THE PAST AND FUTURE HISTORY OF REGULUS

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ABSTRACT

We show how the recent discovery of a likely close white dwarf companion to the well-known star Regulus, one of the brightest stars in the sky, leads to considerable insight into the prior evolutionary history of this star, including the cause of its current rapid rotation. We infer a relatively narrow range for the initial masses of the progenitor system: $M_{10} = 2.3 \pm 0.2\ M_\odot$ and $M_{20} = 1.7 \pm 0.2\ M_\odot$, where M_{10} and M_{20} are the initial masses of the progenitors of the white dwarf and Regulus, respectively. In this scenario, the age of the Regulus system would exceed 1 Gyr. We also show that Regulus, with a current orbital period of 40 days, has an interesting future ahead of it. This includes (1) a common envelope phase, and, quite possibly, (2) an sdB phase, followed by (3) an AM CVn phase with orbital periods $\lesssim 1$ hr. Binary evolution calculations are presented in support of this scenario. We also discuss alternative possibilities, emphasizing the present uncertainties in binary evolution theory. Thus, this one particular star system illustrates many different aspects of binary stellar evolution.

Key words: binaries: spectroscopic – stars: dwarf novae – stars: early-type – stars: individual (Regulus, α Leo) – stars: variables: other

1. INTRODUCTION

1.1. Properties of the Regulus System

Regulus (α Leo; HD 87901) was recently discovered to be a spectroscopic binary which has a likely white dwarf companion of mass $M_{wd} \simeq 0.3\ M_\odot$ and an orbital period of $P_{orb} \simeq 40.11$ d (Gies et al. 2008; hereafter "the inner binary system"). Regulus itself has an inferred mass of $\sim 3.4 \pm 0.2\ M_\odot$. This very bright star has been known for many years to have at least two other companions (BC) which together form a binary system (McAlister et al. 2005). This BC subsystem is located $177''$ from Regulus, too great a distance to have ever directly interacted with the star. The B component (α Leo B; HD 87884) is an $\sim 0.8\ M_\odot$ star of spectral type K2 V; the C component is a very faint M4 V star with a mass of $\sim 0.2\ M_\odot$. The Washington Double Star Catalog (Mason et al. 2001) lists a D component of the system, also having a common proper motion with the system and a separation of $217''$ from component A.

Located at a distance of 24.3 ± 0.2 pc, Regulus is a star of spectral type B7 V with an apparent magnitude of 1.36, making it one of the brightest stars in the sky. The star rotates very rapidly, with a rotational period of 15.9 hr, constituting $\sim 86\%$ of its break-up speed (McAlister et al. 2005). Its rapid rotation causes it to be highly flattened, with an equatorial diameter 32% greater than its polar diameter (4.16 $R_\odot$ and 3.14 $R_\odot$, respectively; McAlister et al. 2005).

There is some debate regarding the age of Regulus. Gerbaldi et al. (2001) estimate it to be ~ 150 Myr old; however, a comparison of its age with that of component B, assumed to be coeval, results in a 100 Myr discrepancy. It is worth noting that the age estimate for Regulus is based largely on the effective temperature of the star. However, the rapid rotation causes a difference of ~ 5000 K between the poles and the equator (McAlister et al. 2005), making this assessment somewhat suspect. Moreover, this estimate assumes that Regulus, with

$M \simeq 3.4\ M_\odot$, has evolved as a single star. As we will show in this paper, the original mass of Regulus was almost certainly much lower, and Regulus has attained its present mass by mass transfer from its close companion. If this scenario is correct, it is difficult to escape the conclusion that the entire Regulus system has a probable age of $\gtrsim 1$ Gyr.

In this paper, we use the fact that Regulus has a white dwarf companion of close to 0.3 $M_\odot$ in a 40 day orbit to reconstruct an approximate past history for the system (Section 2). Based on the current state of the Regulus inner binary, we discuss various possible future channels for the system (Section 3) with one of the most interesting possibilities that it will become an AM CVn binary with a period as short as a few minutes.

2. PRIOR EVOLUTION OF THE INNER REGULUS BINARY

2.1. P_{orb}–M_{wd} Relation

It has been known for a long time that accretion from a companion star can result in very high rotation rates for the accretor. However, in the case of Regulus, no close companion star was known to exist until the discovery by Gies et al. (2008) that Regulus has a companion in a 40 day orbit that is likely a white dwarf. Gies et al. (2008) suggested that matter accreted by Regulus from the envelope of the progenitor of the putative white dwarf was responsible for the high rotation rate. Since only a mass function is measured for the Regulus inner binary, the mass of the unseen companion star is formally limited to $M \gtrsim 0.3\ M_\odot$. Gies et al. (2008) argue against a neutron star companion on the grounds that a $\sim 1.4\ M_\odot$ companion would require an orbital inclination of $i \lesssim 15°$ which has only a small a priori probability of $\sim 3\%$. No formal limit on the orbital eccentricity is given by Gies et al. (2008), but an inspection of their Figure 1 suggests that $e \lesssim 0.05$. This makes it even more unlikely that the unseen companion is a neutron star considering that the loss of even a small amount of matter during the supernova explosion that gave birth to the neutron star would undoubtedly have led to a sizable eccentricity. We

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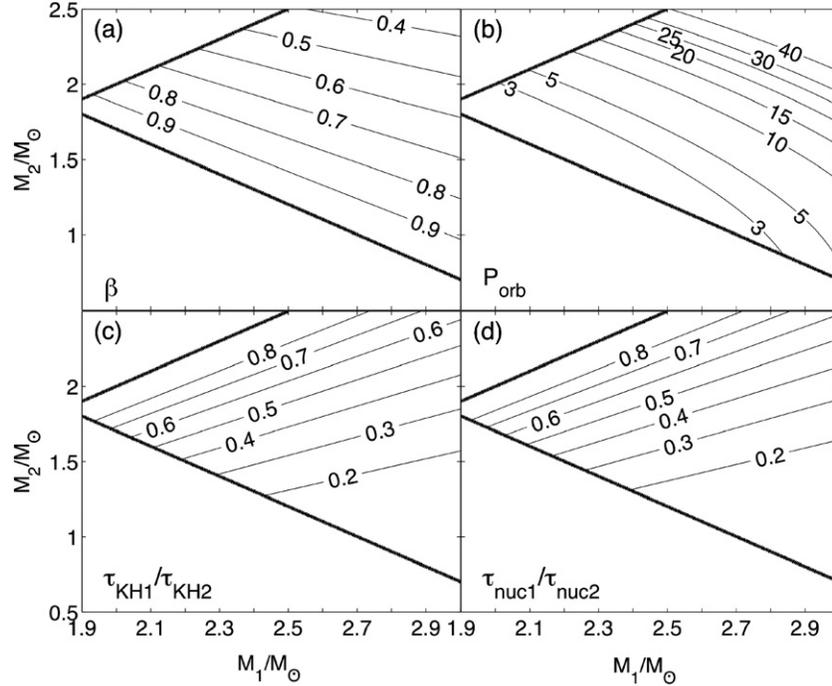
Figure 1. Contours of β, P_{orb}, $\tau_{\mathrm{KH},1}/\tau_{\mathrm{KH},2}$, and $\tau_{\mathrm{nuc},1}/\tau_{\mathrm{nuc},2}$ in the $M_{10}-M_{20}$ plane of the progenitor of the Regulus inner binary. All physically realizable points in the $M_{10}-M_{20}$ plane must lie above the heavy solid line with negative slope -1 (common to all panels) in order to yield a current binary mass of $3.7 \pm 0.2\ M_\odot$. Similarly, all physically meaningful points must lie below the heavy line of equal masses with slope $+1$.

present another argument below that the mass of the unseen companion is almost certainly near $0.3\ M_\odot$.

