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Helium white dwarf mergers as progeny for extreme helium stars

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Abstract. The origin of extreme helium stars poses a significant puzzle for stellar astrophysics. This paper summarizes the observational data concerning extreme helium stars in general, and one, V652 Her, in particular. One proposal involves the merger of two white dwarfs in a binary. Here, the rapid accretion of helium onto a helium white dwarf is used to simulate the merger of two helium white dwarfs. Helium-shell ignition occurs at the boundary between degenerate and non-degenerate helium after sufficient helium has been accreted, causing the star to become a yellow giant. Thereafter, the helium-burning shell burns in to the core, and the star contracts towards the helium main sequence where it will appear as a subdwarf B star. About halfway through this contraction, the model dimensions compare favourably with observations of mass, luminosity, effective temperature, surface composition, pulsation period and pulsation period change in V652 Her. Competing models, such as the 'late thermal pulse' model for example, fail to achieve such agreement. The merged binary white dwarf hypothesis emerges, therefore, as the preferred explanation for the origin of at least some extreme helium stars.

1. Introduction

The likely outcome of the evolution of two stars in a detached binary is a pair of white dwarfs with masses of $\sim 0.6\,M_\odot$ or below. Increasing numbers of such binaries are now being discovered. With no nuclear reserves, their evolution will be dominated by orbital decay as a consequence of gravitational radiation or magnetic-wind braking. Although the decay timescales remain contentious, it is reasonable to hypothesize that a substantial fraction of binary white dwarf orbits will decay completely within a Hubble time. The less massive white dwarf will fill a gravitational potential surface with the same potential relative to its companion causing its surface to spill over onto its companion. Tidal forces will take over and disrupt the less massive star, causing it to form a disorganized envelope, from whence its companion will start to accrete material. In loose terms, this describes the merger of two white dwarfs; a process that should become increasingly common as the stellar population of a galaxy ages.

This paper addresses the question of what happens when two low-mass white dwarfs with degenerate helium cores coalesce. Its motivation is an attempt to explain the evolutionary origin of extreme helium stars, a rare class of luminous stars with highly processed surfaces. The results have already been published elsewhere (Saio & Jeffery 2000). Most of the details are reproduced here to maintain the completeness of these conference proceedings.

2. Extreme Helium Stars

Extreme helium stars (EHes) are rare B- and A-type giant stars with extremely low surface abundances of hydrogen (Jeffery 1996). In most cases they are also characterized by enhancements of CNO-processed, 3α and α-capture products and the majority have $\log L/M > 4$ (as indicated by their surface gravities). A few have significantly lower L/M ratios and do not show 3α and α-capture products in their atmospheres (*e.g.* V652 Her, Jeffery, Hill, & Heber 1999). The major question concerning their evolutionary origin is whether they are the products of single-star or binary-star evolution. The task has been difficult from the outset because, in the normal evolution of single stars from the main sequence to the white dwarf phase, it seemed impossible to remove the hydrogen-rich surface. Two principal hypotheses emerged during the 1980's.

The 'merged binary white dwarf model' (MBWD: Webbink 1984; Iben & Tutukov 1984) considered the accretion of a white dwarf (WD) secondary onto a white dwarf primary, resulting in the ignition of a helium shell in the accreted envelope which forces the star to expand to become a cool giant. Subsequent evolution would follow the canonical post-AGB contraction to the white dwarf track, in the case of a CO+He WD merger, or contraction to the helium main-sequence – possibly giving a subdwarf B star – in the case of He+He WD merger (Iben 1990).

The 'late thermal pulse' model (LTP: Iben et al. 1983) considered what would happen when the helium layer remaining near the surface of a star at the end of AGB evolution was of such a mass that a final thermal pulse would occur after the star had become a white dwarf, also forcing the star to expand rapidly. Again, subsequent evolution would resemble the canonical post-AGB sequence.

The LTP model has been studied extensively in recent years (Iben & MacDonald 1995; Blöcker & Schönberner 1997) and used to discuss the origins of various hydrogen-deficient stars. Part of the success of LTP models has been due to the very large degree of freedom allowed in reproducing a wide range of surface compositions, from s-process elements in R CrB stars (Bond, Luck, & Newman 1979; Lambert & Rao 1994) to very high C and O concentrations in PG1159 and [WC] stars (Werner, Heber, & Hunger 1991; Leuenhagen, Heber, & Jeffery 1996). The LTP model has also been supported by the rapid evolution from WD to cool giant observed in V605 Aql (Pollacco et al. 1992), FG Sge (Herbig & Boyarchuk 1968) and V4334 Sgr (Duerbeck & Benetti 1996), all of which are hydrogen-deficient to some extent. However another part of the success of the LTP model may have been due to the absence of detailed numerical MBWD models. In particular the LTP model cannot account for all EHes, especially the low-luminosity EHe V652 Her.

