On the Evolution and Appearance of a Surviving Companion after a Type Ia Supernova Explosion

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ABSTRACT
One promising method to test progenitor models for Type Ia supernovae is to identify surviving companion stars in historical supernova remnants. A surviving companion will have been strongly affected by its interaction with the supernova ejecta. Here we systematically explore the evolution and appearance of a typical companion star that has been stripped and heated by the supernova interaction during the post-impact re-equilibration phase. We show that, depending on the amount of heating and the amount of mass stripped by the impact or the previous binary mass transfer, such a star may be significantly overluminous or underluminous by up to two orders of magnitude after the supernova relative to its pre-supernova luminosity and discuss the implications of these results for the strategies to be employed in searches for such companions.

Key words: binaries: close – stars: evolution – stars: individual: U Scorpii – supernovae: general – supernovae: Type Ia

1 INTRODUCTION
In recent years, Type Ia supernovae (SNe Ia) have been used successfully as cosmological probes of the Universe (Riess et al. 1998; Perlmutter et al. 1999). However, the nature of their progenitors has remained somewhat of a mystery. There is almost universal agreement that they represent the disruption of a degenerate object; but this is also where the agreement ends. There are numerous progenitor models (for detailed reviews see, e.g., Branch et al. 1995; Ruiz-Lapuente, Canal & Isern 1997), but most of these have serious theoretical/observational problems or do not appear to occur in sufficient numbers to explain the observed frequency of SNe Ia in our Galaxy (\(\sim 3 \times 10^{-3}\) yr\(^{-1}\); Cappellaro & Turatto 1997).

The progenitor models can roughly be divided into three classes: double-degenerate (DD) models, sub-Chandrasekhar models and single-degenerate Chandrasekhar models. The double-degenerate model (Iben & Tutukov 1984; Webbink 1984) involves the merger of two CO white dwarfs with a combined mass in excess of the Chandrasekhar mass (\(\sim 1.4M_\odot\)). While this model has the advantage of being quite common (see, e.g., Iben & Tutukov 1986; Yungelson et al. 1994; Han et al. 1995; Iben, Tutukov & Yungelson 1997; Han 1998; Nelemans et al. 2001), it seems more likely that the disruption of the lighter white dwarf and the accretion of its debris onto the more massive one leads to the transformation of the surviving CO white dwarf into an ONeMg white dwarf which subsequently collapses to form a neutron star (i.e. undergoes accretion-induced collapse; AIC) rather than experience a thermonuclear explosion (Nomoto & Iben 1985; Saio & Nomoto 1985, 1998; Timmes, Woosley & Taam 1994; Mochkovitch, Guerrero & Segretain 1997). There may be a small parameter range where AIC can be avoided, but it is unlikely to account for more than a small number of SNe Ia.

Woosley & Weaver (1995) speculated that a sub-Chandrasekhar-mass white dwarf could produce a SN Ia if helium was ignited violently in a shell surrounding the CO core and triggered a detonation wave that propagated inwards and ignited the CO core (see also Livne & Arnett 1995). While it is not clear whether this can even work in principle, simulations of such explosions show that they do not reproduce the properties of observed SNe Ia (see, e.g., the discussion in Wheeler 1996).

The arguably most favoured class of models at the present time involves single-degenerate scenarios, where the white dwarf accretes from a non-degenerate companion star (Whelan & Iben 1973; Nomoto 1982). In these models, the companion star can be in different evolutionary phases and may either be a hydrogen-rich star or a helium star. One of the major problems with these models is that it is generally difficult to increase the mass of a white dwarf by accretion due to the occurrence of nova explosions and/or helium flashes (Nomoto 1982) which may eject most of the...
accreted mass. There is a narrow parameter range where a white dwarf can accrete hydrogen-rich material and burn it in a stable manner, but this requires rather special circumstances.

One promising channel that has been identified in recent years relates them to supersoft X-ray sources (van den Heuvel et al. 1992; Rappaport, Di Stefano & Smith 1994; Li & van den Heuvel 1997). In this channel, the companion star is a somewhat evolved main-sequence star or subgiant of 2–3 M⊙, transferring mass on a thermal timescale to a white dwarf. In Figure 1 we present a typical binary calculation that illustrates this channel (also see Langer et al. 2000; Han & Podsiadlowski 2003). The initial system consists of a 2.1 M⊙somewhat evolved main-sequence star and a 0.8 M⊙white dwarf. In this calculation we adopted the estimates for the accretion efficiency of Hachisu, Kato & Nomoto (1999) and assumed that any excess matter that could not be accreted by the white dwarf was ejected from the system. As the calculation demonstrates, the white dwarf is able to grow very effectively. When it reaches the Chandrasekhar mass, it has parameters very similar to U Scorpii, a supersoft binary and recurrent nova where the white dwarf is already close to the Chandrasekhar mass (Hachisu et al. 2000; Thoroughgood et al. 2001).