Assuming that the unseen companion to Regulus is a white dwarf, we can show why the 40 day orbit is just what is expected on theoretical grounds. For stars with an initial mass $\lesssim 2.5\ M_\odot$ there is a nearly unique relation between its properties on the giant branch and its He core mass. Since, for Roche-lobe filling donor stars that are lower in mass than the accretor (or even slightly higher), the orbital period depends only on the mass and radius of the donor star, the orbital period at the end of mass transfer from a giant star depends only on the core mass of the donor star. This period−white dwarf mass relation has been studied in detail by Rappaport et al. (1995). They found the following approximate analytic expression:

$$P_{\mathrm{orb}} \simeq 1.3 \times 10^5 M_{\mathrm{wd}}^{6.25} / \left(1 + 4 M_{\mathrm{wd}}^4\right)^{3/2}, \qquad (1)$$

where the orbital period is expressed in days and the white dwarf mass is in units of $M_\odot$. Rappaport et al. (1995) estimated a theoretical uncertainty in the white dwarf mass of $\sim \pm 18\%$ that takes into account uncertainties in the chemical composition, the initial mass of the parent star, and the mixing length parameter. If we solve this expression for M_{wd} with $P_{\mathrm{orb}} = 40.1$ d, we find

$$M_{\mathrm{wd}} \simeq 0.28 \pm 0.05\ M_\odot \qquad (2)$$

(full uncertainty). This is entirely consistent with the measured value of $M_{\mathrm{wd}} \gtrsim 0.3\ M_\odot$.

If we assume that the rotation axis of Regulus, which is measured to be $\gtrsim 75^\circ$ with respect to the line of sight (McAlister et al. 2005), coincides with the normal to the orbital plane, then the orbital inclination angle of the Regulus inner binary should be $i \gtrsim 75^\circ$. That this is the case follows from the assumption that the matter transferred from the progenitor of the white dwarf companion was responsible for spinning up Regulus (see Section 2.4). Therefore, the angular momentum vector of the

orbit and that of the rapidly rotating Regulus should coincide. For $i \gtrsim 75^\circ$, the mass function for Regulus (Gies et al. 2008) yields a mass for the white dwarf of $M_{\mathrm{wd}} = 0.302 \pm 0.017$. Again, this is highly consistent with the theoretical value expected for a white dwarf remnant in a 40 day circular orbit (see Equation (2); Rappaport et al. 1995). Finally, we note that, according to the theoretical scenario for forming the Regulus inner binary, the orbital eccentricity is expected to be $e \lesssim 10^{-4}$ (see Rappaport et al. 1995 and references therein), which can possibly be falsified in the future.

2.2. Constraints on the Primordial Binary

In the evolutionary scenario for the current Regulus inner binary, the progenitor of the white dwarf is the more massive star, while the secondary—the progenitor of the current Regulus—is somewhat less massive. The initial orbital period must be less than 40 days in order for the He core of the primary not to exceed $\sim 0.3\ M_\odot$ (see Equation (1)). When the primary overfills its Roche lobe, its envelope is transferred stably, though not necessarily conservatively, to the secondary. At first, the orbit shrinks due to the transfer of mass from the more to the less massive star. Once the mass ratio reaches unity, the orbit will start to expand. The ratio of the final-to-initial orbital period is given by

$$\frac{P_{\mathrm{orb,f}}}{P_{\mathrm{orb,i}}} = \frac{M_{\mathrm{b,f}}}{M_{\mathrm{b,i}}} \left(\frac{M_{1,\mathrm{f}}}{M_{1,\mathrm{i}}}\right)^{C_1} \left(\frac{M_{2,\mathrm{f}}}{M_{2,\mathrm{i}}}\right)^{C_2}, \qquad (3)$$

where $C_1 = 3\alpha(1-\beta) - 3$ and $C_2 = -3\alpha(1-\beta)/\beta - 3$ (Podsiadlowski et al. 1992). The parameter β is the fraction of the transferred matter retained by the secondary, and α is the specific angular momentum in units of the specific orbital angular momentum of the system carried away by any matter lost from the system. The notation is that "1," "2," and "b" stand for the primary, secondary, and the binary, respectively,

while "f" and "i" indicate final and initial states, respectively. The derivation of Equation (3) involves the assumption that the parameters α and β are constant throughout the mass-transfer phase; this approximation seems justified in light of the other theoretical uncertainties for this phase of the evolution.

In order to study the range of possible progenitor stars for the Regulus inner binary system, we considered primary stars of mass $M_{10} \lesssim 3\ M_\odot$, and secondaries of any mass less than the primary mass. For primaries with $M_{10} \gtrsim 2.5$–$3\ M_\odot$ the core mass that develops would be $M_{core} \gtrsim 0.5\ M_\odot$ and would not leave a remnant consistent with the $0.3\ M_\odot$ white dwarf that is inferred to be orbiting Regulus. For each point in the M_{10}–M_{20} plane we estimated the ratio of thermal timescales, τ_{KH}, and nuclear timescales, τ_{nuc}, for the primary and secondary. Contours of constant timescale ratios are shown in the bottom two panels ((c) and (d)) of Figure 1. We take $\tau_{KH} \propto M^2/(RL)$ and $\tau_{nuc} \propto M/L$, with stellar luminosity and radius scaling like $M^{3.7}$ and $M^{0.8}$, respectively. We then find $\tau_{KH} \propto M^{-2.5}$ and $\tau_{nuc} \propto M^{-2.7}$.

In the top left panel of Figure 1 (panel (a)), we show contours of constant β, the fraction of transferred mass retained by the secondary, in the M_{10}–M_{20} plane. These values are inferred by comparing the initial mass of the primordial binary with current observed mass of $M_{b,f} \simeq 3.4 + 0.3\ M_\odot = 3.7\ M_\odot$. Finally, the top right panel (b) in Figure 1 shows contours of constant initial orbital period that would lead to the observed current value of $P_{orb} = 40$ days. To compute P_{orb} we utilized Equation (3) with β taken from Figure 1(a), and α, the specific angular momentum associated with mass loss, taken to be a constant throughout the mass loss process and to have a typical fiducial value of unity (but see Section 2.5).

If we require that the ratio of thermal timescales for the progenitor stars, $\tau_{KH,1}/\tau_{KH,2}$ be not too different from unity, so that the secondary can retain a sizable fraction of the transferred matter, we can restrict the allowed range of progenitor masses to lie above a particular contour in Figure 1(c). We somewhat arbitrarily choose $\tau_{KH,1}/\tau_{KH,2} \gtrsim 0.4$ in order that the thermal timescales not be too disparate. Similarly, we require that the ratio of nuclear timescales for the progenitor stars, $\tau_{nuc,1}/\tau_{nuc,2}$ be sufficiently different from unity, so that the current Regulus has not already evolved up the giant branch. Since, as we show in Section 2.5, the initial secondary star will spend ~200 Myr with sufficient accreted mass to exceed the mass of the original primary, and subsequently, another ~50 Myr with much more mass than the primary, as it approaches its current mass of $3.4\ M_\odot$, the original mass of the secondary cannot be too close to that of the primary. In order for Regulus not to be more evolved than its current state, we require that $\tau_{nuc,1}/\tau_{nuc,2} \lesssim 0.6$, and we adopt this as a rough upper boundary in the bottom right panel of Figure 1.

