Type Ia Supernovae: Toward the Standard Model?

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Abstract.
In this short review I suggest that recent developments support the conjecture that Type Ia supernovae (SNe Ia) are the complete disruptions of Chandrasekhar–mass carbon–oxygen white dwarfs in single–degenerate binary systems. The causes of the observational diversity of SNe Ia within the context of this standard model, and the implications of the model for young remnants of SNe Ia, are briefly discussed.

INTRODUCTION

The intense current interest in Type Ia supernovae (SNe Ia) is mainly due to their value as distance indicators for cosmology. At a conference on young supernova remnants, however, we’re more concerned with what SNe Ia eject, and what, if anything, they leave behind. Because what they leave behind depends on where they come from, we’re also concerned with the nature of the progenitors of SNe Ia. Those who are interested in SNe Ia as distance indicators are concerned with these issues too.

We have a pretty good idea of what a typical SN Ia ejects. The composition structure of the venerable carbon–deflagration model W7 [1] has passed the test of time as a first approximation to what is ejected: a Chandrasekhar mass, half in the form of low–velocity iron–peak isotopes (initially mostly radioactive $^{56}$Ni); some high–velocity unburned carbon and oxygen; and plenty of intermediate–mass elements such as silicon, sulfur, and calcium in between, around 10,000 km s$^{-1}$. This model, and others that are not too unlike it, give a good account of the spectra of typical SNe Ia [2].

W7 is a specific example of what can be considered to be the standard model for SNe Ia: Chandrasekhar mass ejection following the ignition of carbon at or near the center of a carbon–oxygen (C–O) white dwarf that has been accreting matter from a nondegenerate companion star. In this “single–degenerate” (SD) scenario the donor star survives the explosion of the white dwarf. The Tokyo supernova group has been advocating the standard model for years (see [3] for their most recent review), and recently some others have been moving, more cautiously, toward the
same conclusion (see, e.g., [4] for another recent review). I would like to climb onto this bandwagon because recent developments make it seem to be headed in the right direction. In this short review the emphasis will be on these recent developments; most of the references will be to papers that have been written within the last few years.

OPTIONS

Sub–Chandrasekhar Helium Ignitors

During the 1990s there has been some interest in sub–Chandrasekhar off–center helium–ignitor models, in which the first nuclear ignition occurs at or near the bottom of an accumulated helium layer surrounding a C–O core. Those who have calculated the spectra and light curves of such models have found that they do not match the observations as well as carbon–ignitor models do [5,6,7]. It is unlikely that SNe Ia come from helium–ignitors. If the models change sufficiently, this conclusion can be reexamined.

Double Degenerates

In the “double–degenerate” (DD) scenario, two white dwarfs merge following orbital decay caused by gravitational wave radiation. The mass ejection can be super–Chandrasekhar (up to double–Chandrasekhar, in principle), and no donor star is left behind. The DD scenario has been taken seriously, not so much because of strong evidence in its favor, but because of perceived deficiencies in the rival SD scenario. The main worry about the SD scenario has been that because there are so many ways for the accreting white dwarf to lose mass (e.g., nova explosions, common envelope formation), it may be difficult or impossible for it to reach the Chandrasekhar mass. The DD scenario provides a natural way to assemble a super–Chandrasekhar mass. Another possible problem with the SD scenario is that some circumstellar matter is expected to be present, while no convincing observational evidence for circumstellar matter associated with any SN Ia has been found. Circumstellar matter is not expected in the DD scenario. On the other hand, the main worry about the DD scenario has been that most of those who have tackled the difficult problem of modeling a white–dwarf merger have ended up being pessimistic about getting a SN Ia out of it, rather than a collapse to a neutron star. The problem is that nuclear burning begins in the outer layers and propagates inward, converting the C–O composition to an O–Ne–Mg mixture that eventually must collapse [8,9]. Another worry about the DD scenario is that it may be unable to account for the rate at which SN Ia are observed to occur [10].

