A spherical Chandrasekhar-mass delayed-detonation model for a normal Type Ia supernova

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Abstract. The most widely-accepted model for Type Ia supernovae (SNe Ia) is the thermonuclear disruption of a White Dwarf (WD) star in a binary system, although there is ongoing discussion about the combustion mode, the progenitor mass, and the nature of the binary companion. Observational evidence for diversity in the SN Ia population seems to require multiple progenitor channels or explosion mechanisms.

In the standard single-degenerate (SD) scenario, the WD grows in mass through accretion of H-rich or He-rich material from a non-degenerate donor (e.g., a main-sequence star, a subgiant, a He star, or a red giant). When the WD is sufficiently close to the Chandrasekhar limit ($\sim$ 1.4 $M_\odot$), a subsonic deflagration front forms near the WD center which eventually transitions to a supersonic detonation (the so-called "delayed-detonation" model) and unbinds the star. The efficiency of the WD growth in mass remains uncertain, as repeated nova outbursts during the accretion process result in mass ejection from the WD surface. Moreover, the lack of observational signatures of the binary companion has cast some doubts on the SD scenario, and recent hydrodynamical simulations have put forward WD-WD mergers and collisions as viable alternatives. However, as shown here, the standard Chandrasekhar-mass delayed-detonation model remains adequate to explain many normal SNe Ia, in particular those displaying broad Si II 6355 Å lines. We present non-local-thermodynamic-equilibrium time-dependent radiative transfer simulations performed with CMFGEN of a spherically-symmetric delayed-detonation model from a Chandrasekhar-mass WD progenitor with 0.51 $M_\odot$ of ^{56}Ni **(Fig. 1 and Table 1)**, and confront our results to the observed light curves and spectra of the normal Type Ia SN 2002bo over the first 100 days of its evolution. With no fine tuning, the model reproduces well the bolometric **(Fig. 2)** and multi-band light curves, the secondary near-infrared maxima **(Fig. 3)**, and the spectroscopic evolution **(Fig. 4)**, illustrating the small impact of multi-dimensional processes for this event.

Mergers or collisions of WD-WD systems should fare as well in reproducing the observational properties of normal SNe Ia to compete with the standard SD scenario.

Table 1.   Model parameters and nucleosynthetic yields for selected species at $t =$ 0.5 d past explosion. The ^{56}Ni mass is given at $t \approx 0$. The initial mass and central density of the progenitor WD are 1.41 M$_\odot$ and 2.6×10^9 g cm^{-3} for all models.

Model	ρ_{tr} [g cm^{-3}]	E_{kin} [10^{51} erg]	$v(^{56}Ni)$ [km s^{-1}]	$^{56}Ni_{t=0}$ [M$_\odot$]	Fe [M$_\odot$]	Ca [M$_\odot$]	S [M$_\odot$]	Si [M$_\odot$]	Mg [M$_\odot$]	O [M$_\odot$]	C [M$_\odot$]
DDC10	2.3(7)	1.520	1.16(4)	0.623	0.115	4.10(-2)	0.166	0.257	9.95(-3)	0.101	2.16(-3)
DDC15	1.8(7)	1.465	1.12(4)	0.511	0.114	4.53(-2)	0.197	0.306	1.14(-2)	0.105	2.73(-3)
DDC17	1.6(7)	1.459	1.08(4)	0.412	0.112	4.73(-2)	0.222	0.353	1.79(-2)	0.152	3.80(-3)

Note: Numbers in parenthesis correspond to powers of ten. The deflagration velocity is set to 3% of the local sound speed ahead of the flame for all models; ρ_{tr} is the transition density at which the deflagration is artificially turned into a detonation; E_{kin} is the asymptotic kinetic energy. $v(^{56}Ni)$ is the velocity of the ejecta shell that bounds 99% of the total ^{56}Ni mass.
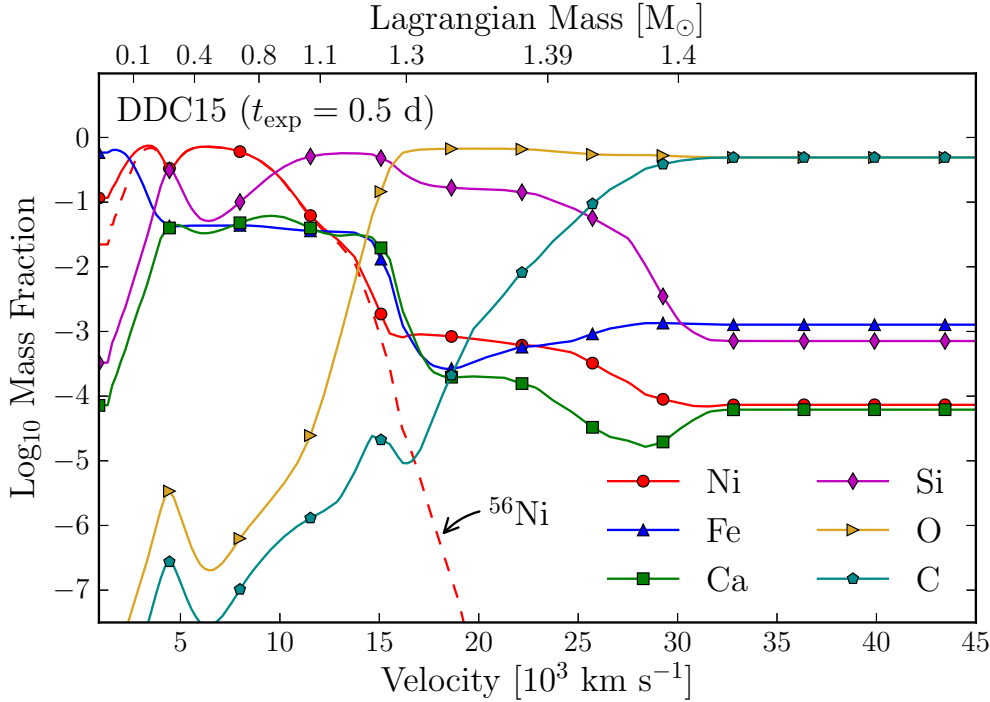