2.3. Parameters of the Primordial Binary

Combining these constraints yields the allowed range of M_{10} and M_{20} (see Figure 2). The most likely primordial masses are $M_{10} \simeq 2.3 \pm 0.2\ M_\odot$ and $M_{20} \simeq 1.7 \pm 0.2\ M_\odot$. The initial orbital period could have been anywhere in the range of $P_{orb} \simeq 1$–15 days. Calculations of grids, and even entire populations, of such mass transfer binaries are given, e.g., in Nelson & Eggleton (2001) and Willems & Kolb (2004). These authors considered only conservative mass transfer, but their detailed evolutionary calculations are nonetheless quite instructive.
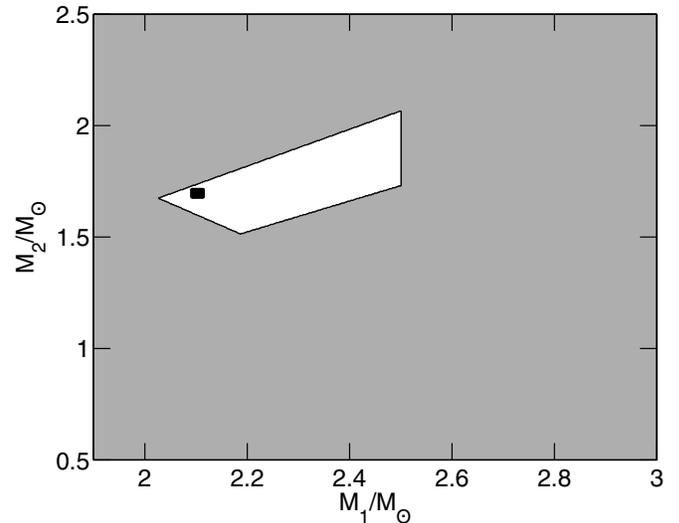
Figure 2. Allowed regions in the M_{10}–M_{20} plane for the progenitor of the Regulus inner binary (see Figure 1). The cutoff for $M_{10} > 2.5\ M_\odot$ indicates the highest mass primary that could yield a white dwarf mass as low as $0.3\ M_\odot$. The black square indicates the initial masses used in the numerical evolution model that produced the best match to the current Regulus (inner binary) system.

2.4. The Origin of the Rapid Rotation

It has long been argued that one way to produce a very rapidly rotating star (e.g., a Be star) is by the accretion of mass and angular momentum from a companion star (e.g., Pols et al. 1991), similar to the origin of the Be phenomenon in Be-/X-ray binaries (Rappaport & van den Heuvel 1982). Generally, a star has to accrete $\lesssim 10\%$ of its initial mass to be spun up to near critical rotation[5] (Packet 1981). But, if the companion is a hard-to-detect degenerate object, it is generally difficult to verify such a mass-transfer scenario (Pols et al. 1991). The discovery of the close degenerate companion to Regulus confirms the mass-transfer hypothesis in this case. Considering that this a nearby, bright star, it also demonstrates how difficult it is to test this scenario in individual cases. Indeed, the majority of intermediate-mass stars rotating near breakup may have such an unseen companion, suggesting that further observational scrutiny is warranted.

2.5. Illustrative Binary Evolution Calculations

In order to check more quantitatively our proposed evolutionary scenario for the formation of the current Regulus system, we carried out a number of binary evolution calculations using a Henyey stellar evolution code. All calculations were carried out with an up-to-date, standard Henyey-type stellar evolution code (Kippenhahn et al. 1967), which uses OPAL opacities (Rogers & Iglesias 1992) complemented with those from Alexander & Ferguson (1994) at low temperatures. We use solar metallicity ($Z = 0.02$), take a mixing length of 2 pressure scale heights, and assume 0.25 pressure scale heights of convective overshooting from the core, following the calibration of this parameter by Schröder et al. (1997) and Pols et al. (1997; for more details, see Podsiadlowski et al. 2002).

We ran binary evolution sequences for a substantial number of initial mass points lying inside the white region of Figure 2. In most, but not all, cases we adopted a value for the angular

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[5] We note that any of the initial masses specified in Figures 1 and 2 transfer more than the requisite amount of mass to spin up Regulus.

momentum loss parameter of $\alpha = 1$. The mass retention fraction, β, is fixed from the initial masses and the current binary mass. Since the values of β typically lie between ~ 0.7 and 1.0, and therefore not much mass is lost, our results are not highly sensitive to the exact choice for α. We have also verified this by running a number of evolutionary models where $\alpha = 0.5$ and $\alpha = 1.5$. The main effect of adopting higher values of α is that the initial orbital period can be longer, and this tends to push the onset of mass transfer more into the regime of early case B mass transfer.
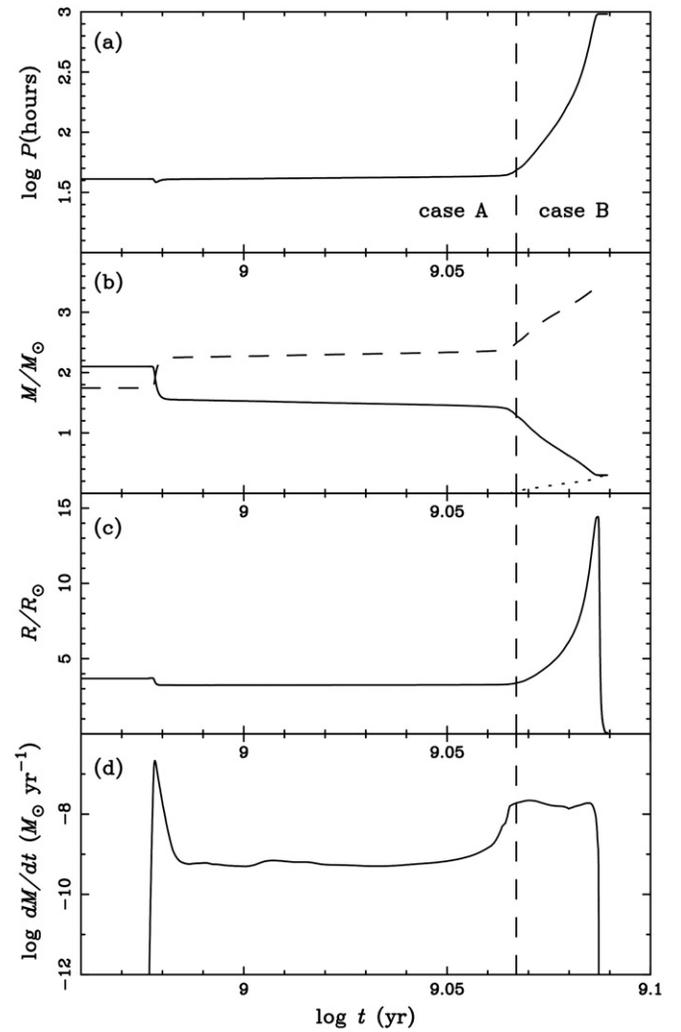
The model which most closely matches the current-day properties of the Regulus system has $M_{10} = 2.1 \ M_\odot$, $M_{20} = 1.74 \ M_\odot$, and $P_{\rm orb} = 40$ hr (1.7 d). This particular choice of initial system parameters is shown as a filled square symbol within the white region of Figure 2. The first of two sets of results from the binary evolution calculation for this model is shown in Figure 3. The four panels show (a) the evolution of $P_{\rm orb}$, (b) the progenitor masses of Regulus (long-dashed curve) and the white dwarf progenitor (solid curve), (c) the radius of the primary (WD progenitor), and (d) the mass transfer rate, $\dot{M}$, onto the progenitor of Regulus. Note that as $P_{\rm orb}$ approaches 40 days (~ 1000 hr), the primary has transferred most of its envelope mass to the progenitor of Regulus, which by then has a mass of $\sim 3.4 \ M_\odot$. At the same time, the primary has developed a $\sim 0.3 \ M_\odot$ degenerate He core (the short-dashed curve in Figure 3, panel (b))—the progenitor of the current white dwarf in the system.[6] Figure 4 shows the evolution of the radius of Regulus during the epoch when it accretes mass from the primary. Note that the radius of Regulus, even during the interval when it is accreting at $\sim 10^{-8} \ M_\odot \ {\rm yr}^{-1}$, never exceeds 4 $R_\odot$ because the mass transfer timescale is substantially longer than the Kelvin–Helmholtz timescale.

