SUB-CHANDRASEKHAR WHITE DWARF MERGERS AS THE PROGENITORS OF TYPE Ia SUPERNOVAE

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ABSTRACT

Type Ia supernovae (SNe Ia) are generally thought to be due to the thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs) with masses near the Chandrasekhar mass. This scenario, however, has two long-standing problems. First, the explosions do not naturally produce the correct mix of elements, but have to be finely tuned to proceed from subsonic deflagration to supersonic detonation. Second, population models and observations give formation rates of near-Chandrasekhar WDs that are far too small. Here, we suggest that SNe Ia instead result from mergers of roughly equal-mass CO WDs, including those that produce sub-Chandrasekhar mass remnants. Numerical studies of such mergers have shown that the remnants consist of rapidly rotating cores that contain most of the mass and are hottest in the center, surrounded by dense, small disks. We argue that the disks accrete quickly, and that the resulting compressional heating likely leads to central carbon ignition. This ignition occurs at densities for which pure detonations lead to events similar to SNe Ia. With this merger scenario, we can understand the type Ia rates and have plausible reasons for the observed range in luminosity and for the bias of more luminous supernovae toward younger populations. We speculate that explosions of WDs slowly brought to the Chandrasekhar limit—which should also occur—are responsible for some of the "atypical" SNe Ia.

Key words: binaries: close – supernovae: general – white dwarfs

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1. INTRODUCTION

Type Ia supernovae (SNe Ia) result from thermonuclear explosions of carbon–oxygen white dwarfs (CO WDs). They are generally thought to be triggered when the WD approaches (for accretion) or exceeds (for a merger) the Chandrasekhar mass, and the density and temperature become high enough to start runaway carbon fusion. This scenario, however, neither naturally leads to explosions that reproduce the observed light curves and remnants nor easily accounts for the variation in SN Ia properties and their dependence on host galaxy. Furthermore, the predicted formation rates are lower than observed.

The above leads us to reconsider the assumptions underlying the standard picture. After reviewing the salient properties of SN Ia (Section 2), we first argue that their rates are easiest to understand if most mergers of CO WDs lead to SN Ia, independent of whether or not the total mass exceeds the Chandrasekhar mass. After a brief discussion of previous sub-Chandrasekhar models (Section 4), we next argue that ignition following mergers is likely (Section 5). We close with some ramifications (Section 6).

2. PROPERTIES OF INDIVIDUAL SNe Ia AND THEIR REMNANTS

The light curves of most SNe Ia are remarkably similar and can be described empirically as a (nearly) single-parameter family, in which timescale and maximum luminosity are tightly correlated, with longer-lasting explosions being more luminous and energetic (Phillips 1993). Underlying this variation is the amount of radioactive ^{56}Ni. From SN Ia spectra, Mazzali et al. (2007) find that this ranges from $\sim$0.1 to 0.9 $M_\odot$. They also infer $\sim$0.1 $M_\odot$ of stable iron-peak elements and an amount of intermediate-mass elements that is such that the total mass of nuclear processed material is roughly constant, just over 1 $M_\odot$. Stritzinger et al. (2006) use peak luminosities to infer similar ^{56}Ni masses, but their total masses, inferred from the times that the ejecta become optically thin, do not cluster, but range from 0.5 to 1.3 $M_\odot$.

From SN Ia spectra, it is also clear that the ejecta are stratified, with iron-peak elements formed deeper inside (Mazzali et al. 2007) and (small amounts of) unprocessed carbon on the outside (Thomas et al. 2007). Hydrogen is absent (Leonard 2007), inconsistent with expectations for a hydrogen-rich progenitor companion with a strong wind or easily entrained envelope.

Studies of SN Ia remnants paint a similar picture. For instance, Badenes et al. (2006) find that for Tycho, models with about twice as much iron peak as intermediate-mass elements best reproduce the X-ray spectrum, consistent with SN 1572A having been a "standard" SN Ia (confirmed beautifully using light echoes; Krause et al. 2008). From the ionization structure, Badenes et al. (2006) infer stratified ejecta, strongly suggesting that the explosion was (partly) supersonic. Comparing the predicted remnant flux, Chandrasekhar-mass models are too luminous. Badenes et al. (2006) attribute this to a breakdown in their one-dimensional remnant models, but it could also indicate a lower mass. A separate clue is that most remnants appear to be evolving into a constant-density medium, with properties like those of the warm interstellar phase and unlike those expected for progenitors with strong, fast winds (Badenes et al. 2007).

