A New Evolutionary Channel for Type Ia Supernovae

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ABSTRACT
We show that long–period dwarf novae offer a promising route for making Type Ia supernovae. For typical dwarf nova duty cycles \( d \sim 0.1 - 0.01 \), mass is accreted by the white dwarf mainly during dwarf nova outbursts at rates allowing steady nuclear burning of most of the accreted matter. Mass gains up to \( \sim 0.4M_\odot \) are possible in this way. Although these are too small to allow a \( 0.7M_\odot \) WD to reach the Chandrasekhar mass, they are sufficient if the WD grew to \( \gtrsim 1M_\odot \) in a previous episode of thermal–timescale mass transfer, i.e. for those long–period dwarf novae which descend from supersoft binaries. A further advantage of this picture is that the supernova always occurs in a binary of small secondary/primary mass ratio, with the secondary having very little remaining hydrogen. Both features greatly reduce the possibility of hydrogen contamination of the supernova ejecta.

Key words: accretion, accretion discs – binaries: general – X–rays: binaries – stars: dwarf novae – supernovae: general – galaxies: stellar content – cosmology: distance scale

1 INTRODUCTION

It is now generally agreed that Type Ia supernovae originate from accreting white dwarfs, and widely accepted that their occurrence signals arrival at the Chandrasekhar mass \( M_{Ch} \approx 1.4M_\odot \). However there is no consensus as to how the white dwarf gains mass (see e.g. Livio, 2001, for a review). Two possibilities are currently discussed. In the first, two white dwarfs merge as their relative orbit shrinks under gravitational radiation (the double–degenerate scenario). In the second possibility, a white dwarf accretes from a non–degenerate companion (the single–degenerate scenario). Observational evidence is currently too sparse to give a strong preference to either picture. However both have serious theoretical drawbacks.

For white dwarf mergers, many authors (Saio & Nomoto, 1985, 1998; Kawai, Saio & Nomoto, 1987; Mochkovitch & Livio, 1990; Timmes, Woosley & Taam, 1994; Mochkovitch, Guerrero & Segretain, 1997) argue that no explosion takes place and that the result is instead a quiet, accretion–induced collapse (AIC), forming a neutron star.

The single–degenerate picture suffers from two main problems. First, growth of the white dwarf mass \( M_1 \) requires efficient nuclear burning of most of the accreted hydrogen. This happens only for accretion rates \( \dot{M} \) satisfying

\[
\dot{M}_1 \lesssim \frac{\dot{M}}{M_1/M_\odot - 0.52} \lesssim \dot{M}_h \approx 2.5\dot{M}_l
\]

where \( \dot{M}_l \approx 3.4 \times 10^{-7} M_\odot\text{yr}^{-1} \) (Nomoto et al., 1979; Fujimoto, 1982). For lower \( \dot{M} \) the burning occurs in nova explosions. These expel matter and leave the white dwarf mass essentially unchanged. For \( \dot{M}/(M_1/M_\odot - 0.52) \gg \dot{M}_h \approx 8.5 \times 10^{-7} M_\odot\text{yr}^{-1} \) not all of the hydrogen is burnt. In some pictures much of the excess is expelled in a radiatively driven wind: in e.g. the strong wind solution of Hachisu et al. (1996) the burning rate is limited by \( \dot{M}_h \). This allows mass growth to continue, but for \( \dot{M} >> \dot{M}_h \) this is clearly an inefficient process, as only a small fraction of the transferred mass is gained by the white dwarf. If there is no significant wind things may be still worse, as the excess accretion will probably form a common envelope around the binary, causing it to merge and become a massive red giant. The second difficulty with this single–degenerate scenario results from the proximity of a large H–rich companion at the time the supernova explodes. This may contaminate the supernova ejecta (Marietta, Burrows & Fryxell, 2000), in conflict with the defining characteristic of Type Ia SNe as having no detectable hydrogen (see, however, Lentz et al. 2002).