2.6. Status of the White Dwarf in the Regulus System

If the $\sim 0.3 \ M_\odot$ companion to Regulus, originally the core of the primordial primary in the system, has a mass below $\sim 0.31 \ M_\odot$, then the star will not burn He to CO and will cool to become a degenerate dwarf. After a time of several hundred Myr, the maximum time allowed since the current Regulus binary has been in existence, such a $\sim 0.3 \ M_\odot$ white dwarf would have cooled to $T_{\rm eff} \lesssim 15,000$ K and a luminosity of $\lesssim 0.02 \ L_\odot$ (see, e.g., Althaus et al. 2001). This is consistent with the limits on the optical and UV emission from such a companion in the presence of Regulus, with a temperature nearly this high and a luminosity $\sim 10^4$ times higher.

If, on the other hand, the companion to Regulus has a mass just slightly in excess of that required for a He star to burn He to CO in thermal equilibrium, i.e., $M \simeq 0.32 \ M_\odot$, then it would still be undergoing nuclear burning at the current epoch. The properties of such a low-mass He star are $R \simeq 0.056 \ R_\odot$, $L \simeq 1.4 \ L_\odot$, and $T_{\rm eff} \simeq 26,000$ K; and the nuclear lifetime is in excess of 1 Gyr (see, e.g., Hurley et al. 2000). Even though such a companion would have a substantially larger luminosity than its degenerate counterpart, it would still not contribute very much light to the Regulus system (i.e., $\lesssim 1\%$) for wavelengths longward of 1700 Å. It even seems unlikely that such a He star would have been detected in the study of B stars (including Regulus) by Morales et al. (2001) using the *IUE* satellite and *EURD* spectrograph on *MINISAT-01*.

Figure 3. Evolutionary parameters as a function of time for the most promising model for the current Regulus system. Panel (a): the evolution of $P_{\rm orb}$; panel (b): the masses of Regulus (long-dashed curve), the primary progenitor of the white dwarf (solid curve), and the He core of the primary (short-dashed curve); panel (c): the radius of the primary, the progenitor of the white dwarf; and panel (d): the mass transfer rate from the primary.
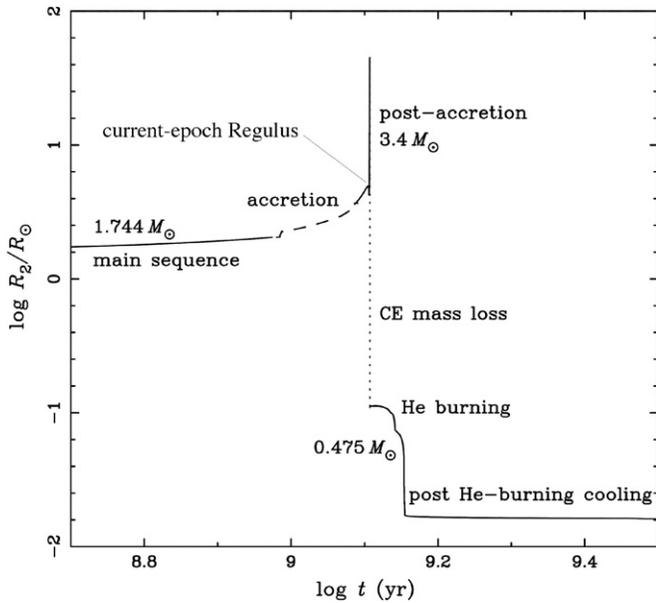
2.7. Age of the Regulus System

One consequence of our scenario is that the age of the Regulus system, including any members bound to the inner binary, must exceed ~ 900 Myr, the time required for the $\sim 2.1 \ M_\odot$ progenitor of the white dwarf to evolve. Thus, all previous age estimates of ~ 50–200 Myr (see, e.g., Gerbaldi et al. 2001) are far too young. The reason for these age discrepancies, in essence, is that Regulus was rejuvenated by the accretion of nearly 1.7 $M_\odot$ of hydrogen-rich material.

3. FUTURE EVOLUTION OF THE INNER REGULUS BINARY

3.1. Regulus Ascending the Giant Branch

In about 100–200 Myr, Regulus will complete its main sequence evolution and begin its ascent of the giant branch (see Figure 4 for times after $10^{9.1}$ yr). The exact time to this phase will depend, of course, upon its current core development. The present orbital separation of the Regulus binary (at $P_{\rm orb} \simeq 40$ d) is $a \simeq 74 \ R_\odot$, and the corresponding Roche-lobe radius

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[6] If the progenitor of the white dwarf had been slightly more massive and, in particular, the He core mass had exceeded $\sim 0.32 \ M_\odot$ (which would still be consistent with the present-day measured mass function), helium would have been ignited nondegenerately in the core (see Section 2.6).

Figure 4. Global view of the evolution of the radius of Regulus, starting from an epoch just before it starts to accrete matter from its companion, the accretion phase (where it reaches its current mass of $\sim$3.4 $M_\odot$), its subsequent evolution up the giant branch, followed by a common envelope (CE) phase. If the system does not merge during the CE phase or start mass transfer shortly thereafter (see Section 3), it then becomes a 0.475 $M_\odot$ core helium burning subdwarf and finally a HeCO white dwarf.

of Regulus is $R_L \simeq 44 \pm 4.7$ $R_\odot$. By the time Regulus fills its Roche lobe, starts mass transfer to its white dwarf companion, and the common-envelope phase commences, it will have developed a ~ 0.48 $M_\odot$ He core.[7] This is the core that is unveiled after the common envelope phase (see the following section).