One particular SN Ia for which a super–Chandrasekhar mass ejection has been suspected is the well observed, peculiar SN 1991T. Its light curve was broader than
the light curves of most SNe Ia, and until the time of maximum brightness its
spectra showed strong lines of Fe III instead of the usual lower–excitation lines of
Si II, S II, Ca II, and O I. Both of these properties suggest an unusually large
ejected mass of $^{56}\text{Ni}$. If the distance to NGC 4527, the parent galaxy of SN 1991T,
is 16.4 Mpc — the distance found from Cepheids for NGC 4536 [11] and NGC 4496A
[12] which have been thought to be co–members with NGC 4527 of a small group
of galaxies on the near side of the Virgo cluster — then SN 1991T appears to
have been too luminous for a Chandrasekhar–mass explosion, so it must have come
from a DD progenitor [13]. But on the basis of a simple model of the light echo
of SN 1991T from interstellar dust in NGC 4527, the maximum distance has been
estimated to be 15 Mpc [14], and recent studies of Cepheids in NGC 4527 have given
$14.1 \pm 0.8 \pm 0.8$ Mpc [15] and $13.0 \pm 0.5 \pm 1.2$ Mpc [16]. (An even shorter distance
of $11.3 \pm 0.4$ Mpc has been obtained from an application of the surface–brightness–
fluctuations technique to NGC 4527 [17].) It now appears that as expected from
its spectrum and light curve, SN 1991T was somewhat overluminous for a SN Ia,
but not so luminous that super–Chandrasekhar mass ejection and a DD progenitor
are required.

It has been inferred from the spectra of SN 1991T that unburned carbon and
freshly synthesized nickel coexisted in velocity space [13], which is not the case in
any published one–dimensional hydrodynamical model for SNe Ia. This character–
istic of SN 1991T, although not directly indicating a DD progenitor, has seemed
to provide further evidence that SN 1991T was different in some distinct way from
normal SNe Ia. Recently, however, the first successful three–dimensional numeri–
cal simulation of a deflagration explosion of a (non–rotating) Chandrasekhar–mass
white dwarf has been carried out [18], and in the resulting model, unburned car–on and freshly synthesized nickel do coexist in velocity space. It will be very
interesting to see whether careful analysis of the spectra of normal SNe Ia reveals
signs (more subtle than in SN 1991T) that the coexistence of carbon and nickel in
velocity space is a general characteristic of SNe Ia.

An important observational development has been the discovery of events such as
SN 1999aa that have normal spectral features near the time of maximum brightness,
but spectra that are intermediate between those of SN 1991T (strong Fe III) and
normal SNe Ia (strong Ca II) a week before maximum [19]. This seems to me
[20] (but see [19]) to make SN 1991T less likely to be physically distinct from
spectroscopically normal SNe Ia.

All of the above results make SN 1991T begin to look more like an event near
one end of a continuum rather than like a physically distinct phenomenon. This is
important, because if the DD scenario is not needed for SN 1991T, then we are left
with little or no evidence that it is needed at all. From time to time other arguments
for a range in the ejected mass of SNe Ia have been advanced (e.g., [21,22]); in
particular it has often been suggested that subluminous SNe Ia like SN 1991bg
eject less than a Chandrasekhar mass, but even for such extremely peculiar events
the arguments for a non–Chandrasekhar mass are not compelling [23]. Given the
absence of positive evidence for DD progenitors, the lack of persuasive evidence for
a range in ejected masses among SNe Ia, and recent developments indicating that the SD scenario is likely to be able to produce SNe Ia (see below), it is tempting to think that those who have concluded that DD mergers make neutron stars rather than SNe Ia may have been correct. (The recent suggestion that a merger makes a neutron star and a SN Ia [24] does not seem promising because in most cases the ejected mass would be too much less than a Chandrasekhar mass.) Of course, if a single SN Ia proves to be too luminous for Chandrasekhar mass ejection (for some candidates see [15]), this conclusion will need to be revised.