The \( \dot{M} \) constraint rules out most candidate progenitor binaries for the single–degenerate scenario. Cataclysmic variables (CVs) generally have mass transfer rates \( -\dot{M}_2 << \dot{M}_1 \) and so are prone to losing the transferred mass in nova explosions. Supersoft X–ray binaries (SSS) are more promising. Here in contrast to CVs the companion/WD mass ratio \( q = M_2/M_1 \) is \( \gtrsim 1 \), and mass transfer shrinks the companion’s Roche lobe relative to the stellar surface. For a companion with a radiative envelope the result is mass transfer on a thermal timescale, i.e. \( \dot{M} = -\dot{M}_2 \sim M_2/t_{KH} \). This is close to the required range if the companion has mass \( M_2 \sim 1M_\odot \).
and thus a Kelvin–Helmholtz timescale $t_{KH} \sim 3 \times 10^7$ yr (van den Heuvel et al., 1992). The white dwarf in such SSS binaries can gain mass. However, systematic calculations (e.g. Langer et al., 2000) show that it may be difficult to grow $M_1$ from a typical value $0.7M_\odot$ all the way to $M_{Ch}$. Thus only systems starting with rather more massive white dwarfs give SNe Ia. This in turn means that the main–sequence progenitor of the white dwarf must itself have been rather massive, significantly reducing the number of systems which can give SNe Ia by this channel. In addition, this type of evolution is vulnerable to the hydrogen contamination constraint. Not only is the companion fairly massive and hydrogen–rich, its Roche lobe offers a large target for the expanding SN shell as the mass ratio $q$ must be $\gtrsim 1$ when the explosion occurs.

In this paper we reconsider the single–degenerate scenario, and offer an alternative that avoids these difficulties.

## 2 LONG PERIOD DWARF NOVAE

We have seen that SSS binaries do not readily produce SNe Ia because the white dwarf mass does not grow enough. The accretion rate is sensitive to the mass ratio $q$, and moves out of the narrow band $\mathbf{1}$ in which efficient mass gain occurs before much mass is transferred. An accretion rate which remains almost constant as $q$ decreases is clearly a major advantage for a plausible progenitor WD binary class.

Only one type of WD binary satisfies this requirement: long–period ($\gtrsim 2$ d) systems where the WD accretes from a low–mass red giant. These systems are driven by the nuclear expansion of the red giant. The helium core mass $M_0$ of this star increases slightly through shell–burning during the binary evolution, causing considerable envelope expansion. The envelope mass is depleted by shell–burning but much more by mass transfer to the white dwarf. Calculations (Webbink, Rappaport & Savonije, 1983; Ritter, 1999) show that the mass transfer rate varies remarkably little while most of the companion’s envelope is transferred, the value of the rate being fixed by the core mass or equivalently the binary period. Eq (36) of Ritter (1999) relates $-M_2$ directly to the companion mass $M_2$ for the case where all the transferred mass is accreted by the white dwarf. Fig. $\mathbf{14}$ shows that for a WD starting at $M_{1,i} = 1M_\odot$ the mass transfer rate $-M_2$ changes by no more than factors $\sim 2$ as $M_2$ decreases from $M_{2,i} \sim 0.6M_\odot$ to $\sim 0.3M_\odot$.

While this is encouraging for a candidate SNe Ia progenitor there appears at first sight to be a major difficulty. The mass transfer rates in such binaries are typically only $\sim 10^{-3} M_\odot\text{yr}^{-1}$, more than a factor 10 short of the steady burning regime $\mathbf{11}$. However we must distinguish the mass transfer rate $-M_2$ from the mass accretion rate $M$. All these long–period systems are so wide that their accretion discs have ionization zones; they are dwarf novae (King et al., 1997). This point was previously neglected but is crucial for modeling these long–period systems correctly. It is probably the shortness of the duty cycle $d$, together with the low space density resulting from their relatively rapid evolution that makes discovery of long–period systems of this type difficult. Accretion on to the white dwarf occurs almost entirely during outbursts, with accretion rates $\sim -M_2/d$ which can therefore be close to the efficient burning regime.

