

THE AGE AND PROGENITOR MASS OF SIRIUS B

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ABSTRACT

The Sirius AB binary system has masses that are well determined from many decades of astrometric measurements. Because of the well-measured radius and luminosity of Sirius A, we employed the TYCHO stellar evolution code to determine the age of the Sirius AB binary system accurately, at 225–250 Myr. Note that this fit requires the assumption of solar abundance and the use of the new Asplund et al. primordial solar metallicity. No fit to Sirius A’s position is possible using the old Grevesse & Sauval scale. Because the Sirius B white dwarf parameters have also been determined accurately from space observations, the cooling age could be determined from recent calculations by Fontaine et al. or Wood to be 124 ± 10 Myr. The difference in the two ages yields the nuclear lifetime and mass of the original primary star, $5.056^{+0.374}_{-0.276} M_{\odot}$. This result yields, in principle, the most accurate data point at relatively high masses for the initial-to-final mass relation. However, the analysis relies on the assumption that the primordial abundance of the Sirius stars was solar, based on membership in the Sirius supercluster. A recent study suggests that its membership in the group is by no means certain.

Subject headings: stars: atmospheres — stars: fundamental parameters — white dwarfs

1. INTRODUCTION

The initial-to-final mass relation (IFMR) for progenitors and white dwarfs is fundamental in understanding a stellar population, interpreting the white dwarf mass and luminosity distributions, and determining the star formation history. Of particular interest is the upper mass limit of a star forming a white dwarf. It is well known that the mass loss in the red giant phases (red giant branch [RGB] and asymptotic giant branch [AGB]) of stars of similar mass and chemical composition shows dispersion. The existence of “horizontal branches” in metal-poor and metal-rich clusters shows that varying amounts of the hydrogen envelope are lost in the RGB or helium-ignition events. For intermediate-mass stars undergoing AGB evolution, the timing of the thermal pulses of the helium shell may produce a dispersion in the resulting white dwarf distribution (e.g., Iben & Renzini 1983). It may therefore be anticipated that the IFMR will show dispersion.

In order to determine empirically the IFMR, it is necessary to study samples of white dwarfs where it is possible to estimate the initial mass of the progenitor. Since there is generally no way of establishing the total lifetimes of white dwarfs in the field population, white dwarfs found in well-studied star clusters have been used. The cluster age is known within some uncertainty, generally from fits to the main-sequence turnoff. In a few clusters, the mass limit below which lithium is not depleted in completely convective low-mass stars and/or brown dwarfs may also be employed. Several Galactic disk clusters ranging in age from of the order 10^8 to 10^9 yr, and with main-sequence turnoff masses from ~ 2 to $>5 M_{\odot}$, have been studied in recent years. These include the Hyades and Praesepe (Claver et al. 2001 is the most recent study), the Pleiades (the single white dwarf has been studied by many authors), NGC 2516 (Koester & Reimers 1996), NGC 3532 (Koester & Reimers 1993), NGC 2168 (Williams et al. 2004), and NGC 2099 (Ka-

lirai et al. 2005). Since it is necessary to measure the masses of the white dwarfs accurately—by means of stellar atmosphere fits to Balmer lines or by measuring the gravitational redshift—the faint white dwarf sequences recently found in the nearest globular clusters (see M4; Hansen et al. 2004) and in older Galactic clusters (NGC 6791; Bedin et al. 2005) are not yet as useful.

The upper end of the IFMR is yielding progenitors with short nuclear-burning phases, and these lifetimes are very dependent on the mass. For several reasons, there must be significant uncertainty in the estimation of the age of such young clusters. First, these clusters do not necessarily have well-populated upper main sequences. Shifts due to rotation, unresolved binaries, and the possible presence of blue stragglers with masses larger than the turnoff mass represent a separate category of problems. Finally, uncertainty in the main-sequence lifetime of stars with convective cores, due to the probable overshooting beyond the simple Schwarzschild boundary, is a theoretical problem. Thus, the uncertainty in the cluster age causes a big uncertainty in the possible progenitor masses of white dwarfs, especially for the youngest clusters. These problems result in considerable uncertainty in establishing the upper mass limit of a star that can form a white dwarf or even in establishing whether such a uniform upper limit exists or not. It is thus extremely important to establish a method to reduce the spread in the progenitor’s mass.

Binaries consisting of a nuclear-burning star and a white dwarf offer another potential source of candidates for the IFMR. If the parameters of the nuclear-burning star can be established with sufficient accuracy that its age can be obtained by fitting its position on the H-R diagram, then the total age of the white dwarf—which is the sum of the nuclear-burning lifetime and cooling age—can also be established. As for the clusters, the nuclear-burning lifetime is used to establish the progenitor mass of the white dwarf.

