

Abundance stratification in Type Ia supernovae – VIII. The 03fg-like SN 2012dn: a double-degenerate merger interpretation

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ABSTRACT

A detailed study using abundance tomography of SN 2012dn, a peculiar Type Ia supernova, is presented. Despite exhibiting a normal peak luminosity, it retains early-phase super-Chandrasekhar (03fg-like) characteristics: weak Fe III, narrow intermediate-mass element, persistent carbon, and the absence of high-velocity Ca II features. Its nebular spectrum is unusually faint due to grey dimming beginning ~ 60 d after maximum and shows [O I] emission, rare in Type Ia supernovae. While a Chandrasekhar-mass density profile reproduces the photospheric phase, it fails at late times. The [O I] emission requires additional low-velocity mass, implying a total ejecta mass of $1.66 M_{\odot}$, including $0.33 M_{\odot}$ of oxygen (with $0.1 M_{\odot}$ in the core). The ^{56}Ni mass is estimated to be $0.45\text{--}0.49 M_{\odot}$, a range set by uncertainties in the grey-extinction correction applied at the nebular phase, and is insufficient on its own to account for the peak luminosity. Stable iron is confined to intermediate layers and absent from both the core and outer ejecta, the latter indicating subsolar progenitor metallicity. Silicon and sulfur span the full ejecta, while carbon extends down to $v \sim 6000 \text{ km s}^{-1}$. These properties favour a double-degenerate CO–CO white dwarf merger scenario. The remaining luminosity deficit may be explained by additional energy input from a weak interaction with a low-mass, carbon-rich circumstellar shell.

Key words: line: identification – nuclear reactions, nucleosynthesis, abundances – radiative transfer – supernovae: general – supernovae: individual: SN 2012dn.

1 INTRODUCTION

Supernovae Type Ia (SNe Ia) are widely believed to result from the thermonuclear disruption of carbon–oxygen white dwarfs in binary systems (W. Hillebrandt & J. C. Niemeyer 2000; P. A. Mazzali et al. 2007), and their width–luminosity relation has made them essential tools in cosmology (M. M. Phillips 1993; S. Perlmutter et al. 1998; A. G. Riess et al. 1998). However, several aspects of these phenomena remain under debate. The exact nature of the progenitor system is still uncertain, with studies unable to conclusively determine whether single or multiple evolutionary channels are responsible (J. Whelan & I. Iben 1973; I. Iben & A. V. Tutukov 1984; M. Livio & P. Mazzali 2018). Similarly, it remains unresolved whether the observed diversity stems from different white dwarf masses, varying explosion mechanisms, or a combination of both. Furthermore, key physical processes, such as the exact conditions for carbon ignition and the specific mechanisms of flame propagation, remain poorly constrained (W. Hillebrandt & J. C. Niemeyer 2000; W. Hillebrandt et al. 2013). There is also a significant variation in peak luminosity among different SNe Ia (spanning $\sim 2\text{--}3$ magnitudes in the B band; e.g.

F. X. Timmes, E. F. Brown & J. W. Truran 2003; W. Li et al. 2011; C. Ashall et al. 2016a, b). This dispersion is attributed to the varying amounts of ^{56}Ni produced during the explosion, but the reasons for this variation are not yet clear (P. A. Mazzali et al. 2001). Furthermore, the wide range of spectroscopic features and their diversity remain difficult to understand despite numerous classification attempts (P. Nugent et al. 1995; S. Benetti et al. 2005; D. Branch et al. 2006; X. Wang et al. 2009).

The event begins with explosive carbon burning when a threshold density of $\sim 2 \times 10^9 \text{ g cm}^{-2}$ is attained (K. Iwamoto et al. 1999), triggering nuclear fusion that starts with the synthesis of the heaviest elements at the core. As the burning front moves outward into lower-density regions, fusion produces progressively lighter elements. This results in a layered ejecta structure (P. A. Mazzali et al. 2007): A core of neutron-rich ^{58}Ni and ^{54}Fe is surrounded by radioactive ^{56}Ni , followed by a layer of intermediate-mass elements (IMEs) like silicon and sulfur. The outermost layers consist of oxygen and carbon (J. T. Parrent et al. 2011; J. M. Silverman & A. V. Filippenko 2012), representing incomplete burning or original white dwarf material.