The mean duty cycle $d$ is presumably itself a function $\mathbf{15}$ of the evolutionary state of the binary, although the lack of understanding of disc viscosity in current theory does not allow one to predict it with any certainty. However for typical values $\sim 0.1$ to a few times $10^{-3}$ one can always find initial white dwarf, donor and core masses which keep the accretion rate during outbursts inside the efficient burning regime $\mathbf{11}$ through most of the evolution. This kind of mass gain therefore works even if wind loss is inefficient for $M > M_h$.

A further advantage for this picture is that the SN Ia explosion must always occur for mass ratios $q < 1$, and indeed generally with very little of the hydrogen envelope of the secondary remaining. This then avoids the second difficulty (hydrogen contamination) afflicting the single–degenerate scenario. The secondary is now a rather smaller target for the expanding supernova shell, and in any case contains little hydrogen.

## 3 SNE Ia PROGENITORS

We have seen from the previous Section that long–period dwarf novae offer a route for making SNe Ia. Fig. $\mathbf{14}$ gives the regions of $M_{1,i}, M_{2,i}$ – space where growth to $M_{Ch}$ may be possible. (This figure assumes conservative mass transfer, but we will show in a future paper that similar results are obtained when this assumption is relaxed.) The required $M_{1,i}$ is somewhat higher than typically results from single–star evolution. This might seem to lead to the same need for massive main–sequence progenitors and thus the same restriction on progenitor numbers as for the SSS channel. However the nuclear–driven evolution discussed here is of course also open to the outcomes of thermal–timescale mass transfer, i.e. the SSS systems we discussed earlier. Many of these, starting from typical white dwarf masses $\sim 0.7M_\odot$, have already increased them to values of the order required.

![Figure 1](image-url)
A New Evolutionary Channel for Type Ia Supernovae

Figure 2. Binary evolution with mass transfer driven by nuclear evolution of the donor on the red giant branch (RGB). All mass lost from the donor is retained by the white dwarf. The mass transfer rate $-\dot{M}_2$ must avoid the upper hatched region for the disc to be unstable to dwarf nova outbursts. The narrow hatched band is the efficient accretion region (1). The assumed duty cycle is 0.004 and the masses of donor, core and white dwarf at the start of this phase are $0.53 M_\odot$, $0.2 M_\odot$ and $1.1 M_\odot$ respectively.

Figure 3. As for Figure 2. Evolution of the donor core and envelope masses, and the white dwarf mass. After $2.3 \times 10^8$ years the white dwarf reaches the Chandrasekhar mass and a Type Ia supernova ensues.

Figure 4. Component masses of potential SN Ia progenitors at the start of the conservative mass transfer phase on the RGB. Systems in the upper hatched region undergo dynamically unstable mass transfer and maybe a common envelope phase, rather than the evolutionary scenario considered here. Systems in the lower hatched region have insufficient mass in the donor envelope to raise the white dwarf to the Chandrasekhar limit. The upper limit on the white dwarf is the Chandrasekhar mass. Potential SN Ia progenitors therefore lie in the clear triangle region, with a minimum white dwarf mass $\sim 1 M_\odot$. The precise value depends on the core mass at this stage, which must be in the approximate range $0.2–0.3 M_\odot$, and the details of mass loss for $M > M_h(M_1/M_\odot - 0.52)$.

We therefore envisage a two–stage process in the growth of $M_1$ towards $M_{Ch}$ (Fig. 4).

First, a SSS system with $M_1 \sim 0.7 M_\odot$ and $M_2 > M_1$ undergoes thermal–timescale mass transfer and increases the white dwarf mass to values $\sim 1 M_\odot$. Thermal–timescale mass transfer stops once the mass ratio $q$ drops below a value $\sim 1$. What happens next to the binary depends on the competition between orbital angular momentum loss (presumably through magnetic stellar wind braking) and nuclear expansion of the secondary (cf Schenker et al., 2002). If the angular momentum loss timescale is shorter than that for nuclear evolution the system becomes a short–period CV, often with some signs of chemical evolution as in AE Aquarii (Schenker et al. 2002). If instead the nuclear evolution timescale is shorter, the system will expand and eventually become the kind of long–period CV we discuss here. For suitable masses $M_{1,1}, M_{2,1}$ and orbital separation at the end of thermal–timescale mass transfer the white dwarf mass can grow to $M_{Ch}$ and produce a SN Ia.