3. V652 Her

V652 Her is an exceptional helium star. It first attracted attention because of the discovery of radial pulsations with a period of 0.108 d (Hill et al. 1981). These pulsations have provided remarkably precise dimensions $(M, L, R, T_{\rm eff})$ for V652 Her which tightly constrain evolution models.

The effective temperature $\log T_{\rm eff} = 4.370 \pm 0.025$ (Lynas-Gray et al. 1984) adopted here was based on ultraviolet spectrophotometry. Baade's method was used by the same authors to determine the radius and hence the luminosity $\log L/L_{\odot} = 3.03 \pm 0.12$. We note that Jeffery et al. (1999) give a slightly higher effective temperature for V652 Her. With a spectroscopic measurement of the surface gravity, the stellar mass has then been obtained directly, as $0.7^{+0.4}_{-0.3} M_{\odot}$ by Lynas-Gray et al. (1984) and $0.69^{+0.15}_{-0.12} M_{\odot}$ by Jeffery et al. (1999).

The pulsations have provided yet more constraints on evolution models since the period was found to be decreasing at a rate $\mathrm{d}P/\mathrm{d}n = -8.3 \times 10^{-9}$d (Kilkenny & Lynas-Gray 1982; Kilkenny, Lynas-Gray, & Roberts 1996) commensurate with a secular contraction. Kilkenny et al. (1996) have also measured the second derivative of the period, $\mathrm{d}^2P/\mathrm{d}n^2 = 1.7 \times 10^{-14}$d.

The earliest observations of pulsation were extremely challenging since, as for β Cepheids, no excitation mechanism for driving the pulsations could be found. It was only the introduction of the OPAL opacities (Rogers & Iglesias 1992) that provided an explanation for why V652 Her should pulsate at all. The existence of an instability "finger" due to high opacity from iron-group elements at temperatures around 10^5 K in hydrogen-deficient stars with $T_{\rm eff} \sim 23\,000$ K was discovered by Saio (1993). The same opacity source drives β Cepheid pulsations. Subsequently, Fadeyev & Lynas-Gray (1996) were able to construct non-linear pulsation models which reproduced the radial-velocity and light curves of V652 Her with substantial precision. Their best models were obtained with $M = 0.72 M_{\odot}$, $T_{\rm eff} = 23\,500$ K, $L = 1062 L_{\odot}$, and $Z = 0.0156$.

For any highly evolved star, the surface chemical composition provides a fossil record of the previous evolution, although it may be difficult to decode. Jeffery et al. (1986, 1999) have shown that the extremely helium-rich surface of V652 Her is > 1 dex underabundant in carbon and oxygen and ~ 1 dex overabundant in nitrogen, indicating that it primarily comprises the residue of CNO-processed material. There is some residual hydrogen, $\sim 1\%$ by numbers, but no evidence of any helium-burning products. The abundances of other elements are typically solar, and the surface composition may be characterized by mass fractions of hydrogen, helium and metals as $X = 0.0017, Y = 0.9825, Z = 0.0158$.

In an attempt to interpret some of the earliest estimates of these quantities, Jeffery (1984) constructed models of a $0.7 M_{\odot}$ mass helium star contracting towards the helium main-sequence. Whilst able to reproduce the observed properties of V652 Her successfully, it was difficult to account for the initial conditions adopted for the evolution sequence – a 'helium-rich horizontal branch' model – within single-star evolution theory.

The LTP model introduced above provides an attractive alternative because it can, in principle, be fine-tuned to match many combinations of observables. However, its principal property is that of a helium-burning shell around a degen-

