Mem. S.A.It. Vol. 78, 549

Memorie della

Is the cosmological use of SNe Ia reliable?

I. Domínguez[1], L. Piersanti[2], O. Straniero[3], and A. Tornambè[3,]

[1] Departmento de Física Teórica y del Cosmos, University of Granada, Spain
e-mail: dominguez@ugr.es
[2] INAF - Osservatorio Astronomico di Teramo, via M. Maggini, 64100, Teramo, Italy
e-mail: piersanti,straniero@oa-teramo.inaf.it
[3] INAF - Osservatorio Astronomico di Roma, via Frascati, Monteporzio Catone, Italy
e-mail: tornambe@oa-teramo.inaf.it

Abstract. We address the reasons which still prevent the understanding of the origin of type Ia Supernovae, namely the nature and the evolutionary history of the progenitor stellar system and the characteristics of the explosive event. This casts doubts on the use of SNe Ia as cosmological distance indicators. We present a realistic evolutionary scenario which, in our opinion, gets rid of several concerns of supernova-like events in double degenerate merging systems. Rotation, which naturally arises in the two stellar components of these systems, is considered along the whole evolution from the pre-merging phase, through the accretion stage, and, finally, to the onset of the dynamically explosive event when the WD attains the rotational Chandrasekhar mass value. The physical properties of the systems determine the "self-regulation" of the accretion process so that the WD can attain the rotational Chandrasekhar limit and Carbon ignition occurs at the center, thus determining an explosion of Supernova Ia proportions. We analyze the expected properties of such systems in the real world as a function of the total mass and explosion time. We find that SNe Ia events can be produced by differentially rotating WDs as massive as $2.2 M_{\odot}$ (higher masses are unrealistic due to evolutionary constraints, although they are not ruled out *a priori* by theoreticians). Moreover, we find that more massive progenitors should occur in young stellar systems (*i.e.* soon after the epoch of the star formation), whilst only low mass progenitors ($\sim 1.4 M_{\odot}$) are expected in old stellar systems.

Key words. Supernovae – Cosmology – White Dwarfs – Accretion – Rotation

1. Introduction

Type Ia Supernovae (SNe Ia)occur both in elliptical (where presumably star formation halted several billion years ago) and spiral galaxies (where star formation is an ongoing process). On the other hand, in ellipticals only type Ia Supernovae are observed. In a typical SN Ia event some 10^{51} erg are delivered and neutrino firework is expected not to occur. Spectra at the maximum epoch do not exhibit Hydrogen lines. Light curves attain a maximum in about 19 days (Conley et al. 2006,and references therein) and decline logarithmically in some months with two different slopes corresponding to the Nickel into Cobalt and Cobalt into Iron decays.

At the beginning, type Ia Supernovae were considered to be very similar, if not identical, each other, but it became soon evident that this hypothesis was not correct since differences up to 2 magnitudes were observed at the maximum epoch. However, in 1993 Phillips showed that for a number of near and well observed SNe Ia, whose distance was *a-priori* determined by means of *bona fide* distance indicators, a linear correlation between maximum luminosity and decline rate of luminosity after maximum there exists. Basing on this evidence, these Supernovae can be considered once again as an homogeneous class and they can be used as "standardized" candles (Phillips 1993; Hamuy et al. 1996). Now, a question remains still open: is this correlation universal, so that it can be safely applied to SNe Ia on cosmological distances?

Recently it has been shown that at any distance scale the magnitude at the maximum epoch correlates with the stellar population from which the type Ia event comes from (Sullivan et al. 2006; Mannucci et al. 2005, 2006,and references therein): luminous (slow declining) SNe Ia occur only where star formation is going on and the SNe Ia rate per unit mass is higher. These results could imply that such Supernovae arise from at least two different stellar progenitors, old and young, and that the differences in the light curves depend on the progenitor properties.

In this respect theory is not helpful since very few is known about the SNe Ia stellar progenitor and the mechanism of the thermonuclear explosion is still under debate.

