The Physics of Cataclysmic Variables and Related Objects
ASP Conference Series, Vol. XXX, 2002
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On the evolution of interacting binaries which contain a white dwarf

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Abstract. We discuss the evolution of white dwarf containing binaries, in particular such systems consisting of a white dwarf and a main sequence star which have the potential to produce a Type Ia supernova. After investigating current problems in connecting observations of supersoft X-ray sources with such systems, we consider two major problems which theoretical models encounter to produce Chandrasekhar-mass white dwarfs: the helium shell burning instability and the white dwarf spin-up. We conclude by suggesting that the formation of Chandrasekhar-mass white dwarfs may be easier when these two problem are considered simultaneously.

1. Introduction

Close binaries consisting of a degenerate and a non-degenerate star — e.g. of an unevolved star and one which has completed its evolution — are not as rare as one might expect. Of Cataclysmic Variables, the main topic of this conference, we know more than 300 (Downes et al. 2001). Such systems are not rarer since stars of different masses have vastly different life times. I.e., while the initially more massive star in a binary may already be “dead”, its companion may still be at the very beginning of its evolution. And as stars spend most of their life on the main sequence, the pairing of a main sequence star and a white dwarf is the most common variety of single degenerate binaries. We will concentrate on such systems in the following.

The combination of a main sequence star and a white dwarf in a close binary system can result in a large number of highly spectacular and astrophysically interesting phenomena. We need a *close* binary, as the spectacle begins when the main sequence star, which expands due to its nuclear evolution — core hydrogen burning —, fills its critical volume and starts to transfer mass onto the white dwarf. Depending on the rate at which the white dwarf receives hydrogen-rich matter, hydrogen burning and subsequently helium burning may occur on top of its C/O-body, either steadily or — more likely — thermally unstable or even