The rates and properties of SN Ia depend on environment, with star-forming galaxies having higher rates of, on average, brighter SN Ia than passively evolving galaxies (e.g., Hamuy et al. 1995; Mannucci et al. 2005; Sullivan et al. 2010). The rate has been suggested to depend on both the mass and star

formation rate (Mannucci et al. 2005), or to simply be a roughly constant fraction, of ∼1%, of the instantaneous WD formation rate (Pritchet et al. 2008; but see Maoz et al. 2010a, whose data suggest a break beyond ∼2 Gyr (their Figure 5)). Consistent with the latter, Raskin et al. (2009) found that SNe Ia are delayed by ∼200–500 Myr from the onset of star formation (as inferred from local environments). Integrated over a Hubble time, ∼0.0023 ± 0.0006 SNe Ia seem to occur for every solar mass formed (Mannucci et al. 2005; Maoz et al. 2010a), with even higher numbers, of $\gtrsim 0.0034$ inferred from galaxy cluster iron abundances (Maoz et al. 2010b).

In summary, the light curves, spectra, and remnants of SNe Ia seem to require center-lit explosions of CO WDs, with masses of $\gtrsim 1 \, M_\odot$. Their progenitor systems likely did not host companions with strong hydrogen-rich winds or loosely bound envelopes. The rate of SN Ia appears to be ∼1% of the WD formation rate, and younger systems produce more luminous explosions.

3. EXPECTED SN Ia RATES

The number of SN Ia per solar mass formed, ∼0.0023, is higher than expected for Chandrasekhar-mass systems, both from counts of suitable intermediate-mass progenitors (e.g., Maoz 2008) and from population synthesis calculations (for recent work, see, e.g., Ruiter et al. 2009; Mennekens et al. 2010). The details are complex and metallicity dependent, but below we elucidate the issues with rates estimated from basic principles (for a more formal analysis, see Greggio 2005).

For the primary in an interacting binary to leave a CO WD, it must be massive enough not to leave a He WD, but not so massive that it forms an ONe WD or neutron star. Using Figures 1 and 2 of Webbink (2008), we estimate a mass range $1.8 \, M_\odot \lesssim M_1 \lesssim 7 \, M_\odot$ (the lower limit exceeds that for single stars because the star needs to ignite helium after its interaction). A Chabrier (2005) initial mass function produces $n_{1.8<M_1<7} = 0.067$ such stars per solar mass formed. To produce a CO WD of $\gtrsim 0.7 \, M_\odot$ (half the Chandrasekhar mass), a $\gtrsim 3.5 \, M_\odot$ primary is required, of which only $n_{3.5<M_1<7} = 0.020$ are formed. For these suitably massive stars, a fraction $f_{\rm bin} \simeq \frac{2}{3}$ is in binaries, and, of those, a fraction $f_{10<P<2000} \simeq 0.2$ have periods between 10 and 2000 days (Duquennoy & Mayor 1991), such that they interact ($P \lesssim 2000$ days), but only after the main sequence, with a fully formed helium core ($P \gtrsim 10$ days).

The further evolution depends on whether mass transfer is stable or not. If it is unstable, common-envelope evolution will drastically shrink the orbit, leading to possible further evolution via the single-degenerate channel (Whelan & Iben 1973). If it is stable, the system remains wide and further evolution leads to a second CO WD as well as a second, unstable mass-transfer phase that shrinks the orbit, as required for the double-degenerate scenario (Webbink 1984; Iben & Tutukov 1984).

For the giants considered here, mass transfer to a less massive companion is generally expected to be dynamically unstable (e.g., Webbink 2008). So one naïvely expects a small fraction $f_{\rm wide}$ left in wide orbits and a near-unity fraction $f_{\rm close}$ left in close orbits. Empirically, however, the first mass-transfer phase sometimes leaves wide orbits (Nelemans et al. 2000; for a discussion, see Webbink 2008), presumably for nearly equal-mass binaries (which may be relatively common; Pinsonneault & Stanek 2006). Indeed, the existence of fair numbers of both double-degenerate binaries and cataclysmic variables suggests

neither fraction is small. Below, we assume $f_{\rm wide} \simeq \frac{1}{3}$ and $f_{\rm close} \simeq \frac{2}{3}$; likely, neither is off by more than 50%.