Figure 1.   Abundance profiles in velocity space for selected species in model DDC15 at the start of our radiative-transfer simulations (0.5 d past explosion). The profile for ^{56}Ni at this time is shown as a dashed line. The upper abscissa shows the Lagrangian mass coordinate. **All but the outermost ~0.01 M$_\odot$ of the WD is burned in these 1D delayed-detonation models.**
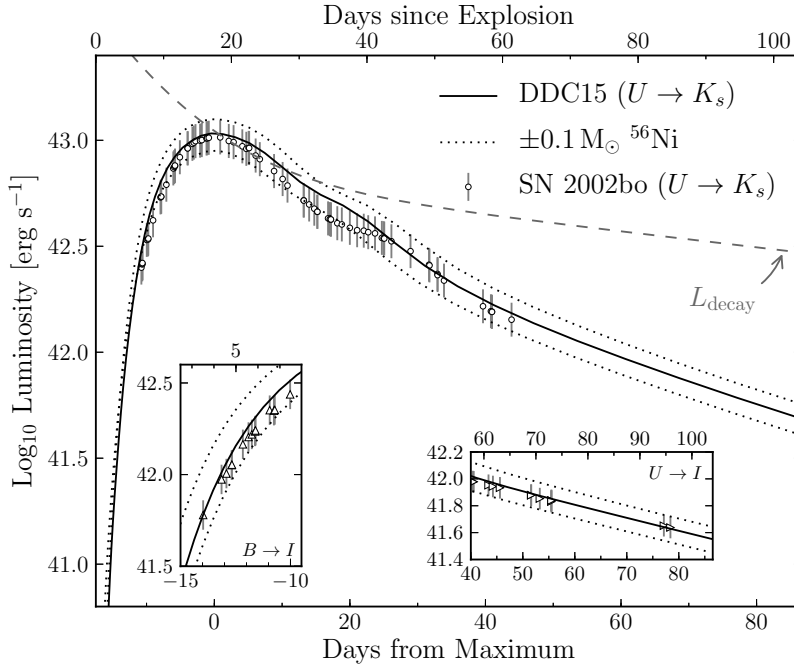
Figure 2. Pseudo-bolometric light curve ($U \rightarrow K_s$) for model DDC15 (solid line) and SN 2002bo (open circles; the error bars take into account measurement, extinction, and distance errors). The grey dashed line shows the instantaneous rate of decay energy. Dotted lines correspond to models with ± 0.1 M$_\odot$ of ^{56}Ni compared to DDC15 (see Table 1). We show close-up views of the $B \rightarrow I$ pseudo-bolometric light curve at early times (left inset), as well as the $U \rightarrow I$ pseudo-bolometric light curve past +40 d (right inset). **The agreement in the bolometric evolution at all times between our model and SN 2002bo suggests our model kinetic energy, ^{56}Ni mass, and ejecta mass are adequate.**
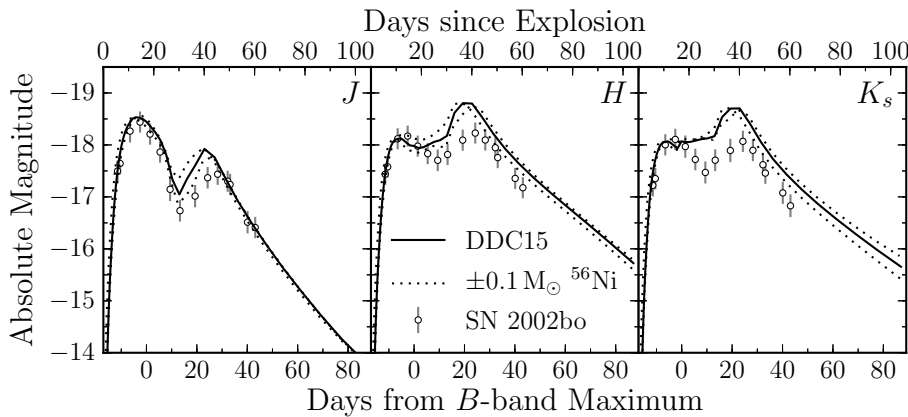