While U Scorpii provides an excellent candidate for a SN Ia progenitor, consistent with theoretical expectations, it would be even better to have a more direct observational test for progenitor models (e.g. Ruiz-Lapuente 1997), in particular since it is quite possible – perhaps even likely – that there is more than one channel that leads to a SN Ia. Such direct tests could involve the detection of hydrogen or helium in the ejecta or the supernova environment, which could come from the outer layers of the exploding object, circumstellar material that was ejected from the progenitor system (e.g. Cumming et al. 1996), or matter that was stripped from the secondary by the supernova interaction and was mixed into the ejecta. A particularly conclusive test would be the detection of a companion star that has survived the supernova explosion in the supernova remnant. At present the detection of a surviving companion would only be feasible in our Galaxy, e.g. in the supernova remnants SN 1006 and Tycho (Ruiz-Lapuente et al. 2002).

A surviving companion can be identified by its expected unusual properties (Marietta, Burrows & Fryxell 2000; Canal, Méndez & Ruiz-Lapuente 2001): (1) it will be a runaway star moving directly away from the centre of the supernova remnant, where the runaway velocity will be similar to the orbital velocity of the companion star in the pre-supernova binary (e.g. 170 km s−1 for a system like U Sco; 20 km s−1 for a symbiotic binary with a giant companion); (2) the secondary will have been strongly affected by its interaction with the supernova ejecta and have an unusual appearance; and (3) the composition of the secondary may show chemical anomalies and be enriched with heavy elements produced in the thermonuclear explosion (similar to what is observed in Nova Sco, a black-hole binary where the companion star has been enriched with supernova material; Israelian et al. 1999; Podsiadlowski et al. 2002).

Marietta et al. (2000) have recently performed the most detailed and most systematic hydrodynamical investigation of the impact of the supernova shell in a SN Ia with hydrogen-rich secondaries of various types, representing different progenitor channels (for earlier studies see Wheeler, Lecar & McKee 1975; Fryxell & Arnett 1981; Taam & Fryxell 1984; Livne, Tuchman & Wheeler 1992). In particular, they showed that main-sequence and subgiant companions will lose 15 per cent of their mass due to the supernova impact, while giant companions will be stripped of almost all of their hydrogen-rich envelopes. Furthermore, the interior of the secondaries will be significantly shock-heated by the supernova impact; as a consequence the immediate post-impact luminosity will be increased dramatically.

It is the purpose of this paper to model the further evolution of a subgiant secondary to clarify the principles that govern their post-impact evolution and to determine their expected appearance which will be useful for searches of sur-

Figure 1. Evolutionary model for a SN Ia progenitor in the supersoft channel (modelling a system similar to U Sco). H-R diagram (top panel) and key binary parameters as a function of time since the beginning of mass transfer (with arbitrary offset). Middle left: Radius of the secondary. Middle right: Orbital period. Bottom left: Mass of the secondary (solid curve) and the white dwarf (dot-dashed curve). Bottom right: Mass-loss rate of the secondary. The secondary initially has a mass of 2.1 M⊙and has already exhausted most of its hydrogen in the core. The white dwarf has an initial mass of 0.8 M⊙and is able to accrete according to the formalism given by Hachisu et al. (1999). The dashed curve in the top panel shows the evolutionary track of a single 2.1 M⊙star, the solid curve the evolutionary track of the secondary during the mass-transfer phase. The phase when the white dwarf is close to the Chandrasekhar mass (∼1.4 M⊙) is indicated in all panels: as a gap in the track in the top panel; by vertical, dashed lines the lower panels.
viving companions in historical SN Ia remnants which are presently under way. In Section 2 we systematically examine the consequences of heating and mass stripping for the evolution and appearance of the secondary and in Section 3 we discuss the implications of these results.

