Binary Paths to Type Ia Supernovae Explosions
Proceedings IAU Symposium No. 281, 2011
R. Di Stefano, M. Orio, & M. Moe, eds.

doi:10.1017/S1743921312014688

The Formation and Evolution of ONe White Dwarfs: Prospects for Accretion Induced Collapse

Enrique García–Berro[1,2]

[1]Departament de Física Aplicada, Universitat Politècnica de Catalunya,
c/Esteve Terrades 5, 08860 Castelldefels, Spain
[2]Institut d'Estudis Espacials de Catalunya,
c/Gran Capità, s/n, Edif. Nexus 104, 08034 Barcelona, Spain
email: `garcia@fa.upc.edu`

Abstract. I review our current understanding of the evolution of stars which experience carbon burning under conditions of partial electron degeneracy and ultimately become thermally pulsing "super" asymptotic giant branch (SAGB) stars with electron-degenerate cores composed primarily of oxygen and neon. The range in stellar mass over which this occurs is very narrow and the interior evolutionary characteristics vary rapidly over this range. Consequently, while those stars with larger masses ($\sim 11\, M_\odot$) are likely to undergo electron-capture accretion induced collapse, those models with smaller masses ($8.5 \lesssim M/M_\odot \lesssim 10.5$) will presumably form massive ($M \gtrsim 1.1\, M_\odot$) white dwarfs. The final outcome depends sensitively on the adopted mass-loss rates, the chemical composition of the massive envelopes, and on the adopted prescription for convective mixing.

Keywords. nuclear reactions, nucleosynthesis, abundances — stars: white dwarfs, AGB and post-AGB, abundances, evolution, interiors

1. Introduction

Stars which develop electron-degenerate cores made of matter which has experienced complete hydrogen, helium, and carbon burning have received only a small fraction of the attention lavished upon stars which develop electron-degenerate cores made of matter which has experienced complete hydrogen and helium burning, but not carbon burning. Because both types of stars form a continuous sequence of luminous giants brighter than regular red giant stars which have electron-degenerate helium cores, they are conventionally named asymptotic giant branch (AGB) stars — those with carbon-oxygen degenerate cores — and super-asymptotic giant branch (SAGB) stars — those with oxygen-neon cores (García–Berro & Iben 1994). A reason for the lack of models in the literature is that computing the conversion of a carbon-oxygen core into an oxygen-neon one is a very delicate and time-consuming task, because in these stellar evolutionary sequences carbon is ignited off-center, and the structure variables vary almost discontinuously through the burning front.

In both AGB and SAGB stars, long periods of hydrogen burning alternate with short thermonuclear runaways of the accumulated helium. During these helium shell flashes, neutron-capture nucleosynthesis produces *s*-process elements in a convective shell, which extends to almost the base of the convective envelope. These elements can be then dredged-up to the surface. This phenomenon is known as the thermally-pulsing (S)AGB phase, depending on the nature of the degenerate core. Actually, depending upon the mass and composition of their main sequence progenitors, the initial mass of the