3.1. Single Degenerates

In principle, the number of CO WDs formed in close orbits with non-degenerate companions, $n_{1.8<M_1<7} f_{\rm bin} f_{10<P<2000} f_{\rm close} \simeq 0.006$ per solar mass, could reproduce the SN Ia rate, and many routes to explosions have been proposed (Iben & Tutukov 1984). No route, however, seems both common and efficient in growing the WD to the Chandrasekhar mass. If mass transfer is too slow, novae occur, which appear to remove as much mass as was accreted (Townsley & Bildsten 2004; possible counterexamples are RS Oph and U Sco). If it is faster, hydrogen burns stably, but only a small range avoids expansion and mass loss (Nomoto et al. 2007).

Empirically, the only efficient systems appear to be the supersoft sources (Rappaport et al. 1994), but those are far too rare (Di Stefano 2010; Gilfanov & Bogdán 2010). We may be missing systems, e.g., rapidly accreting WDs that expanded and hid from X-ray view. However, for such sources—as for many single-degenerate channels—the absence of evidence for hydrogen and wind-blown bubbles is surprising. The lack of convincing solutions to these issues motivates us to look for alternative progenitors.

3.2. Double Degenerates

Given the near-unity mass ratio required to keep a wide orbit in the first mass-transfer phase, the two CO WDs are expected to have similar masses. To estimate the number of double degenerates with total mass exceeding the Chandrasekhar mass, we thus use the number of binaries with sufficiently massive primaries, $n_{3.5<M_1<7} f_{\rm bin} f_{10<P<2000} f_{\rm wide} \simeq 0.0009$ per solar mass formed. This is less than half the required number, which poses a significant problem, especially as some systems will be too wide to merge in a Hubble time.

Indeed, this realization prompted our consideration of sub-Chandrasekhar merger models: if all mergers of CO WDs would lead to SN Ia, one has $n_{1.8<M_1<7} f_{\rm bin} f_{10<P<2000} f_{\rm wide} \simeq 0.003$ possible progenitors, which is consistent with the observations.

Furthermore, sub-Chandrasekhar mergers could explain the observed delay-time distribution. Generally, distributions of formation times are shallower, $\propto t^{-0.5}$ (Pritchet et al. 2008), than those of merger times, $\propto t^{-1}$ (e.g., Greggio 2005). Thus, one expects the SN Ia rate to scale with the WD formation rate. Quantitatively, the scale factor is ∼0.01 (Pritchet et al. 2008), while the fraction of WDs formed in double degenerates is about $f_{\rm bin} f_{10<P<2000} f_{\rm wide} \simeq 0.04$. Thus, ∼25% of the double degenerates should merge fast compared to the progenitor lifetime. But the scaling with WD formation rate will hold only for a duration roughly equal to the lifetime of the lowest-mass progenitor. For $\gtrsim 3.5 \, M_\odot$ progenitors, this will be ∼200 Myr, much shorter than observed, but for $\gtrsim 1.8 \, M_\odot$ stars, it is ∼1.7 Gyr, consistent with the observations.

4. PREVIOUS SUB-CHANDRASEKHAR MODELS

We are not the first to consider sub-Chandrasekhar models for SN Ia. Woosley & Weaver (1994) suggested that single-degenerate sub-Chandrasekhar mass explosions might be triggered by detonations of overlying He layers. However, those lead to stratifications inconsistent with the observations (see Section 2).

In contrast, Sim et al. (2010) studied central detonations of sub-Chandrasekhar WDs (ignoring the ignition mechanism, which we address in Section 5). They found light curves and spectra similar to SN Ia and showed that for more massive WDs, more iron-peak elements were created, with $M_{Ni} \simeq \{0.06, 0.32, 0.58, 0.85\} M_{\odot}$ for $M_{WD} = \{0.88, 0.97, 1.06, 1.15\} M_{\odot}$.

That mass dependence arises because iron-peak elements are produced only in regions that reach $\sim 4 \times 10^9$ K before degeneracy is lifted, which requires a density $\rho \gtrsim 10^7$ g cm^{-3} (to produce intermediate-mass elements requires $\rho \gtrsim 2 \times 10^6$ g cm^{-3}). For the same reason, detonations of near-Chandrasekhar WDs produce too much nickel: almost the whole WD is above the critical density. This conundrum can only be solved by an initial deflagration phase, which allows the WD to expand (Khokhlov 1991). For lower mass WDs, this is not necessary.

5. IGNITION

We argued that the SN Ia rate and delay-time distribution could be understood if mergers of CO WDs lead to SN Ia even for sub-Chandrasekhar total mass. If mergers lead to explosions similar to the detonations of sub-Chandrasekhar WDs, they will appear like SN Ia (Sim et al. 2010). Assuming more massive mergers also produce more ^{56}Ni, the range in luminosity and duration follows naturally, as does the correlation with parent population age.