2 POST-SUPERNova HEATING AND STRIPPING

Immediately after the impact with the supernova ejecta, the secondary will be strongly out of thermal equilibrium and is likely to be significantly puffed up and overluminous (Marietta et al. 2000) estimate that a subgiant may have a luminosity as high as \( \sim 5000 \, L_\odot \)). The subsequent evolution is governed by how the star re-establishes thermal equilibrium, which depends on the amount of heating and mass loss it has experienced. Because these effects have very different consequences for the evolution of the star, the secondary may appear overluminous or underluminous at different times during the equilibration phase, as we will demonstrate below.

For this study we employed a standard Henyey-type stellar evolution code, described in detail in Podsiadlowski, Rappaport & Pfahl (2002), which we have previously used to study the effects of external irradiation and tidal heating in stars (Podsiadlowski 1991, 1996). Since we cannot follow the dynamical interaction of the secondary during the impact phase, we adopt the following procedure to model the effects of mass stripping and supernova heating. We first perform a mass-loss calculation where we take off mass from the star at a very high rate (typically \( 10^{-2} \, M_\odot \, yr^{-1} \)), so that mass loss can be considered essentially adiabatic (except in the outermost layers). To model the residual heating of the envelope (i.e. the extra heating of the part of the envelope that was not stripped off in the supernova impact), we add a constant and uniform heating source to the remaining outer layers of the star with a total luminosity of \( 10^5 \, L_\odot \) for a certain of time and then follow the subsequent re-equilibration of the star. This procedure is of course only very approximate, but should nevertheless be sufficiently realistic to study the basic physical aspects of the problem, the main objective of this paper.

In Figure 2 we present evolutionary tracks in the Hertzsprung-Russell (H-R) diagram illustrating the post-impact equilibration phase for a subgiant (with an initial pre-supernova mass of \( 1 \, M_\odot \)) that was stripped of the outermost \( 0.2 \, M_\odot \) of its envelope by the supernova impact and was heated by various different amounts of energy (as indicated at the beginning of each track). The initial subgiant has a radius of \( 2.5 \, R_\odot \) and is very similar to the model of the secondary shown in Figure 1 at the time of the supernova. In these simulations, the energy was deposited uniformly in the outermost 90 per cent of the radial extent of the star which contained \( 0.57 \, M_\odot \). The energy in the calculation with the largest amount of energy deposited (\( 4 \times 10^{47} \, \text{erg} \)) is close to the energy needed to unbind these layers completely, which we estimate to be \( \sim 4.9 \times 10^{47} \, \text{erg} \). As a consequence, the star is initially very puffed up with a radius of \( 230 \, R_\odot \) and has a luminosity of \( 4300 \, L_\odot \) (cf. Marietta et al. 2000). Because of the large radius and the large luminosity, the thermal timescale of the puffed-up envelope is very short initially, and the star contracts very rapidly along a Hayashi track. After \( 10^3 \, \text{yr} \) its luminosity has dropped to \( 200 \, L_\odot \) and after \( 10^4 \, \text{yr} \) to \( 27 \, L_\odot \). In this context we emphasize that in all the models shown in Figure 2 the evolution is initially much faster than the Kelvin-Helmholtz timescale, \( t_{KH} \), of the pre-supernova subgiant (\( \sim 10^6 \, \text{yr} \) in our case), since the timescale on which the star evolves in the H-R diagram is determined by the thermal timescale of the rapidly evolving outer layers of the star, which can be many orders of magnitude shorter than \( t_{KH} \). (Of course, it will take a full Kelvin-Helmholtz time before the star has re-established thermal equilibrium completely.)

In the calculations with \( 10^{47} \) and \( 2 \times 10^{47} \, \text{erg} \), the evolution is similar although less dramatic. On the other hand, in the case where the star is only heated by \( 5 \times 10^{46} \, \text{erg} \) or is not heated at all, the evolution is dramatically different, and the secondary becomes significantly underluminous during the early thermal re-equilibration phase (with a luminosity of \( \sim 10^{-1} \, L_\odot \) after \( 10^3 \, \text{yr} \) and \( \sim 10^{-2} \, L_\odot \) after \( 10^4 \, \text{yr} \)). This behaviour is similar to the behaviour commonly found in binary mass-transfer calculations where a secondary strongly out of thermal equilibrium can be very underluminous (e.g.

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1 We have tested that the subsequent evolution of the star is not very sensitive to the timescale on which the initial stripping and heating is simulated (as long as it is short compared to the thermal timescale of the outer layers of the star); while the initial appearance may differ substantially for different implementations, the evolutionary tracks and internal structures tend to converge rapidly in the subsequent re-equilibration phase.

