Mon. Not. R. Astron. Soc. **000**, 000–000 (0000) Printed 28 December 2010 (MN LATEX style file v2.2)

# A single-degenerate model for the progenitor of the Type Ia supernova 2002ic

Z. Han[1]⋆, Ph. Podsiadlowski[2]
[1] *National Astronomical Observatories / Yunnan Observatory, the Chinese Academy of Sciences, P.O.Box 110, Kunming, 650011, China*
[2] *University of Oxford, Department of Astrophysics, Keble Road, Oxford, OX1 3RH*

28 December 2010

**ABSTRACT**
Supernova 2002ic was an atypical Type Ia supernova (SN Ia) with evidence for substantial amounts of hydrogen associated with the system. Contrary to previous claims, we show that its unusual properties can be understood within the framework of one of the most favoured progenitor models, the so-called supersoft channel. This requires that the donor star was initially relatively massive ($\sim 3\,\mathrm{M}_\odot$) and that the system experienced a delayed dynamical instability, leading to a large amount of mass loss from the system in the last few $10^4$ yr before the explosion. This can produce the inferred hydrogen-rich circumstellar environment, most likely with a disc-like geometry. However, to apply these models requires a larger accretion efficiency onto the white dwarf than is assumed in present parameterizations. If this is confirmed, it would most likely increase estimates for the frequency of the single-degenerate channel. Based on population synthesis simulations we estimate that not more than 1 in 100 SNe Ia should belong to this subgroup of SNe Ia.

**Key words:** binaries: close – stars: evolution – white dwarfs – supernovae: general

## 1 INTRODUCTION

SN 2002ic was the first Type Ia supernova (SN Ia) for which circumstellar hydrogen has been detected unambiguously (Hamuy et al. 2003). The detection of hydrogen in a SN Ia has long been considered one of the cornerstone observations required to help distinguish between different progenitor models, in particular between single-degenerate models with a hydrogen-rich donor star (Whelan & Iben 1973; Nomoto 1982) and the double-degenerate merger model where two CO white dwarfs merge (Iben & Tutukov 1984; Webbink 1984). However, the amount of circumstellar hydrogen inferred in the case of SN 2002ic is much larger than one would naively have expected if the companion star were a slightly evolved star of a few solar masses as, e.g., in the supersoft scenario (e.g., van den Heuvel et al. 1992; Rappaport, Di Stefano & Smith 1994): estimates range from a minimum of $\sim 0.5\,\mathrm{M}_\odot$ up to $6\,\mathrm{M}_\odot$ (Wang et al. 2004; Chugai & Yungelson 2004; Uenishi et al. 2004; Kotak et al. 2004). Moreover, from the observed interaction of the supernova ejecta with the circumstellar medium (CSM) and the lightcurve one can deduce that this matter must be located within $10^{17} - 10^{18}$ cm of the supernova and hence must have been ejected from the pre-supernova system within the last $\sim 10^4$ yr (this, however, is strongly dependent on the assumed ejection velocity).

Spectropolarimetry observations (Wang et al. 2004) suggest that the supernova exploded inside a dense, clumpy circumstellar environment, quite possibly with a disk-like geometry. Subaru spectroscopic observations (Deng et al. 2004) also provide evidence for an interaction of the SN ejecta with a hydrogen-rich asymmetric circumstellar medium[1]. Interestingly, a few weeks after the explosion, SN 2002ic was almost identical to several previously observed Type IIn supernovae both spectroscopically (Deng et al. 2004) and photometrically (Wood-Vasey, Wang & Aldering 2004). This suggests that, while SN 2002ic was clearly a rare event, it was not a unique one and that there is at least a sub-class of hydrogen-rich SNe Ia. One of the key questions that has not yet been answered is whether this requires a progenitor channel that is completely separate from the bulk of SNe Ia or whether these are just rare events with properties on the tail of the distribution of normal SNe Ia.

Hamuy et al. (2003) suggested that SN 2002ic may have been related to a "Type 1 1/2" supernova, a term coined by

⋆ E-mail: zhanwen@public.km.yn.cn

[1] However, an ejecta-CSM interaction model in which the CSM is approximately spherically symmetric was also proposed to explain the Ca II emission features (Chugai, Chevalier & Lundqvist 2004).

Iben & Renzini (1983) to describe a thermonuclear explosion inside an asymptotic giant branch (AGB) star when the CO core mass approaches the Chandrasekhar mass. SN 2002ic cannot have been a Type 1 1/2 supernova since almost all of the hydrogen must have been ejected from the system before the supernova (i.e., the thermonuclear explosion did not occur inside a hydrogen-rich AGB envelope). However, from the onset of the interaction of the supernova with the CSM (Wood-Vasey, Wang & Aldering 2004) one can deduce that some hydrogen must have been quite close to the system, within $\sim 10^{15}$ cm (Wood-Vasey, Wang & Aldering 2004; Uenishi et al. 2004; Chugai & Yungelson 2004). This requires some truly remarkable fine-tuning since it implies that the last hydrogen was ejected just before the explosion, indeed within a few decades (!) before the explosion. Another problem with this scenario is that theoretical arguments suggest that the hydrogen-rich envelopes in AGB stars are lost in a superwind long before the CO core has come close to the Chandrasekhar mass (Han, Podsiadlowski & Eggleton 1994), except possibly when the metallicity of the star is extremely low[2].