The observational evidence clearly suggests that Supernovae Ia are produced by Carbon-Oxygen (CO) white dwarfs (WDs) accreting mass. When the accreting structure approaches the Chandrasekhar limit, it begins to contract and it heats up. As a consequence C-burning is ignited at the center in highly degenerate physical conditions and, in about 10^4 yr, the explosion and the complete disruption of the WD occurs. On the other hand, the characteristics of the binary systems as well as the properties of the accretion phase are still under hard debate. Only two scenarios have survived so far the challenge of time. These are referred as the Single Degenerate (SD) and the Double Degenerate (DD) scenarios.

In the first case the donor is a normal star with an Hydrogen rich envelope (Whelan & Iben 1973). These systems are well studied and they are associated with a variety of observational events (symbiotic stars, classical novae, cataclysmic variables, dwarf novae, recurrent novae and many others). Unfortunately it is not known whether in some of these systems the accreted matter could be burned into a C-O mixture or the mass of the CO WD should increase up to the Chandrasekhar mass. In the next Section we will discuss why, under reasonable assumptions, we believe that such a system can not be regarded as promising SNe Ia progenitors.

The second scenario envisions a system composed by two tidally interacting WDs with total mass of the order of or greater than the Chandrasekhar mass. In this case the two stars, due to gravitational wave radiation emission, undergo a merging so that the less massive components completely disrupts, thus forming an accretion disk around the more massive one (Iben & Tutukov 1984; Webbink 1984). In this case C-O rich matter is directly accreted. One major concern afflicts the DD scenario: the accretion rate which results after the merging would be so high that off-center carbon ignition occurs well before the WD could attain the limiting mass, thus producing as final outcome not a SNe Ia event, but an O-Ne-Mg white dwarf which eventually collapses into a neutron star (Nomoto & Iben 1985; Saio & Nomoto 1985, 1998). The historical concern about the existence or not of real counterparts of these systems (Robinson & Shafter 1987; Bragaglia et al. 1990; Saffer, Livio & Yungelson 1998; Koen, Orosz & Wade 1998) seems now to have been solved in favor of their existence (Napiwotzki et al. 2005).

In Section 3 we will analyze the problem of the accretion process in DD systems and we will show that, when the rotational effects are taken into account in modelling the binary system, the evolution from the merging of the two CO WDs up to the final explosive outcome is not only possible, but it results mandatory.

2. On the H-accretion process

Accretion of H-rich matter onto WDs is a rather common process in nature. Many differ-

