SURFACE HYDROGEN-BURNING MODELING OF SUPERSOFT X-RAY BINARIES: ARE THEY TYPE Ia SUPERNOVA PROGENITORS?

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ABSTRACT

Nova explosions occur on the white dwarf (WD) component of a cataclysmic variable stellar system that is accreting material lost by a companion. A Type Ia supernova (SN Ia) explosion is thought to result when a WD, in a similar binary configuration, grows in mass to the Chandrasekhar limit. Here, we present calculations of accretion of solar matter, at a variety of mass accretion rates, onto hot (2.3 × 10^4 K), luminous (30 L⊙), massive (1.25, 1.35 M⊙) carbon-oxygen WDs. In contrast to our nova simulations, where the WD has a low initial luminosity and a thermonuclear runaway (TNR) occurs and ejects material, these simulations do not eject material (or only a small fraction of the accreted material), and the WD grows in mass. A hydrogen TNR does not occur because hydrogen fuses to helium in the surface layers, and we call this process surface hydrogen burning (SHB). As the helium layer grows in mass, it gradually fuses either to carbon and oxygen or to more massive nuclei, depending on the WD mass and mass accretion rate. If such a WD were to explode in a SN Ia event, therefore, it would show neither hydrogen nor helium in its spectrum as is observed. Moreover, the luminosities and effective temperatures of our simulations agree with the observations of some of the supersoft X-ray binary sources, and therefore, our results strengthen previous speculation that some of them (CAL 83 and CAL 87, for example) are probably progenitors of SN Ia explosions. Finally, we have achieved SHB for values of the mass accretion rate that almost span the observed values of the cataclysmic variables.

Subject headings: accretion, accretion disks — binaries: close — novae, cataclysmic variables — stars: individual (CAL 83, CAL 87) — supernovae: general

1. INTRODUCTION

It is commonly assumed that Type Ia supernovae (SNe Ia) are the results of thermonuclear runaways (TNRs) in the cores of carbon-oxygen (CO) white dwarfs (WDs) that are members of interacting binary systems and have accreted material from a companion until their masses reach the Chandrasekhar limit (CL) and a carbon detonation/deflagration occurs (Nomoto et al. 1984; Leibundgut 2000, 2001; Hillebrandt & Niemeyer 2000). The binary star systems that evolve to this explosion, however, have not been identified. Given the importance of SNe Ia, both to our understanding of the evolution of the universe and to the formation of iron peak elements in the Galaxy, we must identify the progenitors of these explosions.

The binary scenario was originally proposed by Whelan & Iben (1973), and as a result virtually every type of close binary that contains a WD has been suggested at one time or another. However, based purely on observations, most of the systems that have been proposed cannot be the progenitors because the defining characteristic of an SN Ia outburst is the absence of hydrogen or helium in its spectrum (Filippenko 1997). (We note, however, that SN 2002ic, an SN Ia, did show a shell of hydrogen in its spectrum [Hamuy et al. 2003].) One of the first suggestions was a classical nova (CN) system, but the amount of core material ejected during the nova outburst implies strongly that the WD is decreasing in mass as a result of the outburst (MacDonald 1984; Gehrz et al. 1998; Starrfield 2003). Other suggestions such as symbiotic novae (T CrB or RS Oph, for example) can probably be ruled out because the SN explosion would take place inside the outer layers of a red giant and hydrogen would be present in the spectrum (Marietta et al. 2000; Lentz et al. 2002).

An important development was the discovery of the supersoft X-ray binary sources (SSSs; Trümper et al. 1991) and the suggestions that they were SN Ia progenitors (van den Heuvel et al. 1992, hereafter V92; Branch et al. 1995; Kahabka & van den Heuvel 1997, hereafter KV97). They are luminous, Lν ~ 10^{36–38} erg s^{-1}, with effective temperatures ranging from 30 to 50 eV or higher [(3–7) × 10^5 K]. V92 proposed that their properties could be explained by nuclear burning occurring in the outer layers of a WD at the same rate at which it was being accreted (steady burning hypothesis; Paczyński & Zytkow 1978, Sion et al. 1979, Iben 1982, and Fujimoto 1982a, 1982b). Therefore, the mass of the WD was increasing; it could reach the CL and then explode as an SN Ia (V92). Nevertheless, except for the pioneering work of Sion et al. (1979), no stellar evolution calculations have been done for massive WDs accreting at the high-mass accretion rates required to test the steady burning hypothesis. Calculations were done for lower mass CO WDs by Iben (1982) and Sion & Starrfield (1994), but the luminosities and effective temperatures of their simulations were too low to agree with the observations of SSSs such as CAL 83 or CAL 87 (Greiner 2000), and it was not clear that the WDs that they studied would reach the CL.