Livio & Riess (2003) argued that despite the detection of hydrogen, SN 2002ic could provide evidence in support of a double-degenerate scenario, suggesting that the supernova was caused by the merger of two CO white dwarfs inside a hydrogen-rich common envelope (similar to an earlier suggestion by Sparks & Stecher 1974), but where the common envelope was ejected just a few decades before the explosion. In this model, one would expect a fairly thin shell of hydrogen ejecta, similar to what is seen in planetary nebulae with close binary cores. This appears not to be compatible with the large extent of the hydrogen-rich CSM which ranges from a few $10^{15}$ cm to at least a few $10^{17}$ cm (Wang et al. 2004). Moreover, Chugai & Yungelson (2004) have pointed out that in order to have a merger within 100 yr after the ejection of the common envelope requires a very tight post-common-envelope orbit with an orbital separation of $\sim 2 \times 10^9$ cm. This, in turn, they argue, implies that the energy imparted to the envelope ejecta, which is of order the orbital energy released in the spiral in, would far exceed the kinetic energy deduced for the CSM from Hamuy et al. (2003).

A perhaps more attractive scenario for SN 2002ic links it to the symbiotic channel for SNe Ia (Hachisu, Kato & Nomoto 1999a). In a variant of this scenario, the progenitor would have been a fairly wide binary and the mass donor a massive AGB star or possibly even a Mira variable, where the CSM originates from matter that was stripped off the companion star by an energetic wind from the accreting white dwarf (Hamuy et al. 2003; Deng et al. 2004; Chugai & Yungelson 2004). This requires very efficient stripping to produce the observationally deduced CSM and again a certain amount of fine-tuning, but encounters perhaps with the fewest obvious objections.

In this paper, we ask a more conservative question, namely whether the observed properties of SN 2002ic can be understood within the framework of the more standard single-degenerate model that links SNe Ia to supersoft X-ray sources (van den Heuvel et al. 1992; Rappaport, Di Stefano & Smith 1994), where the companion star initially is a main-sequence star or a slightly evolved star of up to $\sim 3.5\,M_\odot$. Indeed, as we will show in § 2, there is a certain parameter space which may produce systems like SN 2002ic provided that the accretion efficiency onto the white dwarf is somewhat increased. The scenario is speculative, though perhaps arguably less speculative than some of the other proposals for SN 2002ic. In § 3 we discuss the implications of this scenario, in particular what it implies for the overall supernova rates of the supersoft channel, and suggest some observational tests.

[2] SN 2002ic occurred in a dwarf elliptical galaxy and therefore the metallicity could be quite low. This suggest that determining the metallicity in the CSM or the stellar neighborhood of SN 2002ic or some of the other related Type IIn supernovae could provide a useful test of a SN 1 1/2 scenario.

## 2 BINARY EVOLUTION CALCULATIONS

Recently, Han & Podsiadlowski (2004) performed a systematic study of the single-degenerate supersoft channel for SN Ia progenitors in which they carried out detailed binary evolution calculations with the Eggleton stellar evolution code (Eggleton 1971; Eggleton 1972; Eggleton 1973; Han, Podsiadlowski & Eggleton 1994; Pols et al. 1995) for about 2300 close WD binaries to determine the initial parameters of WD binaries in the orbital period – secondary mass ($P_{\rm orb} - M_2$) plane that can lead to a SN Ia. Since this study was not able to follow the accretion history of the white dwarf, Han & Podsiadlowski (2004) adopted the formalism of Hachisu et al. (1999a; 1999b) to determine what fraction of the transferred mass was accreted by the white dwarf.

A typical supersoft model cannot lead to a supernova like SN 2002ic since at the time of the explosion the typical mass transfer rate and consequently systemic mass loss rate tend to be less than $10^{-6}\,M_\odot\,{\rm yr}^{-1}$, which is far too low to explain the observed CSM around SN 2002ic (see, e.g., Fig. 1 of Han & Podsiadlowski 2004 and also Langer et al. 2000). However, the detailed mass-transfer history depends strongly on the initial binary parameters (the initial WD mass, $M_{\rm WD}^0$, the initial secondary mass, $M_2^0$, and the initial orbital period, $P_{\rm orb}^0$). To explain systems like SN 2002ic requires that the mass-transfer rate increases dramatically to values well in excess of $10^{-4}\,M_\odot\,{\rm yr}^{-1}$ when the white dwarf approaches the Chandrasekhar mass. At such rates, very little mass can be accreted by the white dwarf and most of it must be lost from the system. This implies that the WD must have accreted most of its mass before this phase. This type of evolution is indeed realized for binary systems near the upper edge of the allowed parameter space in the $P_{\rm orb} - M_2$ plane (see, e.g., Figs. 1 and 2 of Han & Podsiadlowski 2004), where systems are close to experiencing a delayed dynamical instability.