Figure 2. Evolutionary tracks (solid curves) in the H-R diagram of a \( 1 \, M_\odot \) subgiant that has been stripped of the outermost 0.2\( M_\odot \) of its envelope and has been heated by various amounts of energy by the supernova impact. The amount of energy deposited in the outermost 90 per cent of the star (by radius) is indicated at the beginning of each track. The dashed curves give from left to right the location of the stars at the beginning and \( 10^3 \), \( 10^4 \) and \( 10^5 \, \text{yr} \) after the beginning of each sequence, respectively. The dotted curve shows the evolutionary track of a \( 1 \, M_\odot \) star, and the star symbol indicates the position of the initial, undisturbed model used for the supernova impact simulations. For comparison, the lightly shaded (yellow) region shows the position of a subgiant that had been stripped of \( 0.8 \, M_\odot \) of its envelope (i.e. only has a total mass of \( 0.2 \, M_\odot \) after the impact) between \( 10^3 \) and \( 10^4 \, \text{yr} \) after the supernova.
stripped of the outermost $0.2 \, M_\odot$ by the impact with a supernova (without supernova heating). Top: entropy, middle: temperature, bottom: density, all as a function of radius for the outermost part of the star. The solid curves show the profiles at different times after the stripping (from top to bottom/right to left: immediately after the stripping, after $\sim 100 \, \text{yr}$, $\sim 10^3 \, \text{yr}$, $\sim 10^4 \, \text{yr}$). The dashed curves show the final thermal equilibrium structure.

Figure 3. Evolution of the thermodynamic properties during the thermal equilibration phase for a $1 \, M_\odot$ subgiant that has been stripped of the outermost $0.2 \, M_\odot$ by the impact with a supernova (without supernova heating). Top: entropy, middle: temperature, bottom: density, all as a function of radius for the outermost part of the star. The solid curves show the profiles at different times after the stripping (from top to bottom/right to left: immediately after the stripping, after $\sim 100 \, \text{yr}$, $\sim 10^3 \, \text{yr}$, $\sim 10^4 \, \text{yr}$). The dashed curves show the final thermal equilibrium structure.

Langer et al. 2000; King et al. 2001; Podsiadlowski et al. 2002.

The principal reason for this behaviour is that, in a subgiant whose outer layers have been suddenly stripped off, the layers in the deep interior of the envelope have to expand significantly since the final thermal equilibrium radius is similar to the initial radius. The energy needed to drive this expansion comes from the nuclear luminosity produced in the core of the star, reducing the radiative luminosity that reaches the outer parts of the star. In the case where the star is dramatically out of thermal equilibrium, as is the case here, essentially all the nuclear luminosity is used up in the expansion of the envelope. As a consequence, the very outer layers of the star are no longer re-supplied with energy from below; but because of the continued radiative losses from the surface, the outer layers start to cool dramatically.

To illustrate this behaviour, Figure 3 shows the early evolution of the thermodynamic structure in the outer parts of the envelope for the stripped subgiant in Figure 2 that has not been heated (the region shown contains about 1 per cent of the mass of the star). As the outer layers cool (particularly clearly seen in the drop of the entropy), this outer layer contracts, and the star in fact becomes somewhat undersized relative to its final equilibrium radius (it takes a full Kelvin-Helmholtz time, $\sim 10^6 \, \text{yr}$ in the case shown, for the star to re-establish thermal equilibrium). During this cooling phase, the star evolves roughly along a line of constant radius in the H-R diagram and would have the appearance of an anomalously red subgiant. Since the surface luminosity becomes much smaller than the luminosity inside the star, only a small fluctuation of the luminosity profile (e.g. due to the generally non-linear behaviour of the equilibration process which can drive luminosity waves through the star) may lead to a sudden change of the surface luminosity, and we therefore suspect that such a star would be highly variable.

Because our models were constructed in a very different fashion from the models of Marietta et al. (2000), it is not entirely clear which of our sequences most closely resembles their subgiant case. The fact that the subgiant is stripped of a significant fraction ($\sim 15$ per cent) of its mass certainly implies that the remaining envelope will also be strongly heated. Comparing the radii of our models to the radius ($\sim 9 \, R_\odot$) found by Marietta et al. (2000) then suggests that the sequences with $10^{47}$ and $2 \times 10^{47}$ erg of heating are probably the most comparable. In these sequences, the secondary resembles a typical subgiant with a luminosity of $10–25 \, L_\odot$ after $10^2 \, \text{yr}$ and $6–10 \, L_\odot$ after $10^3 \, \text{yr}$, still significantly overluminous relative the initial model which had a luminosity of $\sim 3 \, L_\odot$.