In contrast, we find in the calculations reported here that the material can burn at mass accretion rates that are far lower than the steady burning rate (a few × 10^{-7} M⊙ yr^{-1}; Kahabka 2004). A hydrogen TNR does not occur because the WD is
sufficiently hot that hydrogen burns in the layers near the surface as it is accreted. We therefore refer to our results as surface hydrogen burning (SHB) to prevent any confusion with steady burning. In § 2, we briefly describe the SSS. In § 3, we describe our evolutionary sequences, and we end with a summary.

2. SUPERSOFT X-RAY BINARIES

The ROSAT all-sky survey (and later pointed observations) established the SSS as a class of X-ray emitting systems (Trümper et al. 1991). A recent catalog can be found in Greiner (2000), and a discussion of their binary properties can be found in Cowley et al. (1998). Two systems have orbital periods of 1.04 days (CAL 83) and 10.6 hr (CAL 87) that are longer than those of typical CNe. Unfortunately, there is a large range in the luminosities and effective temperatures reported for a given system (Greiner 2000). Part of the difficulty is that for the systems studied by ROSAT, only a small region of the emitted spectrum is visible in the detectors and large corrections have to be applied to the observations (KV97).

The tabulated luminosities and effective temperatures of the two best-studied sources are (1) CAL 83: \( L = (0.7–6) \times 10^{38} \) ergs s\(^{-1}\) and \( T_{\text{eff}} = (5–6) \times 10^3 \) K (Parmar et al. 1998). The analyses of XMM Reflection Grating Spectrometer spectra of CAL 83 imply a temperature \( T_{\text{ss}} \sim 5 \times 10^4 \) K (Paerels et al. 2001). (2) CAL 87: \( L = (3–5) \times 10^{36} \) ergs s\(^{-1}\) and \( T_{\text{eff}} = (6–9) \times 10^3 \) K (Parmar et al. 1997). The WD masses are, as yet, undetermined, but the temperatures and luminosities imply WD radii. Observed properties for a number of SSSs (values taken from the above references or Greiner 2000) are shown in a theoretical H-R diagram (Fig. 1) along with the results of our calculations (described below). The systems shown in this figure are CAL 83, CAL 87, RX J0019.8+2156 (RX J0019), RX J0925.7–4758 (RX J0925), 1E 0035.4–7230 (1E 0035), and RX J0439.8–6809 (RX J0439). RX J0019 and RX J0925 are in our Galaxy; CAL 83, CAL 87, and RX J0439 are in the LMC; and 1E 0035 is in the SMC.

While CAL 87 appears to be less luminous than CAL 83, it is an eclipsing binary with an eclipse depth of 2 mag (Cowley et al. 1990). An XMM observation suggests that we are seeing only the accretion disk in X-rays and the WD must be more luminous (Orio et al. 2004). A factor of 2 increase in luminosity would place it in top of our results for 1.35 \( M_\odot \). The WD is probably this massive (Cowley et al. 1998).

3. SHB SEQUENCES FOR SSSs

We use the one-dimensional, fully implicit, Lagrangian, hydrodynamic computer code described in Starrfield et al. (1998, 2000) with one major change. The nuclear reaction network used in those papers was that of Weiss & Truran (1990). In this work, we use the pp+cn+rp network of F. X. Timmes.\(^6\) We also use the equation of state of F. X. Timmes (Timmes & Arnett 1999; Timmes & Swesty 2000) and the OPAL opacities (Rogers et al. 1996). We include the accretion energy as described in Shaviv & Starrfield (1988), although it is far smaller than the nuclear energy.