The critical remaining question is whether merger products become sufficiently hot to ignite. This has been addressed partly by recent simulations, which include careful treatment of the equation of state and of nuclear burning (Yoon et al. 2007; Lorén-Aguilar et al. 2009; Pakmor et al. 2010). These show qualitative differences between mergers of unequal and equal-mass binaries.[5] If one WD is significantly lighter (and thus larger), mass transfer leads to its total disruption, with the material wrapped around the more massive companion; the merger product has a core that is cooler and rotates more slowly than the envelope. Any nuclear processing happened at the core–envelope interface, as likely would any subsequent ignition (Nomoto & Iben 1985; Yoon et al. 2007). Thus, we do not think such mergers lead to SN Ia.

If instead the two WDs have more equal masses, as expected for CO+CO binaries (Section 3.2), the merger remnant is fully mixed and hottest in the center. Initially, it rotates differentially, but this is dissipated, and one is left with a core holding $\sim 80\%$ of the mass and rotating at a uniform rate near the mass-shedding limit, surrounded by a somewhat sub-Keplerian, very dense, partially degeneracy-pressure-supported "disk" with a steep surface density gradient ($\Sigma \propto r^{-5}$).

In the simulations of Lorén-Aguilar et al. (2009) and Pakmor et al. (2010), the mergers of equal-mass WDs do not become hot enough to ignite carbon burning, except for masses above $\sim 0.9 M_{\odot}$. The explosion of the resulting $\gtrsim 1.8 M_{\odot}$ remnant, however, leads to a subluminous SN Ia. This is not surprising: generally, merger remnants have central densities similar to those of the (more massive of the) pre-merger WDs. For a $0.9 M_{\odot}$ WD, the central density is $\sim 1.5 \times 10^7$ g cm^{-3}, and thus little ^{56}Ni will be produced (see Section 4), leading to a subluminous explosion.[6]

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[5] What constitutes "equal" is not yet known, though 0.8 and 0.6 $M_{\odot}$ is not. For reference, in the range 0.6–0.9 $M_{\odot}$, to have central densities within a factor of two requires $\Delta M \lesssim 0.13 M_{\odot}$.

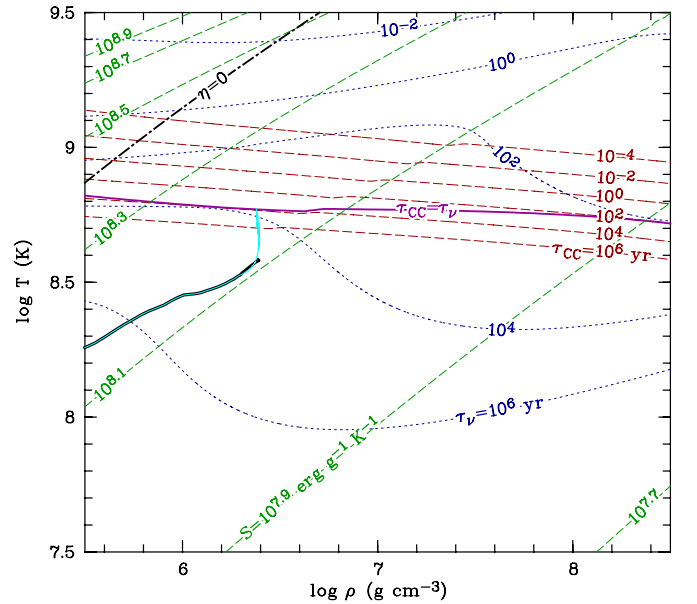[6] The rare mergers of even more massive WDs should lead to more luminous explosions.

Figure 1. Temperature–density profile of the remnant of a merger of two $0.6 M_{\odot}$ CO WDs. The thin cyan curve shows the profile from the simulations of Lorén-Aguilar et al. (2009), and the thick black curve the one that results from mixing the central convectively unstable region. After its formation, the remnant will accrete and become denser and hotter, evolving at constant entropy (green dashed, diagonal contours) as long as the accretion timescale is shorter than $\tau_{\nu} = C_V T / \varepsilon_{\nu}$ and $\tau_{CC} = C_V T / \varepsilon_{CC}$, the timescales on which neutrinos can cool and carbon fusion can heat the core (blue dotted and red dashed contours, respectively). The magenta solid curve shows where ignition occurs ($\tau_{\nu} = \tau_{CC}$) and the thick black dot-dashed one where degeneracy is lifted (normalized electron chemical potential $\eta = 0$). (The entropies S, specific heats C_V, and gain/loss rates ε were calculated using routines from the stellar evolution code MESA (http://mesa.sourceforge.net); Paxton et al. 2010; uncertainties in ε_{CC}, while large, do not influence our conclusions.)