### Delayed dynamical instability

For a given initial orbital period and initial white dwarf mass, the maximum initial secondary mass is determined by the condition that mass transfer must be dynamically stable. This depends mainly on the mass ratio. For radiative stars, the critical mass ratio is typically $\sim 3$ (see, e.g., Podsiadlowski, Rappaport & Pfahl 2002 [PRP]; Han & Podsiad-

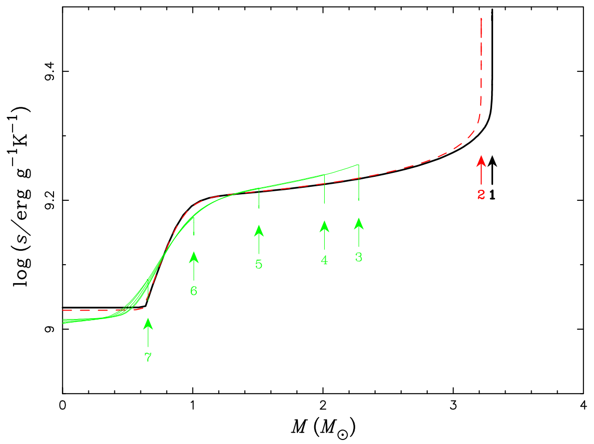


**Figure 1.** Evolution of the specific entropy profile of the mass donor as a function of time for the binary calculation shown in Figures 2 and 3. The thick solid curve shows the profile at the onset of mass transfer. The mass transfer rate starts to run away when the high entropy outer region has been lost, and the subsequent evolution of the star is adiabatic (thin solid curves).

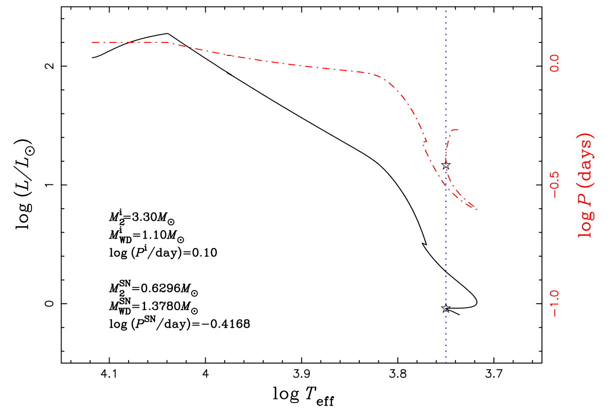


**Figure 2.** Luminosity of the mass donor (solid curve, left axis) and binary orbital period (dot-dashed curve, right axis) as a function of effective temperature for a binary evolution calculation applicable to SN 2002ic. The initial masses of the mass donor and white dwarf are $3.3\,\mathrm{M}_\odot$ and $1.1\,\mathrm{M}_\odot$, respectively, and the initial orbital period is 30 hr. At the time of the explosion (indicated by a vertical dotted line), the secondary has a mass of $0.63\,\mathrm{M}_\odot$ and the orbital period is $\sim 9$ hr.

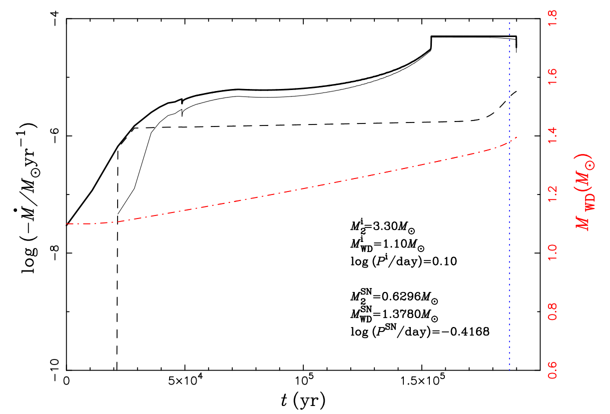


**Figure 3.** The evolution of the mass transfer rate (thick solid curve), mass loss rate from the system (thin solid curve) and WD accretion rate (dashed curve) as a function of time for the binary calculation in Figure 2 (left axis). Note the high mass-loss rate in the last $3 \times 10^4$ yr before the explosion (limited to $0.5 \times 10^{-4}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$). The dot-dashed curve shows the evolution of WD mass (right axis). The vertical dotted curve again indicates the time of the explosion.

lowski 2004). For radiative stars, however, it is well known that this instability is significantly delayed (Hjellming & Webbink 1987; PRP) and that substantial mass transfer can occur before its onset.

This behaviour can be understood from the evolution of the entropy profile of the donor star. A radiative star has a strongly rising specific entropy in the outer layers of the star (see Fig. 1). As long as the star has this entropy spike, it generally can adjust its radius to fit whatever the changing Roche-lobe radius requires. But when the flatter entropy profile in the inner region is exposed, the star starts to behave more like a convective star (which has a flat entropy profile) which tend to expand when mass is taken off adiabatically. At this point, the mass transfer rates start to increase dramatically and may even run away, i.e., lead to dynamical mass transfer. The delay time depends on the mass of the star but is typically of order $10^5$ yr for a star of several $\mathrm{M}_\odot$ (see, e.g., Fig. 12 of PRP), in which a significant amount of mass can be transferred.