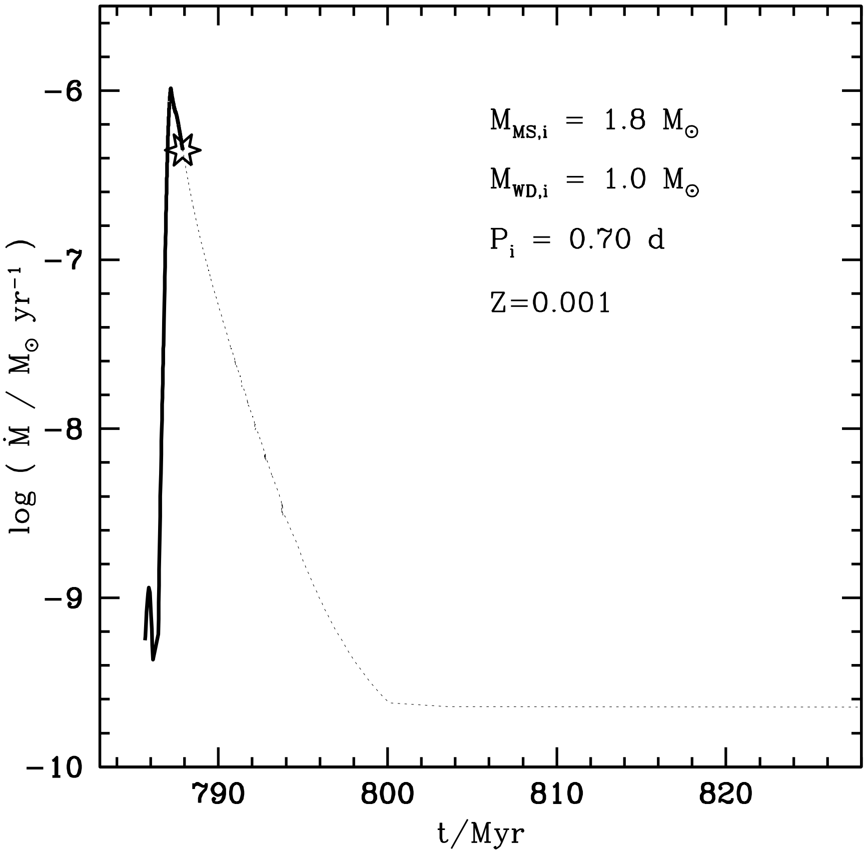

Figure 1. Evolution of the mass transfer rate as function of time, for a binary consisting initially of a $1.8\,M_\odot$ main sequence star and a $1\,M_\odot$ white dwarf in a 0.7 d orbit. The line is drawn fully until the white dwarf reaches $1.4\,M_\odot$ (star symbol). The calculation is continued assuming the compact star can accrete further (dotted part of the line; cf. Langer et al. 2000). The first phase of high mass transfer rates may correspond to the supersoft X-ray sources. After its decay ($t > 800\,$Myr), the system is CV-like; only the beginning of this second phase of low mass transfer rates is shown.

explosive. Here, we discuss such systems which have the potential to explode the whole white dwarf, i.e. to produce a Type Ia supernova.

2. Supersoft X-ray Sources

The regime of steady nuclear burning in the outer layers of an accreting C/O-white dwarf is essential to produce Chandrasekhar-mass white dwarfs — the currently favoured Type Ia supernova progenitors (Livio 2000). In order to achieve this, the white dwarf accretion rate needs to remain in a very limited range