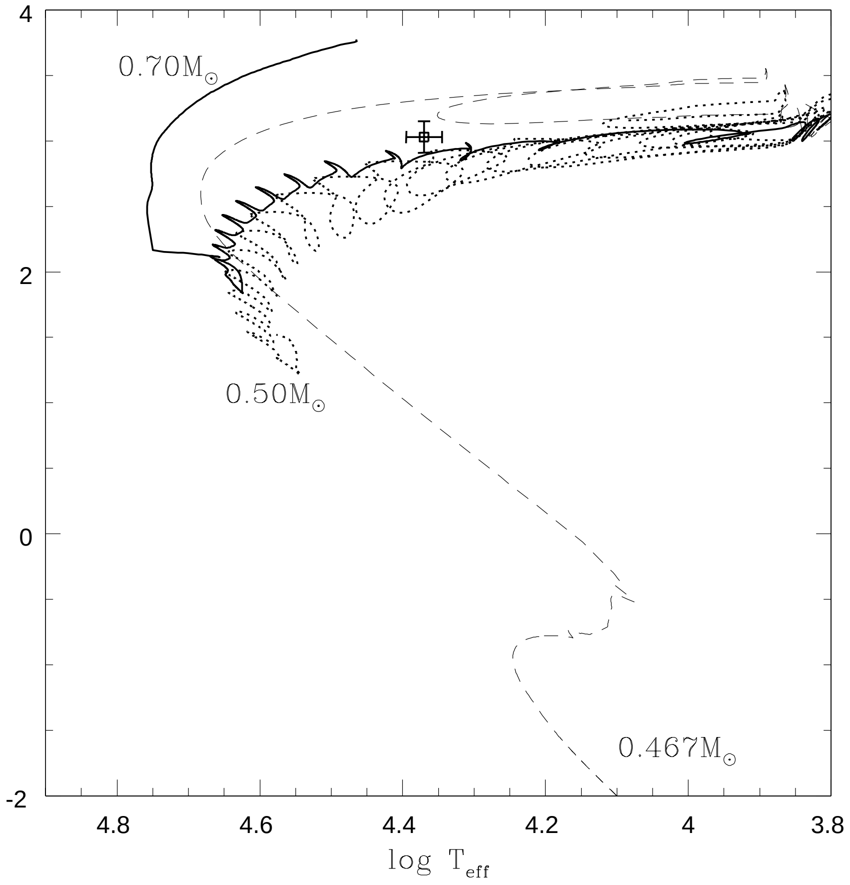

Figure 1. Evolutionary tracks starting with an accreting white dwarf of $0.4\,M_{\odot}$. The accretion was stopped when the total mass became $0.5\,M_{\odot}$ (dotted line) or $0.7\,M_{\odot}$ (solid line). The dashed line indicates the part in which accretion is switched on. The square with error bars shows the approximate position of V652 Her (Lynas-Gray et al. 1984)

erate carbon-oxygen core. Models with such properties are entirely inconsistent with the observations of V652 Her (Saio & Jeffery 2000).

4. Evolution Models

We have calculated evolutionary models starting with a low-mass white dwarf rapidly accreting helium-rich material ($Y = 0.98, Z = 0.02$). For the initial accretion phase, which is considered as a rough approximation of the merging process of a double white dwarf system, we have adopted an accretion rate of $1 \times 10^{-5}\,M_{\odot}\,\mathrm{yr}^{-1}$, which is about a half of the Eddington limit accretion rate for white dwarfs. Initial masses (M_{i}) of white dwarfs considered are $0.3\,M_{\odot}$ and $0.4\,M_{\odot}$. The accretion was stopped when the total mass increased to a pre-determined final mass. Considering that the final mass should be smaller

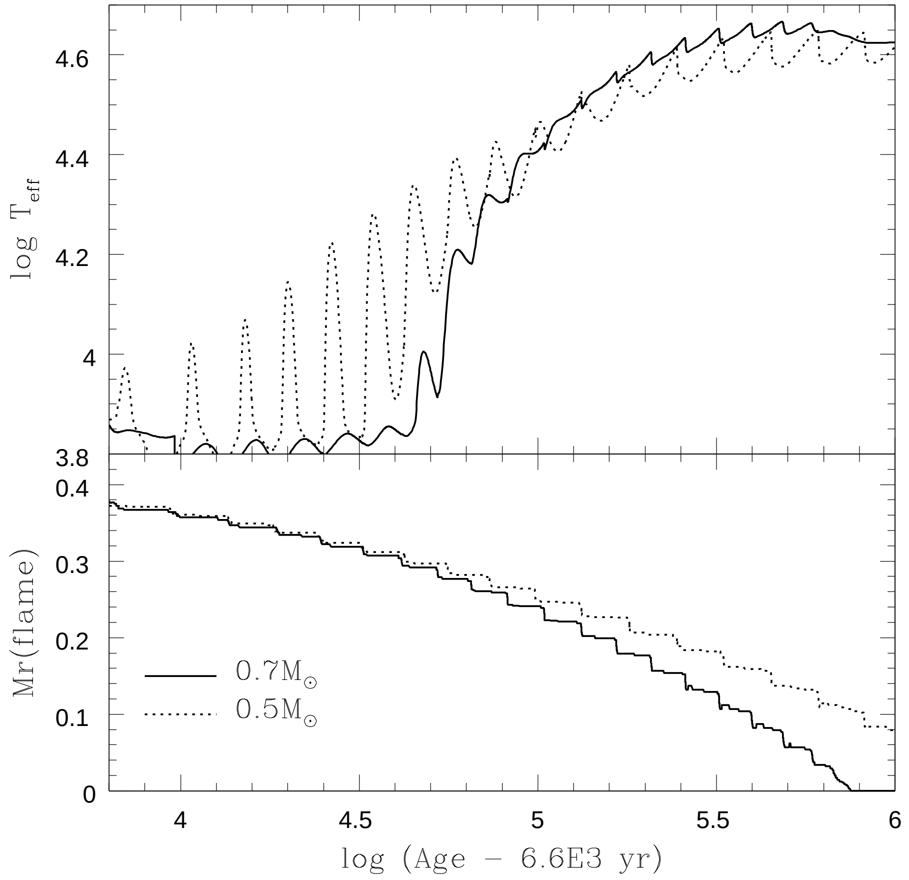

Figure 2. Evolutionary changes of the position of helium burning shell (lower panel) and the effective temperature (upper panel). The abscissa presents time after the first helium ignition. The initial mass is $0.4\,M_\odot$ for both cases.