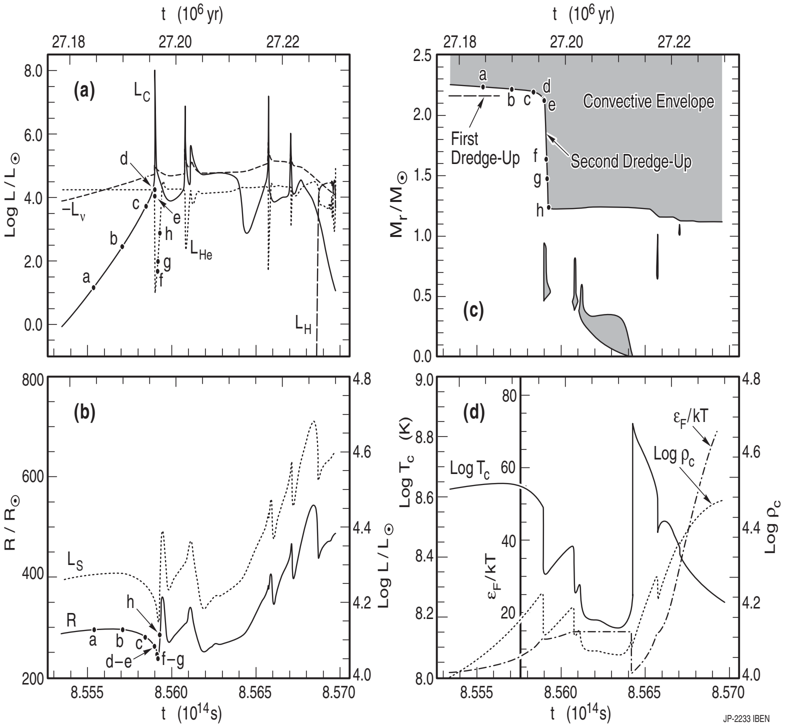

Figure 1. Global and internal characteristics of a $9\,M_\odot$ SAGB model during the carbon-burning phase. In the upper left-hand panel (a) are shown the carbon-burning luminosity $L_{\rm C}$, the helium-burning luminosity $L_{\rm He}$, the hydrogen-burning luminosity $L_{\rm H}$ and the neutrino loss rate $-L_\nu$. Stellar radius R and luminosity $L_{\rm S}$ are shown in the lower left-hand panel (b) and the location of the boundaries of convective layers are shown in the upper right-hand panel (c). Central temperature $T_{\rm c}$, density $\rho_{\rm c}$, and the electron Fermi energy $\epsilon_{\rm F}$ divided by kT are shown in the lower right-hand panel (d).

helium-exhausted core of a thermally-pulsing AGB star ranges from a minimum of $\sim 0.5\,M_\odot$ to a limit of $\sim 1.1\,M_\odot$. In contrast, the initial mass of a carbon-exhausted core of a thermally-pulsing SAGB star extends from the later upper limit to well above $\sim 1.3\,M_\odot$.

In the pioneering studies of the evolution of stars within this range of masses (Nomoto 1984, 1987) the emphasis was placed on the evolution of the degenerate core, and more specifically in the formation of oxygen-neon cores with masses larger than $1.37\,M_\odot$. These early studies focused primarily on exploring the electron-capture accretion induced collapse of these very massive cores, and disregarded the evolution of the also very massive envelopes of these stars. Consequently, they did not take into account that once carbon is exhausted in the central regions of these stars, hydrogen is re-ignited and a thermally pulsing phase ensues. The ultimate fate of these stars depends sensitively on the competition between the core-growth rate and the mass-loss rate, which in turn is determined by the metallicity of the envelope, and thus by the characteristics of the dredge-up. Thus, determining the final result of the evolution of this kind of stars requires following in detail the evolution of both the inner core and of the envelope. In the following I summarize the main results of self-consistent fully evolutionary studies of these stars. However, for the sake of conciseness only a brief overview of the very interesting physical phenomena occurring during the carbon burning phase in this mass interval will be given, and I refer the interested reader to the series of papers by Ritossa *et al.* (1996), García–Berro *et al.* (1997), Iben *et al.* (1997), Ritossa *et al.* (1999), the more recent studies of Siess (2006, 2007, 2009, 2010) which confirm the main findings of the previous papers, and Poelarends *et al.* (2008). Also, the possible outcomes of the evolution of SAGB stars will be analyzed, but I will not discuss here other interesting aspects, like the possible contribution of this range of masses to r-process nucleosynthesis (Ning *et al.* 2007, Wanajo *et al.* 2006).

2. Overview of the Carbon-Burning Phase

Before studying in some detail the evolution of these stars, a cautionary remark is in order, as the evolution in this narrow range of masses is extremely dependent on the initial mass of the star. For instance, for most of the mass interval, carbon is ignited off-center, but for the high-mass end carbon ignition occurs in the central layers. The occurrence of the second dredge-up episode (see below) also sensitively depends on the mass, as do many subtleties of the evolution. Thus, I choose to show only the evolution of just one star. The rest of the details can be found, as said, in the above mentioned papers.