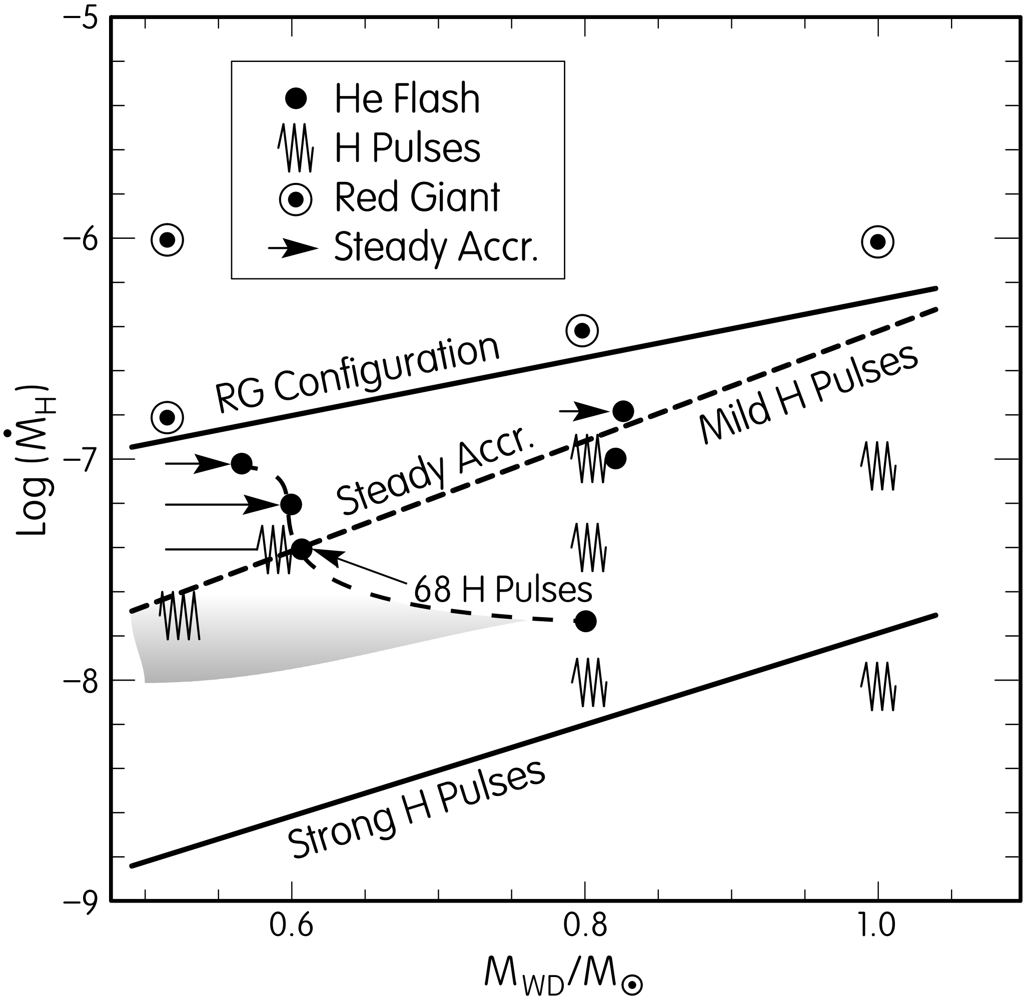

Fig. 1. Possible final outcome of H-accreting WD in the parameter-space $M_{WD} - \dot{M}$ (see text).

ent outcomes of such a process are well known and well studied. However, whether the long time evolution would produce the increase in mass of the C-O core up to the Chandrasekhar limit is an open question. In this respect theory gives rather compelling negative answers, as depicted in Fig. 1. First of all it has to be remarked that if rotational effects are neglected in the evolution of H-accretion WDs, it is impossible to obtain as a final outcome a CO WD as massive as $\sim 1.4 M_\odot$. In fact, also when assuming that the accreted Hydrogen is nuclearly processed in a quasi-stable regime (*i.e.* for $10^{-7} < \dot{M} < 10^{-8} M_\odot/yr$), the corresponding He-buffer which is piled becomes partially degenerate. As a consequence, when 3α reaction is ignited at the bottom of the He shell a mild He flash results, thus inflating the external layers. In this case the matter previously accreted is completely lost via a common envelope episode due to the interaction with the companion. When different H-accretion regimes are considered, the scenario becomes even worse for an explosive outcome: in fact for $\dot{M} < 10^{-8} M_\odot/yr$ the accreted matter is soon lost via strong nova-like H pulses, whilst for $\dot{M} > 10^{-7} M_{\odot}/yr$ a common envelope configuration is rapidly attained, so that the growth in mass is prevented at all (Cassisi et al. 1998; Piersanti et al. 1999, 2000, 2001).

However, the effects of stellar rotation on the evolution of WDs accreting H-rich matter have to be considered even if in Single Degenerate systems the two components are far enough that the corresponding angular velocity as determined by the previous evolution of both components is small as compared to that in the Double Degenerate case. Yoon, Langer & Scheithauer (2004) have shown that rotation may stabilize the burning via 3α reactions at the bottom of an He shell piled up as direct accretion of He-rich matter onto a C-O WD. This is not a straightforward occurrence but the stabilization of the He-burning can really occur in nature. Therefore, the key point is if also in the case of WD accreting Hydrogen in a stable regime He-burning can become stable. We believe that this cannot occur. As matter of fact, H and He-burning shell can not be simultaneously active in a steady state unless very extreme physical conditions (see *e.g.* Fujimoto et al. 1984).