The freshly synthesized ^{56}Ni decays through the $^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$ chain (T. Pankey 1962; S. A. Colgate & C. McKee 1969) releasing γ -rays and positrons that thermalize with the expanding ejecta, producing optical photons. These photons escape

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when opacity decreases as the ejecta dilute, constituting the main power source of their light curve.

The majority of events are classified as normal, characterized by relatively homogeneous observables (A. V. Filippenko 1997), typically exhibiting absolute magnitudes in the *B* band of (M_B) -19.1 ± 0.06 mag (C. Ashall et al. 2016b). Their early spectra display multiple lines of singly ionized IMEs, mainly Si II $\lambda 6355$, S II, Mg II, Ca II, and neutral O. As the spectra evolve, Fe-group elements are revealed and ions such as Fe II and Fe III start appearing. These events largely overlap with the spectroscopic ‘core normal’ or ‘broad-line’ supernova (SN) Ia classes according to the classification scheme of D. Branch et al. (2006), and fall within the low-velocity-gradient (LVG) or high-velocity-gradient groups in the scheme of S. Benetti et al. (2005).

Subluminous events, termed 91bg-like, are 1.5–2.5 mag fainter than normal SNe Ia, reaching peak M_B values as low as ~ -16.85 (e.g. SN 1991bg; S. Taubenberger et al. 2008; C. Ashall et al. 2016b). These underluminous transients are characterized by strong [O I] and Ti II absorption lines near 7400 and 4450 Å, respectively. They are classified as ‘cool’ by D. Branch et al. (2006) or ‘faint’ in the scheme of S. Benetti et al. (2005).

Hot, bright events, termed 91T-like (J. T. O’Brien et al. 2024; M. M. Phillips et al. 2024), are typically about 0.5 mag brighter than normal events (A. Gal-Yam 2017) and are characterized by weak early Si II $\lambda 6355$, strong Fe III lines, and weak Ca II H&K (P. A. Mazzali, I. J. Danziger & M. Turatto 1995; C. J. Aouad et al. 2022, 2024). These events belong to the ‘shallow silicon’ group according to D. Branch et al. (2006), or are part of the LVG group according to S. Benetti et al. (2005).

Another peculiar set of events has emerged, classified as 2003fg-like (D. A. Howell et al. 2006b; C. Ashall et al. 2021; J. Lu et al. 2021, 2026; G. Dimitriadis et al. 2022; M. R. Siebert et al. 2023a; T. Nagao et al. 2024; S. Bose et al. 2026). These events exhibit early spectra characterized by narrow, multiple lines of IMEs, particularly silicon and sulfur, with weak or absent Fe III lines, a notable lack of high-velocity Ca II features, and strong C II $\lambda\lambda$ 6578, 6582 features that persist for weeks after maximum light. They also feature slow ejecta velocities along with a generally low ionization state that persists into the nebular phase (C. Ashall et al. 2021). For a comparison see Figs 1 and 2. Photometrically, these events stand apart from other SN subtypes. Although their light curves are broad, they lack the secondary near-infrared (NIR) maximum typically observed around +10 d in the *H* band of normal SNe Ia. Their *i*-band peak occurs after the *B*-band maximum, and they also show no distinct *H*-band break, suggesting that the synthesized ^{56}Ni is buried within a dense shell (C. Ashall et al. 2021). Some of them exhibit significant bolometric dimming a few months after *B*-band maximum, causing their light curves to deviate from expected radioactive decay paths. Notable examples include SN 2012dn (S. Taubenberger et al. 2019), SN 2009dc (S. Hachinger et al. 2012), and LSQ14fmg (E. Y. Hsiao et al. 2020a). Additionally, they often display unusually blue early colours and high ultraviolet (UV) luminosities (P. J. Brown et al. 2014). While sharing these traits, their luminosities vary widely ($M_B \approx -19$ to -21). Some of the most luminous examples, such as SN 2003fg ($M_B = -20.18 \pm 0.05$; D. A. Howell et al. 2006c), SN 2009dc ($M_B = -20.09 \pm 0.17$; S. Taubenberger et al. 2011; M. Yamanaka et al. 2016), and SN 2007if ($M_B = -20.54 \pm 0.04$; C. Akerlof et al. 2007; R. A. Scalzo et al. 2010; S. Taubenberger et al. 2013a), reach luminosities intermediate between the 91T-like subclass (J. T. O’Brien et al. 2024) and the superluminous SNe (T. J. Moriya 2026). These high luminosities suggest ejecta masses