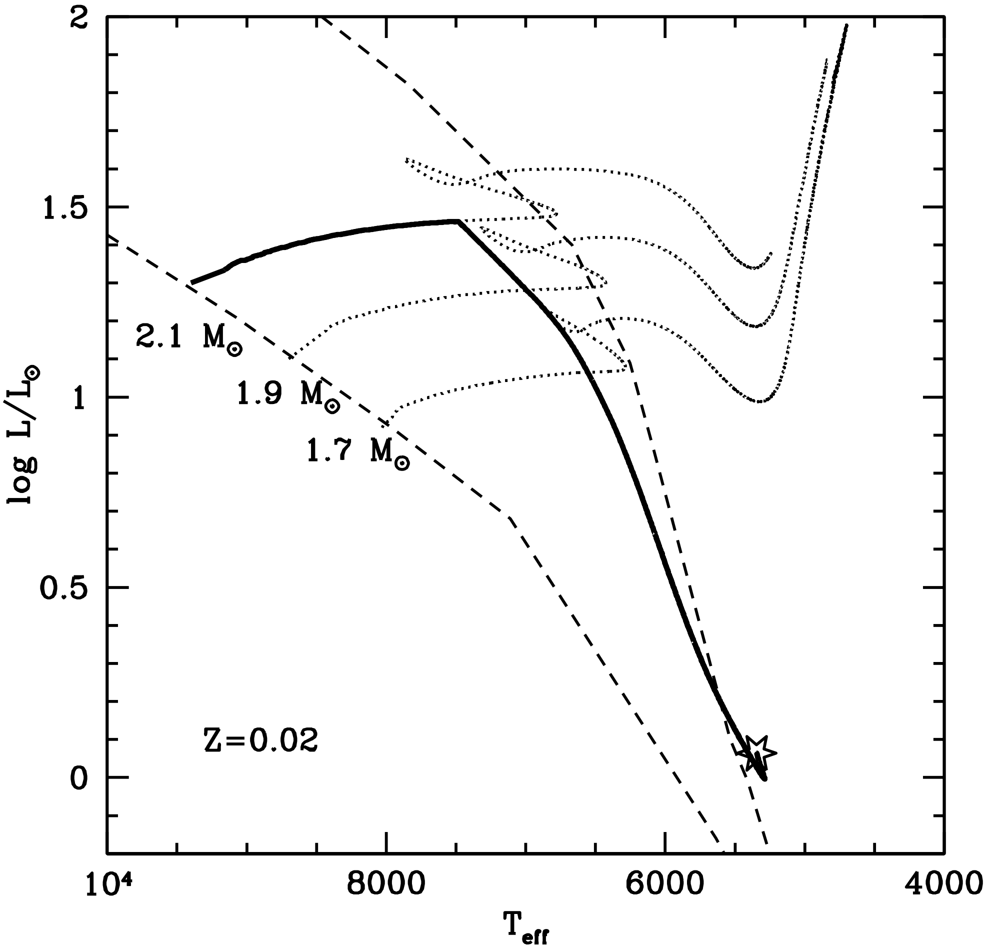

Figure 2. Evolution in the HR diagram of a $2.1\,\mathrm{M}_\odot$ donor star having an $0.8\,\mathrm{M}_\odot$ white dwarf in an orbit with a period 1.23 d (thick solid line). The track ends at a time when the white dwarf mass reaches $1.4\,\mathrm{M}_\odot$ (star symbol). For comparison, evolutionary tracks for single stars with $2.1\,\mathrm{M}_\odot$, $1,9\,\mathrm{M}_\odot$, and $1.7\,\mathrm{M}_\odot$ (dotted lines), and the zero and terminal age main sequence (dashed lines) are shown.

(Nomoto & Kondo 1991), which — for a main sequence donor star — translates into a very limited range of donor star masses: roughly $1.5\,\mathrm{M}_\odot \ldots 2.5\,\mathrm{M}_\odot$ (Hachisu et al 1996; Li & van den Heuvel 1997; Langer et al. 2000). The lower limit comes from the constraint that the donor star should be more massive than the white dwarf in order to obtain high enough accretion rates. I.e., $\dot{M} \simeq M_{\rm d}/\tau_{\rm th}$, $M_{\rm d}$ being the mass of the donor star and $\tau_{\rm th}$ its thermal time scale. Once the white dwarf becomes more massive than the donor, the mass transfer leads to a widening of the orbit and the mass transfer rate drops by many orders of magnitude (cf. Fig. 1).