The Sirius system is the fifth or sixth nearest stellar system to the Sun⁴ and is certainly one of the best studied binary systems including a white dwarf component. One does not want

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⁴ Depending on the actual distance to the recently discovered, very high proper motion star SO 025300.5+165258, estimated to be within 2.4–3.6 pc (Teegarden et al. 2003).

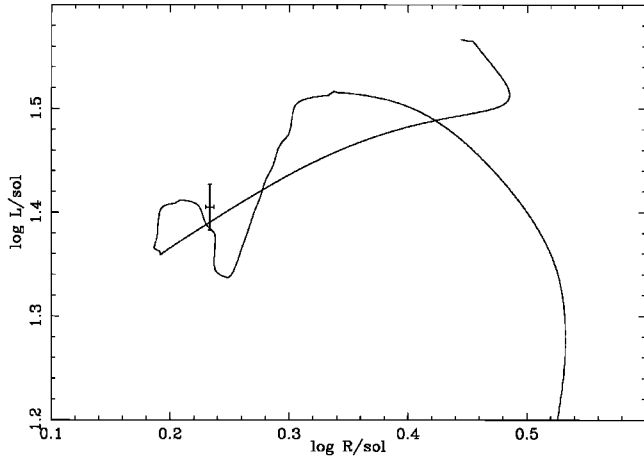


FIG. 1.—The log luminosity vs. log radius TYCHO evolutionary track beginning with an underluminous starting pre-main-sequence model. The position of Sirius A with error bars is shown and is fit by the track within 1σ at a total (pre-MS + MS) age of 237.5 ± 12.5 Myr, about $\frac{1}{7}$ of its main-sequence lifetime.

to employ a white dwarf in a binary that is close enough that interactions might affect the mass-loss phases in the late stages of the progenitor's evolution. However, the orbit is eccentric with a period of about 50 years. At periastron, the components are just within 7 AU of each other (van de Kamp 1971). This is probably well enough separated so that any interaction during the AGB phase of the original primary (now B) would have been minimal. Significant interaction would probably have circularized the orbit. We therefore assume that Sirius B evolved in a manner like that of a single star.

An excellent trigonometric parallax, accurate to better than 1%, is available from the *Hipparcos* satellite mission as well as from several good ground-based studies. Using the bolometric energy distribution and effective temperature determination, the luminosity of Sirius A is known to about 4% accuracy. Using the ESO Very Large Telescope Interferometer, Kervella et al. (2003) obtained a superb measurement of the diameter of Sirius A, accurate to about 0.75%. One may then avoid very direct use of the T_{eff} estimates of Sirius A. Robust parameter (T_{eff} , $\log g$)-determinations for Sirius B are also available from space observations. Finally, a recent reexamination of the plethora of astrometric data on the binary orbit (J. B. Holberg 2005, in preparation) results in mass estimates of both “A” and “B” components that are accurate to within 1%–2%.

Improvements in opacities, the equation of state, and other treatments in modern stellar evolution codes now make possible fits to nuclear-burning stars on the H-R diagram, especially those on or near the main sequence (Young & Arnett 2005). Robust, consistent ages for (nondegenerate) binary stars with well-determined luminosities, masses, radii, and temperature have been determined (Young et al. 2001).

In § 2 of this Letter, we employ this code to fit the position of Sirius A and estimate the age with an error estimate. This gives the systemic age from which to subtract the cooling age of B in § 3 to obtain the estimate of its progenitor mass and its uncertainty. We then summarize and discuss an important caveat in § 4.

2. THE FITTING OF SIRIUS A IN AN H-R-LIKE DIAGRAM

The mass adopted for Sirius A is $2.02 \pm 0.03 M_{\odot}$ (J. B. Holberg 2005, in preparation). Note that this new astrometric

study yields a mass about 5% smaller than some earlier determinations of Sirius A. (The smaller orbit also yields a smaller mass for Sirius B.) The adopted radius of Sirius A is $1.711 \pm 0.013 R_{\odot}$ (Kervella et al. 2003), and the resulting luminosity is $L/L_{\odot} = 25.4 \pm 1.3$. Since the luminosity and radius are more directly measured than the T_{eff} , these will be the quantities fitted in an L - R equivalent of the H-R diagram.