**SINGLE DEGENERATES**

A very attractive feature of the SD scenario is that if the accreting white dwarf does manage to approach the Chandrasekhar mass, it is more likely than a merging pair of white dwarfs to actually explode, because unlike in the DD case burning will begin in the dense inner layers and propagate outward. On the issue of whether the white dwarf can get to the Chandrasekhar mass, there have been important recent developments. It has been argued [25] that at the fairly high desired accretion rates ($10^{-7}$ to $10^{-6} \, M_\odot \, y^{-1}$) the white dwarf develops a strong fast ($\lesssim 1000 \, \text{km} \, \text{s}^{-1}$) wind that stabilizes the mass-transfer process and enables common-envelope evolution and ruinous mass loss from the system to be avoided. Both main-sequence donors and red-giant donors of appropriate masses and initial separations from the white dwarf now appear to be able to drive it to the Chandrasekhar mass [26,27,28]. According to recent more detailed and selfconsistent calculations, which take into account the evolution of the structure of the main sequence donor, the mass transfer rate, and the orbit, it turns out that even with less optimistic assumptions about the role of the fast wind it is possible for the white dwarf to reach the Chandrasekhar mass for a variety of initial parameters [29]. For some systems it is not even a very close call, i.e., if the white dwarf did not explode at 1.4 $M_\odot$ it could reach as much as 2 $M_\odot$. Given these recent results, the tables seem to have been turned: it now appears that SD systems with main sequence donors should not fail to produce Chandrasekhar–mass SNe Ia. (And because the accretion rate does not remain low enough long enough to build up a dangerously massive helium layer, SD systems with main–sequence donors do not produce sub–Chandrasekhar helium–ignitors.)

Observational support for the SD scenario with main–sequence donors is provided by the existence of supersoft x–ray sources [30,31] and recurrent novae [32,33] in which a massive white dwarf is accreting at a suitably high rate and appears to be on its way to the Chandrasekhar mass.

SD systems with main sequence donors cannot produce SNe Ia in stellar populations much older than a Gyr. It will be interesting to see the approach of [29] applied to SD systems with red giant donors, which are needed in the standard model to produce the SNe Ia that are observed to occur in older populations.

As for the doubt about the SD scenario because of the lack of evidence for circumstellar matter — the existing upper limits on the amount of circumstellar mat-
ter from optical, radio, and x-ray observations are interesting but not sufficiently stringent to rule out the SD scenario [34,35]. I’m not aware of any important observational developments on this issue during the last few years. The detection of circumstellar matter associated with SNe Ia should be a high priority for observers, but if there is a fast wind from the white dwarf, the circumstellar density will be lower than expected previously, and detection may be very difficult.

**DIVERSITY**

If we suppose that the standard model is correct for all SNe Ia, so the ejected mass is always 1.4 M$_\odot$, then what causes the observational diversity? The primary physical variable almost certainly is M$_{\text{Ni}}$, the ejected mass of $^{56}$Ni. The higher the value of M$_{\text{Ni}}$, the higher the peak luminosity; also, because radioactivity is responsible for heating the ejecta, the higher the temperature and the opacity [36] and the broader the light curve [37,38]. Thus it is likely that the observed correlation between light-curve width and peak luminosity is mainly due to a range in M$_{\text{Ni}}$. The temperature also determines which features appear in the early-time spectra [6,39,40]. If M$_{\text{Ni}}$ is sufficiently high ($\gtrsim 0.8$ M$_\odot$?) then Fe III lines, instead of the usual lower-excitation lines, become prominent. If M$_{\text{Ni}}$ is sufficiently low ($\lesssim 0.4$ M$_\odot$?), Ti II lines accompany the usual lines (and because a strong Ti II absorption blend falls right in the middle of the $B$ band, the $B-V$ color becomes quite red).

What causes the range in M$_{\text{Ni}}$? Perhaps the most likely cause is a range in the carbon-to-oxygen ratios of the white dwarfs, since fusing carbon releases more energy than fusing oxygen. The C/O ratio is expected to be determined primarily by the main-sequence mass and the metallicity of the progenitor of the white dwarf [41]. In the three-dimensional modeling cited above [18], the amount of nuclear burning does appear to depend strongly on the C/O ratio.

Not all of the observational diversity can be attributed to M$_{\text{Ni}}$. Photometrically, it appears that a two-parameter empirical correction (using both the light-curve decline parameter, $\Delta m_{15}$, and the maximum-light color, $B-V$) is both necessary and (so far) sufficient to standardize the SN Ia peak luminosities [42,43]. Spectroscopically, a clear indication that SNe Ia cannot be fully described by a one-parameter sequence is that some events such as SN 1984A have only the usual spectral features but they are unusually broad and blueshifted, indicating that the ejecta are not unusually hot as in the case of SN 1991T but that an unusually large amount of mass has been ejected at high velocity ($\sim 20,000$ km s$^{-1}$) [44,45]. This may mean that most SNe Ia are pure subsonic deflagrations while the high-velocity events like SN 1984A are delayed detonations, in which the deflagration makes a transition to a supersonic detonation with the result that the density of the high-velocity layers is much higher than in a pure deflagration. (For a recent review of the propagation of nuclear burning fronts in SNe Ia, see [46].) Why two SNe Ia that produce similar amounts of M$_{\text{Ni}}$ would have different modes of burning propagation remains to be
understood; or perhaps not understood — it could be just a matter of chance [47]. (The observed correlation between SN Ia properties and the characteristics of the stellar population at the SN site [47,48] at least proves that the outcome is not entirely unrelated to the initial conditions.)

