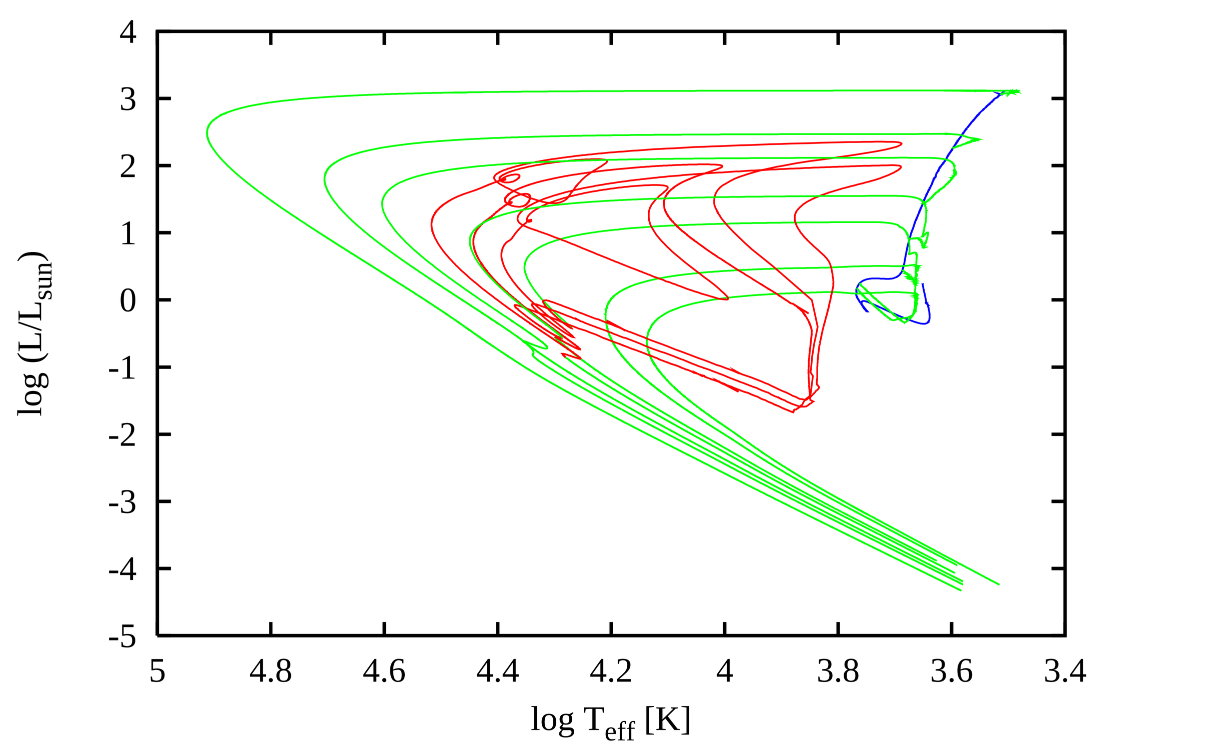

Figure 1: Hertzsprung-Russell diagram (HRD) with complete evolutionary tracks of red giant remnants of different masses (from above: 0.414, 0.331, 0.300, 0.259, 0.234, 0.195 and 0.179 $\mathrm{M}_\odot$). The blue line shows the 1 $\mathrm{M}_\odot$ track. Note that the post-RGB evolution depends only on the model's actual structure and not on the details of previous mass loss phases. Two of the models suffer hydrogen shell flashes on the cooling branch (red curves; 0.259 $\mathrm{M}_\odot$: one flash; 0.234 $\mathrm{M}_\odot$: two flashes).

The occurrence of hydrogen shell flashes in some He-WD models (in our case $M_{\rm WD} = 0.234$ and 0.259) is caused by a geometrically thin burning shell, where hydrogen is converted into helium mainly via the CNO cycle (see Driebe et al. (1999) for a recent account).

Contrary to C/O-white dwarfs ($M_{\rm WD} > 0.45\,\mathrm{M}_\odot$, carbon/oxygen core), He-WDs continue to burn hydrogen via the pp cycle along the cooling branch. The residual burning leads to an unexpected slowed-down cooling behaviour, especially for models with $M < 0.2\,\mathrm{M}_\odot$: less massive He-white dwarfs cool significantly slower than more massive ones, in contrast to C/O-white dwarfs and He-white dwarf models without nuclear burning.