Assuming mass transfer starts at or near the end of the main sequence and that the thermal–timescale phase has little effect on the core mass of the donor when it reaches the base of the RGB, the minimum donor mass which reaches the RGB with core mass $\geq 0.2 M_\odot$ is $\sim 2 M_\odot$. For massive donors (mass ratios $q \geq 3–4$) sustained thermal–timescale mass transfer leads to dynamical instability (Hjellming 1989; Kalogera & Webbink 1996; Kolb et al. 2000). This delayed dynamical instability limits the maximum donor mass before the onset of nuclear evolution.
fore the thermal–timescale phase to \(\sim 3M_\odot\). Thus the donor mass at the start of mass transfer is limited to the approximate range \(2 \sim 3M_\odot\). Future work involving accurate numerical modelling of the thermal–timescale evolution will refine this simple picture.

4 CONCLUSIONS

We have shown that long–period dwarf novae offer a promising channel for making Type Ia supernovae. In particular the white dwarf mass can be raised to the Chandrasekhar value without the need to invoke fairly massive and thus rare main–sequence progenitors. Moreover there is very little danger of hydrogen contamination of the supernova ejecta.

Clearly more work is needed. In particular we need to calculate the birthrate of such systems and compare this with the inferred rate \(\sim 3 \times 10^{-3} \text{ yr}^{-1}\) of SNe Ia per galaxy. This in turn requires an extensive grid of models. We shall return to this problem in a future paper.

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The two-stage process proposed for progenitors of SNe Ia. A significantly nuclear-evolved $\sim 2.5 M_\odot$ star transfers mass to a $\sim 0.7 M_\odot$ white dwarf. The high mass ratio $q$ leads to mass transfer on the timescale of the donor’s thermal reaction to mass loss. In some cases there is an initial phase of non-conservative super-Eddington accretion at $\sim 10^{-6} M_\odot \text{yr}^{-1}$. Conservative mass transfer begins as the mass ratio approaches unity and the accretion rate passes through the stable hydrogen burning band $\sim 10^{-7} M_\odot \text{yr}^{-1}$. The star appears as a supersoft X-ray binary during this phase, and the white dwarf accretes a few tenths of a solar mass. Once $q$ attains values $\lesssim 1$ mass transfer proceeds on a nuclear timescale. Initially the accreted mass is lost in nova explosions so the white dwarf mass does not grow. Eventually the system reaches the regime discussed in this paper, where most transferred mass is burnt and retained by the WD during dwarf nova outbursts.

Figure 5. The two-stage process proposed for progenitors of SNe Ia. A significantly nuclear-evolved $\sim 2.5 M_\odot$ star transfers mass to a $\sim 0.7 M_\odot$ white dwarf. The high mass ratio $q$ leads to mass transfer on the timescale of the donor’s thermal reaction to mass loss. In some cases there is an initial phase of non-conservative super-Eddington accretion at $\sim 10^{-6} M_\odot \text{yr}^{-1}$. Conservative mass transfer begins as the mass ratio approaches unity and the accretion rate passes through the stable hydrogen burning band $\sim 10^{-7} M_\odot \text{yr}^{-1}$. The star appears as a supersoft X-ray binary during this phase, and the white dwarf accretes a few tenths of a solar mass. Once $q$ attains values $\lesssim 1$ mass transfer proceeds on a nuclear timescale. Initially the accreted mass is lost in nova explosions so the white dwarf mass does not grow. Eventually the system reaches the regime discussed in this paper, where most transferred mass is burnt and retained by the WD during dwarf nova outbursts.