To summarize, it seems likely that within the SD scenario the observational diversity can be attributed mainly to differences in $M_{\text{Ni}}$, and secondarily to differences in the amount of mass ejected at high velocity (whether both deflagrations and delayed detonations are actually involved or not). There are plenty of other things that might contribute to the diversity, probably to a lesser extent: local composition asymmetries in the ejecta of deflagrations (e.g., clumps of iron–peak elements surrounded by intermediate–mass elements, embedded in unburned C–O [18]); global shape asymmetries of the ejecta in delayed detonations caused by the transition taking place at a point (or points) rather than simultaneously everywhere on a spherical shell [50]; a range of metallicities of the white dwarf [51,52]; the orientation of the donor star with respect to the line of sight of the observer [53]; effects associated with differences in the white–dwarf rotation speeds which, owing to angular momentum acquired during the accretion process, are expected to range up to a significant fraction of the break–up speed [29]; and global shape asymmetries caused by a strong magnetic field of the progenitor white dwarf [54].

**IMPLICATIONS FOR YOUNG SUPERNova REMNANTS**

According to the standard model SN Ia ejecta should consist of 1.4 $M_\odot$ of heavy elements from the white dwarf, accompanied by some hydrogen–rich mass knocked off the donor star: about 0.15 $M_\odot$ from a main–sequence star and about 0.5 $M_\odot$ from a red giant [53]. Most of this mass should be deep inside the supernova ejecta, expanding at low velocity, less than 1000 km s$^{-1}$ [53,55]. The surviving donor star probably has peculiar surface abundance ratios: no lithium, beryllium, or boron; enhanced carbon; and perhaps enhanced iron–group elements caused by fallback of some of the lowest–velocity supernova ejecta [29,53]. A main sequence donor will have a space velocity (determined primarily by its pre–explosion orbital velocity) of more than about 450 km s$^{-1}$ [56] and, having been pretty badly shaken up by its encounter with the supernova ejecta, it will be quite overluminous, as high as 5000 L$_\odot$ [53,56] before its swollen envelope relaxes back into equilibrium on a thermal timescale. A red giant donor will be moving faster than about 100 km s$^{-1}$ [56], and because it will have been stripped of most but not quite all of its envelope it will continue to look like a red giant throughout the SNR phase [53]. Both kinds of donor stars will remain inside their associated SNRs during the lifetime of the remnants.

Were any of the historical Galactic supernovae produced by SNe Ia? SNe 1006 and 1572 (Tycho’s supernova) are often cited as possibilities, but the arguments are not completely convincing. The heliacal risings and settings of SN 1006 have been
used to make a much improved estimate of its peak apparent magnitude, which leads to a peak absolute visual magnitude, \( M_V \), in the range \(-15.9\) to \(-17.4 \) \([57]\). Normal SNe Ia have \( M_V \approx -19.4 \), so if SN 1006 was a SN Ia it would seem to have been a peculiar one. If the luminosity was low then \( M_{Ni} \) also was low, and not much iron (\(< 0.1 M_\odot\)) should be found in the remnant. (This is true whether SN 1006 was a peculiar weak SN Ia, a SN Ib/c, or some other kind of peculiar event.) If SN 1572 was a SN Ia then it may also have been a peculiar one, because its light curve appears to have been very fast for a SN Ia and its peak absolute visual magnitude has been estimated to be \(-18.64 \pm 0.31 \) \([57]\), a bit subluminous for a SN Ia and implying a reduced iron content in the Tycho remnant, too. The discovery in SN 1006 or 1572 of a star having the expected properties of a SN Ia donor would be exciting because it would confirm both that the event really was a SN Ia and that it was produced by a SD progenitor system; on the other hand, establishing the absence of a donor star would not rule out the SD scenario if we’re not completely sure that these events were SNe Ia. To the extent that the Balmer-dominated remnants in the LMC are thought to have been SNe Ia because they resemble the remnants of SNe 1006 and 1572, then the case that the LMC events were SNe Ia may also not be compelling.

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