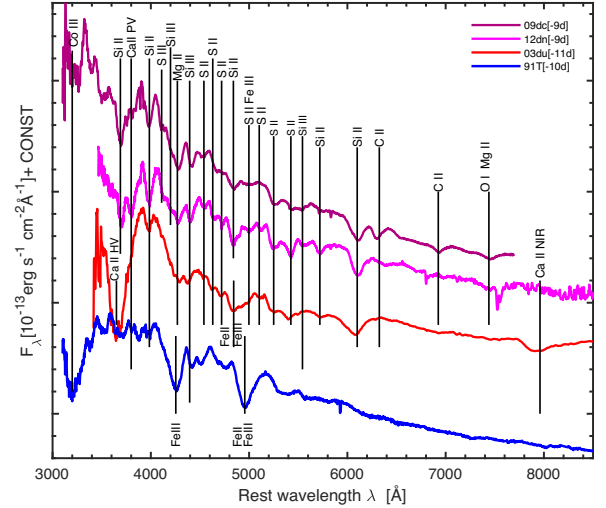


Figure 1. The early spectra of the 03fg-like SNe 2012dn and 2009dc compared to SN 1991T, and the normal SN 2003du, highlighting their distinct IME-dominated features and weak Fe III signatures discussed in the text.

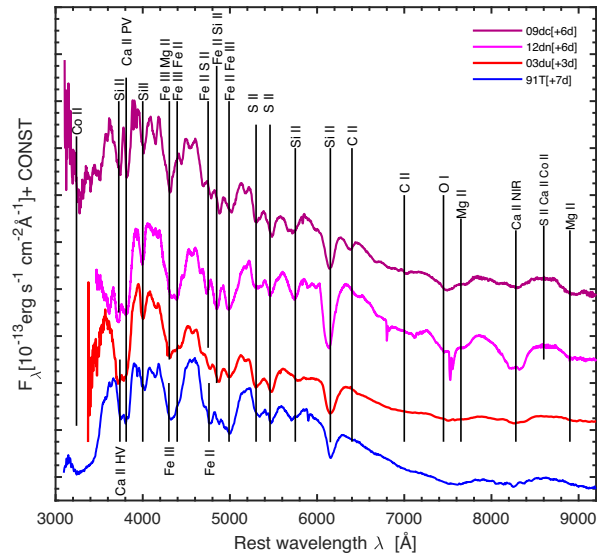


Figure 2. Spectra 1 week after *B* maximum of the 03fg-like SNe 2012dn and 2009dc compared to SN 1991T, and the normal SN 2003du.

exceeding the Chandrasekhar limit, (M_{Ch}), earning them the ‘super-Chandrasekhar (SC)’ designation. However, several 03fg-like objects, including ASASSN-15hy (J. Lu et al. 2021), SN 2006gz (M. Hicken et al. 2007), and SN 2012dn (this study), exhibit luminosities similar to normal SNe Ia. Despite their standard peak magnitudes, they retain the class’s defining spectroscopic features, making them vital for probing the diversity of the most luminous SNe Ia.