One issue with Sirius A is that it is a chemically peculiar A1 V dwarf, so that a direct determination of the interior chemical composition is not possible. However, it has been believed for a long time that Sirius is a member of a large moving group near the Sun called the “Sirius supercluster” (Hertzsprung 1909; Eggen 1983). (We reassess this issue in the last section of the Letter, however.) The “core” of this association is the Ursa Major “dipper” stars. Metallicity estimates for the group members (that are not chemically peculiar) are generally consistent with solar (Palous & Hauck 1986). Eggen (1992) compared the abundances of the Sirius and Hyades superclusters and concluded that the former is deficient by about -0.18 dex in $[\text{Fe}/\text{H}]$ compared with the Hyades group. The latter is believed to exceed solar by about this amount. There is no guarantee that appreciable dispersion in metallicity does not exist among the group. We nonetheless can do no better than assume the solar X , Z values below.

However, a new solar abundance scale determined from three-dimensional non-LTE calculations of the solar atmosphere (Asplund et al. 2004 and references therein) has significantly lower abundances of oxygen, carbon, and nitrogen. The overall heavy-element abundance parameter for the Sun decreases to a primordial value of $Z = 0.014$. The new scale jeopardizes the excellent agreement of the “standard solar model” with the helioseismology observations (Bahcall et al. 2005), although a new study attempts to remedy this, retaining the Asplund et al. values (Young & Arnett 2005). We have adopted the new scale for the calculations described below.

Figure 1 shows the results of running the TYCHO code (Young & Arnett 2005) to fit the position of Sirius A. The model included wave-driven mixing and diffusion. The former is a way of accounting for the “overshooting” of the convective core based on physics, rather than a prescription involving the ratio of the mixing length to scale height. The microphysics for opacities, reaction rates, and the equation of state appear numerically similar to those of Ventura et al. (1998). The inclusion of these effects produces only a small effect at the best-fit age of 237.5 ± 12.5 Myr. Radiative levitation was not included. A perfect fit would require a lower metallicity or an increase in mass of a few hundredths of solar mass. The evolution was begun well up the Hayashi track and followed throughout the pre-main sequence (MS). The best-fit age includes the pre-MS evolution. No pre-MS accretion was included. The best-fit age is constrained primarily by the radius determination.

The precision with which the Sirius A radius and luminosity are known is such that the use of the new solar abundance scale matters greatly. In particular, *no reasonable fit can be achieved* if the old scale (Grevesse & Sauval 1998) were adopted. When the $2.02 M_{\odot}$ track for the old solar scale crosses the correct radius on its main-sequence track, the luminosity is $\log(L/L_{\odot}) = 1.26$, several σ below the observed value. The new solar abundances result in lower interior opacities, and so the star has a smaller radius at a given luminosity and vice versa.

Another estimate of the radius of Sirius A is reported by Decin et al. (2003) using the Short Wavelength Spectrometer

on the *Infrared Space Observatory*. This measurement is far less precise, and the Kervella et al. (2003) angular diameter is within its 5% errors.

3. THE COOLING AGE AND PROGENITOR MASS OF SIRIUS B

An accurate T_{eff} determination is also essential for measuring the cooling age of Sirius B. Holberg et al. (1998) employed space ultraviolet *Extreme Ultraviolet Explorer* and *International Ultraviolet Explorer* spectrophotometry to estimate $24,790 \pm 100$. The estimate of Barstow et al. (2005), using an optical spectrum of extraordinarily high signal-to-noise ratio, obtained with the Space Telescope Imaging Spectrograph on the *Hubble Space Telescope* is $25,193 \pm 37$ (an internal error only). We adopt $T_{\text{eff}} = 25,000 \pm 200$.

The astrometric reanalysis of J. B. Holberg (2005, in preparation) results in a measurement of $1.00 \pm 0.01 M_{\odot}$ for the mass of Sirius B. Barstow et al. (2005) obtained $T_{\text{eff}} = 25,193$ K (as stated above) and $\log g = 8.528 \pm 0.05$ from fits to the Balmer line profiles. In the following paragraphs we shall apply cooling sequences to obtain the cooling age of Sirius B. These also yield a second relationship (besides the surface gravity) between the radius and mass— $R = R(M, T_{\text{eff}})$. Solving for the mass, one obtains $0.978 \pm 0.005 M_{\odot}$, if the cooling sequences of Wood (1995) are used, or $0.003 M_{\odot}$ less, if those of Fontaine et al. (2001) are employed. Using their gravitational redshift measurement of $80.42 \pm 4.83 \text{ km s}^{-1}$ —yielding the ratio M/R —with the Wood sequences, Barstow et al. (2005) obtain $1.02 \pm 0.02 M_{\odot}$. Note that these mass determinations are generally below previous estimates in earlier literature. For this study, we shall adopt $1.00 \pm 0.02 M_{\odot}$ for Sirius B.