Figures 2 and 3 show a binary evolution calculation which may be applicable to SN 2002ic. The WD binary has an initial orbital period of 30 hr and initially consists of a $1.1\,\mathrm{M}_\odot$ CO WD and a somewhat evolved secondary of $3.3\,\mathrm{M}_\odot$, which has a central hydrogen mass fraction of 0.3 at the beginning of mass transfer. Mass transfer initially occurs on a thermal timescale, but is dynamically stable; the mass transfer rate (thick solid curve) rises quickly over the first $5 \times 10^4$ yr to $\sim 5 \times 10^{-6} M_\odot \mathrm{yr}^{-1}$, well in excess of the rate the white dwarf can accrete (dashed curve of Fig. 3), and most of the transferred mass is lost from the system (thin solid curve of Fig. 3). The mass transfer continues to grow more slowly for the next $10^5$ yr. At this point, the secondary has completely lost the high entropy spike (see the profile marked '3' in Fig. 1), and the system starts to encounter the delayed dynamical instability, where the radius of the secondary can no longer adjust to just fill its Roche lobe radius, and the mass transfer rate increases dramatically. We cannot follow the subsequent evolution of the system properly and therefore fixed the maximum transfer rate at $0.5 \times 10^{-4}\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$, assuming that the system would survive as a mass-transferring binary (see § 3.2 for further discussion). This means that in our calculations the secondary was allowed to overfill its Roche lobe by a moderate amount (the formal radius of the secondary at the time of the explosion exceeded the Roche lobe by $\sim 17\%$). When the system encounters the delayed dynamical instability, the WD mass has grown to $1.31\,\mathrm{M}_\odot$. It continues to grow until it explodes as a SN Ia $\sim 3 \times 10^4$ yr later. In this final phase, the system is expected to lose mass at a rate well in excess of $10^{-4} M_\odot \mathrm{yr}^{-1}$ (the total mass lost in this phase is $\sim 1.5\,\mathrm{M}_\odot$). At the time of the explosion the orbital period is only 9 hr and the secondary has a mass of $0.63\,\mathrm{M}_\odot$.

One of the key points in this scenario is that the time to the encounter of the delayed dynamical instability is completely determined by the initial entropy profile of the secondary and the evolution of the binary parameters, which in turn depends strongly on the angular momentum loss associated with the mass loss from the system. This time cannot significantly exceed $2 \times 10^5$ yr and this is the only time the WD has to grow to reach the Chandrasekhar mass. Whether this scenario can produce a SN Ia, therefore depends both on the initial white dwarf mass (more massive white dwarfs are favoured, since it is then easier to reach the Chandrasekhar mass) and most importantly on the accretion efficiency. In order to be able to grow the WD mass sufficiently in the above calculation, we had to *arbitrarily increase* the accretion efficiency by a factor of 2.5 over the value assumed in our standard model (i.e. the model based on the efficiency calculations by Hachisu et al. 1999b). Whether this is at all reasonable or not will be discussed further in the next section.

## 3 DISCUSSION

### 3.1 The accretion efficiency

One of the major physical uncertainties in the scenario for SN 2002ic presented here is whether the efficiency for accretion onto the white dwarf is indeed as large as required (2.5 times the value assumed in our canonical model). The accretion efficiency is in general quite uncertain and depends on rather uncertain physics, e.g., the occurrence of nova explosions and helium flashes and the associated mass loss, the details of a disc wind that is assumed to carry away the excess mass that cannot be accreted (Kato & Hachisu 1994), etc. In particular, none of the present estimates take into account the role of the rotation of the accreted material. Yoon & Langer (2004) recently showed for the case of helium-accreting white dwarfs that rotation dramatically changes the evolution of the white dwarf: it generally reduces the violence of helium flashes, it may even suppress them, and hence is expected to increase the accretion efficiency and the parameter range for which white dwarfs can grow efficiently. On the other hand, the critical explosion mass may increase well above the standard Chandrasekhar mass (up to $\sim 1.8\,M_\odot$; Yoon & Langer 2005), i.e., require even more mass to be accreted. Whether the net effect is to increase the efficiency to the value required here is not clear at the moment.

However, we can at least make a plausibility check by comparing the "accretion rates" (more precisely the core growth rates) of the CO cores in AGB stars with the rate required for SN 2002ic. These are shown in Figure 4 for AGB stars from 2.5 to $6.3\,M_\odot$, both as a function of core mass and central degeneracy parameter. Note that real AGB stars do not reach such high CO core masses as shown in the figure since they eject their envelopes before. These calculations were done without mass loss in order to be able to estimate the core accretion rate. They do, however, remain CO cores for the masses shown and would ultimately ignite carbon in the center leading to a thermonuclear runaway (sometimes referred to as a 1 1/2 supernova). Only the more massive AGB stars ignite carbon off-center and are converted into ONeMg stars (as, e.g., discussed in Iben 1974). Our integration on the AGB uses relatively large timesteps which suppresses thermal pulsations; therefore the accretion rate on the CO core is only correct in a time-averaged sense. Moreoever, this exercise is certainly not a proof of higher accretion efficiencies; this still requires much more detailed work, as discussed earlier. As seen from Figure 4, the core growth rates varies by almost a factor of 3 in the region of interest (i.e., above a core mass of $1\,M_\odot$) and can be larger by more than of a factor of 2 than the critical rate, shown as a dotted curve in the left panel, used in the Hachisu et al. (1999b) parameterization. The highest rates are comparable to the rates required in the scenario presented above, suggesting that the assumption of a higher accretion efficiency is at least not *a priori* unreasonable.