Mass-Radius-Relation

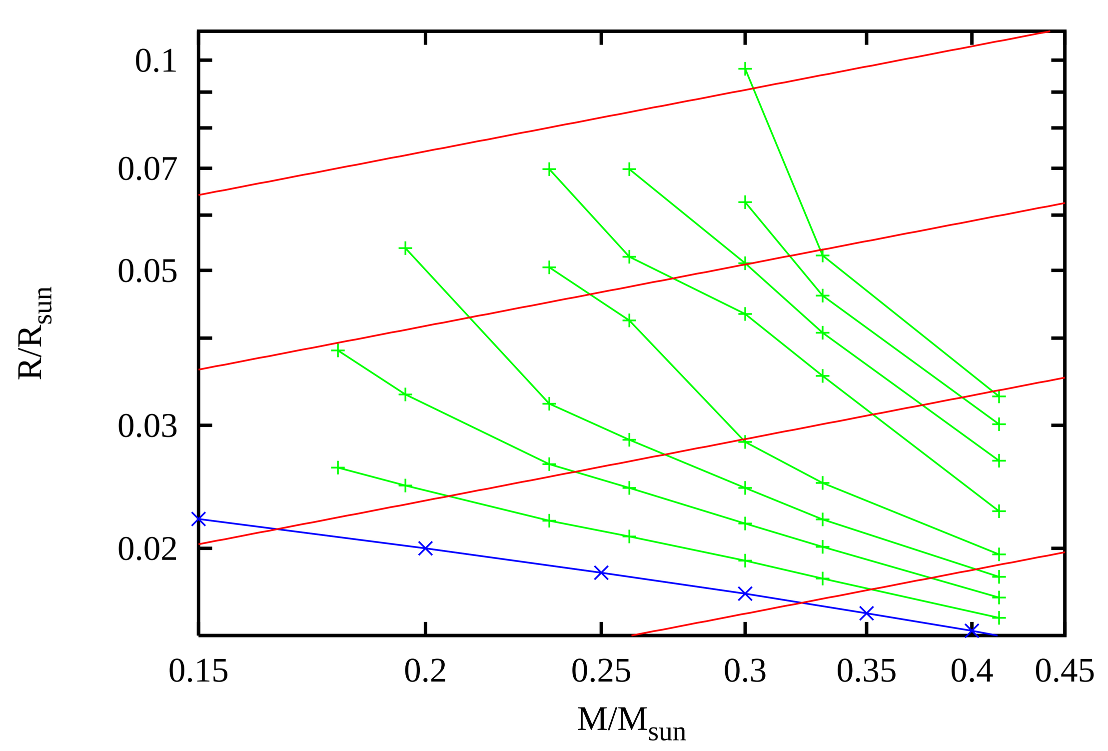

Figure 2: Mass-radius relation for He-WDs at different $T_{\rm eff}$, calculated from our evolutionary models from $T_{\rm eff} = 40000$ K (upper green line) down to $T_{\rm eff} = 5000$ K (lower green line) in steps of $\Delta T_{\rm eff} = 5000$ K. For comparison also the $T = 0$ K relation of Hamada & Salpeter (1961) for pure helium models (blue line) is given. Along the red lines gravity is constant, with (from above) $\log g = 6.0, 6.5, 7.0$ and 7.5).

Our mass-radius relation for helium white dwarfs (Fig. 2) shows large evolutionary effects and deviations from the $T = 0$ K relation of Hamada & Salpeter (1961). Note that temperatures larger than 10 000 K are not reached by RGB remnants of too low a mass (see Fig. 1). The strong dependence of our relation on $T_{\rm eff}$ reflects mainly the decrease of the hydrogen envelope mass due to residual hydrogen burning.