Most intriguingly, SN 2012dn is one of the very few SNe Ia known to exhibit nebular [O I] emission. Within the 03fg-like subgroup, this feature has also been observed in SN 2021zny (G. Dimitriadis et al. 2023) and SN 2022pul (M. R. Siebert et al. 2023b). Other examples of [O I]-emitting SNe Ia include SN 2010lp (S. Taubenberger et al. 2013b), ASASSN-20jq (S. Bose et al. 2025), and iPTF14atg (M. Kromer et al. 2016).

Proposed scenarios for 03fg-like SNe can be broadly described as: (i) explosions of rotating or magnetized SC white dwarfs (S. C. Yoon & N. Langer 2005); (ii) interaction with a dense, H-poor circumstellar medium, where an additional luminosity component arises from ejecta–envelope interaction (P. Heflich & A. Khokhlov 1996; S. Hachinger et al. 2012; U. M. Noebauer et al. 2016) (see also the core-degenerate scenario; W. M. Sparks & T. P. Stecher 1974; M. Livio & A. G. Riess 2003; E. Y. Hsiao et al. 2020b; C. Ashall et al. 2021); and (iii) the violent merger of two C–O white dwarfs whose combined mass exceeds M_{Ch} (D. A. Howell et al. 2006a; R. Pakmor et al. 2010; R. A. Scalzo et al. 2010).

Mapping ejecta stratification has proven essential for unraveling the spectroscopic diversity of these events (M. Stehle et al. 2005; P. A. Mazzali et al. 2008; M. Sasdelli et al. 2014; C. Ashall et al. 2016b; C. J. Aouad et al. 2022, 2024). This approach reveals potential progenitor-explosion channels and helps determine the reliability of specific subclasses as cosmological distance indicators. Furthermore, it allows for a clearer understanding of the underlying physics of these objects, such as the energetics of the explosion and the extent of nuclear burning.

The paper is organized as follows: Section 2 presents the observational data, and Section 3.1 describes the modelling code and techniques employed. Our spectroscopic results are detailed across three sections: Section 3 covers the photospheric phase, Section 4 examines the nebular phase, and Section 5 presents the resulting chemical stratification. In Section 6, we generate a bolometric light curve based on these abundance results to test their consistency. Finally, Section 7 evaluates potential progenitor and explosion channels, followed by our summary in Section 8.

2 DATA

2.1 Host galaxy, distance and reddening

SN 2012dn was discovered on 2012 July 8.52 UT in the SA(s)c spiral galaxy ESO462-016 (G. Bock, J. T. Parrent & D. A. Howell 2012) with a redshift of 0.010 177 (C. M. Springob et al. 2005). Several distance moduli, μ , for the host galaxy have been reported. Based on the galaxy’s recessional velocity and using $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$, N. K. Chakradhari et al. (2014) and P. J. Brown et al. (2014) estimate $\mu = 33.15 \pm 0.15$ and $\mu = 33.32 \pm 0.20$ mag, respectively. Tully–Fisher measurements vary, with values of $\mu = 33.15 \pm 0.52$ mag (C. M. Springob et al. 2007) and $\mu = 33.19 \pm 0.69$ mag (D. J. Lagattuta et al. 2013). J. T. Parrent et al. (2016) adopts $\mu = 33.15 \pm 0.15$ mag, S. Taubenberger et al. (2019) uses $\mu = 33.26 \pm 0.20$ mag, while M. Yamanaka et al. (2016) adopts $\mu = 33.15$ mag, based on the work of G. Theureau et al. (2007). We adopt $\mu = 33.26 \pm 0.20$ mag and a total reddening of $E(B - V) = 0.09$ (comprising 0.05 from the Milky Way and 0.04 from the host), following S. Taubenberger et al. (2019). This extinction is consistent with J. T. Parrent et al. (2016) and M. Yamanaka et al. (2016) (who use 0.10), though lower than the 0.18 assumed by N. K. Chakradhari et al. (2014). Reported $\Delta m_{15}(B)$ values also vary between 0.92 (N. K. Chakradhari et al. 2014; M. Yamanaka et al. 2016), 0.97 (S. Taubenberger et al. 2019), and 1.08 (J. T. Parrent et al. 2016).