The temporal evolution of several interesting characteristics during the carbon-burning phase of an otherwise representative star of $9\,M_\odot$ are shown in Figure 1. As can be seen in the top left panel of this figure, carbon is initially ignited off-center (a result of the efficient neutrino cooling during the previous evolution of the core), in a very strong flash ($L \sim 10^8\,L_\odot$). As a consequence, an interior convective region develops (top right panel) in response to the very rapid injection of nuclear energy. This convective shell persists during a substantial period of time, after which a good fraction of the carbon in this region has been nuclear-processed to oxygen and neon. The nuclear energy release causes expansion of the overlying layers, and accordingly, helium burning almost ceases. The conditions of the interior are such that carbon is again ignited off-center and the same sequence of events occurs. Only during the third flash does the burning front reach the center. Note that the propagation of the nuclear flame is very slow and only asymptotically reaches the center of the star, and that after a period during which it extends into the region where carbon has been partially depleted, the outer edge of the convective shell recedes (in mass) to an almost stationary value. During this phase the carbon abundance in the convective shell decreases only because of burning in the shell and not because of dilution by mixing with carbon-depleted matter from above. The carbon-burning luminosity remains at a relatively high, constant value ($L_{\rm C} \sim 5\times10^4\,L_\odot$). The progression of the burning front towards the center is found to be in agreement with analytical results (Timmes & Woosley 1992):

$$v \simeq \left(\frac{c\epsilon_{\rm nuc}}{\kappa\rho E}\right)^{1/2}$$

where c is the speed of sound, $\epsilon_{\rm nuc}$ is the rate of nuclear energy generation, κ is the opacity, ρ is the density, and E is the energy density, all calculated just behind the flame front. However it is worth mentioning that as the flame front reaches the center its width becomes narrower; this is the reason it approaches the central regions only asymptotically. Actually, resolving the progression of the flame front is a tough task, as its width during the very last stages of the carbon burning phase can be as small as 3 km.

As can be seen in the lower left panel of Figure 1 the temporal evolution of radius and the luminosity are parallel, a consequence of the transparency of the envelope. Note, however, that the surface of the star is almost decoupled from the deep interior. This is why the early calculations of Nomoto (1984, 1987), in which only the evolution of

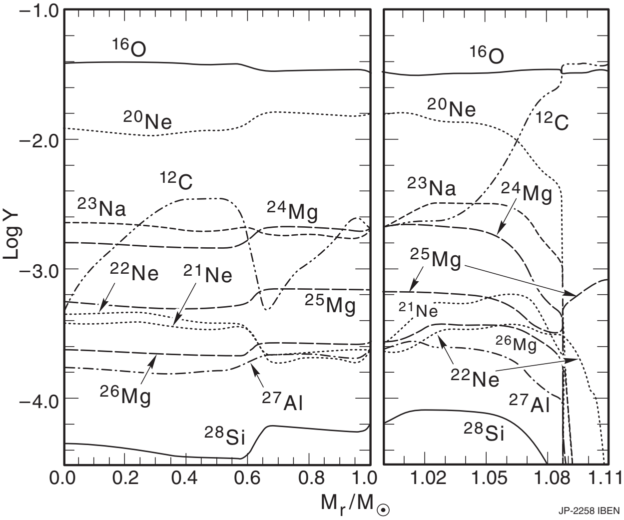

Figure 2. Abundances by number of several isotopes in the helium-exhausted interior at the end of the carbon-burning phase.

the degenerate core was followed, yielded reasonable results. Nevertheless, it is quite apparent from the upper right panel of Figure 1 that the occurrence of the second dredge-up — which has important consequences for the ultimate evolution of these stars since it pollutes the envelope of the star with nuclear-processed material and modifies its metallicity, and hence the mass-loss rate — is intimately related to the first carbon flash.