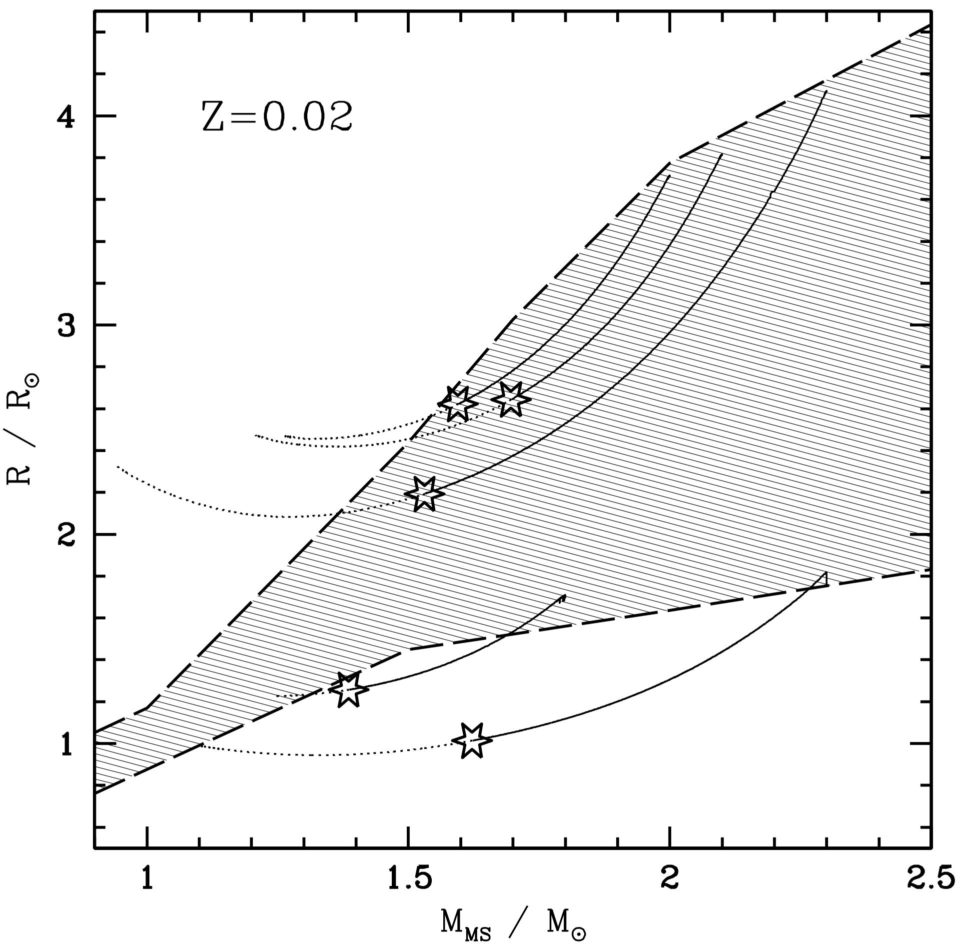

Figure 3. Evolutionary tracks of main sequence donor stars with white dwarf companions throughout the thermally unstable mass transfer phase are shown in the mass-radius diagram. As in Fig. 1, it is $M_{\rm WD} < 1.4\,\mathrm{M}_\odot$ for the solid part of the lines, and — for illustrative purpose — $M_{\rm WD} > 1.4\,\mathrm{M}_\odot$ for the dotted part. Hatching identifies the area of core hydrogen burning single stars, bounded by the zero age (lower dashed line) and terminal age main sequence mass-radius relations (upper dashed line). The two lower tracks correspond to systems with the smallest possible initial periods, i.e. where the main sequence donor fills its Roche lobe early during core hydrogen burning (cf. Langer et al. 2000, for more details).

The single degenerate SN Ia progenitor scenario has the advantage over other scenarios that it may have observed counterparts: the supersoft X-ray sources. Indeed, steady nuclear burning in a white dwarf results in effective temperatures of $0.5\ldots1\times10^6\,$K, and a luminosity of the order of the white dwarf's Eddington luminosity — which roughly fits to the observed supersoft sources (Greiner 2000). About half of them are also binaries with orbital periods of the order of one day. However, the following two problems with this idea have been discussed recently. First of all, so far neither the white dwarf nor the main sequence companion have ever been unambiguously identified in any of the sources. And secondly, some of the systems have orbital periods which appear too short to allow for a main sequence star fitting into the system. We believe that both problems are connected and may have their root in the fact that the main sequence donor stars are quite extraordinary: unlike normal main sequence stars, their interior grossly deviates from thermal equilibrium.

Fig. 2 shows the evolution of a $2.1\,\mathrm{M}_\odot$ donor star in the HR diagram, from hydrogen ignition until and throughout much of the mass transfer evolution. Its luminosity can be seen to drop by as much as a factor of 30, mostly due to the mechanical work which the expanding envelope has to provide against the stellar gravitational potential. Only if the envelope expansion time were large against its thermal time scale could the mechanical energy loss be compensated by the core's nuclear fusion; this is not the case here. Thus, the donor star is extremely underluminous.

The thermal time scale mass transfer is initiated by the shrinkage of the orbit as a consequence of angular momentum conservation, as long as $M_\mathrm{d} > M_\mathrm{WD}$: the Roche lobe filling main sequence star is squeezed into a continuously shrinking volume. Fig. 3 demonstrates that the stellar radius can fall much below the zero-age main sequence mass-radius relation. Consequently, orbital periods can be achieved which are smaller by a factor f than periods corresponding to unperturbed main sequence stars filling their Roche lobes. For conservative systems, this factor is given by

$$f = P_\mathrm{min}/P_\mathrm{i} = \left(\frac{4q_i}{(q_i+1)^2}\right)^3 , \qquad (1)$$

with $q_i = M_\mathrm{WD,i}/M_\mathrm{MS,i}$, and the index i referring to the initial situation, i.e. to the time before the mass transfer. I.e., for reasonable initial mass ratios, say $q_i > 0.4$, periods of up to a factor of 2 smaller than with unperturbed donors are achieved. Thereby, orbital periods of 4 hours and smaller are conceivable with the thermal time scale mass transfer scenario (Langer et al. 2000).