In conclusion we guess that it does not exist an evolutionary path via H-accretion which could lead to the formation of a CO core as massive as $1.4 M_{\odot}$. So far a full self-consistent evolution of such a kind has not been performed.

3. Modeling the evolution of DD systems

According to the observational evidence, DD systems do exist, their components can undergo a merging process with a certain frequency and in some cases the total mass of the merging system if higher than the Chandrasekhar limit (Napiwotzki et al. 2005).

However, in the canonical scenario of stellar evolution (no rotation), such systems are not promising as SNe Ia progenitors since the accretion rate resulting after the merging of the two components is so high that Carbon burning is ignited in the outermost layers when the total mass is far from $1.4 M_{\odot}$ and the corresponding outcome is the formation of an O-Ne-Mg WD. Once again, as in the case of the Single Degenerate scenario, rotational effects deserves interesting news.

Details about the numerical modelling are given elsewhere (Piersanti et al. 2003b); here we focus our attention on the evolution of a DD system initially composed by two WDs, having the same mass ($0.8 M_{\odot}$) and with a separation of $\sim 1 R_{\odot}$. Note that theoretical investigations strongly support the existence of such a system (Tornambè 1989; Iben & Tutukov 1984).

The evolution can be divided into three major phases. Initially, due to the combined action of shear friction and tidal forces, the two components spin up until their rotation rates become synchronized with that of the orbital revolution (Webbink & Iben 1988; Iben, Tutukov & Fedorova 1998). Note that, once synchronization is attained, it will maintained up to the merging stage. The heating produced by the frictional stresses determines a substantial change in the thermal profile of the two stars (Iben, Tutukov & Fedorova 1998); moreover also the external properties are modified, so that the structure results hotter and more luminous.

The second phase starts when the two WDs merge so that the less massive component (the more expanded) completely disrupts, thus forming a thick disk from which matter flows to the companion. What the real initial value of the accretion rate is, is unknown, but it must be so high as the Eddington limit. However, for rotating WDs which accrete C-O rich matter the initial value of the accretion rate is the only free parameter which has to be fixed and, fortunately, as we are going to show, this choice does not affect the further evolution at all (for details see Piersanti et al. 2003a).

The onset of the accretion process is a dramatic phase: thermal energy is stored in the external layers, while angular momentum is stored in the entire structure which spins up. Due to the combined effect of these two processes, the accreting structure rapidly expands, thus attaining a critical configuration: at the equator gravitational and centrifugal forces become equal. In this condition, only the matter inside the corresponding critical radius can be considered as representative of a true stellar structure described by the standard set of equations of stellar evolution. As a matter of fact, in this physical conditions no more matter can be added to accreting structure. Probably, in the real world matter is lost from the WD equatorial zones and it comes back to the WD at the polar ones, anyway the total mass of the WD remaining fixed. To describe this situation, one can imagine that accretion comes to a halt and it can resume only if and when, for some physical reason, the structure recedes from the critical condition. It is as if there exists a gate which can be closed or open, depending on the actual physical conditions of the accreting WD. This is what occurs in the real world.

The accretion process comes to halt for a while, so that the heat excess localized into the external is removed via thermal diffusion toward the inner zones. As a consequence the structure contracts and, hence, it spins up. However, due to the redistribution of angular momentum, the angular velocity increases more slowly than the critical one. The net consequence is that the WD recedes from the critical condition.