than $2M_\mathrm{i}$, we have adopted final masses of $M_\mathrm{f} = 0.8, 0.7, 0.6$ and $0.5\,M_\odot$ for $M_\mathrm{i} = 0.4\,M_\odot$, and $M_\mathrm{f} = 0.6$ and $0.5\,M_\odot$ for $M_\mathrm{i} = 0.3\,M_\odot$. The computational method is the same as in Saio & Nomoto (1998) except that opacities have been obtained from OPAL95 tables (Iglesias & Rogers 1996).

Figure 1 shows evolutionary tracks for the cases of $M_\mathrm{f} = 0.5\,M_\odot$ and $0.7\,M_\odot$ with $M_\mathrm{i} = 0.4\,M_\odot$. The evolutionary tracks for the other cases are similar. The triple-alpha reaction is ignited at $M_r = 0.413\,M_\odot$ when the total mass has increased to $0.466\,M_\odot$ (for $M_\mathrm{i} = 0.3\,M_\odot$ these quantities are $0.278\,M_\odot$ and $0.5\,M_\odot$, respectively). It led to a shell-flash with a peak nuclear luminosity of $7.7 \times 10^7\,L_\odot$ (4.2×10^5 for $M_\mathrm{i} = 0.3\,M_\odot$). As the released energy migrates into the envelope, the radius as well as luminosity increases so that the star becomes a yellow giant in $\sim 10^3$yr. Accretion is stopped when the total mass reaches a pre-determined final mass, which occurs during the yellow-giant phase. Evolutionary tracks after the accretion phase are shown by solid ($M_\mathrm{f} = 0.7\,M_\odot$)

and dotted ($0.5\,M_\odot$) lines in Fig. 1, while the accretion phase is shown by a dashed line. The position of V652 Her is also shown.

The helium-burning shell moves inward with repeating shell flashes as described by Saio & Nomoto (1998). Figure 2 shows the temporal variation of the mass coordinate of the helium-burning shell, M_r(flame), and the effective temperature. Each flash phase corresponds to each sudden change in M_r(flame) in Fig 2. As the flame moves inward, the effective temperature increases gradually, although it fluctuates due to shell flashes. When $M_r(\text{flame}) \sim 0.25 M_\odot$, the star enters the instability region on the HR diagram for radial pulsations. It takes about 10^5yr for the flame to reach $M_r \sim 0.25\,M_\odot$, and about 10^6y to reach the center. The evolution timescale becomes longer as the star get closer to the helium zero-age main sequence. Since only 10% or less of helium is burnt during a shell flash, the star has a structure similar to that of a helium main-sequence star when the flame reaches the center.

Convective regions occur above the helium-burning shell during shell flashes and at the surface during the most redward excursion of the evolutionary tracks. Only the first flash was strong enough for the shell convection zone to reach close to the surface.

Figure 1 shows that evolutionary tracks toward the helium main sequence pass near the position of V652 Her. The luminosity of models in inter-flash phases around the position of V652 Her is mainly determined by the mass interior to the helium-burning shell, *i.e.,* M_r(flame). This is the reason why our models have a luminosity insensitive to the total mass and much lower than those of post-AGB models with the same total masses (Jeffery 1988, Saio 1988).

Thus the 'merged binary white dwarf' hypothesis for the progenitors of low-luminosity extreme helium stars satisfies the requirement for the position on the HR diagram. This scenario predicts that the luminosity of the low-luminosity extreme helium stars is distinctively lower than that of normal extreme helium stars. This property seem to appear in the luminosity-frequency histogram for extreme helium stars shown by Jeffery (1996).

5. Radial Pulsations

Since many extreme helium stars show pulsations, and since the primary comparison target V652 Her shows well-defined radial pulsations with a secular period change, these can be used as a further strong constraint on the evolutionary models.