### 3.2 The pre-supernova mass loss

A second uncertainty in this scenario is related to the final mass-loss phase which we cannot treat properly with our code, since multi-dimensional and possibly hydrodynamical effects start to become important. In our calculation, the secondary overfilled its Roche lobe by about 49% at its most extreme; this is likely to lead to the formation of a common-envelope (CE) phase surrounding both binary components. Whether this leads to a dramatic spiral-in and the ultimate merger of the components or not is not so clear. At least initially the envelope will be in co-rotation with the binary, which implies that at least initially there is no friction to extract energy from the orbit and drive a spiral-in. Moreover, if the density in the CE is low (as is, e.g., expected to be the case for donors with radiative envelopes; Podsiadlowski 2001), only a moderate shrinking of the orbit is required to inject enough energy into the CE to eject the excess mass. In this case, a moderate orbital shrinking may drive a *frictionally driven wind*[3]. Because of the large rotation of the system, this wind would be expected to be very anisotropic, most likely resemble an equatorial outflow (perhaps confined to within 30° of the orbital plane as in the case of SS 433; Blundell et al. 2001) and have a velocity of order or somewhat lower than the orbital velocity of the binary. This is consistent with the inferred measurement of the wind velocity from the H$\alpha$ P-Cygni profile of $\sim 100\,\mathrm{km\,s^{-1}}$ (Kotak et al. 2004). We also note that there may be mass loss through one or both of the outer Lagrangian points (L2 and/or L3). This could produce a circumbinary, disc-like structure that may affect the spectral evolution of the supernova ejecta (see Mazzali et al. 2005). It is also possible that there exists a bipolar outflow, though it is not clear whether this would affect the SN interaction.

There is, however, another interesting possibility, namely that the spiral-in runs away and leads to the complete merging of the CO WD with the secondary. Once the CO WD has settled at the centre of the merger product, the envelope will expand to red-giant dimensions and the object resemble an AGB star, except that it already has a rather massive CO core of $1.35\,M_\odot$; the final product will be *an object that may never be able to evolve from a single star* (see the discussion in § 1). In this case, it may be easier for the core to grow to reach the Chandrasekhar mass. Moreover, the final phase is expected to be accompanied by

[3] Such frictionally driven orbital evolution was not included in our binary calculation.

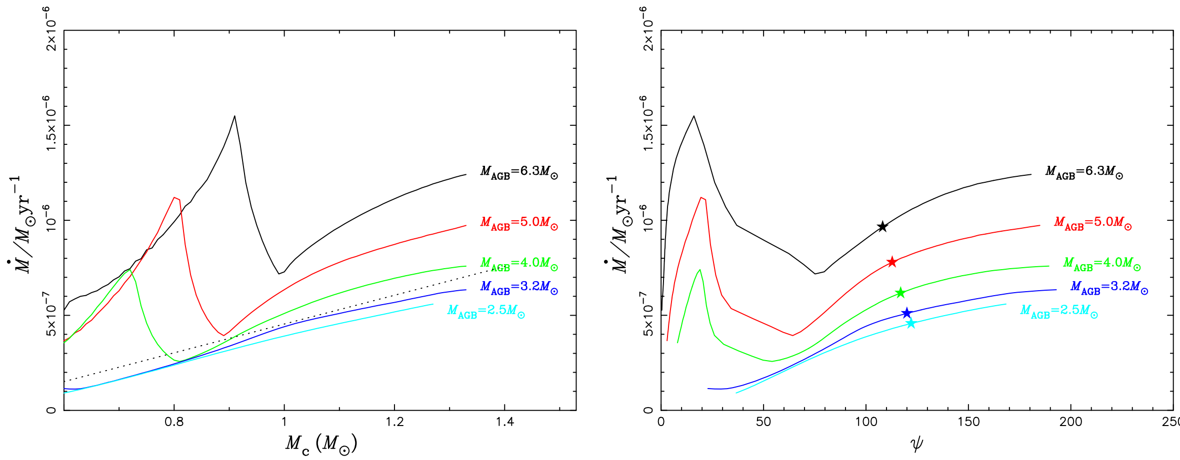


**Figure 4.** Core growth rate for different ($Z = 0.02$) AGB stars with masses from 2.5 to $6.3\,\mathrm{M}_\odot$(as indicated) without convective overshooting as a function of core mass (*left panel*) and as a function of the central degeneracy parameter $\psi$ (*right panel*). The dotted curve shows the critical (i.e. maximum) accretion rate of hydrogen-rich material onto a CO WD from Hachisu et al. (1999b). The stars in the right panel indicate when the core mass is $1.1M_\odot$.

a superwind phase (note, it is not a classical superwind in an AGB star that is driven by MIRA pulsations, but the mass loss must be so high to resemble a superwind), possibly producing the type of CSM inferred for SN 2002ic. In this case, SN 2002ic could indeed be related to a SN 1 1/2 (Hamuy et al. 2003), but avoid many of the problems of a single-star scenario.

