Merging white dwarfs and thermonuclear supernovae

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Thermonuclear supernovae result when interaction with a companion reignites nuclear fusion in a carbon–oxygen white dwarf, causing a thermonuclear runaway, a catastrophic gain in pressure and the disintegration of the whole white dwarf. It is usually thought that fusion is reignited in near-pycnonuclear conditions when the white dwarf approaches the Chandrasekhar mass. I briefly describe two long-standing problems faced by this scenario, and the suggestion that these supernovae instead result from mergers of carbon–oxygen white dwarfs, including those that produce sub-Chandrasekhar-mass remnants. I then turn to possible observational tests, in particular, those that test the absence or presence of electron captures during the burning.

1. The current paradigm and its problems

A thermonuclear or type Ia supernova (SN Ia) is generally thought to be produced by a carbon–oxygen white dwarf that accretes matter relatively slowly, on time scales of \( \gtrsim 10^6 \) year (limited by the rate at which heat from accretion and possible nuclear processing can be radiated, viz. the Eddington luminosity; for reviews see [1,2]). As the white dwarf accretes, its interior is heated, but it does not reach ignition, because at temperatures of \( \gtrsim 10^8 \) K, neutrino cooling becomes efficient enough to balance the heating (figure 1). However, as the white dwarf approaches the Chandrasekhar mass, the density in its core becomes so high that fusion becomes possible at lower temperatures (in partly pycnonuclear conditions; figure 1). Once this happens, a runaway ensues, stopping only when degeneracy is lifted, and thermal pressure can expand and cool the region. The process triggers a burning front that proceeds through the white dwarf, generating the energy that eventually disrupts it.
The above is physically plausible, but it has two well-known problems. I briefly describe these below, before turning to the alternative proposed by myself and others.

(a) The paucity of possible progenitor systems

Over the age of the Universe, for every Solar mass of stars formed, approximately \(0.0023 \pm 0.0006\) SN Ia seem to occur [5,6]. Because approximately 0.22 white dwarfs are expected for every Solar mass formed (the remainder being in low-mass stars that are still alive), one infers that a surprisingly high fraction, of approximately 1 per cent, of all white dwarfs eventually produce SN Ia. Comparing different galaxies, the instantaneous SN Ia rate similarly seems to be approximately 1 per cent of the white-dwarf formation rate [7].

Most SN Ia models invoke ‘single-degenerate’ progenitors, in which a white dwarf accretes from a non-degenerate companion [8]. In principle, ample numbers of such binaries exist, and several routes to explosions have been proposed [9]. No route, however, seems both common and efficient.

The main problem is that, if mass transfer is slow, unstable hydrogen fusion in the accreting matter causes novae, which in most cases appear to remove as much mass as was accreted [10] (though white dwarfs in cataclysmic variables are more massive than in their progenitors [11]). If accretion is faster, hydrogen burns stably, but only in a small range of accretion rate can expansion and mass loss be avoided [12] (for the effect of helium flashes, see [13]). Empirically, the best-suited systems are the supersoft X-ray sources [14], but those are far too rare to explain the SN Ia rates [15,16]. We may be missing systems, for example, more rapidly accreting white dwarfs that expanded and hid from X-ray view [17]. However, for such sources—as for many single-degenerate channels—the lack of evidence for (entrained) hydrogen in SN Ia is surprising (unless the explosion can somehow be delayed, as in the ‘spin-up/down’ model [18,19]).
Another class of SN Ia models invoke ‘double degenerates’, where one white dwarf merges with another [9,20]. As ignition is not expected during the merger (except perhaps for unusually massive, \(\gtrsim 0.9 \, M_\odot\) white dwarfs [21]), it is usually assumed that an explosion will follow only if the combined mass exceeds the Chandrasekhar mass. This is rare, however, and both theoretical [3,22,23] and empirical [24] rate estimates fall well below the SN Ia rate. Furthermore, the observed number of supersoft symbiotic progenitors with the required massive white dwarfs is substantially smaller than that expected [25].