For the cooling ages of white dwarfs, most cluster white dwarf studies in the last 10 years have used the evolutionary models of Wood (1992, 1995). For reasons stated below, we will use primarily a new sequence by Fontaine et al. (2001). Both calculations used 50% carbon–50% oxygen cores and the relatively thick outer layers of helium and hydrogen predicted by most evolutionary calculations of the AGB phase.

The Fontaine et al. calculations incorporate several new treatments of physics (G. Fontaine 2005, private communication). First, the equation of state of Saumon et al. (1995) for H and He in the partially ionized envelope, and a new treatment of carbon in the same regime, was employed. Second, the conductive opacity tables of Hubbard & Lampe (1969) and Itoh & Kohyama (1993 and references therein) were “fused together,” rather than treated as completely separate. Third, no discontinuities in the chemical composition profile are allowed. Diffusion at the interfaces is calculated. Fourth, a full stellar structure is evolved from the center to the top of the atmosphere, not a simple “Heney” core that excludes the envelope. Fifth, a robust and accurate finite-element technique (developed by P. Brassard) is used, as opposed to finite differences as in most other codes. We thus have adopted these sequences to estimate the cooling age of Sirius B. Having said this, it is interesting and reassuring that the $1.00 M_{\odot}$ C, O sequence of M. Wood (2005, private communication) reaches a cooling age of 123.3 Myr at 25,000 K, while the Fontaine et al. (2001) sequence with identical parameters reaches 123.6 ± 10 Myr.

Error bars in the “final” mass of Sirius B are as stated above. The uncertainty in the mass and systemic age (§ 2) leads to a nuclear lifetime for the progenitor in the range of 101–126 Myr.

For determining the initial mass, we consider errors due to (1) uncertainty in the final mass and (2) uncertainty in the

systemic age (§ 2). We shall also consider a possible additional uncertainty due to the different results obtained from the TYCHO and “Padova” codes, and an uncertainty due to the unknown carbon-oxygen abundance profiles throughout the core.

For most recent papers on white dwarf sequences, such as Ferrario et al. (2005, hereafter F05), the Padova stellar evolution models of Girardi et al. (2002) were used to get the nuclear lifetime and the initial progenitor mass. For this Letter, for self-consistency with § 2, we present first the calculations of these using the TYCHO code.

While TYCHO incorporates physical treatments available in 2005 (rather than several years earlier for the Padova literature calculations), the principal difference between the two results may be the treatment of mixing beyond the traditional Schwarzschild core boundary. Girardi et al. (2002) use an “overshoot” prescription based on a single parameter. As alluded to in § 2, TYCHO includes the effects of hydrodynamics in the convective boundary and radiative regions in a predictive, physically motivated fashion. This treatment may give more accurate predictions of core sizes, and thus of luminosities, radii, and nuclear lifetimes.

From the TYCHO calculations, the masses that bracket the above range in the progenitor’s nuclear lifetime are 5.43 and $4.78 M_{\odot}$, with a mean of $5.056 M_{\odot}$. The uncertainty in the cooling age (due to that of the white dwarf mass) contributes errors of only -0.171 and $+0.262 M_{\odot}$. The uncertainty in the age of the binary system contributes -0.213 and $+0.273 M_{\odot}$. When added in quadrature, these values yield the mass range stated previously. If we employ instead the Girardi et al. (2002) tables, again for nuclear lifetimes of 101 and 126 Myr, the mean value of the initial mass is only slightly larger at $5.132^{+0.28}_{-0.23} M_{\odot}$. Thus, we may also conclude that the physical treatment of the convective boundary region by TYCHO and the overshoot prescription of the Padova group agree pretty well near $5 M_{\odot}$. In any case, the uncertainties in the initial mass from this analysis are smaller than for any massive cluster white dwarf included in F05.

An additional source of uncertainty in the cooling age not considered here is that due to the carbon-oxygen abundance distribution in the core. As stated previously, the white dwarf cooling calculations of Fontaine et al. (2001) simply employ a 50%–50% mixture. The usual practice in the published analyses of the cluster white dwarfs is, as stated previously, to use Wood’s calculations with the same mixture. Other available calculations from Wood are for pure carbon and for pure oxygen compositions.