With this mass-radius-relation Driebe et al. (1998) derived the mass of the He-WD companion of the MSP PSR J1012+5307 with the spectroscopic data of van Kerkwijk et al. (1996) and Callanan et al. (1998):

	Callanan et al. (1998)	van Kerkwijk et al. (1996)
$\log g [\mathrm{cm/s^2}]$	6.34 ± 0.20	6.75 ± 0.07
$T_{\rm eff}$ [K]	8670 ± 300	8550 ± 25
$M_{\rm He-WD} [\mathrm{M}_\odot]$	0.16 ± 0.02	0.16 ± 0.02
$M_{\rm He-WD,D} [\mathrm{M}_\odot]$	0.15 ± 0.02	0.19 ± 0.02
$M_{\rm pulsar,K} [\mathrm{M}_\odot]$	1.43 ± 0.25	1.81 ± 0.25
$M_{\rm pulsar,C} [\mathrm{M}_\odot]$	1.59 ± 0.30	2.00 ± 0.30

Table 1: $\log g, T_{\rm eff}$ and derived masses ($M_{\rm He-WD}$) for the PSR J1012+5307 He-WD. $M_{\rm He-WD,D}$: He-WD mass from Driebe et al. (1998). $M_{\rm pulsar,K}$: pulsar mass based on the mass ratio $M_{\rm pulsar}/M_{\rm He-WD} \approx 9.5 \pm 0.3$ (van Kerkwijk et al. 1998, priv. comm.) and $M_{\rm He-WD,D}$. $M_{\rm pulsar,C}$: pulsar mass based on the mass ratio from Callanan et al. (1998) ($M_{\rm pulsar}/M_{\rm He-WD} \approx 10.5 \pm 0.5$) and $M_{\rm He-WD,D}$.

The age of PSR J1012+5307

From our cooling models we found a white dwarf age of $\approx 6 \cdot 10^9$ yrs in excellent agreement with the pulsar's spin-down age of $7 \cdot 10^9$ yrs (see Fig. 3). The cooling age is significantly lower when hydrogen burning is not considered (see Fig. 4).