3. Helium shell flashes

As discussed above, supersoft X-ray sources may be compatible with the scenario of accreting white dwarfs which burn hydrogen steadily. However, not for all accretion rates for which hydrogen burns steadily does helium burning proceed steadily as well. As discussed by Cassisi et al. (1998) and Kato & Hachisu (1999), helium shell burning may instead become unstable. The corresponding instability can be modelled by computing helium accreting C/O-white dwarfs — which simulates continuous hydrogen shell burning. Helium shell burning can become unstable due to two ingredients. Firstly, the helium-rich layers may become somewhat degenerate, especially for small accretion rates. And secondly, the larger the white dwarf mass the smaller is the radius of the degenerate C/O-core, and the smaller is the geometrical thickness of the helium burning shell.

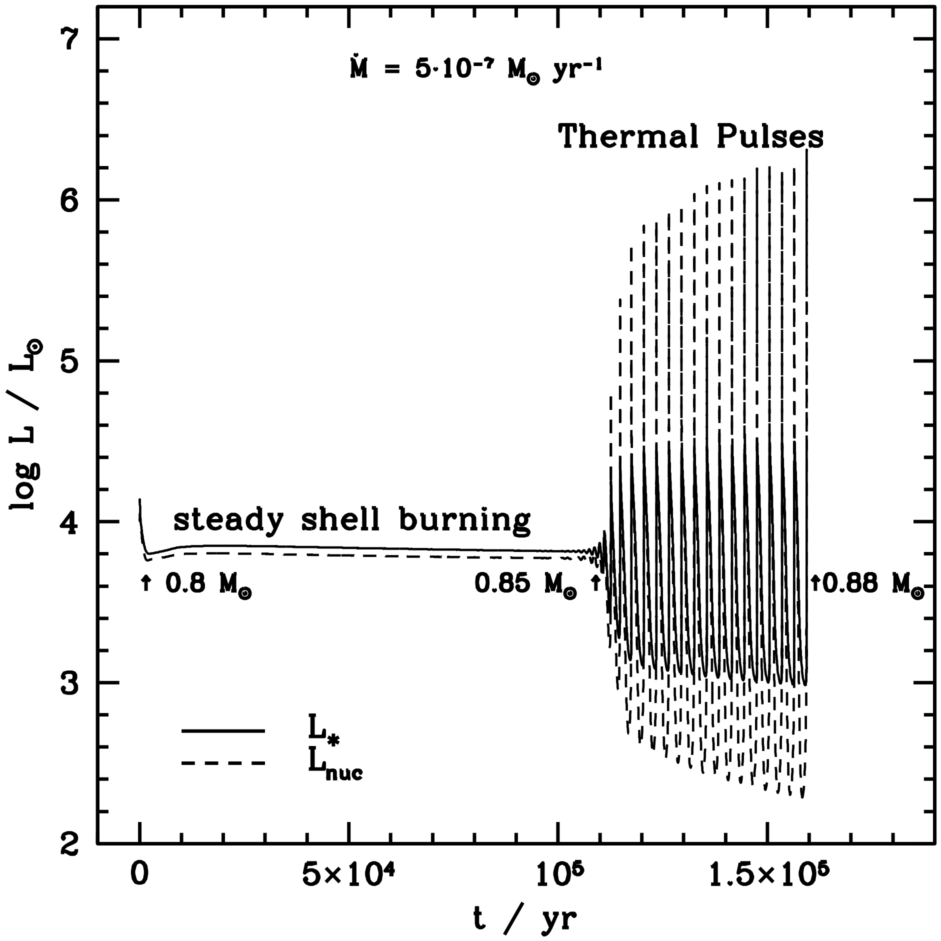

Figure 4. Stellar and nuclear luminosity as function of time for a C/O-white dwarf model starting at $0.8\,\mathrm{M}_\odot$, which accretes helium at a constant rate of 5×10^{-7} $\mathrm{M}_\odot$ yr^{-1} (cf. Scheithauer 2000).

And thin helium burning shells undergo the same thermal instability which drives the thermal pulses in evolved AGB stars — even if the helium shell is non-degenerate.