Figure 2 shows the chemical composition of the core (left panel) and, using a larger scale, that of the transition region between the core and the envelope of our fiducial model (right panel). The most relevant features of the chemical profiles in the core are the following. Firstly, note that the core is predominantly carbon- and oxygen-rich, and that the magnesium abundance is significantly smaller. Actually, in a large region of the core, ^{23}Na is more abundant than ^{24}Mg. The reason for this is that at the temperatures relevant for carbon burning in these stars, the reaction $^{12}\mathrm{C}+^{12}\mathrm{C}\longrightarrow^{24}\mathrm{Mg}$ is strongly suppressed. The second important fact is that carbon is not completely depleted in a sizable part of the core. In fact, non-negligible amounts of carbon ($\log Y \sim -2.5$) can be found in a region comprising $0.4 \lesssim M/M_{\odot} \lesssim 0.7$. The fraction of unburned carbon is, however, smaller in the case of stars with slightly larger masses. This is a consequence of the progression toward the center of the carbon burning front (García–Berro *et al.* 1997). This has implications for accretion induced collapse, in the event that a white dwarf or a degenerate core of a SAGB star of initially $\sim 1.1\,M_{\odot}$ can grow in mass to reach the effective Chandrasekhar limit of $\sim 1.37\,M_{\odot}$ (Miyaji & Nomoto 1987). In such a case carbon will ignite before oxygen does and the energy released by the burning of even small amounts of carbon (∼2%) is sufficent to completely disrupt the star (Gutiérrez *et al.* 1996; Gutiérrez *et al.* 2005). Note also the absence of ^{22}Ne in the very outer layers of the carbon-rich degenerate core, where this element has been converted to ^{25}Mg. On top of these regions a helium-rich buffer exists (not shown). The mass of this buffer is on the order of $10^{-2}\,M_{\odot}$, but depends somewhat on the initial mass of the star. This has implications for the occurrence of ONe white dwarfs (Gil–Pons *et al.* 2003). An estimate of novae produced by ONe white dwarfs can be easily made. At typical mass-transfer rates of 10^{-9} to $10^{-8}\,M_{\odot}\,\mathrm{yr}^{-1}$, approximately $10^{-5}\,M_{\odot}$ must be accumulated before a nova outburst occurs. Assuming that mixing between the accreted matter and white dwarf matter results in a hydrogen profile extending $\sim 10^{-5}\,M_\odot$ into the white dwarf (Fujimoto & Iben 1992) and that approximately twice that mass is ejected in the explosion, the neon-free layer will be removed in $\sim 10^3$ outbursts. If the mass of the companion is $\sim 0.5\,M_\odot$, and if the high mass-transfer rate stops when the mass of the companion falls below $\sim 0.3\,M_\odot$, roughly 2×10^4 neon-rich explosions will occur every $\sim 10^4$ yr. Thus, 1 out of 20 novae will exhibit neon excesses. Finally, on top of the buffer a massive hydrogen-rich envelope ($M_{\rm env} \sim 7.9\,M_\odot$) can be found. As will be shown below, the thickness and metallicity of the envelope are crucial elements determining whether the core is able to grow to the Chandrasekhar mass and undergo electron-capture accretion induced collapse, or instead an ONe white dwarf is formed.

3. Possible Outcomes of SAGB Stars

In all models — except for the $11\,M_\odot$ star, in which electron captures in the degenerate core start very early in the evolution — as carbon burning becomes increasingly less important in driving the evolution, the core contracts rapidly and the temperature at the H-He discontinuity increases to such an extent that hydrogen burning is reactivated. Eventually, the He buffer increases in mass, the temperature rises, and a thermonuclear flash ensues. This causes helium to be exhausted in a short time ($\sim$1 yr), while the rapid injection of energy at the base of the helium buffer expands the overlying mass shells. This, in turn, causes the H-He discontinuity to expand and cool and, consequently, the hydrogen burning shell is extinguished. Subsequently, the H-He moves inwards — a consequence of not having enough energy to locally support the mechanical structure of the hydrogen-rich envelope — its temperature increases again, and the entire process is repeated. In summary, long periods ($\sim$200 yr) of quiescent hydrogen burning, in which $\log L_{\rm H} \simeq 4.8$, alternate with short periods in which almost the entire helium buffer is burned, and the helium luminosity reaches $\log L_{\rm He} \simeq 6.5$. This process is known as a thermal pulse. Thermal pulses are interesting from a nucleosynthetic point of view, since during a thermal pulse a small, short-lived convective region is formed. In our case, during the course of a thermal pulse $\sim 13\%$ of ^{22}Ne formed in the reactions experienced by ^{14}N and its progeny during helium burning is converted to ^{25}Mg through the reaction $^{22}{\rm Ne}+\alpha \longrightarrow {}^{25}{\rm Mg}+{\rm n}$, releasing enough neutrons to drive *s*-process nucleosynthesis. Moreover, the temperature reached during a thermal pulse is high enough ($T \sim 3.0\times 10^8$ K) to drive the so-called "hot bottom burning" process (Ventura & D'Antona 2011).