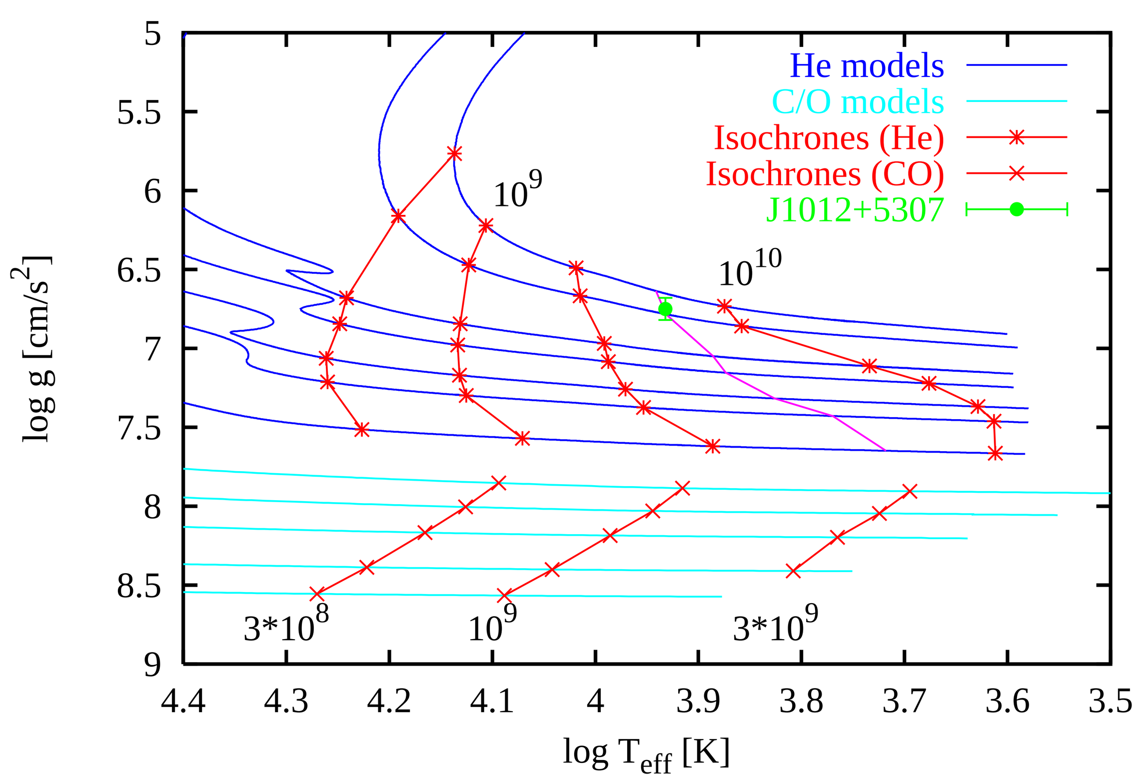

Figure 3: $\log g - \log T_{\rm eff}$ diagram with evolutionary tracks for He-WDs (Driebe *et al.* (1998), see Fig. 1) and for C/O-WDs (Blöcker (1995), masses from above: 0.524, 0.605, 0.696, 0.836, 0.940 (light blue curves, $\log g > 7.7$), resp. Also shown are the position of the companion of the MSP PSR J1012+5307 (green, data from van Kerkwijk *et al.* 1996) and isochrones (red lines) for cooling ages of $\tau = 3 \cdot 10^8$ yrs, $1 \cdot 10^9$ yrs, $3 \cdot 10^9$ yrs and 10^{10} yrs (from left to right, last isochrone only for He-white dwarfs). The isochrones for the He-WDs are turned over and shifted to the left because hydrogen burning slows down the evolution so much. The pink line denotes the isochrone $\tau = 6 \cdot 10^9$ yrs which fits the position of the white dwarf in the PSR J1012+5307 system.