Fig. 4 gives an example: a C/O-white dwarf of initially $0.8\,\mathrm{M}_\odot$ which accretes at a rate of 5×10^{-7} $\mathrm{M}_\odot$ yr^{-1} undergoes stable helium shell burning for more than 10^5 yr, accreting thereby $0.05\,\mathrm{M}_\odot$. During this stage, the system might represent a supersoft X-ray source (cf. Sect. 2). However, the helium shell becomes violently unstable once the white dwarf mass grows further. And clearly, the amplitude of the instability grows the more massive the white dwarf becomes.

The helium shell burning instability has two consequences. As Fig. 4 implies, not only the nuclear luminosity ($\int_M \varepsilon_{nuc} dM$) becomes large at the peak of the instability, but also the surface luminosity. Quickly, values exceeding the white dwarf's Eddington luminosity are achieved. This will lead to radiation driven mass loss from the white dwarf (cf. Kato & Hachisu 1999), which questions whether it can ever reach the Chandrasekhar limit.

Secondly, even though the helium shell instability proceeds on a time scale which is long compared to the hydrodynamic time scale — i.e. there is no mass ejection due to the inertia of the expanding envelope — the white dwarf may be driven to obtain a large radius. Being in a compact binary, this may result in a contact or common envelope situation in which the least hazardous thing happening to the white dwarf would again be: it may lose its extended envelope and fail to reach the Chandrasekhar mass.

4. White dwarf spin-up

As we have seen above, it is not easy for a white dwarf to accrete in such a way that it can grow to the Chandrasekhar limit. However, there is one more problem which has not been mentioned yet: the angular momentum problem. Most white dwarfs accrete via an accretion disk. Therefore, the specific angular momentum of the accreted matter may correspond to that of matter rotating at Keplerian speed at the white dwarf equator, i.e.

$$j = 3 \times 10^{17} \sqrt{\frac{M}{\mathrm{M}_\odot} \frac{R}{0.01\,\mathrm{R}_\odot}}\ \ \mathrm{cm}^2\,\mathrm{s}^{-1} \quad . \tag{2}$$

It may be a good approximation to neglect the angular momentum in the white dwarf before it starts accreting — both, observations (Heber et al. 1997; Koester et al. 1998) and stellar evolution models (cf. Fig. 5) find small spin rates of isolated white dwarfs. However, assuming the white dwarf always rotates as a solid body implies that it approaches critical rotation as

$$\Omega = \frac{\omega}{\omega_{\mathrm{crit}}} = \frac{3}{4k^2} \left(1 - \left(\frac{M_{\mathrm{WD,i}}}{M_{\mathrm{WD}}} \right)^{4/3} \right) \tag{3}$$

with ω and ω_{crit} being its rotation and critical rotation frequency (Langer et al. 2000). With a gyration constant of $k = 0.4$ (Ritter 1985) this means that white dwarfs with an initial mass of $M_{\mathrm{WD,i}} = 0.6\,\mathrm{M}_\odot$, $0.8\,\mathrm{M}_\odot$, and $1.0\,\mathrm{M}_\odot$ reach critical rotation at $0.71\,\mathrm{M}_\odot$, $0.96\,\mathrm{M}_\odot$, and $1.20\,\mathrm{M}_\odot$, respectively.

The real situation may be worse, as the time scale to transport the angular momentum from the white dwarf surface into its degenerate core need to be considered. Clearly, any finite angular momentum redistribution time makes the white dwarf envelope reach critical rotation earlier (cf. Yoon & Langer 2002, Yoon et al. 2002). Without any doubt, if Chandrasekhar mass white dwarfs are responsible for Type Ia supernovae, there must be a way to remove angular momentum from the accreting stars of from the accreted material. At present, it is an open question of how this can be achieved (cf. Livio & Pringle 1998).