### 3.3 Frequency estimates

Supernovae similar to SN 2002ic clearly form a relatively rare subclass of SNe Ia; no more than perhaps 1 in 100 SNe Ia can be of this type (Hamuy et al. 2003; Deng et al. 2004; Chugai, Chevalier & Lundqvist 2004; Wood-Vasey, Wang & Aldering 2004). Therefore the evolutionary channel leading to a SN Ia has to be a rare one, and a certain amount of fine-tuning is not only acceptable, but is required. In the delayed dynamical instability scenario, the white dwarf has to be quite massive initially ($\gtrsim 1.0\,\mathrm{M}_\odot$), since the amount of mass that can be accreted before the dynamical instability sets in is limited. This also implies that the secondary mass has to be relatively large initially ($\gtrsim 3\,\mathrm{M}_\odot$), since the critical mass ratio for a delayed dynamical instability is $\sim 3$. Moreover, at the time of the instability the WD mass has to be already close to the Chandrasekhar mass ($\sim 1.35\,\mathrm{M}_\odot$), since very little mass can be accreted subsequently. To estimate the frequency for our scenario, we did not perform another large series of binary calculations with an increased accretion efficiency. Instead, we re-evaluated the outcome for our 2300 sequences from Han & Podsiadlowski (2004), examining which of our sequences would fulfil the above constraints for SN 2002ic if the accretion efficiency were increased by a factor of 2.5. The results of this exercise are shown in Figure 5, which shows the expected fate in the orbital period – secondary mass ($\log P_{\rm orb} - M_2$) plane for different initial WD masses. The stars indicate sequences that have the correct properties for SN 2002ic. Altogether 18 out of our 2300 sequences satisfy these constraints.

We used these constraints to perform full binary population synthesis calculations to estimate the frequencies of supernovae of this type. Figure 6 compares the evolution of birthrates for a constant star formation rate (of $3.5\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$; left panel) and a single star burst (right panel) both for a typical SN Ia (thick curves) and a delayed dynamical scenario (thin curves), where we varied the binary population synthesis parameters over a reasonable range (see Han & Podsiadlowski 2004 for further discussion). The main result of these simulations is that the expected overall rate for a delayed dynamical scenario is about a factor of 200 lower than the overall SN Ia rate (see the left panel of Fig. 6), although at early times (within $\sim 2\times10^8$ yr) of a star burst it is lower by only a factor of 10 or less. These estimates are consistent with the rarity of observed supernovae similar to SN 2002ic and independent estimates. This type of SNe Ia could therefore be used to trace star formation, with a time delay somewhat longer than for core collapse supernovae and shorter than for the bulk of "normal" SNe Ia, of which these form the youngest sub-class.

## 4 CONCLUSIONS

The most important conclusion of this study is that SN 2002ic, even though it clearly had an atypical progenitor evolution, can still be understood within the framework of the arguably most favoured single-degenerate channel which links SNe Ia to supersoft X-ray sources. Even within this channel, progenitors display substantial diversity, and this may be able to account at least in part for the observed diversity of SNe Ia. SN 2002ic may represent an extreme case with a donor star near the upper mass ($\sim 3-3.5\,\mathrm{M}_\odot$) allowed in this channel and may have experienced a delayed dynamical instability where the mass loss from the system increased dramatically just in the last few $10^4$ yr before the explosion. If this is the case, SN 2002ic may in fact provide useful constraints on the supersoft channel and help to calibrate some of the important physical input parameters. In particular, as we have shown here, this model requires a significantly larger accretion efficiency (by at least a factor of 2) than assumed in the parameterization by Hachisu et al.