The timescale on which the surface luminosity evolves after the supernova impact is determined mainly by the thermal timescale of the envelope which depends, among other factors, on the evolutionary phase of the initial subgiant, the amount of mass that has been transferred to the companion before the supernova and the amount of mass stripped by the supernova impact itself. To illustrate this sensitivity we performed a similar series of thermal equilibration calculations for the same initial subgiant but where we stripped off the outermost $0.8 \, M_\odot$, and heated the remaining outer 83 per cent in radius containing $0.03 \, M_\odot$, by various amounts of energy from $5 \times 10^{45} \, \text{erg}$ to $3.5 \times 10^{46} \, \text{erg}$; the latter is close to the energy needed to unbind the envelope in this case ($\sim 3.7 \times 10^{46} \, \text{erg}$). Because of the lower remaining mass, the star evolves much more rapidly. In Figure 2 the shaded (yellow) region shows the location of the secondary in the H-R diagram between $10^3$ and $10^4 \, \text{yr}$ in these calculations. Note that, in all cases, the secondary is significantly underluminous (by up to a factor of 10) – even in the strongly heated case – and may have the appearance of a main-sequence star similar to the Sun (but with much lower gravity).

3 DISCUSSION AND CONCLUSIONS

In this paper we have examined the evolution of a typical subgiant secondary (as expected in one of the most popular progenitor models for SNe Ia) that has been heated and stripped by the impact of a supernova shell. We have demonstrated that the secondary may be significantly underluminous or overluminous at different times during the post-impact phase when it tries to re-establish thermal equilibrium. This depends on the amount of heating it has experienced and the amount of envelope mass that has been stripped of the outermost 0.8 $M_\odot$ thermal equilibration phase for a 1 $M_\odot$ (without supernova heating).

In our calculations we regularly observe sudden changes of the luminosity profile, where the star suddenly brightens by an order of magnitude or more in a single time step and subsequently continues to cool. However, at present this behaviour is not well resolved numerically.

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stripped off by the impact or has been lost by mass transfer before the explosion. Based on our calculations, we typically expect its luminosity $10^3$ yr after the impact to be within an order magnitude of the pre-supernova luminosity (either above or below). If the outer envelope cools dramatically (which happens if most of the internal luminosity goes into driving internal expansion), the secondary may become extremely underluminous. While it would be quite faint, it would be a rather unusual, extremely red and probably highly variable subgiant that should stand out because of its anomalous appearance. Even if it has the appearance of a more typical subgiant, where it may in fact be somewhat hotter (more yellow) than a standard subgiant, one may be able to see changes in its appearance on a human timescale because of the short thermal timescale of the outermost layers (which may be many orders of magnitude shorter than the Kelvin-Helmholtz timescale of the pre-supernova star).

The main implication for searches of surviving companion stars in historical supernova remnants is that, in order to be able to rule out a subgiant companion with any degree of confidence, one has to go to much fainter magnitudes than previously assumed (down to a luminosity of $\sim 10^{-2} L_\odot$ for a $10^3$ yr-old remnant, a luminosity of $\sim 10^{-6} L_\odot$ for a $10^4$ yr-old one). We still expect that it will have an appearance and/or show signs of variability that makes it easily identifiable as the supernova companion (in addition to its runaway space velocity and possible chemical anomalies).

If no plausible candidate for a subgiant companion is found at this level or for any other type of pre-supernova companion, this would give some weight to other, presently less favoured progenitor models where no companion is expected (e.g., the double-degenerate merger model) or where the companion may already have become a very cool white dwarf (provided that there is a long time delay between the white-dwarf accretion phase and the supernova, as expected in some models).