Figure 3. Near-infrared (JHK_s) light curves for model DDC15 (solid lines) compared to SN 2002bo (dereddened; open circles). Dotted lines correspond to models with ± 0.1 M$_\odot$ of ^{56}Ni compared to DDC15 (see Table 1). **Our models reproduce the observed secondary maximum in these bands, resulting from an ionization shift and the sudden strengthening of Co II emission.**
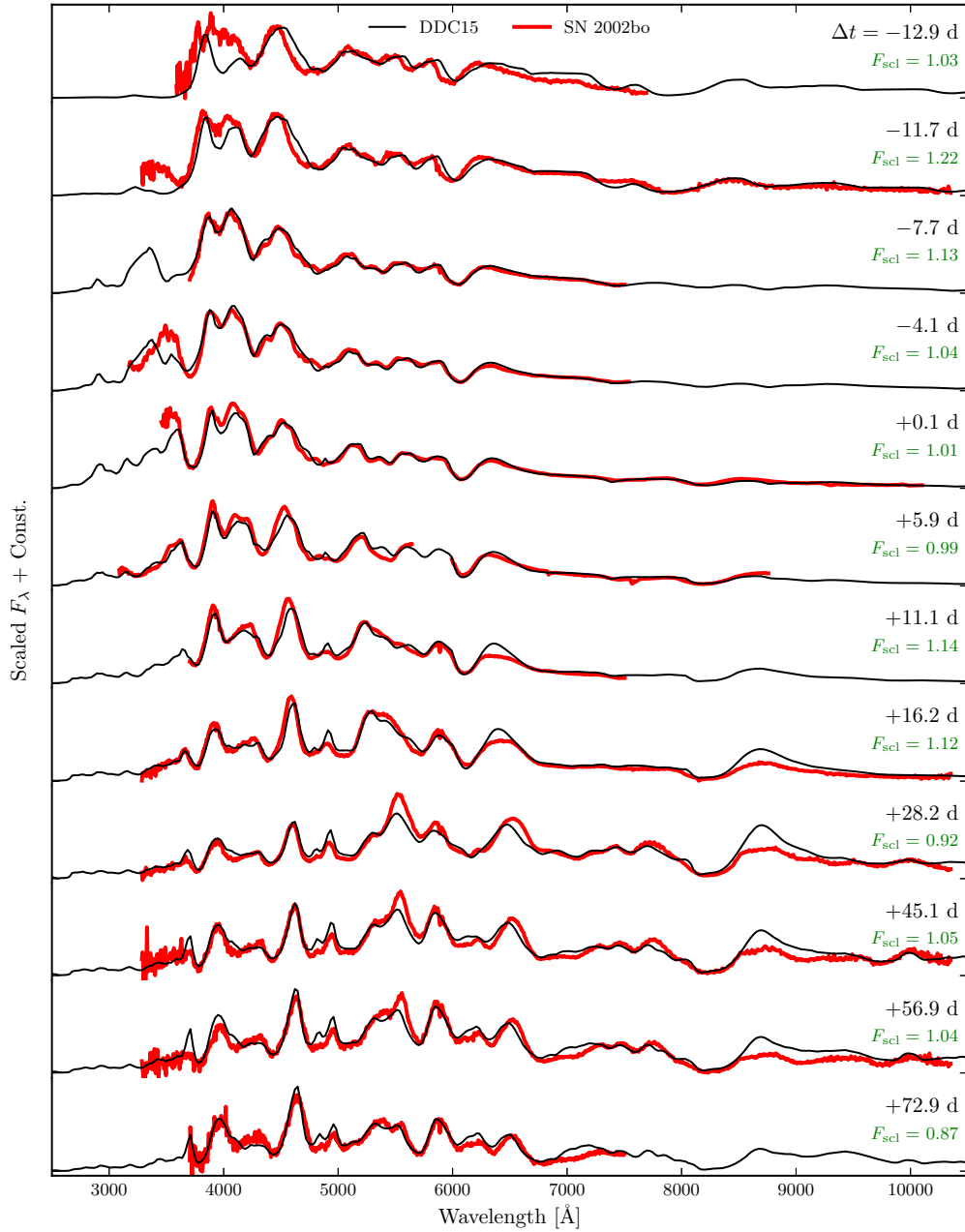
Figure 4. Spectroscopic evolution of model DDC15 (black) compared to SN 2002bo (red), between −12.9 d and +72.9 d from bolometric maximum. The tickmarks on the ordinate give the zero-flux level. The observed spectra have been deredshifted, dereddened, and scaled to match the absolute *V*-band magnitude inferred from the corresponding SN Ia photometry. An additional scaling ($F_{\rm scl}$; green label) has been applied to the observed spectra to reproduce the mean synthetic flux in the range 4000–6000 Å. **Note the broad Si II 6355 Å absorption feature characteristic of so-called "high-velocity" SNe Ia.**