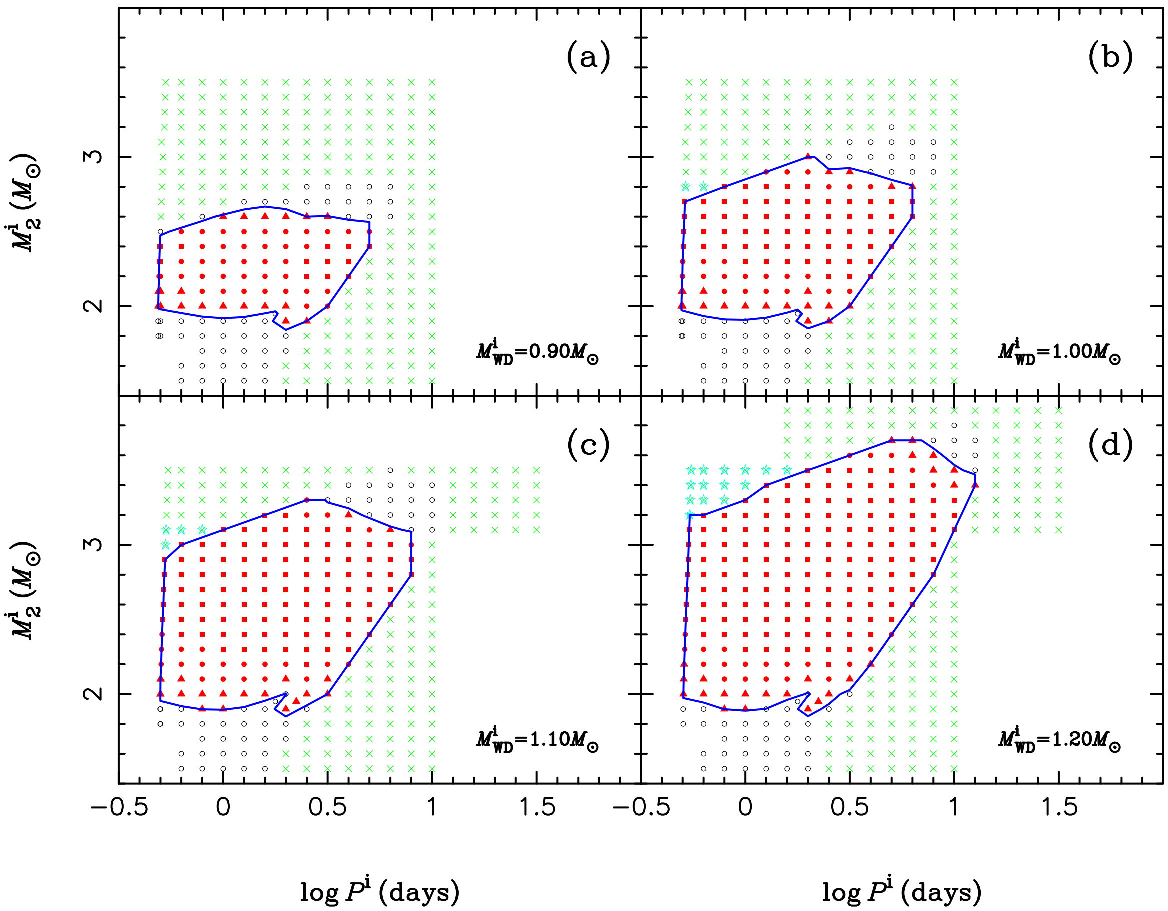


**Figure 5.** Estimated parameter regions for a delayed dynamical instability in the orbital period – secondary mass ($\log P_{\rm orb} - M_2$) plane for different initial WD masses, $M_{\rm WD}$, as indicated. The solid contours enclose the parameter regions for which a WD binary is expected to explode as a SN Ia in the canonical model. The stars indicate the parameter regions for a delayed dynamical instability, as may be applicable to SN 2002ic.

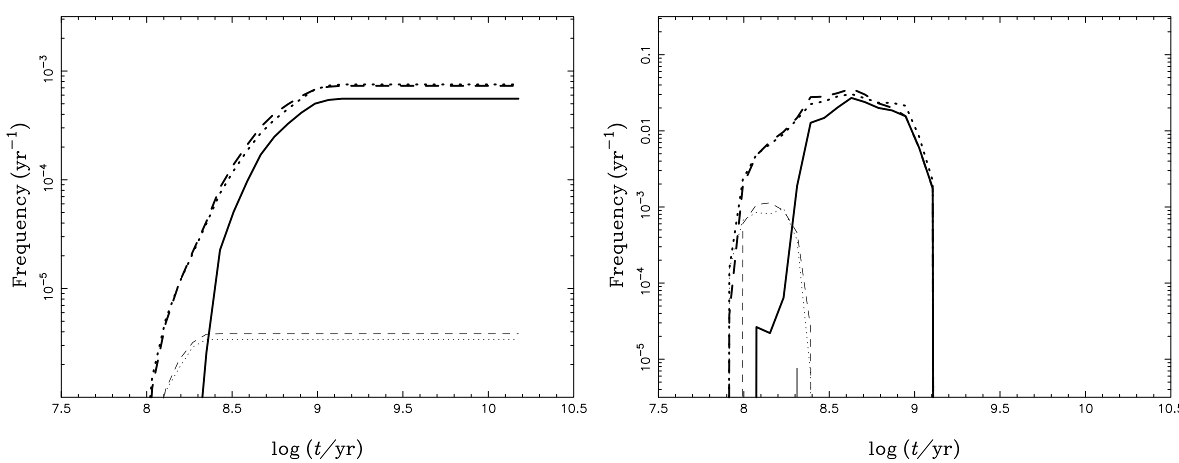


**Figure 6.** *Left panel:* the evolution of birthrate of SNe Ia for a constant Pop I star-formation rate ($3.5\,{\rm M}_\odot\,{\rm yr}^{-1}$). The thick curves are for a "normal" SNe Ia, while the thin ones curves are for SNe Ia from the "delayed dynamical" channel. The solid, dashed and dotted curves are for different CE-ejection parameters, $\alpha_{\rm CE} = \alpha_{\rm th} = 1.0, 0.75, 0.5$, respectively (see Han & Podsiadlowski 2004 for further details). *Right panel:* similar to the left panel, but for a single star burst of $10^{11}\,{\rm M}_\odot$.