Our initial model is obtained by evolving a WD through a CN outburst. Once all the ejected material is expanding faster than the escape speed, has reached radii exceeding \( 10^{13} \) cm, and is optically thin, we remove it from the calculations. We then take the remnant WD and allow it to cool to \( \sim 10^{7} \, L_\odot \) before restarting accretion. We do this for three nova cycles, take the remnant WD from the last cycle, and then begin accretion when the WD luminosity has decreased to \( \sim 30 \, L_\odot \). (This luminosity is that found for V1974 Cyg 3 yr after outburst; Shore et al. 1997). We rezone our initial model so there are 95 zones covering the entire WD (our results are independent of the number of zones but not the zone mass; see below). The initial model has an outer boundary mass of \( 10^{-22} \, M_\odot \), a surface zone mass of \( 10^{-5} \, M_\odot \), and a temperature exceeding \( 7 \times 10^7 \) K. (We report the effects of the initial luminosity on the evolution in a later paper.) We used this procedure to calculate initial models for 1.25 and 1.35 \( M_\odot \) WDs. The core composition was 50% carbon and 50% oxygen. Solar composition material was accreted onto these WDs at a range of mass accretion rates. The metallicity of the LMC is about one-third that of the solar neighborhood, so we will study the effects of metallicity in a future paper. This will be important since metallicity clearly affects the evolution of SNe Ia (Timmes et al. 2003), and the range of \( z \) over which SNe Ia are currently being studied implies that they have different metallicities.

We begin the evolution with a bare CO core. In sequence 4, for example, we find that with a surface zone temperature of \( 7 \times 10^7 \) K and density of \( 10^4 \) g cm\(^{-3}\), the energy generation (\( \varepsilon_{\text{nuc}} \)) rises quickly to \( 10^4 \) ergs g\(^{-1}\) s\(^{-1}\). The outer layers are strongly heated by this energy release, and after 15 yr of evolution, \( T_{\text{ss}} \) (the temperature in the surface zone) \( = 2.7 \times 10^8 \) K, \( \varepsilon_{\text{nuc}} = 3.5 \times 10^4 \) ergs g\(^{-1}\) s\(^{-1}\), and \( L_{\text{SHB}} = 1.3 \times 10^{38} \) ergs s\(^{-1}\). It is now sufficiently hot in the surface zone so that it takes less time than the time step (\( \sim 2 \times 10^4 \) s) for all the infalling hydrogen to burn to helium in this zone. In addition, some of the helium is already burning to carbon in this zone. We designate this process SHB. Similar behavior, hydrogen burning out in the surface zone, occurs in all sequences listed in Table 1. The helium mass fraction declines to zero somewhat deeper into the WD and would have too small an abundance to be seen in the spectrum if this WD were to explode.

We find SHB at both WD masses but, for brevity, present only part of the results for 1.35 \( M_\odot \) in Table 1 and Figure 1. The results for other masses, and a detailed discussion of all our evolutionary sequences, will appear elsewhere (S. Starrfield et al. 2004, in preparation). The rows in Table 1 are the mass

\( 6 \) See http://www.cococubed.com/code_pages/net_pphotcno.shtml.
accretion rate (in units of \(M_\odot\) yr\(^{-1}\)), the length of time in years that we have followed the evolution, the amount of mass accreted (in units of \(M_\odot\)), the temperature \(T_\text{eff}\) and rate of energy generation \(\dot{e}_\text{acc}\) in the surface zone (sz), the luminosity, and the effective temperature (in units of both K and eV) of the evolutionary sequence. They are tabulated at the time we end the evolution. We stopped the evolution in sequences 3, 4, and 5 when the central density approached values at which carbon burning, not included in our network, should have begun. Sequence 1 exhibited a TNR in the helium layer after \(\sim 5 \times 10^7\) yr of evolution, but insufficient energy was released to directly eject any material. This sequence achieved a peak temperature in the TNR exceeding \(7 \times 10^8\) K and will be redone with a larger network. The other evolutionary sequences were hotter and not as degenerate when helium burning began so that no flash occurred. The final rows give the composition at the interface (CI) between the accreted matter and the core matter near or at the end of evolution.

Our results show that SHB occurs at \(1.35 M_\odot\) for values of the mass accretion rate typically observed in cataclysmic variables (CVs). This implies that if a post-CN system, with a massive WD, can arrive at a configuration where mass transfer onto the WD begins when the WD is still hot and luminous, then the mass of the WD will grow even if it is accreting at a rate normally observed only for CVs. The system does not have to be accreting or near to the canonical steady burning rate for the WD to grow in mass to the CL.

Our most important result is that in none of our sequences is there any hydrogen (and little helium) left in the surface mass zones on the WD. Additional sequences done with finer mass zoning at the surface \(10^{-7} M_\odot\) or 100 times smaller than the sequences in this Letter) show that hydrogen and helium reach only to a depth of \(\sim 10^{-8} M_\odot\). This implies that if such a structure were to explode in an SN Ia outburst, then there would be insufficient hydrogen or helium to appear in the spectrum (Lentz et al. 2002).