Note, however, that since a 3.4 $M_\odot$ star will ignite helium in its core, its post-CE remnant will continue to burn helium. In the case of a successful common-envelope ejection (see Section 3.2) it will appear as an sdB star in a very short-period binary for $\sim 10^8$ yr (e.g., Maxted et al. 2001; Han et al. 2002), and ultimately produce a hybrid HeCO white dwarf (see Section 3.3.2).

3.2. Common Envelope Phase

Once mass transfer from the evolved Regulus to its white dwarf companion commences, it will quickly become dynamically unstable (due to the extreme mass ratio of the two stars), and a common envelope phase will ensue. The relation between the initial orbital separation of $a_i \simeq 76$ $R_\odot$, and the post-common-envelope separation, a_f is given by

$$\left(\frac{a_f}{a_i}\right) \simeq \frac{M_{\rm core,Reg} M_{\rm wd}}{M_{\rm Reg}} \left(M_{\rm wd} + \frac{2 M_{\rm env,Reg}}{\lambda \eta r_{\rm L1}}\right)^{-1}, \quad (4)$$

where λ is the inverse binding energy of the core of Regulus with its envelope, in units of

$$R_{\rm Reg}/(G M_{\rm core,Reg} M_{\rm env,Reg}),$$

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[7] We note that whether Regulus fills its Roche lobe during or after helium core burning (when it has already developed a CO core) depends critically on the amount of convective overshooting. For a significantly lower value than our preferred value of 0.25 pressure scale heights, Regulus would only fill its Roche lobe after helium core burning, by which point the hydrogen-exhausted core would be considerably more massive (0.7–0.8 $M_\odot$).

η is the fraction of the orbital binding energy that goes into ejecting the common envelope, and $r_{\rm L1}$ is the size of the Roche lobe of Regulus in units of the initial orbital separation (see, e.g., Webbink 1984; Pfahl et al. 2003). For the parameters of the Regulus–white dwarf binary, this expression yields $a_f/a_i \simeq 0.0046\lambda\eta$. The corresponding post-common envelope orbital period of the binary, now consisting of a ~ 0.5 $M_\odot$ HeCO dwarf and a 0.3 $M_\odot$ white dwarf, is $P_{\rm orb} \simeq 40 (\lambda\eta)^{3/2}$ minutes. For plausible values of $\lambda\eta \simeq 0.1$–1 (see, e.g., Dewi & Tauris 2000, 2001; Podsiadlowski et al. 2003), the post-CE orbital periods would likely range between $\sim$2 and 40 minutes, respectively, if both of the compact stars were degenerate. Given that the HeCO star is expected to still be burning He at the end of the common-envelope phase, and that its radius would be no smaller than ~ 0.1 $R_\odot$, the actual range of post-CE orbital periods is probably limited to between $\sim$40 and $\sim$20 minutes if a merger of the cores is to be avoided (see Section 3.3.1 for more details). If the two dwarfs do effectively merge, they would produce a rapidly rotating giant with unusual properties (see Section 3.3.1).

3.3. Post-Common-Envelope Phase

#### 3.3.1. Possible Outcomes of the CE Spiral-in

After the common envelope phase, the final orbital separation should be $a \simeq 1/3 \eta\lambda$ $R_\odot$, where, as discussed above, the product $\eta\lambda$ reflects the efficacy of the common-envelope process, and is expected to be in the range of 0.1–1. What happens to the binary pair consisting of the 0.3 $M_\odot$ He white dwarf companion of Regulus and the ~ 0.48 $M_\odot$ core of Regulus depends critically on the uncertain value of $\eta\lambda$. If the 0.3 $M_\odot$ dwarf is degenerate, it will have a radius of 0.017 $R_\odot$, and would fit well inside its Roche lobe, nearly independent of $\eta\lambda$. (If it is still undergoing He burning, its radius would be $\sim$3 times larger.) The 0.48 $M_\odot$ core of Regulus, on the other hand, is still burning He to CO in its core, and will have a radius of ~ 0.1 $R_\odot$ until the He burning phase has ended, and the HeCO remnant becomes degenerate (see Figures 4 and 6). This phase lasts for $\sim$100 Myr.

This implies that there is a minimum period of $\sim$20 minutes for the post-CE system. If the ejection efficiency ($\eta\lambda$) is too low, the orbital energy released in the spiral-in will not be able to eject the common envelope, and the two compact objects, the 0.48 $M_\odot$ core and the 0.3 $M_\odot$ white dwarf, will merge inside the common envelope. This would likely produce a rapidly rotating single giant with possibly some very unusual chemical properties (perhaps similar to the unusual, rapidly rotating carbon star V Hydrae (Kahane et al. 1996); also see FK Comae stars (Bopp & Stencel 1981) for related earlier-type counterparts).

If the common envelope is ejected, the subsequent evolution depends on the post-CE orbital period, since it determines the timescale on which either of the two compact components will achieve contact and start to transfer mass again. Immediately after a successful common-envelope ejection, both components (by definition) will underfill their Roche lobes, but the binary orbit will continue to decay because of gravitational wave emission. The time for orbital decay is

$$t = 68 \left[P_{\rm orb,CE}^{8/3} - P_{\rm orb}^{8/3} \right] {\rm Myr}, \quad (5)$$

where $P_{\rm orb,CE}$ is the orbital period (in hours) immediately after the common envelope, and $P_{\rm orb}$ is the orbital period at time t later. The system remains a detached binary until either of the two components starts to fill its Roche lobe.