We have calculated envelope models along the evolutionary tracks and obtained complex eigenfrequencies using the linear non-adiabatic radial pulsation code described by Saio (1995). Helium-rich stellar envelopes around the location of V652 Her on the HR diagram are known to be unstable against pulsation due to the Z-bump kappa-mechanism (Saio 1993). The fundamental radial mode is overstable in the range $4.26 \leq \log T_{\rm eff} \leq 4.43$ and the first overtone is overstable in the range $4.34 \leq \log T_{\rm eff} \leq 4.43$ for $M_f = 0.7\,M_\odot$. These ranges are almost independent of M_f. Near the position of V652 Her, both fundamental and first overtone pulsations are overstable in the linear analysis. However, the first overtone component has not been detected in the observed light and velocity curves (Lynas-Gray et al. 1984; Lynas-Gray & Kilkenny 1986; Hill et al. 1981; Jeffery

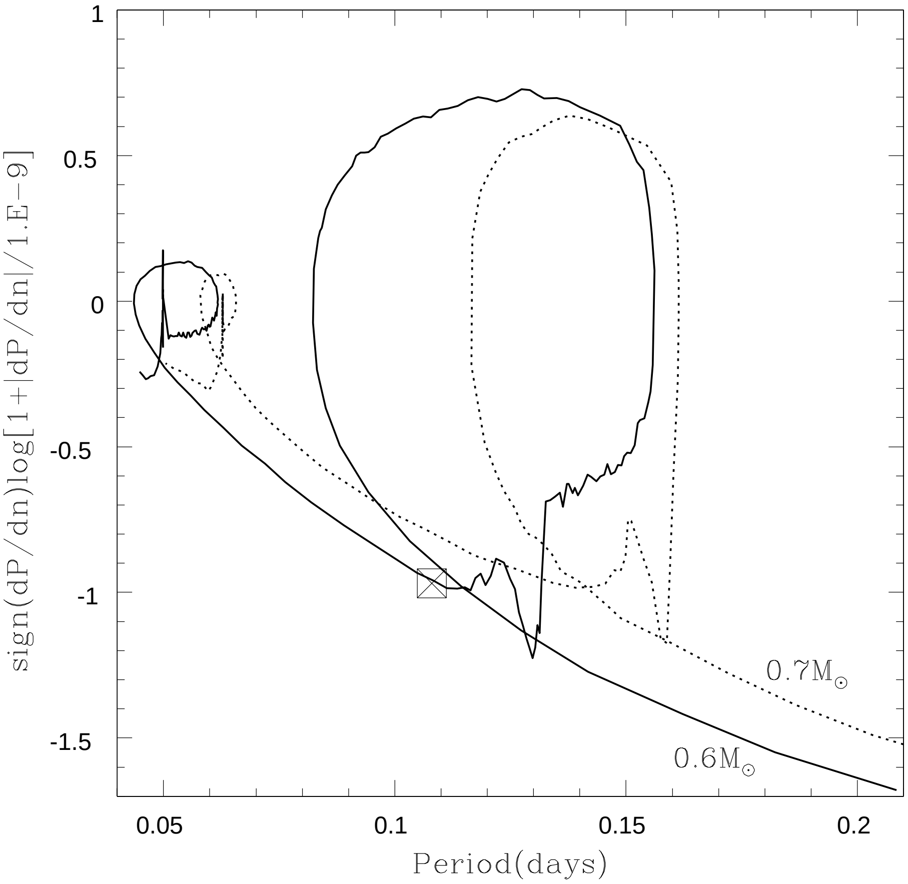

Figure 3. The rate of period change versus period for 0.7 and 0.6 $M_\odot$ cases, where dP/dn is the period change per cycle in days. The crossed square indicates the observed period and the period change rate of V652 Her (Kilkenny et al. 1996).

& Hill 1986), nor in nonlinear models by Fadeyev & Lynas-Gray (1996). It may mean that the amplitude of the first overtone is very small, or that the heavy element abundance of V652 Her is smaller than 0.02 so that the first overtone is stable.

Since we now know the age and pulsation period at any point along an evolutionary track, we can obtain the rate of period change $\mathrm{d}P/\mathrm{d}t$ by simple numerical differentiation. Figure 3 shows the period change (in days) *per cycle* (n), $\mathrm{d}P/\mathrm{d}n = P(\mathrm{d}P/\mathrm{d}t)$, as a function of period P for the overstable fundamental mode. The cases of $M_f = 0.6M_\odot$ and $0.7M_\odot$ with $M_\mathrm{i} = 0.4\,M_\odot$ are shown.

As seen in this figure, $\mathrm{d}P/\mathrm{d}n$ changes sign during the evolution in the Z-bump instability region. In an inter-flash phase the star contracts so that the period decreases ($\mathrm{d}P/\mathrm{d}n < 0$) while in a flash phase the envelope expands and hence $\mathrm{d}P/\mathrm{d}n > 0$.