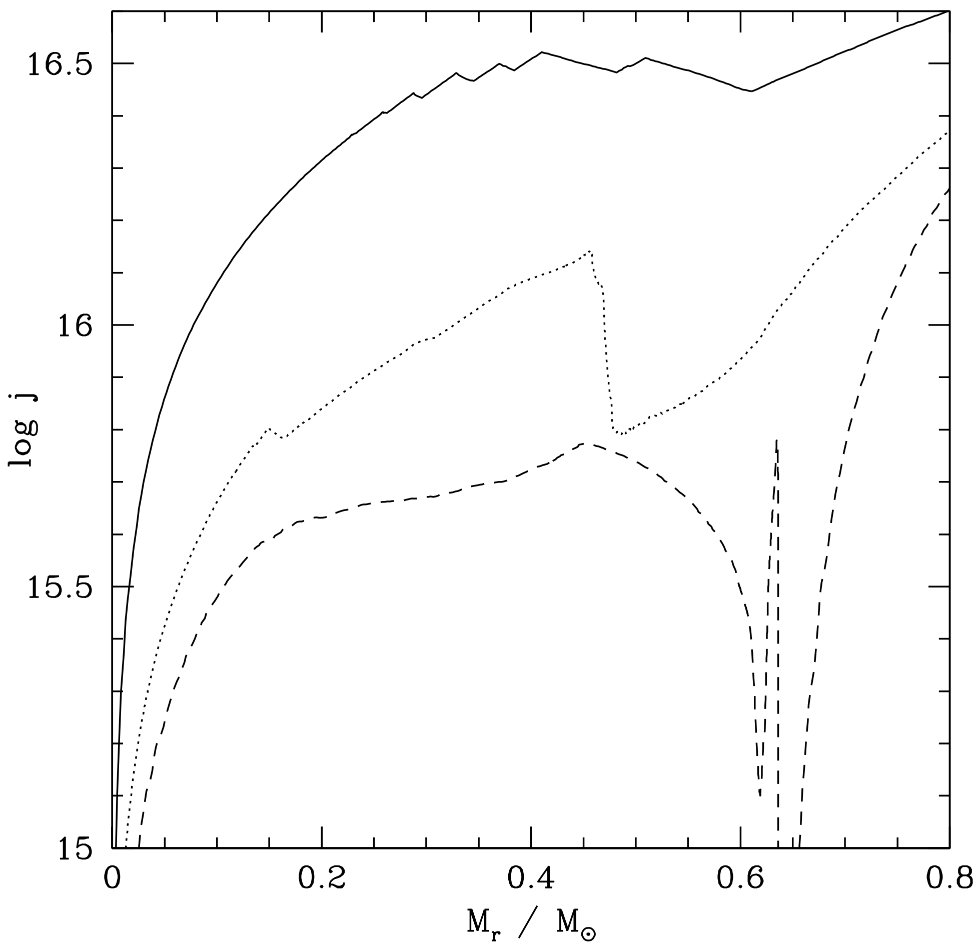

Figure 5. Logarithm of the local specific angular momentum (in $cm^2\,s^{-1}$) as function of the Lagrangian mass coordinate inside the star, for three different times during the evolution of a $3\,M_\odot$ single star model which was computed including the physics of rotation (cf. Langer et al. 1999): at core hydrogen exhaustion ($t \simeq 3.3\,10^8$ yr, solid line), during core helium burning ($t \simeq 3.8\,10^8$ yr, dotted line), and between the 14th and the 15th thermal pulse on the AGB ($t \simeq 4.4\,10^8$ yr, dashed line). The inner $\sim 0.6\,M_\odot$ of the last model show that the white dwarf formed in this sequence has a small average specific angular momentum of about $3 \times 10^{15} cm^2\,s^{-1}$.

5. Outlook

Type Ia supernovae exist, and their spectra appear most consistent with models of exploding Chandrasekhar-mass white dwarfs (Höflich et al. 1998). I.e., there is likely a solution to the problem of unstable shell burning and spin-up in accreting white dwarfs. There may be one promising line of though which combines both: to investigate the effect of rotation on the behaviour of the burning shells. In preliminary models, Yoon & Langer (2002) find that rapidly rotating white dwarfs can stabilise their otherwise unstable helium shells. In the near future, we will investigate this effect in detail in order to understand whether it has the potential to alleviate the problem of forming Chandrasekhar-mass white dwarfs.

Acknowledgments. This work has been supported by the Nederlandse Organisatie voor Wetenschappelijk Ondersoek grant No. 614.21.015, and by the Deutsche Forschungsgemeinschaft through grant No. La 587/15-2

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