(1999b). Another implication of this is that it most likely suggests that the parameter range for the initial binary parameters that can lead to a SN Ia is much larger than in previous studies (e.g. Han & Podsiadlowski 2004; Fedorova, Tutukov & Yungelson 2004), increasing estimates for the frequency of this channel and making them more consistent with the observed frequency, thereby alleviating one of the major objections to it (see e.g. Fedorova et al. 2004).

SNe Ia like SN 2002ic should be rare events, since the parameters of the progenitor systems are very restricted. We estimate that not more than 1 in 100 SNe Ia should fall into this subclass. Since they require an intermediate-mass secondary, they should only be found in stellar populations with relatively recent star formation (with the last $\sim 3 \times 10^8$ yr). Unlike a SN 1 1/2, the system still has a companion star at the time of the explosion which may interact with the supernova ejecta. Another potential test of the model is the amount of hydrogen found in the surrounding circumstellar medium (CSM). In this model, the maximum mass is limited to the mass of the companion star and the mass in the nearby CSM cannot reasonably exceed $\sim 2\,M_\odot$, which is substantially less than some of the more extreme estimates at present (see § 1). In addition, one may expect that most of this material should form a disk-like outflow (or possibly even a circumbinary disc).

## ACKNOWLEDGEMENTS

We are grateful to an anonymous referee for his/her useful comments. This work was in part supported by a Royal Society UK-China Joint Project Grant (Ph.P and Z.H.), the Chinese Academy of Sciences under Grant No. KJCX2-SW-T06, and Natural Science Foundation of China under Grant Nos. 10433030 and 10521001 (Z.H.) and a European Research & Training Network on Type Ia Supernovae (HPRN-CT-20002-00303).

## REFERENCES

Blundell, K.M., Mioduszewski, A.J., Muxlow, T.W., Podsiadlowski, Ph., & Rupen, M.P., 2001, ApJL, 562, L79
Chugai N.N., Yungelson L.R., 2004, Astronomy Letters 30, 65
Chugai N.N., Chevalier, R.A., Lundqvist, P., 2004, MNRAS, 355, 627
Deng J., et al., 2004, ApJ 605, L37
Eggleton P.P., 1971, MNRAS, 151, 351
Eggleton P.P., 1972, MNRAS, 156, 361
Eggleton P.P., 1973, MNRAS, 163, 179
Fedorova A.V., Tutukov A.V., Yungelson L.R., 2004, Astronomy Letters 30, 73
Hachisu, I., Kato, M., & Nomoto, K., 1999a, ApJ, 522, 487
Hachisu, I., Kato, M., Nomoto, K., Umeda, H., 1999b, ApJ, 519, 314
Hamuy M. et al., 2003, Nat. 424, 651
Han, Z., Podsiadlowski, Ph., 2004, MNRAS, 350, 1301
Han, Z., Podsiadlowski, Ph., & Eggleton, P.P., 1994, MNRAS, 270, 121
Hjellming, M.S., Webbink, R.F., 1987, ApJ, 318, 794
Iben, I., Jr., 1974, ARA&A, 12, 215
Iben, I., Jr., & Renzini, A., 1983, ARA&A, 21, 271
Iben, I., Jr., & Tutukov, A.V., 1984, ApJS, 54, 335
Kato, M., Hachisu, I., 1994, ApJ, 437, 802
Kotak, R., Meikle, W.P.S., Adamson, A. & Leggett, S.K., 2004, MNRAS, 354, L13
Langer, N., Deutschmann, A., Wellstein, S., Höflich, P. 2000, A&A, 362, 1046
Livio M., Riess A.G., 2003, ApJ 594, L93
Mazzali et al. 2005, ApJ, 623, L37
Nomoto, K., 1982, ApJ, 253, 798
Podsiadlowski, Ph., 2001, in Evolution of Binary and Multiple Star Systems, eds Ph. Podsiadlowski et al. (San Francisco, ASP), p. 239
Podsiadlowski, Ph., Rappaport, S., Pfahl, E., 2002, ApJ, 565, 1107 (PRP)
Pols, O., Tout, C.A., Eggleton, P.P., Han, Z., 1995, MNRAS, 274, 964
Rappaport, S., Di Stefano, R., & Smith, J.D., 1994, ApJ, 426, 692
Sparks, W.M., & Stecher, T.P., 1974, ApJ, 188, 149
Wang L., Baade D., Höflich P., Wheeler, C., Kawabata, K. & Nomoto, K., 2004, ApJ 604, L53
van den Heuvel, E.P.J., Bhattacharya, D., Nomoto, K., & Rappaport, S., 1992, A&A, 262, 97
Webbink, R.F., 1984, ApJ, 277, 355
Whelan, J., & Iben, I., Jr., 1973, ApJ, 186, 1007
Wood-Vasey, W.M., Wang, L., Aldering, G., 2004, ApJ, 616, 339
Uenishi, T., Suzuki, T., Nomoto, K., Hachisu, I., 2004, Rev. Mex. A&A, 20, 219
Yoon, S.-C., Langer, N., Scheithauer, S., 2004, A&A, 425, 217
Yoon, S.-C., Langer, N., 2005, A&A, 435, 967