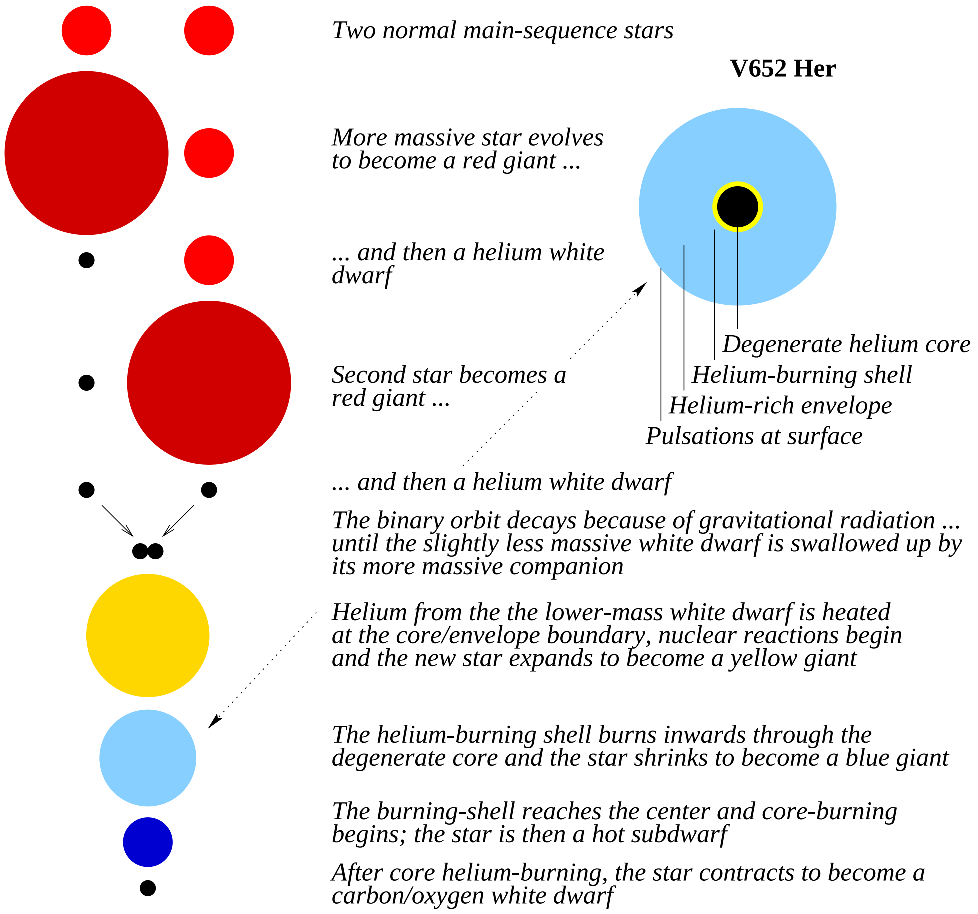

Figure 4. Illustration of the merged-binary white dwarf evolution model for V652 Her (Saio & Jeffery 2000).

The position of V652 Her in the $P - \mathrm{d}P/\mathrm{d}n$ plane is shown in Fig. 3 by a crossed square. The observed rate of change agrees with the theoretical value for $M_f = 0.6\,M_\odot$ for $M_i = 0.4\,M_\odot$.

The measured second derivative of the period $\mathrm{d}^2P/\mathrm{d}n^2$ is much higher (by a factor of 10^2) than indicated by those theoretical models which do reproduce $\mathrm{d}P/\mathrm{d}n$, although the sign is right. The cause of the discrepancy is not clear. One possible explanation may be that the location of the helium-shell flash in the $P - \mathrm{d}^2P/\mathrm{d}n^2$ plane is sensitive to the initial conditions and final mass. It appears that $\mathrm{d}^2P/\mathrm{d}n^2$ varies sufficiently both during and between helium-shell flashes that a closer agreement is possible.

6. Discussion

We have calculated rapidly accreting white dwarf models as a rough approximation for what would be expected when a low-mass double white dwarf binary system coalesce.

Several short-period low-mass double white dwarf systems are known to exist (Saffer, Liebert, & Olszewski 1988; Bragaglia et al. 1990; Marsh, Dhillon, & Duck 1995; Marsh 1995; Moran, Marsh, & Bragaglia 1997; Holberg et al. 1995). The mass of the primary component of such a system is estimated to be similar to or less than $0.4\,M_{\odot}$, and the secondary mass is comparable with it. These white dwarfs should consist of mostly helium because the core helium flash does not occur unless the helium core mass becomes about $0.45\,M_{\odot}$. Nelemans et al. (2000) have reconstructed their possible previous evolution from binaries with initial masses of $\sim 2 + 2\,M_{\odot}$. On reaching the WD+WD stage, such a binary system loses angular momentum due to gravitational wave emission or magnetic-field interaction so that the separation decreases gradually. If the secondary mass is comparable with the primary, when the secondary fills its critical Roche lobe, a runaway mass transfer to the primary is expected to lead to the coalescence of the binary system. Among the known double white dwarf systems, three systems have periods short enough to coalesce within the Hubble time (Marsh 1995, Marsh et al. 1995; Moran et al. 1997). These systems are candidates for the progenitors of our models which make the merging scenario to produce low-luminosity extreme helium stars viable. A synopsis of the complete evolutionary history that is emerging for V652 Her is given in Fig. 4.