Hence, matter and angular momentum can be accreted again until the critical conditions are attained once more. From this considerations, it follows that the accretion process becomes finely tuned by the physical properties of the stellar structure (on a time scale which is determined mainly by the heat transfer efficiency) and not by the conditions of the external matter which flows to the WD. Now we have a star continuously receding from, and attaining again the critical conditions. Since accretion occurs through finite episodes, only a mean accretion rate is well defined. If such a process continued indefinitely, with no additional physics coming into play, the mean accretion rate would decrease with time. This is because, as time goes by, the process of receding from the critical conditions becomes more and more difficult to be managed by the accreting star (less heat to be transferred). Thus, absent additional physical processes which keep it alive, the self-tuned accretion mechanism would come to a definitive halt well before the Chandrasekhar mass is attained.

Two physical processes occur which save the day: (1) a secular instability which occurs when the rotational energy of the accreting white dwarf exceeds about 10 % of the gravitational binding energy, and (2) gravitational wave radiation (GWR) which sets in when, in response to the instability, the WD structure adopts a triaxial form with a quadrupole moment. Triaxial configurations, known as Jacobi ellipsoids (Chandrasekhar 1970) and the process of angular momentum loss by gravitational wave radiation are both well understood, thus eliminating the need for additional assumptions or use of free parameters. A third, long lived, phase ensues. As in the previous phase, the rate at which the accreting WD recedes from the critical conditions is determined by its structural properties and not by the external matter. The accretion process thus continues to occur in a self-regulated fashion. At a certain point of the evolution, the conditions to lose energy via GWR emission are no longer fulfilled. This occurs, however, when the Chandrasekhar mass limit for non-rotating structures has been already effectively achieved or by-passed. Once the rotational velocity is further reduced, carbon burning is ignited at the center of the WD, giving rise to a SN event. Fig. 2 reports the history of the accretion rate all along the discussed evolutionary phases.

4. Outcomes of the explosion and cosmological predictions

Domínguez et al. (2006) have evolved dynamically the rotating WDs models which result from the accretion process described before. The adopted explosion scheme is the ''Delayed Detonation Model" by Khokhlov (1991). This choice implies the need of a free parameter, the transition density at which the deflagration wave turns into a detonation. Models of masses ranging between 1.4 and 1.5 solar masses have been analyzed. Differentially rotating WDs may be stable up to several solar masses but here rigid body rotation has been assumed so that the corresponding Chandrasekhar limit is $\sim 1.5 M_{\odot}$. The transition density has been kept constant for all the experiments, since this is the only reasonable choice to disentangle the

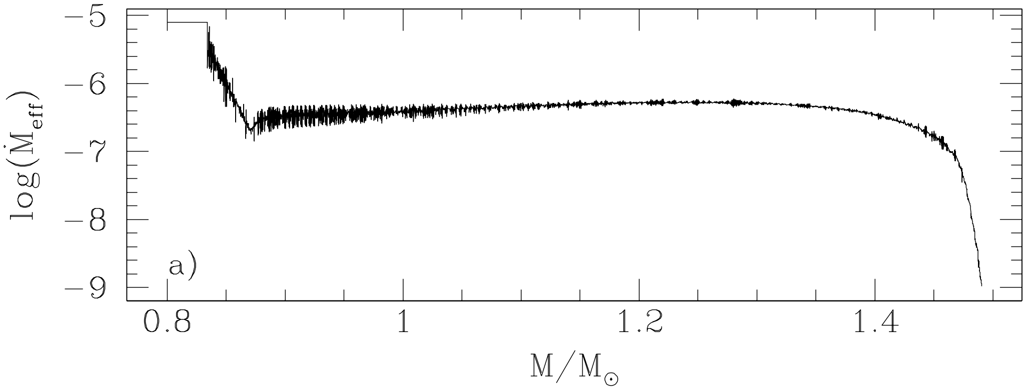

Fig. 2. Time evolution of the accretion rate during all the evolutionary phases experienced by the accreting WD (see text).