2.2 Spectra

The spectra used in this study were retrieved from the Weizmann Interactive Supernova Data Repository (WiSeREP; O. Yaron & A. Gal-Yam 2012) and are listed in Table 1. The original spectro-

scopic observations and data reductions were published by J. T. Parrent et al. (2016), B. E. Stahl et al. (2020), M. J. Childress et al. (2016), and S. Taubenberger et al. (2019). Following C. J. Aouad et al. (2022, 2024), flux calibration in the U, B, V, R, I was performed by multiplying the spectra with a low-order smoothed spline using the photometric data of S. Taubenberger et al. (2019).

2.3 Photometric evolution and late-time dimming

The photometry of SN 2012dn (S. Taubenberger et al. 2019), reveals a distinct light-curve evolution. While the peak luminosity is comparable to normal SNe Ia, the post-maximum decline is highly unusual; starting ~ 60 d post-maximum, the light curves fade significantly faster than standard events. A comparison with the normal SN 2003du (Fig. 3) highlights a nearly wavelength-independent (grey) luminosity deficit across all $UBVRI$ bands through day 300 (quantified in Appendix A; see also Section 4). Similar late-time behaviour has been observed in other 03fg-like candidates such as SN 2006gz (K. Maeda et al. 2009), LSQ14fmg (E. Y. Hsiao et al. 2020a), and SN 2009dc (S. Taubenberger et al. 2011), though the onset in SN 2012dn is notably earlier.

The physical origin of the late-time luminosity deficit remains uncertain. S. Taubenberger et al. (2019) examined several possible explanations, namely enhanced γ -ray or positron escape, clumping, an infrared catastrophe (IRC), and dust formation. Early positron escape appears unlikely, as reproducing the observed deficit would require unrealistically low ejecta masses (S. Taubenberger et al. 2019). Moreover, recent observations favour efficient positron trapping in normal SNe Ia at epochs far later than those considered here (G. Loloudas et al. 2009; W. E. Kerzendorf et al. 2014, 2017; C. Fransson & A. Jerkstrand 2015; O. Graur et al. 2016; B. J. Shappee et al. 2017). As also noted by S. Taubenberger et al. (2019), strong clumping does not resolve the discrepancy, since reducing the positron optical depth would simultaneously reduce the γ -ray optical depth, producing an early decline incompatible with the relatively slow light-curve evolution of SN 2012dn.

Likewise, an IRC appears unlikely. At ~ 300 d, the nebular spectrum remains dominated by thermally excited [Fe II] emission, while the detection of [O I] and [Ca II] indicates that the ejecta remain in the thermal regime. More broadly, no convincing evidence for an IRC has been reported in normal SNe Ia (G. Loloudas et al. 2009; W. E. Kerzendorf et al. 2014; O. Graur et al. 2016).

Taken together, these arguments leave dust as the most plausible explanation for the observed luminosity deficit (N. K. Chakradhari et al. 2014; J. T. Parrent et al. 2016; M. Yamanaka et al. 2016; T. Nagao, K. Maeda & M. Yamanaka 2017; S. Taubenberger et al. 2019). In particular, the interpretation in terms of newly formed dust within the ejecta (S. Taubenberger et al. 2019), is supported by theoretical models predicting dust condensation in Type Ia ejecta at relatively early epochs (~ 100 – 300 d; T. Nozawa et al. 2011) and by the delayed onset of the luminosity deficit after maximum light, which is more naturally explained by dust forming within the expanding ejecta than by pre-existing dust. However, the nearly wavelength-independent fading, accompanied by little or no colour evolution, disfavours conventional interstellar-like dust, instead favouring either unusually large grains (A. Aguirre 1999) or optically thick dust clumps (S. Taubenberger et al. 2019). In the latter scenario, the clumps shield newly formed grains from the intense radiation field, relaxing the requirement for rapid growth to unusually large grain sizes while naturally producing the observed near-grey attenuation. Nevertheless, without near- and far-infrared observations at the

Table 1. Spectra of SN 2012dn and modelling parameters.