The merger frequency of double HeWD systems in the Galaxy is theoretically estimated to be ~ 0.006 yr^{-1} by Han (1998), and ~ 0.02 yr^{-1} by Iben, Tutukov, & Yungelson (1997). The known low-luminosity helium stars have effective temperatures in a range of $4.3 \leq \log T_{\rm eff} \leq 4.5$ (Jeffery 1996). It takes $\sim 6 \times 10^4$ yr for a merged star to evolve in this temperature range (Fig. 2). Combining the evolution time and the above estimates for the merger frequency, we obtain $\sim 4 \times 10^2 - 10^3$ for the number of the low-luminosity helium stars in the Galaxy.

Now, let us estimate from observational data the number of low-luminosity helium stars in the Galaxy. Combining the known number of RCrB and HdC stars ($\sim$ 30) with the distribution in the Galaxy, Lawson et al. (1990) have estimated that $\sim 200 - 300$ RCrB and HdC stars exist in the Galaxy. That is, multiplying the observed number with a factor of ~ 10 yields the actual number of RCrB and HdC stars in the Galaxy. Compared with RCrB/HdC stars, the low-luminosity helium stars are about 10 times fainter in bolometric luminosity and $\sim$ 30 times in visual luminosity because of the bolometric correction. It means that the volume in which low-luminosity helium stars are observed in the Galaxy is $\sim$ 30 times smaller than in the case of RCrB/HdC stars, if both distributions are more or less planar. Therefore, multiplying the observed number of low-luminosity helium stars by $\sim$ 300 yields a rough estimate for the number in the Galaxy. We know four low-luminosity helium stars in the above temperature range; V652 Her, LSS 3184 (Drilling, Jeffery, & Heber 1998), LS IV+6°2 (Jeffery 1998), and HD 144941 (Harrison & Jeffery 1997). Combining this number with the above multiplying factor yields $\sim 10^3$ for the number of low-luminosity helium stars in the Galaxy, which is surprisingly consistent with the number predicted from the merged white-dwarf scenario.

The surface composition of V652 Her, consisting of CNO-processed helium and no helium-burning products (Jeffery et al. 1999), is consistent with our models. Since the first flash was so strong, the outer boundary of the convective

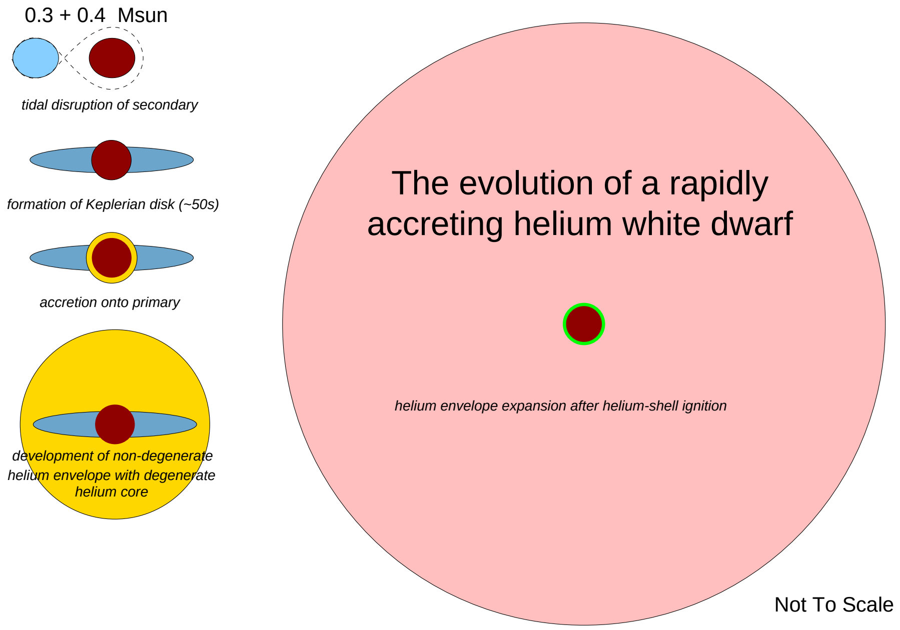

Figure 5. Conceptualisation of the merger of two helium white dwarfs.

shell reached close to the surface. In the convective shell, 3% (by mass) of the helium was converted to carbon. However, the enhanced carbon abundance has been covered by further accretion of helium. Since the subsequent shell flashes were weak and hence the convective shell was thin, helium burning products were not mixed into the atmosphere.