The $5 M_{\odot}$ sequence calculated from TYCHO produces very nearly a $1 M_{\odot}$ core at the end of the AGB evolution, which suggests that the prescription for mass loss in the red giant phases is fairly accurate. The resulting white dwarf has a carbon abundance of 15% throughout the inner $0.45 M_{\odot}$, comprised of the former convective He-burning core. The carbon abundance increases from 35% to 40% moving outward through the region processed by He shell burning, with a narrow ($\sim 0.01 M_{\odot}$) spike of 60% carbon where He burning is incomplete. At low He abundances, the Y_{He}^3 dependence of the triple- α reaction favors the $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$ reaction over triple α . More massive cores with higher entropy favor the production of ^{16}O over ^{12}C . Convective He-burning cores also tend to grow at low Y_{He} due to increased opacity. This process as well as any nonconvective mixing process that mixes He into the core at low abundance will increase the destruction of ^{12}C , resulting in an oxygen-dominated core (Arnett 1996, p. 227). Pure carbon white dwarf cooling models are thus excluded for this mass

range, which favor a shorter cooling time. Therefore, using the simple mixture is the best choice of available cooling sequences. However, the additional error to the cooling time, due to not matching the true abundance profile, is not well constrained.

4. CONCLUSIONS AND A CAVEAT

The result of this analysis is a spread in the possible progenitor mass of Sirius B that is generally smaller than those in the young clusters cited above. In a parallel paper by F05, Sirius B provides a valuable “anchor point” in the high-mass part of the IFMR, which is plotted therein (their Fig. 1).

The conclusions as to the Sirius B progenitor mass obviously depend on the fit to the Sirius A luminosity and radius being a valid measure of the systemic age. The “Achilles heel” of the analysis may be the assumption of solar composition for the primordial abundance of the two stars. Since there is no way to measure directly the primordial abundance of either the chemically peculiar A star or the white dwarf, we have relied on the assumption that it is a member of the Sirius supercluster and that these stars have generally been shown to have abundances indistinguishable from solar. It must be acknowledged that, in the recent study of King et al. (2003), it appears by no means certain that Sirius—so distant from the Ursa Major core—is a member of the Sirius supercluster. These authors estimate an age of 500 ± 100 Myr for the supercluster from main-sequence turnoff fits. Using Strömgren photometry, Asiain et al. (1999) estimate 520 ± 160 Myr. These values are substantially larger than the estimates from previous literature (e.g., 240 Myr; Eggen 1983). They are appreciably larger than the systemic age of 225–250 Myr determined in this Letter for Sirius. There is no way, if this analysis is based on sound assumptions, that the Sirius age can be 400 Myr. King et al. (2003) emphasize that they have not determined that the supercluster is coeval or that the stellar abundances are the same.

If we were to consider the possibility that the interior abundances of Sirius A are not determined, we would have to consult

the comprehensive study by Nordström et al. (2004) of 7566 nearby, single F and G dwarfs to see what the abundance distribution is. For the subsample within 40 pc of the Sun, and at estimated ages near 1 Gyr or less, the [Fe/H] determinations (see their Fig. 28) range from about -0.3 to $+0.2$, with a mean value near -0.02 to -0.06 (the former if the sample is restricted to the subsample with age estimates considered to be accurate). As mentioned in § 2, the fit would actually improve (although its already within 1σ), if the assumed metallicity (Z) were decreased. At the extreme, with $Z = \frac{1}{2}$ solar, a good fit can be achieved at an age of 375 ± 19 Myr, over 50% larger. (The metal-poor star begins with a smaller radius and higher T_{eff} , and must evolve farther through its main-sequence phase to reach the observed radius and luminosity.) This systemic age would correspond to a much lower progenitor mass of $3.61 \pm 0.125 M_{\odot}$. This unlikely outcome would make Sirius a seriously discrepant data point in the IFMR (F05).

On the other hand, we may note that most stars in the solar neighborhood have close to solar abundances. The analysis in this Letter is self-consistent within the stated assumptions. As a point in the overall IFMR for disk stars, it can be seen in F05 that the solar abundance Sirius B point has a somewhat higher white dwarf mass or a somewhat lower initial mass than most of the similar white dwarfs in NGC 2516, M35, and the Pleiades but overlaps the error bars of most of these. Marigo (2001) gives a careful treatment of AGB mass loss and predicts that a solar metallicity $5.06 M_{\odot}$ star should produce almost exactly a $1 M_{\odot}$ white dwarf. (We remarked earlier that the TYCHO code does also.) In summary, this result appears to provide a strong confirmation of stellar theory.

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