(A color version of this figure is available in the online journal.)

We now turn to the simulation of the merger of two $0.6 M_{\odot}$ WDs of Lorén-Aguilar et al. (2009). This mass is close to the empirical mean mass of WDs ($\sim 0.65 M_{\odot}$; Tremblay & Bergeron 2009), and thus, in our picture, the merger should lead to a typical SN Ia. From the simulation, the remnant's central density and temperature are $\sim 2.5 \times 10^6$ g cm^{-3} and $\sim 6 \times 10^8$ K, respectively. This would appear to be close to what is required for ignition, but since the central $\sim 0.07 M_{\odot}$ is convectively unstable (Figure 1), the temperature will be reduced rapidly, on a convective turnover time. The region's average entropy, $s/k \simeq 16$ per ion and ~ 1.3 per electron, corresponds to a core temperature of $\sim 3.8 \times 10^8$ K.

While this merger remnant is too cold (and insufficiently dense) to produce an SN Ia, it could explode later. One possible heating mechanism is the accretion of the thick disk, which will lead to an increase in density and thus to compressional heating. Assuming the source remains at the mass-shedding limit and in roughly solid-body rotation (e.g., due to magnetic fields; Section 5.1 below), the density will increase to $\sim 3 \times 10^7$ g cm^{-3} (for a cold WD; Geroyannis & Hadjopoulos 1989). If the contraction is fast enough to be (nearly) adiabatic, the central temperature would increase to $\sim 1.4 \times 10^9$ K (Figure 1), easily hot enough to ignite.

The timescale for compressional heating is $\tau_H = (M_{core}/M_{disk})\tau_{acc}$, where $M_{core}/M_{disk} \simeq 5$ is the core-to-disk mass ratio, and τ_{acc} is the disk accretion timescale, which we

estimate using the usual α formalism,

$$\tau_{\rm acc} = \frac{M_{\rm disk}}{\dot{M}} = \alpha^{-1} \left(\frac{r_{\rm disk}}{h}\right)^2 \tau_{\rm dyn}$$

$$\simeq 2h \left(\frac{\alpha}{0.01}\right)^{-1} \left(\frac{r_{\rm disk}/h}{4}\right)^2 \left(\frac{\Omega}{0.2\,{\rm s}^{-1}}\right)^{-1}. \quad (1)$$

Here, $\dot{M}$ is the accretion rate, and $r_{\rm disk} \simeq 0.02\,R_\odot$, $h \simeq 0.0055\,R_\odot$, and $\tau_{\rm dyn} = \Omega^{-1} \simeq 5\,{\rm s}$ are the disk radius, scale height, and dynamical time (with numerical values from Lorén-Aguilar et al. 2009; note that their Table 1 lists outer disk radii; their Figure 3 shows that most mass is at much smaller radius).

Thus, we find that the remnant is heated on a timescale $\tau_{\rm H} \simeq 5\tau_{\rm acc} \simeq 10\,{\rm hr}$, which is much shorter than the neutrino cooling and carbon burning timescales even at the ignition line (where both are $\sim 3 \times 10^3$ yr, see Figure 1). Therefore, neutrino cooling can be ignored, and compressional heating will continue until the disk is exhausted or the fusion timescale has become shorter than the accretion timescale. From Figure 1, the latter happens when $\rho \simeq 1.6 \times 10^7\,{\rm g\,cm}^{-3}$ and $T \simeq 10^9$ K, which is slightly before disk exhaustion (at $\rho \simeq 3 \times 10^7\,{\rm g\,cm}^{-3}$; see above). At this point, a nuclear runaway is inevitable.