The low-luminosity extreme star LSS 3184 has very similar properties ($T_{\rm eff}$ and $\log g$) to V652 Her (Drilling et al. 1998) and pulsates with a period of 0.106 d (Kilkenny et al. 1999). Drilling et al. (1998) have shown that its atmosphere contains CNO-processed matter *and* carbon from helium burning. Such a chemical composition would result from a merger model if the mass accreted after the end of the initial helium flash is small; *i.e.* if the mass of LSS 3184 is smaller than that of V652 Her and around $0.5\,M_\odot$. There is observational support for this conjecture. Woolf & Jeffery (2000) used Baade's method to measure its radius as $R = 2.3 \pm 0.1\,R_\odot$. Together with the surface gravity $\log g = 3.35$ determined by Drilling et al. (1998), LSS 3184 has a mass $M = 0.42 \pm 0.12\,M_\odot$.

A more puzzling problem is that V652 Her retains a small concentration of hydrogen ($\sim 0.2\%$ by mass, Jeffery et al. 1999). In a non-turbulent spherically symmetric merging process, the accreted material would settle on top of any residual hydrogen envelope possessed by the progenitor white dwarf. The real merging process is turbulent and three-dimensional, so that substantial mixing will occur. For example, some of the hydrogen could be expelled outwards during the initial dynamical phase to settle later on the surface of the merged product, or substantial mixing could occur throughout the surface layers during the merger process. Only $\sim 10^{-3}\,M_\odot$ of hydrogen-rich material in the progenitor system, mixed through the product envelope, would be required to explain the hydrogen observed in V652 Her. Two-dimensional calculations which include some surface hydrogen on the white dwarfs, consider what mixing processes occur during initial mass transfer, and follow the surface hydrogen abundance through the complete accretion/shell-flash process are required before the surface abundances can be used as final arbiters of the evolution question.

We have attempted to anticipate some of the processes likely to occur during the merger process (Fig. 5). These have been partially preempted by Benz et al. (1990) in their models for the merger of 0.9 and 1.2 $M_{\odot}$ white dwarfs. At the point where tidal disruption occurs, material from the secondary would be dispersed to form a thick Keplerian disk around a degenerate core in hydrostatic equilibrium. This process takes palce on a dynamical timescale, $\sim$ 50s in the case of the simulation by Benz et al. (1990). The material in the disk will be fully mixed. Viscous forces will drag most of the material from the Keplerian disk onto the surface of the primary. Some material may reach escape velocities and be ejected from the disk. Turbulent flow or shear-mixing at the star/disk boundary may provide some mixing between the primary core and the accreted material. As the accreted mass increases, the envelope will expand to exceed the disk radius just after helium-shell ignition. At this point the remnant disk continues to orbit within the stellar envelope. Assimilation into the expanding star will continue until all Keplerian material has been captured.

Following expansion to giant dimensions, contraction through shell-flashes and passage through the Z-bump instability zone, the subsequent evolution of our mass-accreted helium white dwarf models will bring them to the helium main sequence where they will appear as hot subdwarfs. With masses slightly greater than $0.5\,M_{\odot}$, and hydrogen-poor surfaces, they might be expected to appear as subdwarf O or B stars.

Subdwarf B stars are generally recognized to be helium main-sequence stars with masses in the region of 0.5 to $0.6\,M_{\odot}$. However, they have very hydrogen-rich atmospheres and are extremely numerous. The scarcity of He+He WD binaries and the helium-rich surfaces of their descendants probably excludes them as normal sdB progenitors.

On the other hand, a small number of helium-rich subdwarf B stars has been detected in low-dispersion surveys (*e.g.* Green, Schmidt, & Liebert 1986). Practically nothing is known about these stars at present beyond their general spectral characteristics (Jeffery et al. 1997). If they are also the products of mass-accreted WD evolution then, because the contraction time between helium-shell ignition and the helium main sequence ($\sim 10^6$y) is very short compared with the helium main-sequence lifetime ($\sim 10^8$y) there should be many more such subdwarfs than extreme helium stars like V652 Her and LSS 3184, as appears to be the case.

7. Conclusion

We have examined the merged binary white dwarf hypothesis for the origin of low-luminosity (or high-gravity) extreme helium stars. We have approximated the merging process by spherical rapid accretion onto a low-mass helium white dwarf. We have found that the evolutionary path of such a model passes close to the position of the low-luminosity helium star V652 Her. We have obtained the pulsation periods and their time derivatives for models along the evolutionary tracks. We have found that the observed period and period change rate for V652 Her as well as its position on the HR diagram would be reproduced by a model with an initial mass slightly less than $0.4\,M_\odot$ and a final mass between $0.6\,M_\odot$ and $0.7\,M_\odot$. The observed second derivative of the period and the surface hydrogen abundance in V652 Her are both larger than the values predicted in our models; further detailed modeling should indicate that these discrepancies can be resolved. We have also found that the predicted number of low-luminosity helium stars in the Galaxy is consistent with observation.

We conclude that the merged binary white dwarf hypothesis, as represented by an accreting helium white dwarf model, provides a viable explanation for the evolutionary origin of at least some extreme helium stars. These helium stars will evolve to become hot subdwarfs close to the helium main sequence.

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