During a thermal pulse the third dredge-up occurs. This phenomenon is in essence identical to the second dredge-up. Energy is radiated from the region where helium burning produces it. A large fraction of energy is absorbed by the radiative zone below the base of the convective envelope, forcing matter in it to expand and cool. Finally, the increase in flux in this region forces the base of the convective envelope to move inward with respect to mass. The rate at which the H-He discontinuity moves outward and the degree of dredge-up determine the chemical enrichment of the envelope, and therefore the ultimate fate of SAGB stars. This is because the mass-loss rate depends on the metallicity of the envelope, which depends on the prescription adopted for determining the position of the inner edge of the convective envelope (Gil–Pons *et al.* 2005, 2007). However, in contrast to what occurs for normal AGB stars, the number of thermal pulses necessary to remove the massive envelope is in this case very large, $\sim 10^3$ (Poelarends *et al.* 2008). Following the evolution during the thermally pulsing phase is thus a hard task, and we rely on approximations. The synthetic models of Izzard & Poelarends (2006) and Poelarends *et al.* (2008) predict that, when standard prescriptions for the mass-loss rate are adopted, single stars with masses smaller than $\lesssim 10.5\,M_\odot$ will produce ONe white dwarfs with masses $\lesssim 1.3\,M_\odot$, while stars with masses larger than that value will grow in mass before the envelope is ejected, and will reach the effective Chandrasekhar mass.

If the SAGB star belongs to a binary system, an ONe white dwarf with mass larger than $1.1\,M_\odot$ can be formed for a broad range of orbital parameters (Gil–Pons & García–Berro 2001, 2002). In this case the white dwarf can accrete mass from the secondary and the central density can eventually become larger than the threshold for electron captures on the ashes of carbon burning, as occurs for single stars with masses larger than $\sim 10.5\,M_\odot$. As previously mentioned, in both cases the final evolution depends sensitively on the final abundances of ^{12}C, ^{16}O, ^{20}Ne, and ^{24}Mg, and the final outcome (explosion or collapse) is crucially dependent on the adopted prescription for convective mixing (Gutiérrez *et al.* 1996, 2005). In any case, it is clear that at least some of these stars will produce produce massive ONe white dwarfs. The evolution of these white dwarfs and their mass-radius relation have been consistently studied by Althaus *et al.* (2005) and Althaus *et al.* (2007), respectively.

4. Observational Status

The existence of a substantial population of ultramassive white dwarfs has been recently reviewed critically by Vennes & Kawka (2008). Their findings have unveiled the existence of a handful of very massive white dwarfs. The most promising candidates are NLTT 14307 ($M \simeq 1.24\,M_\odot$), NLTT 43827 ($M \simeq 1.31\,M_\odot$), NLTT 31372 ($M \simeq 1.11\,M_\odot$), NLTT 44986 ($M \simeq 1.26\,M_\odot$), and NLTT 52728 ($M \simeq 1.24\,M_\odot$). This evidence supports the findings of Catalán *et al.* (2008), who found that the initial to final mass relationship becomes steeper for progenitors masses larger than $\sim 6\,M_\odot$. Also, Dobbie & Baxter (2010) have recently discovered a massive white dwarf (WD J0646−203) in the open cluster NGC 2287. This white dwarf has a mass $M \simeq 1.12\,M_\odot$, making it the most massive open cluster degenerate identified to date. Moreover, the cooling age of this object ($t_{\rm cool} \sim 170$ Myr) is consistent with it having descended from a single heavy-weight intermediate-mass star, lending support to theoretical predictions. Additionally, Gänsicke *et al.* (2010) have also discovered two white dwarfs with oxygen-rich atmospheres. The very high oxygen abundance of these stars and the lack of carbon in their spectra cannot be explained by modern stellar evolutionary calculations of post-AGB stars, and the only possibility we are left with is that they are the end-product of the evolution of SAGB stars which have been deprived of their hydrogen- and helium-rich atmospheres. Moreover, there are strong indications that these white dwarfs are indeed massive. Of course, the observed number of nearby hot ultramassive white dwarfs could be the result of both single stellar evolution and double white dwarf mergers. However, the observed number of these stars in the solar neighborhood is difficult to reconcile (Dobbie *et al.* 2006) with the population predicted by binary evolution models which adopt a plausible Galactic white dwarf merger rate ($\sim 10^{-3}$ yr^{-1}). Thus, at least some of these white dwarfs should be the descendants of SAGB stars.