Regulus: Past, Present and Future
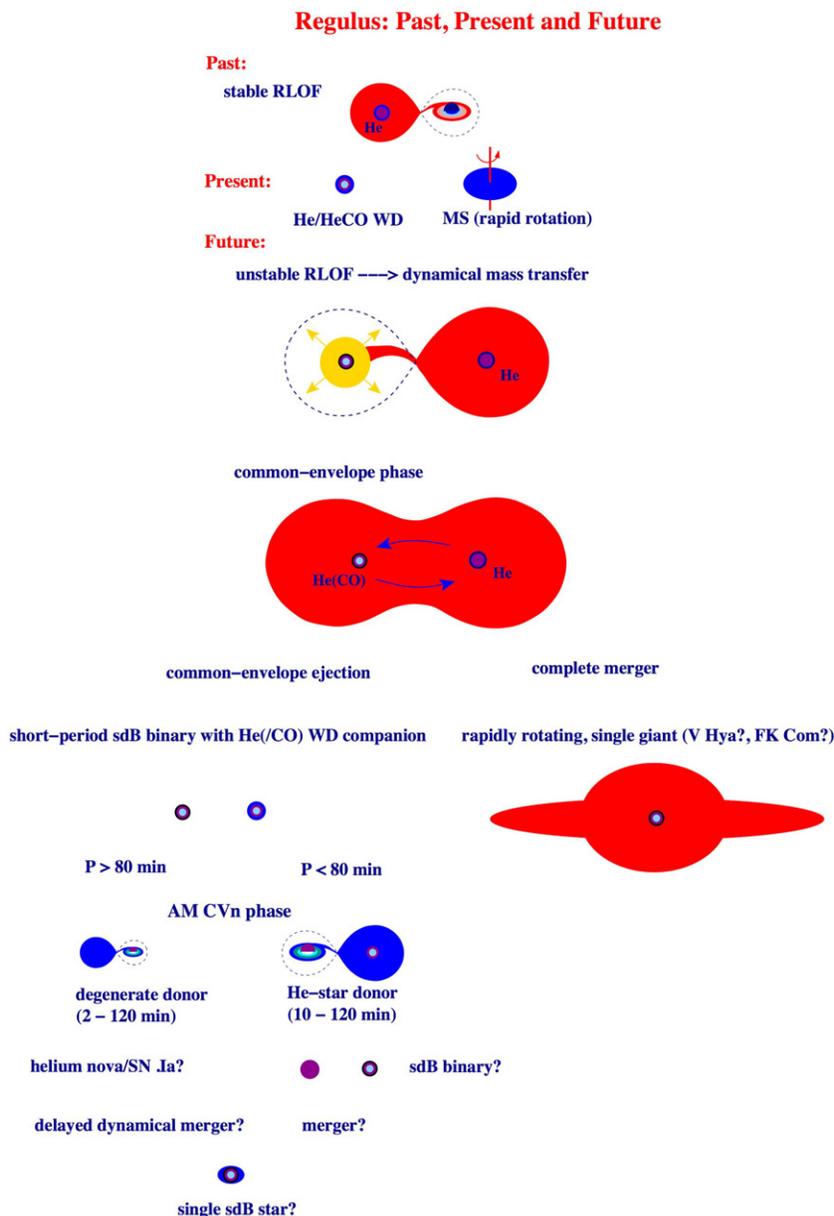
Figure 5. Evolutionary scenario: past, present, and future, for the Regulus inner binary. Illustrative constituent masses and orbital periods corresponding to the different evolutionary phases are: (1) past progenitors—$M_{10} \simeq 2.3$ $M_\odot$; $M_{20} \simeq 1.7$ $M_\odot$; $P_{orb} \simeq 1$–15 days; (2) present—$M_{Reg} \simeq 3.4$ $M_\odot$; $M_{wd} \simeq 0.3$ $M_\odot$; $P_{orb} \simeq 40$ days; (3) future—unstable Roche-lobe overflow; starts with system parameters in (2), but with Regulus having developed ~ 0.5 $M_\odot$ He core; (4) common envelope—spiral in of the white dwarf into the envelope of Regulus; (5) post-common envelope phase—leads to (a) a binary consisting of compact objects in an orbit with $P_{orb} \gtrsim 20$ minutes (the former core of Regulus now appears as an sdB star), or (b) the system merges completely to form a rapidly rotating single giant; (6) ultracompact binary—depending on the post-CE envelope orbital period, the orbit decays due to the emission of gravitational waves to P_{orb} between ~ 2 and ~ 20 minutes, and the system then appears as an AM CVn system.

If the immediate post-CE orbital period is $\lesssim 80$ minutes, the 0.48 $M_\odot$ helium-burning component will start to fill its Roche lobe while it is still burning helium in the center, and mass transfer will start from the more massive helium-burning star to the 0.3 $M_\odot$ white dwarf. The system will now become an AM CVn star with a helium-star donor (e.g., Nelemans et al. 2001). The stability of the mass transfer is addressed in Section 3.3.3.

On the other hand, if the post-CE orbital period is longer than ~ 80 minutes,[8] the helium-burning star will have completed helium-core-burning and become a degenerate, much smaller HeCO white dwarf (see Figures 4 and 6) before the system

becomes semi-detached again. In this case, the lighter and physically larger white dwarf will fill its Roche lobe first, and mass transfer will take place from the lighter white dwarf to the more massive HeCO white dwarf. The system will again appear as an AM CVn binary (see, e.g., Nelemans et al. 2001), but in this case with either a degenerate donor star with $P_{orb} \simeq 2$ minutes and $M \simeq 0.3$ $M_\odot$, or with a He-burning star with $M \simeq 0.32$ $M_\odot$ and $P_{orb} \simeq 13$ minutes.

Figure 5 illustrates these different evolutionary paths in a "scenario" diagram.

3.3.2. Evolution of the Exposed Core of Regulus

Once the core of Regulus has been exposed after the common-envelope phase, it will evolve as an isolated He star of mass

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[8] Note that such periods are somewhat longer than anticipated from our simplistic expression for the ejection of a common envelope based on energetic arguments (i.e., Equation (4)).
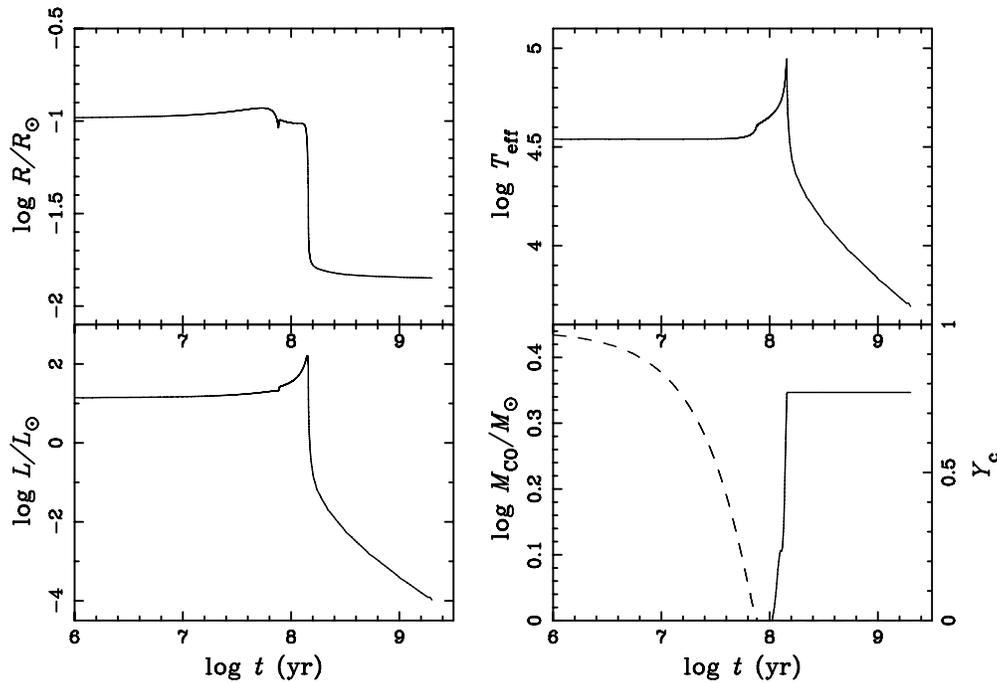
Figure 6. Evolution of an isolated He star of mass 0.475 $M_\odot$. The first three panels show the evolution with time of the radius, $T_{\rm eff}$, and luminosity. The mass of the CO core (solid curve; left scale) and the central He abundance (dashed curve; right scale) of the star are plotted as functions of time in the bottom right panel.

0.475 $M_\odot$ until it or its companion white dwarf fill its respective Roche lobe. As mentioned above, which star first fills its Roche lobe depends on the orbital period immediately following the common-envelope phase. To help understand this, we show in Figure 6 the evolution of an isolated He star of mass 0.475 $M_\odot$. The first three panels show the evolution with time of the radius, $T_{\rm eff}$, and luminosity. After ~140 Myr, the star has completed its He burning, and contracts from ~ 0.1 $R_\odot$ to its final degenerate radius of ~ 0.015 $R_\odot$. The mass of the CO core and the central He abundance of the star are plotted as functions of time in the bottom right panel. The CO core reaches a final mass of ~ 0.34 $M_\odot$.