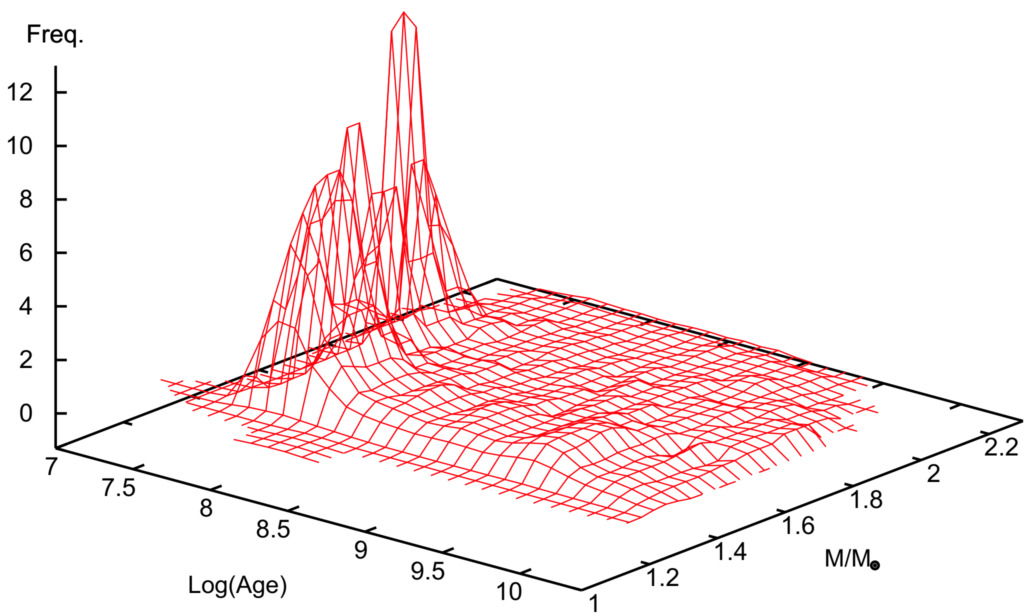

Fig. 3. Frequency of DD systems which can represent SNe Ia progenitors as a function of the total mass of the system and of the evolutionary time.

effects of rotation on the observational properties of explosive events. As described in detail in Domínguez et al. (2006) the properties of models with different total mass are very similar each other. In fact, the luminosity depends on the amount of ^{56}Ni synthesized during the explosion, which, on its side, depends mainly on the the density at which the burning occurs. The latter is determined by the expansion during the deflagration phase whose time length is determined by the transition density which is maintained constant in our experiments. Nonetheless, rotation and braking efficiency in the pre-ignition stage produce a spread in binding energies and ignition densities at the explosion time. According to the numerical results, more massive models have greater binding energies but also higher ignition densities; hence, a larger amount of energy has to be spent to unbind the WD, thus implying a smaller final kinetic energy and a larger completely incinerated zone. Moreover, electron captures are also favored in the inner high density region and finally the production of ^{56}Ni does not show a monotonic dependence with the ignition density, binding energy and total mass.

This would suggest that the time from the onset of deflagration to the transition to a detonation should be related with a physical property of the progenitor, such as rotation and/or total mass. In fact it has been found that in 3D simulations the number of igniting sparks depends on rotation (Kuhlen et al. 2006) and in the context of the 3D Pulsating Reverse Detonation explosion models (PRD - Bravo & García-Senz 2006), the number of sparks determines the amount of ^{56}Ni produced in the explosion. We have also computed the corresponding LCs in 1D and we found a range in the maximum M_{bol} of ~ 0.1 mag.

By assuming that the spread in the observational properties of SNe Ia is due to a spread in the total mass of the progenitor DD systems, which in the real world can be as high as $0.8M_{\odot}$ if differential rotation is considered, some interesting correlation between the explosive events and the corresponding stellar population can be drawn (see Fig.3).