(b) The difficulty of reproducing SN Ia properties

In degenerate matter, a thermonuclear runaway will proceed to completion unless degeneracy is lifted, and thermal pressure can expand and cool matter. After initial ignition, what happens depends on the conditions. For sufficiently high overpressure in a sufficiently large region (where what is ‘sufficient’ remains to be understood [26]), a detonation is triggered: a shock strong enough to cause neighbouring matter to ignite and burn, in turn. Because a detonation proceeds supersonically, the white dwarf has no time to expand, and the initial density everywhere determines the endpoint of the runaway. For a near-Chandrasekhar-mass white dwarf, most matter is at very high density and thus far too much \(^{56}\text{Ni}\) is produced.

For a near-Chandrasekhar-mass white dwarf, however, the energy release even from fusion up to \(^{56}\text{Ni}\) does not lead to strong overpressure, and a deflagration is more likely, where neighbouring regions are ignited by a heat wave rather than by a shock. Because a deflagration is subsonic, the white dwarf expands as the burning front progresses. Thus, burning takes place at lower density, reaching lower peak temperatures and producing less \(^{56}\text{Ni}\). Unfortunately, the burning front appears to be too slow, making it impossible to produce sufficiently energetic explosions [2].

Another problem is that both pure detonation and pure deflagration models do not naturally reproduce the range in SN Ia properties, which trace a (nearly) single-parameter family, reflecting a roughly factor 5 range in the amount of \(^{56}\text{Ni}\) that is synthesized [27,28]. The earlier-mentioned issues can be resolved with the ad hoc assumption that an initial deflagration transitions into a detonation [29]. If so, the timing of the transition could determine how far the white dwarf expanded and thus how much \(^{56}\text{Ni}\) was produced. Even with this assumption, however, it remains unclear why the outcome would depend on the population which the progenitor is in, i.e. why, as is observed, more luminous SN Ia preferentially occur in younger populations [30,31].

2. Sub-Chandrasekhar-mass mergers as SN Ia progenitors?

SN Ia could be understood more easily if they arose from sub-Chandrasekhar-mass white dwarfs. Because, for increasing mass, a larger fraction is dense enough to produce \(^{56}\text{Ni}\) (\(\rho \gtrsim 10^7 \, \text{g cm}^{-3}\)), a range of \(^{56}\text{Ni}\) mass would be expected. Also, because more massive white dwarfs are the progeny of shorter-lived stars, younger populations should preferentially host luminous SN Ia. Encouragingly, pure detonations of white dwarfs with masses between 0.9 and 1.2 \(M_\odot\) reproduce the range in SN Ia properties, including roughly their lightcurves and spectra [32,33]. Not clear yet, however, is whether the distribution in luminosity can also be matched easily.

The difficulty for sub-Chandrasekhar-mass white dwarfs is to get them hot enough to ignite. To overcome neutrino losses, they have to be heated on a rather fast, \(\lesssim 10^4\) year, time scale (figure 1). One possibility is that carbon fusion is not triggered directly, but indirectly by a detonation wave started by a thermonuclear runaway in a thick helium layer surrounding the core [34]. These ‘double detonation’ models, however, predict abundances in the outer ejecta—produced in the helium envelope—that are not seen in SN Ia [2] (discussions continue about whether these effects can be reduced by helium layers that are thinner [35,36] or have mixed in carbon [37]). Another possibility is that fusion gets ignited during a merger that involves at least one massive, \(\gtrsim 1 \, M_\odot\), white dwarf [21]. Those, however, have expected rates even lower than those of super-Chandrasekhar-mass mergers, and thus probably are too rare.
Our alternative is that SN Ia result generally from mergers of carbon–oxygen white dwarfs, including those with sub-Chandrasekhar total mass [3]. Both theoretical [3] and empirical [24] rates are a factor 3 or so higher than near-Chandrasekhar rates, making them consistent with the SN Ia rate. Furthermore, the expected range in mass matches that for which detonations yield sufficient $^{56}\text{Ni}$. The questions are whether fusion is ignited, and whether this triggers a detonation.

From simulations, the outcome of a white-dwarf merger depends strongly on whether the masses are similar (where ‘similar’ is within approx. 0.1 M$_\odot$ [38,39]). If they are not, the remnant consists of an almost unaffected core of the more massive white dwarf, surrounded by a hot envelope of the disrupted lower-mass one. For these, further evolution probably leads to ignition at low density, stable burning and, therefore, not to an SN Ia (see [40]).