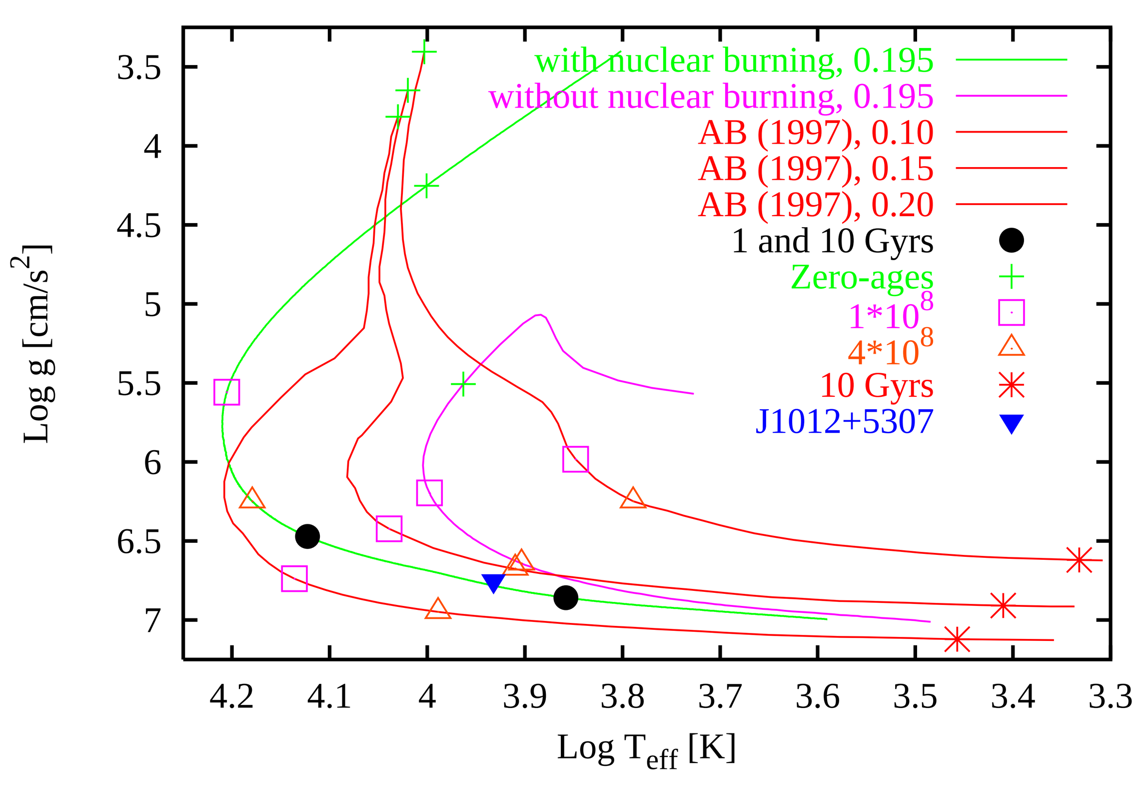

Figure 4: $\log g - \log T_{\rm eff}$ diagram with our tracks for $M = 0.195\,\mathrm{M}_\odot$ with and without consideration of nuclear burning (green and pink line). Also shown are the tracks of Althaus & Benvenuto (1997) for $M = 0.1, 0.15$ and $0.2\,\mathrm{M}_\odot$ (AB, red lines, no burning) as well as time marks for different cooling stages as indicated. Additional circles mark cooling ages of our evolutionary model of 1 and 10 Gyr, resp. All ages are counted from a pre-white dwarf stage close to $T_{\rm eff} = 10\,000$ K. The filled triangle marks the position of the PSR J1012+5307 white dwarf.

Other MSP systems

We studied a couple of other He-WDs in MSP systems (see Fig. 5) assuming the correspondence of white dwarf cooling age and pulsar spin-down age. Using our white dwarf models (see Fig. 3) we determined the effective temperatures of the MSP companions. The results are shown in Table 2. Obviously, the consideration of fully evolutionary He-WD models is crucial for the determination of the effective temperature.

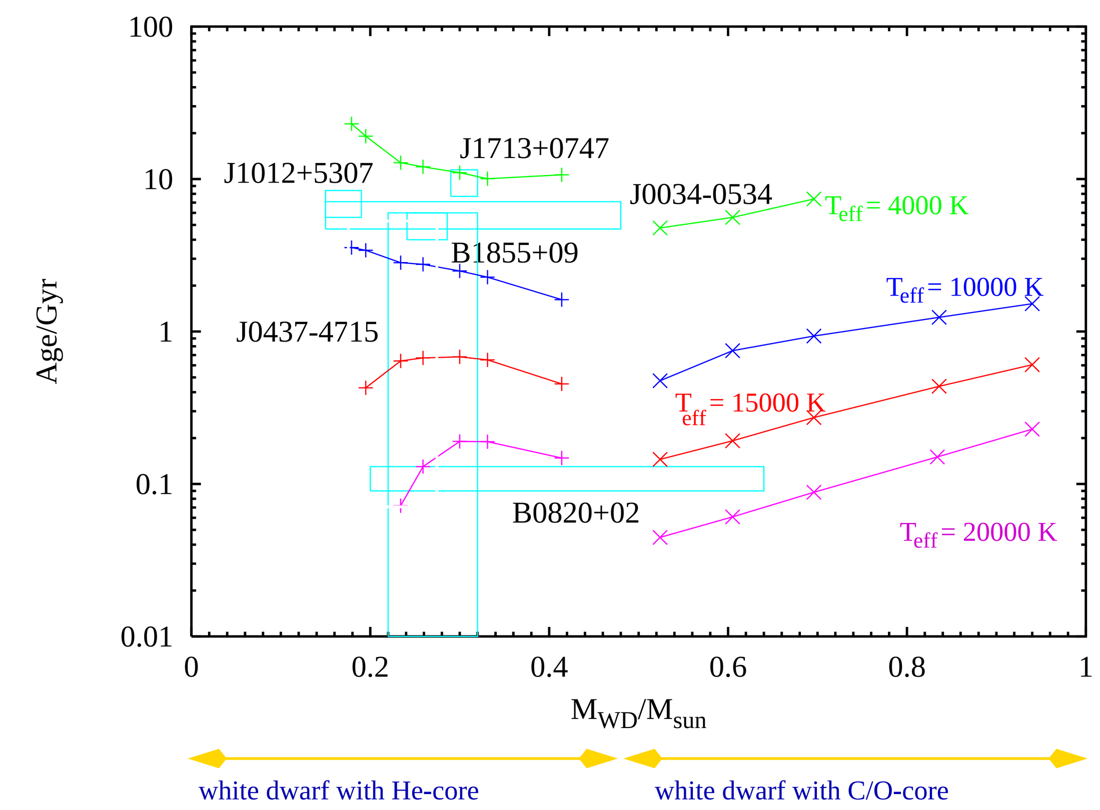

Figure 5: Ages of millisecond pulsar systems as a function of the white dwarf companion mass. Derived cooling ages of white dwarfs with helium and carbon/oxygen core are given for different effective temperatures. Also shown is the possible white dwarf mass range for 6 MSP systems based on pulsar measurements (see Burderi et al. 1998) and the pulsars' spin-down ages. Estimations of the white dwarf effective temperature for these systems are summarized in Table 2. Note, that for J0437-4715 only an upper limit of $\tau_{\rm spin-down}$ is known.