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REFERENCES

Branch, D., Livio, M., Yungelson, L. R., & Boffi, F. R., Baron, E. 1995, PASP, 107, 1019
Canal, R., Méndez, J., & Ruiz-Lapuente, P. 2001, ApJ, 550, L53
Cappellaro, E., & Tutazio, M. 1997, in Ruiz-Lapuente, P., Canal, R., & Isern, J., eds, Thermonuclear Supernovae (Kluwer, Dordrecht), p. 77
Cumming, R. J., Lundqvist, P., Smith, L. J., Pettini, M., & King, D. L. 1996, MNRAS, 283, 135 5
Fryxell, B. A., & Arnett, W. D. 1981, ApJ, 243, 994
Hachisu, I., Kato, M., & Nomoto, K. 1999, ApJ, 522, 487
Hachisu, I., Kato, M., Kato, T., Matsumoto, K., & Nomoto, K. 2000, ApJ, 534, L89
Han, Z. 1998, MNRAS, 296, 1019
Han, Z., & Podsiadlowski, Ph. 2003, MNRAS, in preparation
Han, Z., Podsiadlowski, Ph., & Eggleton, P. F. 1995, MNRAS, 272, 800
Iben, I., Jr., & Tutukov, A. V. 1984, ApJS, 54, 335
Iben, I., Jr., & Tutukov, A. V. 1986, ApJ, 311, 753
Iben, I., Jr., & Tutukov, A. V., & Yungelson, L. R. 1997, ApJ, 475, 291
Israelian, G., Rebolo, R., Basri, G., Casares, J., & Martin, E. L. 1999, Nat, 401, 142
King, A. R., Shenker, K., Kolb, U., & Davies, M. B. 2001, MNRAS, 321, 327
Langer, N. Deutschmann, A., Wellstein, S., & Höflich, P. 2000, A&A, 362, 1046
Li, X.-D., & van den Heuvel, E. P. J. 1997, A&A, 322, L9
Livne, E., & Arnett, D. 1995, ApJ, 452, 62
Livne, E., Tuchman, Y., & Wheeler, C. J. 1992, ApJ, 399, 665
Marietta, E., Burrows, A., & Fryxell, B. 2000, ApJS, 128, 615
Mochkovitch, R., Guerrero, J., & Segretain, L. 1997, in Ruiz-Lapuente, P., Canal, R., & Isern, J., eds, Thermonuclear Supernovae (Kluwer, Dordrecht), p. 187
Nelemans, G., Yungelson, L. R., Portegies Zwart, S. F., & Verbunt, F. 2001, A&A, 365, 491
Nomoto, K. 1982, ApJ, 253, 798
Nomoto, K., & Iben, I., Jr. 1985, ApJ, 297, 531
Perlmutter, S., et al. 1999, ApJ, 517, 565
Podsiadlowski, Ph. 1991, Nat, 350, 136
Podsiadlowski, Ph. 1996, MNRAS, 279, 1104
Podsiadlowski, Ph., Nomoto, K., Maeda, K., Nakamura, T., Mazzali, P., & Schmidt, B. 2002, ApJ, 567, 491
Podsiadlowski, Ph., Rappaport, S., & Pfahl E. 2002, ApJ, 565, 1107
Rappaport, S., Di Stefano, R., & Smith, J. D. 1994, ApJ, 426, 692
Riess, A., et al. 1998, AJ, 116, 1009
Ruiz-Lapuente, P. 1997, Science, 267, 1813
Ruiz-Lapuente, P., Canal, R., & Isern, J. 1997, Thermonuclear Supernovae (Kluwer, Dordrecht)
Ruiz-Lapuente, P., Cameron, F., Smartt, S., Kurnucz, R., Méndez, J., Canal, R., Filippenko, A., & Chornock, R. 2002, in Hillebrandt, W. & Leibundgut, B., eds, From Twilight to High-light: the Physics of Supernovae (Springer, Berlin), p. 140
Saio, H., & Nomoto, K. 1985, A&A, 150, L21
Saio, H., & Nomoto, K. 1998, ApJ, 500, 388
Taam, R. E., & Fryxell, B. A. 1984, ApJ, 279, 166
Timmes, F. X., Woosley, S. E., & Taam, R. E. 1994, ApJ, 420, 348
Thoroughgood, T. D., Dhillon, V. S., Littlefair, S. P., Marsh, T. R., & Smith, D. A. 2001, MNRAS, 327, 1323
van den Heuvel, E. P. J., Bhattacharya, D., Nomoto, K., Rappaport, S. 1992, A&A, 262, 97
Webbink, R. F. 1984, ApJ, 277, 355
Wheeler, J. C., Lecar, M., & McKee, C. F. 1975, ApJ, 200, 145
Wheeler, J. C. 1996, in Wiers R. A. M. J., Davies, M. B., & Tout, C. A., eds, Evolutionary Processes in Binary Stars (Kluwer, Dordrecht), p. 307
Whelan, J., & Iben, I., Jr. 1973, ApJ, 186, 1007
Woosley, S. E., & Weaver, T. A. 1994, ApJ, 423, 371
Yungelson, L. R., Livio, M., Tutukov, A. V., & Saffer, R. 1994, ApJ, 420, 336