For similar-mass white dwarfs, however, the remnants are hot throughout, and consist of rapidly rotating cores surrounded by thick, dense discs. Initially, the core is not hot enough to ignite fusion—nor dense enough to produce $^{56}\text{Ni}$—but as the disc accretes or the remnant spins down (helped by, for example, strong magnetic fields that could be generated in the strongly differentially rotating remnant), it will be compressed and heated further (figure 1). The time scale would probably be the viscous one—hours to days—much faster than any relevant cooling time scale. An open question is where ignition takes place. If magnetic braking is important (as in a protostar or accreting pulsar), then dissipation will be far from the remnant and ignition likely in the core. If accretion dominates, then dissipative heating may lead to ignition in the outer regions [40].

### 3. Observational tests

It seems unlikely that the question of the nature of the progenitors of SN Ia will be resolved theoretically, and hence one has to turn to observational tests. So far, most have focused on trying to distinguish between the single- and double-degenerate scenario, with conflicting results: no signature of a (former) companion in early SN Ia lightcurves [41–44] or in SN Ia remnants [45,46], yet evidence for circumstellar medium [47,48].

A different test would be to distinguish between a near- or sub-Chandrasekhar mass. One clue is that in the near-Chandrasekhar case, where the explosion has to start with a deflagration, electron captures during this relatively slow phase are important, leading to the production of approximately 0.1 M$_\odot$ of stable iron-peak elements, much of which is $^{58}\text{Ni}$ (see [49] and references therein). By contrast, for sub-Chandrasekhar models, where the density is much lower, and the explosion has to be a fast detonation, the only source of the neutrons required to produce stable iron-peak elements is $^{22}\text{Ne}$. This is produced during helium burning (via $^{14}\text{N}(a,\gamma)^{18}\text{F}(e^-,\nu_e)^{18}\text{O}(a,\gamma)^{22}\text{Ne}$, where the $^{14}\text{N}$ is left by the CNO cycle), and wherever the temperatures become hot enough to produce $^{56}\text{Ni}$, the excess neutrons end up mostly in $^{54}\text{Fe}$ and $^{58}\text{Ni}$ [32], with a mass of approximately $(58/14)X_{\text{CNO}} \simeq 4$ per cent of the mass of $^{56}\text{Ni}$; hence, the mass of $^{58}\text{Ni}$ should be $\lesssim 0.02$ M$_\odot$ for a typical SN Ia with 0.6 M$_\odot$ of $^{56}\text{Ni}$.

Given the above, an observational test would be to look for evidence for a core dominated by stable elements. Arguably the most direct measurement of the amount of $^{58}\text{Ni}$ has been carried out from mid-infrared fine-structure lines in SN 2005df (in the nebular phase, when all $^{56}\text{Ni}$ has decayed). (Note that in other analyses often a near-Chandrasekhar explosion is assumed indirectly, for example, in using the W7 model [28].) These yield an estimate of approximately 0.01 M$_\odot$ of nickel, which is much more consistent with a sub-Chandrasekhar model [50] (note that these authors argued that even this small mass was evidence for electron captures, but they did not consider the effect of $^{22}\text{Ne}$). Similarly, the meteoritic abundance of nickel is approximately 5 per cent of that of iron [51], which is more easily understood in sub-Chandrasekhar models (as already noted in earlier studies [1,32]).

By contrast, the presence of an inert, colder core is inferred from flat-topped line profiles [52]. It is unclear, however, whether this cold core reflects a lack of heating, or rather enhanced cooling in an ‘infrared catastrophe’ [53]. Evidence for an inert core also comes from differences...
in line profiles for lower and higher ionization states [54], differences that correlate with other SN Ia properties and are plausible for delayed-detonation, near-Chandrasekhar models [55]. It is not yet known what to expect for sub-Chandrasekhar explosions, but nebular spectroscopy nevertheless seems one of the most promising ways of determining whether SN Ia result from near- or sub-Chandrasekhar-mass objects. Ideally, one would study supernovae that cover not only a range in SN Ia properties but also a range in host metallicity (with which $^{56}$Ni should scale linearly for sub-Chandrasekhar models; for near-Chandrasekhar models, the dependence is more complicated [56]).

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