On the other hand, the progenitor mass of several sub-luminous type II-P supernovae (Hendry *et al.* 2005, 2006; Maund *et al.* 2005; Li *et al.* 2007) has been estimated. These works have reached the conclusion that very likely these explosions were powered by stars with masses larger than $\sim 9\,M_\odot$, thus giving support to the existence of an electron-capture supernovae channel for the most massive SAGB stars. In particular, Hendry *et al.* (2006) identified the progenitor of SN 2004a in pre-explosion images and showed that most likely the progenitor was a red supergiant with a mass $9^{+2}_{-2}\,M_\odot$. This mass is very similar to those of SN 2004gd, $8^{+4}_{-2}\,M_\odot$ (Hendry *et al.* 2005), and SN 2005cs,

$9^{+3}_{-2}\,M_\odot$ (Maund *et al.* 2005). All these supernovae are Type II-P. Also, more recently Li *et al.* (2007) have identified the progenitors of the Type II-P supernovae SN 2006my in NGC 4651, and SN 2006ov in M61. Their respective progenitor masses are, respectively, $10^{+5}_{-3}\,M_\odot$ and $15^{+5}_{-3}\,M_\odot$. All in all, it seems quite plausible that Type II-P supernovae originate from heavy-weight intermediate-mass stars, while the lower mass-end of SAGB stars results in ultramassive white dwarfs.

To conclude this section I would like to stress that recently, increasing attention has been paid to studying the asteroseismological properties of massive ZZ Ceti stars (Córsico *et al.* 2004), since it opens the interesting possibility of probing the physical mechanisms operating in their very dense interiors and their internal chemical composition. This has been motivated by the discovery of pulsations in the star BPM 37093 (Kanaan *et al.* 1992), a massive ZZ Ceti star which has a mass of $1.05\,M_\odot$ and an effective temperature $T_{\rm eff}$ $\sim$11,800 K, and which, therefore, should have a sizable crystallized core. It is interesting to note at this point that this mass is very close to the theoretical lower limit ($\sim$$1.05\,M_\odot$) for an ONe white dwarf to be formed. Nonetheless, the small number of detected periods (eight) in the light curve of BPM 37093 renders conclusive asteroseismological inferences in this case very difficult. However, a reliable measure of the rate of change of the period of this white dwarf will allow us to directly probe the chemical composition of its degenerate core, thus confirming (or not) the common belief that low-mass SAGB stars produce massive white dwarfs.

5. Summary and Discussion

I have reviewed our current understanding of the evolution of stars that experience carbon burning under conditions of partial electron degeneracy and become thermally pulsing SAGB stars. These stars encompass a very narrow mass range, between $\sim$$8\,M_\odot$ and $\sim$$11\,M_\odot$, although the precise boundaries depend sensitively on the metallicity at the ZAMS and on the amount of overshooting. I have also reviewed how carbon is burned in these stars and why they develop a thermally pulsing phase. Moreover, I have shown that, most likely, the low-mass end of this range of masses produces massive ONe white dwarfs, while the degenerate core of heavy-weight intermediate-mass stars would probably grow in mass and undergo electron captures on the ashes of carbon burning. Specifically, I have shown that the initial mass range for core collapse after SAGB evolution depends on the competition between the core-growth rate and the mass-loss rate of the SAGB star. Efficient mass loss leads to a shorter duration of the SAGB phase, and the core does not reach the effective Chandrasekhar mass. On the other hand, the rate of core growth depends on how fast hydrogen is burned and, hence, on two crucial factors: the existence of hot bottom burning and the efficiency of the third dredge-up. Whether these stars collapse to neutron star dimensions or explode as supernovae depends on the amount of unburnt carbon in the degenerate ONe core resulting from the previous evolution and on the adopted prescription for convective mixing.

The observational status of the field has also been reviewed. In particular, I have shown that a handful of white dwarfs with accurate mass determinations are rather massive. This strongly suggests that at least some SAGB would end their lives as ONe white dwarfs. This evidence is further supported by the recently discovery of a population of white dwarfs with oxygen-rich atmospheres. However, the searches for the progenitors of sub-luminous type II-P supernovae have resulted in the identification of three red supergiants with masses $\lesssim 9\,M_\odot$. In summary, the precise value of the mass separating the formation of ONe white dwarfs and supernovae is still a matter of debate.