Thus, the critical timescale for the exposed core of Regulus to complete its nuclear burning and contract to a degenerate state is ~140 Myr. From Equation (5) above we see that the original (i.e., post-CE) orbital period would have to be in excess of ~80 minutes in order for the HeCO star to avoid filling its Roche lobe at $P_{\rm orb} \simeq 20$ minutes, and for the system to shrink via gravitational wave loses to $P_{\rm orb} \simeq 2$ minutes when the He white dwarf would first overflow its Roche lobe (see Sections 3.3.1 and 3.3.3). If the lower-mass He star is still undergoing He burning (e.g., for a mass of ~0.32 $M_\odot$) then $P_{\rm orb}$ would be ~13 minutes rather than 2 minutes.

### 3.3.3. Illustrative Calculations of an AM CVn Phase

In Figure 7 we show the evolution that results when the post-CE orbital period is 90 minutes. This allows sufficient time for the HeCO dwarf to complete its He burning before gravitational radiation losses bring the system into Roche-lobe contact. The first star to fill its Roche lobe and thereby become the donor star is the 0.3 $M_\odot$ He white dwarf. The initial orbital period at the start of mass transfer is ~2 minutes (13 minutes if the low-mass He star is a bit more massive and is still undergoing He burning). The mass transfer rate from the lower to the higher mass white dwarf is stable. It starts at a rate of $\dot{M} \simeq 3 \times 10^{-6}$ $M_\odot$ yr^{-1} and steadily declines over

the ensuing billion years to $\lesssim 10^{-12}$ $M_\odot$ yr^{-1}. The details of the evolution of the constituent masses, $P_{\rm orb}$, and $\dot{M}$ can be seen in Figure 7. The later parts of the binary evolution can, in fact, be computed semianalytically (see, e.g., Rappaport et al. 1983; Eggleton 2007). We find $P_{\rm orb} \simeq 30\, t_8^{3/11}$ minutes, and $\dot{M} \simeq 6 \times 10^{-11} t_8^{-14/11}$ $M_\odot$ yr^{-1}, where t_8 is the time in units of 10^8 years from the start of mass transfer. Such a system would be observed as an AM CVn star (see, e.g., Nelemans 2001).

In Figure 8 we show the evolution that results when the post-CE orbital period is 40 minutes. In this case, the orbital decay time is sufficiently short that the post-CE ~ 0.48 $M_\odot$-helium star does not have sufficient time to complete He burning and cool to a degenerate state where its radius is smaller than that of the 0.3 $M_\odot$ He white dwarf. In this case, mass transfer starts when the helium star is still burning helium in its core (i.e., in its hot subdwarf phase), and mass is transferred from the hot subdwarf to the 0.3 $M_\odot$ He white dwarf. Initially, mass transfer proceeds on the thermal timescale of the helium star due to the fact that the donor is the more massive star. However, after an initial phase of very high $\dot{M}$, the mass ratio quickly inverts, and the subsequent mass transfer is driven entirely by the angular momentum loss due to gravitational radiation. Note that, nuclear burning turns off soon after the helium star has lost a significant amount of mass (by this stage, the central helium abundance has been reduced from 0.98 to 0.74, causing the shrinking of the star and the associated dip in the mass-transfer rate). The subsequent evolution of the binary is similar to that in Figure 7, except that the now degenerate donor star is helium-depleted and oxygen- and carbon-enriched.

3.3.4. The Final Fate of the System

For the binary evolution calculations shown in Figures 7 and 8 any nuclear burning on the accreting star was suppressed. Unfortunately, the details of the accretion and the amount of mass lost from the system in the process of accretion and
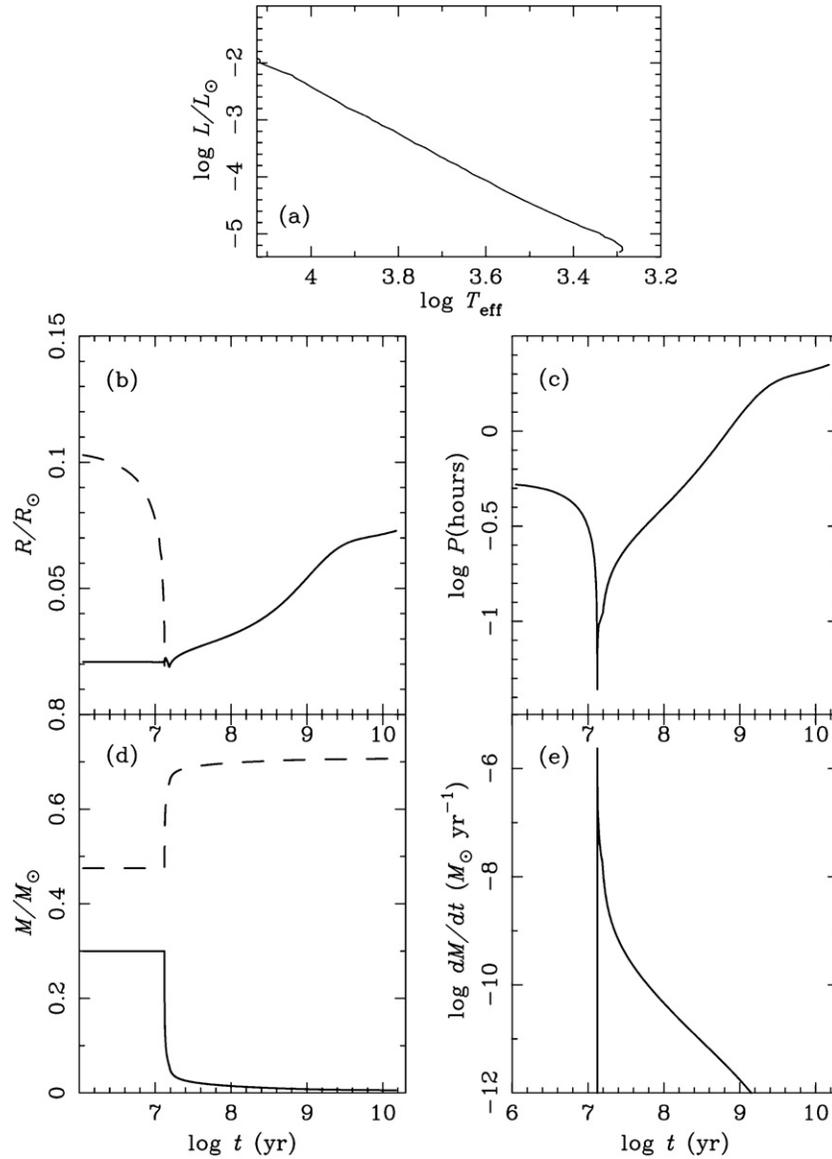
Figure 7. Illustrative post-CE evolution of the 0.3 $M_\odot$ white dwarf and the HeCO remnant core of Regulus. The post-CE orbital period was taken to be 90 minutes. After mass transfer from the 0.3 $M_\odot$ white dwarf to the HeCO dwarf commences, the system would resemble an AM CVn system with a degenerate donor star. The top panel (a) is an HR diagram for the accreting HeCO white dwarf. The four panels showing the temporal evolution of the system are for (b) the radius of the donor star (He white dwarf, solid curve) and the Roche-lobe radius (dashed curve); (c) orbital period; (d) constituent masses (white dwarf of initial mass 0.3 $M_\odot$, solid curve; HeCO star of initial mass 0.475 $M_\odot$, dashed curve); and (e) mass transfer rate, $\dot{M}$. Note that a post-CE orbital period as long as 90 minutes is not very probable for the Regulus system.

nuclear burning are highly uncertain, and at this stage we can only speculate on the final evolution. In the AM CVn case with a degenerate donor (Figure 7), the helium in the accreting HeCO white dwarf will at some point reignite in the helium shell under degenerate conditions, producing a helium nova or even a mild thermonuclear runaway (possibly producing a ".Ia supernova"; see Bildsten et al. 2007). If helium burning continues afterwards, the accretor may swell up significantly beyond its Roche lobe, and the system may merge completely, producing a single helium-burning hot subdwarf (most likely a helium-rich sdO star; Stroer et al. 2007).