We also find that for sequences 2, 3, and 4, as the mass accretion rate increases, the abundance of \(^{12}\)C decreases and that of \(^{16}\)O increases. In sequence 1 the helium TNR was responsible for fusing the nuclei to the top of the included network (mass 20), and sequence 5 was sufficiently hot to burn almost all the nuclei to this mass. Therefore, we predict that the C/O ratio in the topmost layers of the ejecta (observed first and moving the fastest) will vary between SN Ia explosions and, when measured, would provide an estimate of the accretion rate prior to the SN Ia explosion.

The accretion rate in sequence 5 is above the assumed steady burning rate, but it still undergoes SHB and does not grow rapidly to large radii and shut off accretion. A sequence was evolved with an accretion rate of \(1.6 \times 10^{-6} M_\odot\) yr\(^{-1}\), and it expanded to large radii after 30 yr of evolution.

Much larger amounts of mass were accreted onto these WDs than in our previous studies of accretion onto low-luminosity WDs done for studies of CN outbursts (Starrfield et al. 2000 and references therein). In one case (sequence 5), the mass of the WD increased from 1.35 to \(\sim 1.38 M_\odot\) and the central density grew to \(2 \times 10^9\) g cm\(^{-3}\). Clearly, these calculations need to be extended with carbon burning reactions included in the nuclear reaction network.

We compare the results of our calculations to the observations in Figure 1, which plots both the luminosity \(L_{\text{SHB}}\) and effective temperature of the sequences together with the observations in a theoretical H-R diagram. The final value for each of our sequences is plotted as an asterisk, and they are connected by a line to guide the eye. The observed ranges for the SSSs are plotted as boxes. CAL 83 and 1E 0035.4 fall close to the results for \(1.25 M_\odot\), while CAL 87 and RX J0925 fall close to the results for \(1.35 M_\odot\). We predict that these four systems probably contain massive hot WDs accreting at high rates and growing to the CL. While CAL 87 falls below the line for \(1.35 M_\odot\) because it eclipsed the WD is probably more luminous. The other two SSSs are more problematic. RX J0019 and RX J0439 are in a region of the H-R diagram suggesting that they either contain lower mass WDs or are recovering from an extended traverse to cooler effective temperatures. Given the uncertainties in the observations and the fact that we have only begun this study, the agreement is encouraging.

4. SUMMARY

We have investigated the effects of accretion at high rates onto luminous \((30 L_\odot)\), hot \((T_{\text{eff}} = 2.3 \times 10^5\) K), and massive \((1.25 \text{ and } 1.35 M_\odot)\) WDs. We find quiescent burning of hydrogen and helium in the surface layers and, thereby, the growth
of the WD to the CL. Quiescent burning occurs at a large range of mass accretion rates, and the luminosities and effective temperatures of our evolutionary sequences agree with those observed for the SSS, which makes it probable that systems such as CAL 87 and CAL 83 are the progenitors of SNe Ia. We also find, for all but the lowest mass accretion rate, that all the accreted hydrogen and helium is transformed to at least carbon and oxygen in the surface mass zones. If one of our evolutionary sequences were to explode as an SN Ia, then there would be less than $10^{-6} M_\odot$ of hydrogen and helium in the expanding layers, which is unobservable (Lentz et al. 2002). We also find that the ratio of C/O in the surface zones is a function of the mass accretion rate and should vary from one SN Ia explosion to another.

An exciting implication of this study is that a CV binary system can produce either a CN or an SSS depending primarily on the luminosity of the WD when accretion is initiated after a CN outburst. Therefore, we propose first that a CN and an SSS may be two different phases of the evolution of the same binary system and, second, that a CV system may evolve from an SSS to a CN or the reverse at different times of its evolution.

We also find the following: (1) If CAL 83 is a 1.25 $M_\odot$ WD, then it is accreting at a rate between $2 \times 10^{-8}$ and $8 \times 10^{-8} M_\odot$ yr$^{-1}$. This is less than the steady burning mass accretion rate. (2) If CAL 87 is a 1.35 $M_\odot$ WD, then it is also accreting at a rate between $2 \times 10^{-8}$ and $8 \times 10^{-8} M_\odot$ yr$^{-1}$. Since CAL 87 is eclipsing, we assume that we are observing only a fraction of the energy emitted by the WD. (3) Our initial models were computed by accreting onto WDs that had just experienced a CN explosion but had not yet cooled to low luminosities. If this evolution is realized in nature, then we predict a link between the CN and SSS that results in SN Ia explosions. (4) Sequences 3, 4, and 5 have accreted a great deal more material than found in studies of accretion onto cool WDs. We feel confident that if we were to continue the evolution for the necessary time, then they would reach the Chandrasekhar limit. Thus, they satisfy the conditions necessary to be considered as strongly viable candidates for the progenitors of SN Ia explosions.