Acknowledgements

This work was partially supported by AGAUR, by MCINN grant AYA2008-04211-C02-01, by the European Union FEDER funds, and by the ESF EUROGENESIS project (grant EUI2009-04167).

References

Althaus, L. G., García–Berro, E., Isern, J., & Córsico, A. H. 2005, *A&A*, 441, 689

Althaus, L. G., García–Berro, E., Isern, J., Córsico, A. H., & Rohrmann, R. D. 2007, *A&A*, 465, 249

Catalán, S., Isern, J., García–Berro, E., & Ribas, I. 2008, *MNRAS*, 387, 1693

Córsico, A. H., García–Berro, E., Althaus, L. G., & Isern, J. 2004, *A&A*, 427, 923

Dobbie, P. D., Napiwotzki, R., Lodieu, N., Burleigh, M. R., Barstow, M. A., & Jameson, R. F. 2006, *MNRAS*, 373, L45

Dobbie, P. D. & Baxter, R. 2010, *American Institute of Physics Conference Series*, 1273, 31

Fujimoto, M. & Iben, I., Jr. 1992, *ApJ*, 399, 646

Gänsicke, B. T., Koester, D., Girven, J., Marsh, T. R., & Steeghs, D. 2010, *Science*, 327, 188

García–Berro, E. & Iben, I. 1994, *ApJ*, 434, 306

García–Berro, E., Ritossa, C., & Iben, I., Jr. 1997, *ApJ*, 485, 765

Gil–Pons, P. & García-Berro, E. 2001, *A&A*, 375, 87

Gil–Pons, P. & García-Berro, E. 2002, *A&A*, 396, 589

Gil–Pons, P., García-Berro, E., José, J., Hernanz, M., & Truran, J. W. 2003, *A&A*, 407, 1021

Gil–Pons, P., Suda, T., Fujimoto, M. Y., & García-Berro, E. 2005, *A&A*, 433, 1037

Gil–Pons, P., Gutiérrez, J., & García-Berro, E. 2007, *A&A*, 464, 667

Gutiérrez, J., García–Berro, E., Iben, I., Jr., Isern, J., Labay, J., & Canal, R. 1996, *ApJ*, 459, 701

Gutiérrez, J., Canal, R., & García–Berro, E. 2005, *A&A*, 435, 231

Hendry, M. A., *et al.* 2005, *MNRAS*, 359, 906

Hendry, M. A., *et al.* 2006, *MNRAS*, 369, 1303

Iben, I., Jr., Ritossa, C., & García–Berro, E. 1997, *ApJ*, 489, 772

Izzard, R. G. & Poelarends, A. J. T. 2006, *Mem. SAI*, 77, 840

Kanaan, A., Kepler, S. O., Giovannini, O., & Diaz, M. 1992, *ApJ*, 390, L89

Li, W., Wang, X., Van Dyk, S. D., Cuillandre, J.-C., Foley, R. J., & Filippenko, A. V. 2007, *ApJ*, 661, 1013

Maund, J. R., Smartt, S. J., & Danziger, I. J. 2005, *MNRAS*, 364, L33

Miyaji, S. & Nomoto, K. 1987, *ApJ*, 318, 307

Ning, H., Qian, Y.-Z., & Meyer, B. S. 2007, *ApJ*, 667, L159

Nomoto, K. 1984, *ApJ*, 277, 791

Nomoto, K. 1987, *ApJ*, 322, 206

Poelarends, A. J. T., Herwig, F., Langer, N., & Heger, A. 2008, *ApJ*, 675, 614

Ritossa, C., García–Berro, E., & Iben, I., Jr. 1996, *ApJ*, 460, 489

Ritossa, C., García–Berro, E., & Iben, I., Jr. 1999, *ApJ*, 515, 381

Siess, L. 2006, *A&A*, 448, 717

Siess, L. 2007, *A&A*, 476, 893

Siess, L. 2009, *A&A*, 497, 463

Siess, L. 2010, *A&A*, 512, A10

Timmes, F. X. & Woosley, S. E. 1992, *ApJ*, 396, 649

Vennes, S. & Kawka, A. 2008, *MNRAS*, 389, 1367

Ventura, P. & D'Antona, F. 2011, *MNRAS*, 410, 2760

Wanajo, S., Nomoto, K., Iwamoto, N., Ishimaru, Y., & Beers, T. C. 2006, *ApJ*, 636, 842