MSP system	$T_{\rm eff,WD} [K]$
J0034-0534	6000. . . 8000
J0437-4715	>7000
J1012+5307	7000. . . 9000
J1713+0747	4000. . . 5000
B0820+02	20000. . . 22000 (He core)
B0820+02	15000. . . 18000 (C/O core)
B1855+09	7000. . . 9000

Table 2: Estimates of $T_{\rm eff}$ of white dwarf companions in MSP systems if $\tau_{\rm spin-down} = \tau_{\rm WD}$ (see Fig. 5) is assumed.

Summary

⇒ Our He-WD models show residual hydrogen burning down to very low effective temperatures, resulting in cooling ages of the order of Gyr, i. e. the same order of magnitude as spin-down ages of millisecond pulsars.

⇒ The mass-radius-relation for He-WDs shows significant evolutionary effects due to the residual nuclear burning.

⇒ Ongoing hydrogen burning in He-WDs is provided by large envelope masses which decrease with increasing white dwarf mass $M_{\rm WD}$ ($\approx 10^{-3}\ \mathrm{M}_\odot$ for $M_{\rm He-WD} = 0.2\ \mathrm{M}_\odot$ compared to $\approx 10^{-6}\ \mathrm{M}_\odot$ for $M_{\rm C/O-WD} = 1.0\ \mathrm{M}_\odot$, see Blöcker et al. 1996)

⇒ Contrary to the heavier C/O white dwarfs He-WDs cool down the slower the smaller the white dwarf mass.

⇒ Hydrogen shell flashes occur *only* in the mass range from $M_{\rm WD} = 0.21$ to $0.30\,\mathrm{M}_\odot$. (see Driebe et al. 1999) These mass limits can be explained by quenching effects, either due to the increasing geometrical thickness of the burning region with decreasing core mass (lower limit), or due to efficient cooling of the thin burning shell (upper limit).

⇒ For the PSR J1012+5307 system we derived a cooling age of 6 Gyr for the white dwarf companion, consistent with the pulsar's spin-down age of 7 Gyr.

⇒ From our calculations we determined $(T_{\rm eff}, g)$ data for white dwarf companions of other MSP systems assuming $\tau_{\rm WD} = \tau_{\rm spin-down}$.

References

Alberts, F., Savonije, G.J., van der Heuvel, E.P.J. 1996, *Nature* **380**, 676
Blöcker, T. 1995, *A&A* **297**, 727
Blöcker, T., Herwig, F., Driebe, T., Bramkamp, H., Schönberner, D. 1996, The impact of evolutionary envelope masses on the evolution of white dwarfs; In: *White Dwarfs*, eds.: J. Isern, M. Hernanz, E. Garcia-Berro; Dodrecht, Kluwer
Burderi, L., King, A. R., Wynn, G. A. 1998, *MNRAS* **300**, 1127
Callanan, P. J., Garnavich, P. M., Koester, D. 1998, *MNRAS* **298**, 207
Castellani, V., Luridiana, V., Romaniello, M. 1994, *ApJ.* **428**, 633
Driebe, T., Schönberner, D., Blöcker, T., Herwig, F. 1998, *A&A* **339**, 123
Driebe, T., Blöcker, T., Schönberner, D., Herwig, F. 1999, *A&A* in press
Hansen, B. M. S., Phinney, E. S. 1998a, *MNRAS* **294**, 557
Hansen, B. M. S., Phinney, E. S. 1998b, *MNRAS* **294**, 569
Iben Jr., I., Tutukov, A.V. 1986, *ApJ.* **311**, 742
van Kerkwijk, M.H., Bergeron, P., Kulkarni, S.R. 1996, *ApJ.* **467**, L89
Kippenhahn, R., Thomas, H.-C., Weigert, A. 1968, *Zs. f. Astrophysik* **69**, 265
Nicastro, L., Lyne, A. G. Lorimer, D. R. et al. 1995, *MNRAS* **273**, L68
Sarna, M. J., Antipova, J., Muslimov, A. 1998, *ApJ.* **499**, 407

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