First of all it has to be noted that on the very long term (from about 4 to 13 Gyrs) mainl standard mass binary systems survive and merge. Thus it should be expected that the SNe Ia population in nearby elliptical galaxies (as in those at redshifts up to, say, 1.5) belong to this class of about $1.4M_{\odot}$ objects. On the other hand, in near-by spirals and in galaxies with on-going star formation at redshift greater than 1.5 there should be a rather consistent contamination of type Ia SNe from the more massive progenitors family. Moreover, for some observational bias, it could happen that the massive (and more luminous) events may dominate the high-z sample for, say, $z \geq 2$.

In conclusion, current estimates on the cosmological evolution, which have been obtained basing on events up to $z \sim 1$, remain still valid also in the light of this new possible interpretation of type Ia SNe progenitors.

The same occurs for nuclear pollution which is only marginally changed.

References

Bragaglia, A., Greggio, L., Renzini, A., & D'Odorico, S. 1990, ApJ, 365, 13

Bravo, E., & García-Senz, D. 2006, ApJ, 642, 157

Cassisi, S., Iben, I.Jr, & Tornambè, A. 1998, ApJ, 496, 376

Chandrasekhar, S. 1970, Phys. Rev. Lett., 24, 611

Conley, A., and 26 coauthors 2006, AJ, 132, 1707

Domínguez, I., Piersanti, L., Bravo, E., Tornambè, A., Straniero, O., & Gagliardi, S. 2006, ApJ, 644, 21

Fujimoto, M.Y., Iben, I.Jr., Chieffi, A., & Tornambè, A. 1984, ApJ, 287, 749

Hamuy, M., Phillips, M.M., Suntzeff, N.B., Schommer, R.A., Maza, J., & Aviles, R. 1996, AJ, 112, 2391

Iben, I.Jr., & Tutukov, A.V. 1984, ApJS, 54, 335

Iben, I.Jr., Tutukov, A.V., & Fedorova, A.V. 1998, ApJ, 503, 344

Khokhlov, A. 1991, A& A, 245, 114

Koen, C., Orosz, J.A., & Wade, R.A. 1998, MNRAS, 300, 695

Kuhlen, M., Woosley, S.E., & Glatzmaier, G.A. 2006, ApJ, 640, 407

Mannucci, F., & 7 coauthors 2005, A& A, 433, 807

Mannucci, F., Della Valle, M., & Panagia, N. 2006, MNRAS, 370, 773

Napiwotzki, R., Karl, C.A., Nelemans, G., et al. 2005, ASPC, 334, 375

Nomoto, K.I., & Iben, I.Jr. 1985, ApJ, 297, 531

Phillips, M.M. 1993, ApJ, 413, 105

Piersanti, L., Cassisi, S., Iben, I.Jr., & Tornambè, A. 1999, ApJ, 521, 59

Piersanti, L., Cassisi, S., Iben, I.Jr., & Tornambè, A. 2000, ApJ 535, 932

Piersanti, L., Cassisi, S., & Tornambè, A. 2001, ApJ 558, 916

Piersanti, L., Gagliardi, S., Iben, I.Jr., & Tornambè, A. 2003a, ApJ 583, 885

Piersanti, L., Gagliardi, S., Iben, I.Jr., & Tornambè, A. 2003b, ApJ, 598, 1229
Robinson, E.L., & Shafter, A.W. 1987, ApJ, 332, 296
Saffer, R.A., Livio, M., & Yungelson, L.R. 1998, ApJ, 502, 394
Saio, H., & Nomoto, K.I. 1985, A&A, 150, 21
Saio, H., & Nomoto, K.I. 1998, ApJ, 500, 388
Sullivan, M., and 16 coauthors 2006, ApJ, 648, 868
Tornambè, A. 1989, MNRAS, 239, 771
Webbink, R.F. 1984, ApJ, 277, 355
Webbink, R.F., & Iben, I.Jr. 1988, in Faint Blue Stars, ed. A.G. Davis Philip, D.S. Hayes, and J.W. Liebert (Schenectady: L. Davis), p. 445
Whelan, J., & Iben, I.Jr. 1973, ApJ 186, 1007
Yoon, S.C., Langer, N., & Scheithauer, S. 2004, A&A, 425, 217