5.1. Complications

Above, we argued it is plausible that merger remnants will heat up sufficiently to ignite carbon, but we made a number of simplifying assumptions that deserve further study. First, the "alpha" formalism may be inappropriate for estimating the accretion timescale for a small, massive, and thick disk. Instead, the relevant timescale may be the much longer cooling timescale of the envelope (Yoon et al. 2007). If transport of angular momentum is the determining factor, however, our timescale is the correct order-of-magnitude estimate. Second, as the accretion rate is highly super-Eddington, a (strong) wind may form, which may diminish or enhance the compression depending on its specific angular momentum. Third, accretion could heat the envelope significantly. For cold WDs, rapid accretion leads to off-center ignition (e.g., Nomoto & Iben 1985), but it likely is less important when the WD core is hot. Fourth, we assumed the remnant core rotates roughly uniformly. This is found in the merger simulations (Lorén-Aguilar et al. 2009, and references therein), but may reflect artificial viscosity associated with smooth particle hydrodynamics. A strongly differentially rotating remnant would be less dense and suffer less from compressional heating.

If differential rotation is present, it also leads to additional effects that we ignored. It drives a number of processes that tend to eliminate it (Piro 2008). In particular, it will wind up magnetic fields until their energy is of order the differential rotation energy, $B \approx (I\Omega\Delta\Omega/R^3)^{1/2}$. With $I\Omega \simeq 10^{50}\,{\rm g\,cm}^2\,{\rm s}^{-1}$ and $R \simeq 0.0125\,R_\odot$, the inferred field ranges from $\sim 10^9$ G if differential rotation is driven by the accretion ($\Delta\Omega \simeq \tau_{\rm H}^{-1} \simeq 10^{-5}\,{\rm s}^{-1}$) to $\sim 10^{11}$ G if it is due to the merger ($\Delta\Omega \simeq \Omega \simeq 10^{-1}\,{\rm s}^{-1}$). Empirical evidence for field generation comes from arguably the best candidate WD merger remnant, RE J0317−853. This WD is massive, $M \simeq 1.35\,M_\odot$,[7] spins rapidly, $P = 725$ s, and has a strong, $B \simeq 340$ MG magnetic field (Barstow et al. 1995). Such strong fields, if they emerge

sufficiently fast, would also spin down the WD through magnetic dipole emission or through coupling with the accretion disk and/or a wind (as may have happened for RE 0317−853). The concomitant loss of rotational support would add to, or might even dominate, the compressional heating due to accretion.

A separate issue is that to produce SN Ia, we require detonations. Spontaneous detonations are very difficult initiate (e.g., Niemeyer & Woosley 1997; Seitenzahl et al. 2009), although our case is helped by having a large super-critical region. Furthermore, at our relatively low central density, burning is in the distributed rather than flamelet regime, which may help a possible deflagration transition to a detonation (Niemeyer & Woosley 1997).

A final complication is the assumed composition. Merger simulations so far have used carbon and oxygen only, but $\sim 1\%$ of the mass will be helium. If this is burned during the merger, about 10^{49} erg would be generated, roughly doubling the thermal energy of the remnant and possibly leading to carbon ignition.

6. CONCLUSIONS

We have argued that SNe Ia result generally from mergers of CO WDs, even those with sub-Chandrasekhar total mass. If true, a number of interesting consequences arise. First, the merging WDs should have total masses between double the lowest and highest possible CO WD masses, i.e., $1\,M_\odot \lesssim M_{\rm tot} \lesssim 2.4\,M_\odot$ (though ignition during the merger may cause a break in properties at $\gtrsim 1.8\,M_\odot$; Pakmor et al. 2010). This range could account for "super-Chandrasekhar" SN Ia (e.g., Howell et al. 2006; Scalzo et al. 2010). As the typical total mass will depend on the population's age, it also explains the empirical age–luminosity relation.

Second, the rate of mergers—and thus of SN Ia—may show a break at ~ 1.7 Gyr (the lifetime of a $\sim 1.8\,M_\odot$ star), likely being more sensitive to the WD formation rate beforehand (Pritchet et al. 2008) and to the merger-time distribution thereafter. Such a break may have been observed (Maoz et al. 2010a; but see Maoz et al. 2010b).

Third, ignition will likely take place in rapidly rotating objects (possibly) surrounded by small disks. This may have interesting consequences for the explosion dynamics (Pfannes et al. 2010), the initial shock breakout (Piro et al. 2010), early-time spectra (Mazzali et al. 2005), and the supernova remnants.

Finally, we speculate that WDs slowly pushed to the Chandrasekhar mass—such as should be produced in single-degenerate systems—are partly responsible for the population of "atypical" SN Ia. Further contributions to that population might come from mergers that ignite during the merger proper and from unequal-mass mergers that ignite off-center and/or explode only partially.

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[7] In the context of our scenario, the existence of this object is puzzling. It may be the result of an unequal-mass merger.

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