In the case of an AM CVn binary with a nondegenerate helium donor (Figure 8), the accreting white dwarf will experience a central helium flash when its mass reaches the critical helium-flash mass ($\sim 0.48\ M_\odot$). The system will probably survive the helium flash, although the system may become detached, and the accretor will now become a hot subdwarf.

4. DISCUSSION

We have discussed quantitatively the interesting past and future history of Regulus. The entire evolutionary scenario is summarized in Figure 5. We have shown how the present 40 day orbital period of Regulus and its 0.3 $M_\odot$ white dwarf companion match very well the P_{orb}–M_{wd} relation predicted by stellar evolution theory. The masses of the progenitor stars are inferred to fall in the range of $M_{10} \simeq 2.3 \pm 0.2\ M_\odot$ and $M_{20} \simeq 1.7 \pm 0.2\ M_\odot$. Our best numerically computed model is $M_{10} = 2.1\ M_\odot$, $M_{20} = 1.74\ M_\odot$, $P_{orb} = 40$ hr (1.7 d). In this scenario, the age of the Regulus system would exceed 1 Gyr.

In the future, Regulus will undergo a common envelope phase wherein the white dwarf will spiral into, and eject, the envelope of Regulus. If the envelope of Regulus is too tightly bound, then the system may merge, forming a rapidly rotating single giant
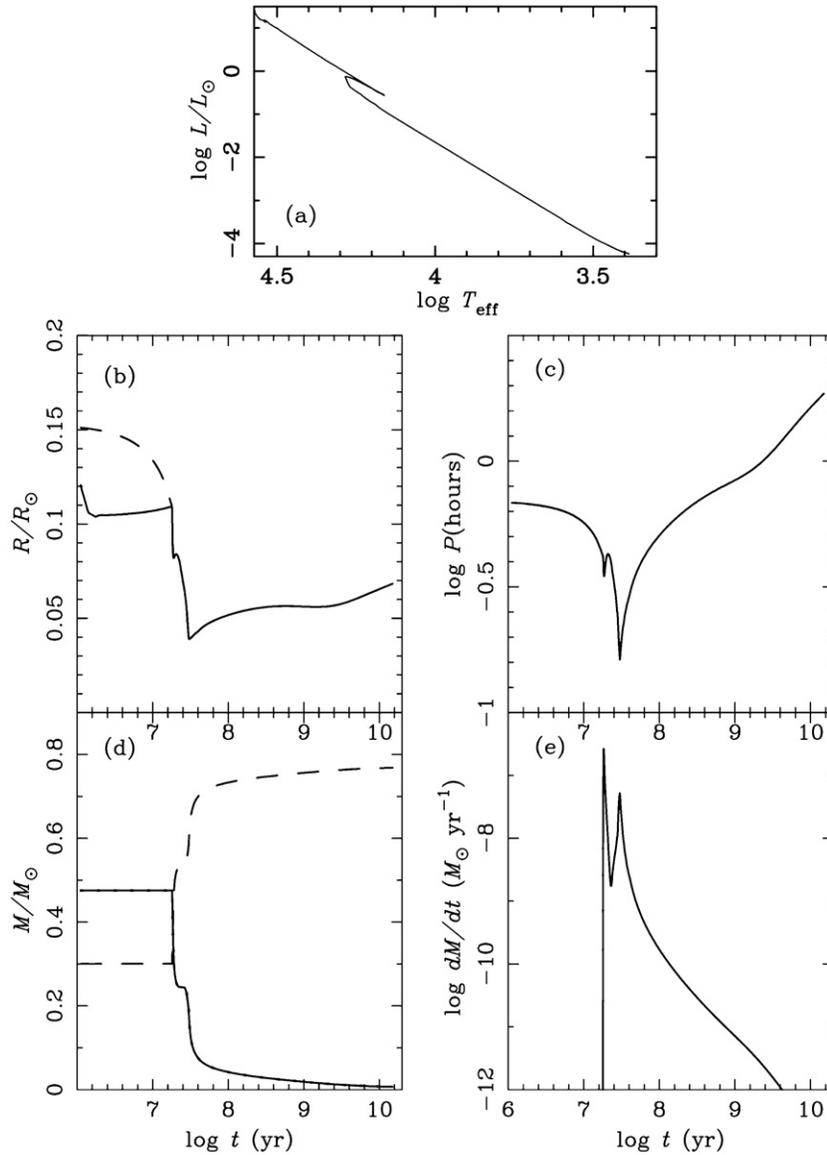
Figure 8. Illustrative post-CE evolution of the 0.3 $M_\odot$ white dwarf and the HeCO remnant core of Regulus. The post-CE orbital period was taken to be 40 minutes. After mass transfer from the 0.48 $M_\odot$ HeCO dwarf to the 0.3 $M_\odot$ white dwarf commences, the system would resemble an AM CVn system with a helium-star donor. Note that P_{orb} at first contact is $\sim$21 minutes, and then decreases to $P_{orb} \simeq 10$ minutes before the orbit starts to expand. The various panels and their description are otherwise the same as in Figure 7.

with unusual properties, possibly related to V Hya and FK Com stars. If, on the other hand, the common envelope halts at orbital periods between $P_{orb} \simeq 20$ and 80 minutes, the result will be a compact binary consisting of a HeCO dwarf of mass 0.48 $M_\odot$ which will start transferring mass to the 0.3 $M_\odot$ white dwarf companion (i.e., the current companion of Regulus). For longer post-CE orbital periods, the gravitational wave decay timescale is sufficiently long to allow the HeCO star to complete He burning and to cool to a largely degenerate state. The system would then come into Roche-lobe contact at very short orbital periods ($P_{orb} \simeq 2$–13 minutes). In both of these latter two cases, the ensuing mass transfer will likely be stable (at least initially) and lead to an AM CVn system whose orbital period, after reaching a minimum, will slowly grow to $\sim$20 minutes within $\sim$20 Myr, and to $\sim$40 minutes by $\sim$200 Myr. Nuclear burning on the accreting dwarf is difficult to compute, and we leave this for a future exercise. Such burning activity could cause the donor to swell up, and this, in turn, could cause the compact binary to merge.

Currently we are seeing Regulus as an apparently ordinary star in the middle of an extraordinary evolutionary journey.

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