UT Date 2012	JD ^a	Epoch ^b (d)	Telescope/Instr.	log L [$L_{\odot}$]	v (km s ⁻¹)	T_{ph} (K)
10/07 ^c	118.5	−14.1	Gemini-S / GMOS-S	9.10	14 000	15 100
11/07 ^d	119.8	−12.8	Lick-3m / KAST	9.190	13 250	13 980
14/07 ^c	122.5	−10.1	FLWO-1.5M / FAST	9.470	12 850	13 250
15/07 ^c	123.5	−9.8	Gemini-S / GMOS-S	9.500	12 550	12 990
16/07 ^d	125.0	−7.6	Keck1 / LRIS /	9.570	12 350	12 395
19/07 ^c	127.5	−5.1	Gemini-S / GMOS-S	9.600	12 000	11 398
20/07 ^e	129.0	−3.6	ANU-2.3m / WiFes	9.630	11 600	11 285
23/07 ^c	131.5	−1.1	Gemini-N / GMOS	9.670	11 200	10 800
27/07 ^c	135.5	+2.9	Gemini-N / GMOS	9.600	10 200	9875
29/07 ^c	137.5	+4.9	FTS / FLOYD-S	9.560	9500	9486
30/07 ^c	138.5	+5.9	Gemini-N / GMOS	9.550	9100	9438
04/08 ^c	146.5	+13.9	FTS / FLOYD-S	9.440	7100	8449
-	423.3	+290.9	ESO 8.2m/FORS2-ISAAC	-	-	-
Nebular Phase ^f						

Notes. ^aJD − 2456 000 − ^bRest-frame time, since B maximum, ^c(J. T. Parrent et al. 2016), ^d(B. E. Stahl et al. 2020), ^e(M. J. Childress et al. 2016), ^f(S. Taubenberger et al. 2019).

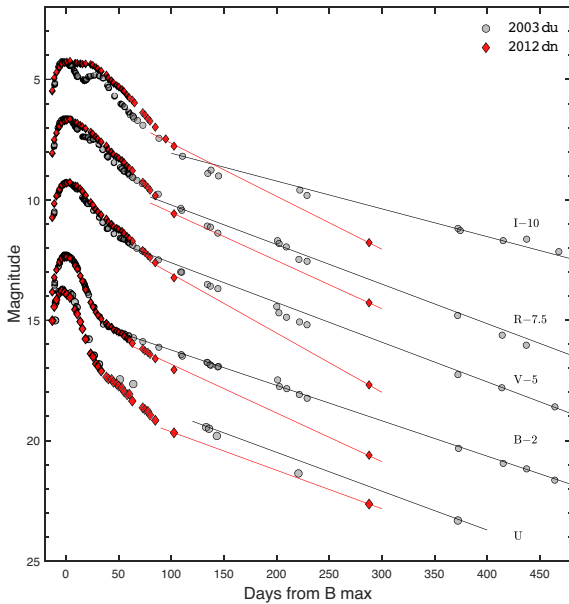


Figure 3. *UBVRI* light curves of SN 2012dn compared to the ones of SN 2003du (V. Stanishev et al. 2007) normalized at peak. The evolution of SN 2012dn exhibits a notable wavelength-independent (grey) extinction that persists across all bands through the late phases.

nebular epoch, the origin and physical properties of the dust remain difficult to constrain observationally.