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REFERENCES

Branch, D., Livio, M., Yungelson, L. R., Boffi, F. R., & Baron, E. 1995, PASP, 107, 1019
Cowley, A., Schmidtke, P., Crampton, D., & Hutchings, J. 1990, ApJ, 350, 288
———. 1998, ApJ, 504, 854
Filippenko, A. V. 1997, ARA&A, 35, 309
Fujimoto, M. Y. 1982a, ApJ, 257, 752
———. 1982b, ApJ, 257, 767
Gehrz, R. D., Truran, J. W., Williams, R. E., & Starrfield, S. 1998, PASP, 110, 3
Greiner, J. 2000, NewA, 5, 137
Hamuy, M., et al. 2003, Nature, 424, 651
Hillebrandt, W., & Niemeyer, J. 1996, A&A, 35, 181
Iben, I., Jr. 1982, ApJ, 259, 244
Kahabka, P. 2004, in Compact Stellar X-Ray Sources, ed. W. Hillebrandt & B. Leibundgut (Heidelberg: Springer), in press (astro-ph/0212037)
Kahabka, P., & van den Heuvel, E. P. J. 1997, ARA&A, 35, 69 (KV97)
Leibundgut, B. 2000, A&A Rev., 10, 179
———. 2001, ARA&A, 39, 67
Lentz, E., Baron, E., Hauschildt, P. H., & Branch, D. 2002, ApJ, 580, 374
MacDonald, I. 1984, ApJ, 283, 241
Marietta, E., Burrows, A., & Fryxell, B. 2000, ApJS, 128, 615
Nomoto, K., Thielemann, F.-K., & Yokoi, K. 1984, ApJ, 286, 644
Orio, M., Ebisawa, K., Heise, J., & Hartmann, W. 2004, in Compact Binaries in the Galaxy and Beyond, ed. E. Sion & G. Tovmassian, in press (astro-ph/0402040)

Paczynski, B., & Zytkow, A. N. 1978, ApJ, 222, 604
Paerels, F., Rasmussen, A. P., Hartmann, H. W., Heise, J., Brinkman, A. C., de Vries, C. P., & den Herder, J. W. 2001, A&A, 365, L308
Parmer, A. N., Kahabka, P., & Hartmann, H. W. 1997, A&A, 323, L33
Parmer, A. N., Kahabka, P., Hartmann, H. W., Heise, J., & Taylor, B. G. 1998, A&A, 332, 199
Rogers, F. J., Swenson, F. J., & Iglesias, C. A. 1996, ApJ, 456, 902
Shaviv, G., & Starrfield, S. 1988, ApJ, 335, 383
Shore, S. N., Starrfield, S., Ake, T., & Hauschildt, P. H. 1997, ApJ, 490, 393
Sion, E. M., Acierno, M. J., & Tomczyk, S. 1979, ApJ, 230, 832
Sion, E. M., & Starrfield, S. 1994, ApJ, 421, 261
Starrfield, S. 2003, in From Twilight to Highlight: The Physics of Supernovae, ed. W. Hillebrandt & B. Leibundgut (Heidelberg: Springer), 128
Starrfield, S., Sparks, W. M., Truran, J. W., & Wiescher, M. C. 2000, ApJS, 127, 485
Starrfield, S., Truran, J. W., Wiescher, M. C., & Sparks, W. M. 1998, MNRAS, 296, 502
Timmes, F. X., & Arnett, D. A. 1999, ApJS, 125, 277
Timmes, F. X., Brown, E. F., & Truran, J. W. 2003, ApJ, 590, L83
Timmes, F. X., & Swesty, D. 2000, ApJS, 126, 501
Trümper, J., et al. 1991, Nature, 349, 579
van den Heuvel, E. P. J., Bhattacharya, D., Nomoto, K., & Rappaport, S. A. 1992, A&A, 262, 97 (V92)
Weiss, A., & Truran, J. W. 1990, A&A, 238, 178
Whelan, J., & Iben, I. Jr. 1973, ApJ, 186, 1007