3 PHOTOSPHERIC PHASE MODELS

3.1 Modelling technique

Radiative-transfer calculations are performed using the Monte Carlo code developed by P. A. Mazzali & L. B. Lucy (1993) and extended later by L. B. Lucy (1999) and P. A. Mazzali (2000). The code is described extensively in M. Stehle et al. (2005), S. Hachinger (2011), S. Hachinger et al. (2017), and C. Ashall & P. A. Mazzali (2020). Assuming homologous expansion, a sharp photosphere is imposed at velocity v_{ph} (where $R_{\text{ph}} = v_{\text{ph}} \cdot t$), emitting a blackbody continuum with luminosity $L =$

$4\pi(v_{\text{ph}}t)^2 \sigma T_{\text{ph}}^4$. This luminosity is discretized into photon packets that undergo Thomson scattering and Sobolev line interactions within the atmosphere with bound-bound emissivity treated via a branching scheme (P. A. Mazzali 2000). Through estimators, the code calculates, in each shell, the mean intensity, $J = \int_0^\infty J_\nu d\nu$ and the frequency moment, $\langle \nu \rangle = \frac{\int_0^\infty \nu J_\nu d\nu}{\int_0^\infty J_\nu d\nu}$. These define the radiation temperature T_{R} and dilution factor W , via: $\frac{h(\nu)}{kT_{\text{R}}} = 3.832$ and $W(r) = \frac{J(r)}{B(T_{\text{R}}(r))}$. Using T_{R} , W , and $T_{\text{e}} \simeq 0.9 T_{\text{R}}$, the code updates ionization and excitation via the modified nebular approximation (P. A. Mazzali & L. B. Lucy 1993; P. A. Mazzali 2000). Radiative equilibrium is enforced (L. B. Lucy 1999). Packet propagation and level populations are iterated until convergence. The emergent spectrum is then obtained from a formal solution of the radiative-transfer equation using the converged source function. To initiate the modelling, the code requires a fixed density profile, the time since explosion t , a bolometric luminosity L_{bol} , the photospheric velocity v_{ph} , and the chemical abundances for every shell. These parameters are manually optimized to match the observed spectra. As the ejecta expand and dilute over time, the photosphere recedes in velocity space, revealing deeper layers.

We examined 12 spectra ranging from day −14 to +14 relative to B -band maximum. We employed two distinct density profiles, illustrated in Fig. 4, corresponding to two different explosion models: a fast deflagration (W7; K. Nomoto, F. K. Thielemann & K. Yokoi 1984) and a delayed detonation model (DD2; K. Iwamoto et al. 1999). These profiles have been consistently applied across previous studies in this series, ensuring a standardized comparison across different SNe. Our synthetic spectra provide an exceptional fit to the observed features and flux levels across the entire wavelength range (see Fig. 5). Input parameters for the modelling are summarized in Table 1.

3.2 The pre-maximum spectra

Figs 6, 7 and 8 present synthetic spectra from day −14.1 to −5.1. At these early epochs, relatively high photospheric velocities are required compared to SNe 2009dc, 1999aa, iPTF16abc, and 2003du at similar phases. Higher velocities imply lower temperatures for a given luminosity, which is necessary to reproduce the observed low ionization.

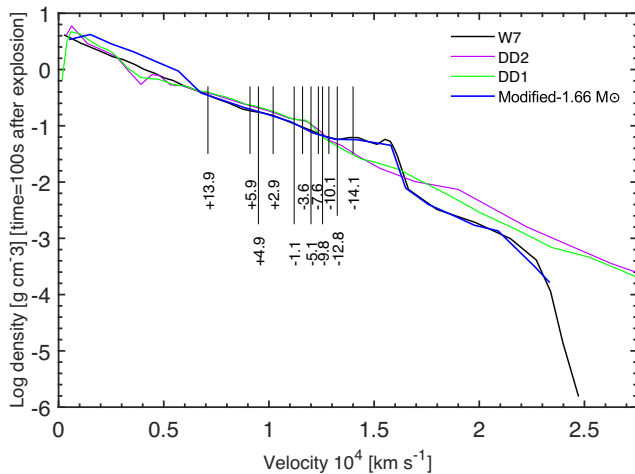


Figure 4. Density profiles for the W7, DD1, DD2, and DD3 models, all scaled to an epoch of 100 s. The blue line shows our adopted density structure, modified to a total ejecta mass of $1.66 M_{\odot}$. Vertical lines indicate the photospheric velocities of the synthetic spectra at their respective epochs relative to *B*-band maximum light.

Fe-group elements: Unlike normal or 91T-like SNe, the early spectra of SN 2012dn and other 03fg-like events (e.g. SN 2006gz; M. Hicken et al. 2007) lack visible Fe III lines (C. Ashall et al. 2021). The 4250 Å feature is dominated by Mg II, as in normal SNe Ia rather than by Fe III as in 91T-like events. Likewise, the shallow 5000 Å feature is driven primarily by Si II $\lambda\lambda 5041, 5056$ instead of the strong Fe III absorption typically seen in both normal and 91T-like SNe.

For $v > 15000 \text{ km s}^{-1}$, no iron is required in our models, with the maximum allowable iron mass fraction being less than 0.0001. This is significantly lower than the solar value ($X(\text{Fe}_{\odot}) = 0.001$, M. Asplund et al. 2009). To further constrain this, we computed synthetic spectra with metallicities of $Z = Z_{\odot}$ and $Z = 18 Z_{\odot}$, as shown in Fig. 9. Increasing the iron content in the outermost layers overestimates the early-time flux and introduces noticeable discrepancies in IME features. Specifically, the Si II $\lambda\lambda 5041, 5056$ lines are better reproduced with subsolar abundances, whereas solar levels introduce unwanted Fe III influence near 4900 Å. Furthermore, higher iron abundances enhance backscattering, which heats the photosphere and shifts the ionization balance from Si II towards Si III. This results in the strengthening of the Si III $\lambda\lambda 4552, 4567, 4574$ multiplet near 4300 Å, which is absent in the spectra of SN 2012dn.

The low iron abundance aligns with studies of the host galaxy of SN 2012dn, which consistently report subsolar metallicities ranging from ~ 0.4 to $0.8 Z_{\odot}$ (J. T. Parrent et al. 2016; S. Taubenberger et al. 2019; M. J. Childress et al. 2016). Furthermore, the lack of iron-group elements reduces UV line blanketing (P. A. Mazzali et al. 2014), explaining both the extreme UV brightness and the unusually blue pre-maximum ($U - B$) colours observed in SN 2012dn, SN 2009dc, and other 03fg-like events (J. M. Silverman et al. 2013; P. J. Brown et al. 2014; S. Taubenberger et al. 2019; J. Lu et al. 2021). Our synthetic ($U - B$) colour evolution reproduces the observations remarkably well (Fig. 10), supporting the consensus that this subclass preferentially occurs in low-metallicity progenitors (M. Childress et al. 2011; C. Ashall et al. 2021).

Going inwards, the iron mass fraction increases to 0.1 at $12000 < v < 12300 \text{ km s}^{-1}$. This stable iron (i.e. ^{54}Fe), which could not have originated from ^{56}Ni decay at such an early stage, must be the result of explosive nucleosynthesis (M. Tanaka et al. 2011; C. J. Aouad et al. 2022). It is necessary to absorb UV flux and reprocess it to longer wavelengths.

Typically, ^{56}Ni is identified by a prominent Co III line $\lambda\lambda 3287, 3305$, observed near 3200 Å. Unfortunately, the spectra available for SN 2012dn do not cover this range, making it challenging to determine an accurate amount of ^{56}Ni .

Calcium: Unlike normal SNe Ia, SN 2012dn exhibits a weak high-velocity (HV) Ca II H&K feature, a characteristic of 03fg-like SNe (S. Taubenberger et al. 2019; C. Ashall et al. 2021). In normal and transitional events, such as SN 2003du and SN 1999aa, the HV and photospheric (PV) Ca II components blend into a single deep absorption dominated by the HV contribution (M. J. Childress et al. 2014; A. Dutta et al. 2021; C. J. Aouad et al. 2022, 2024). In SN 2012dn, however, no HV component is detected, and the blue-side absorption is instead produced mainly by Si II $\lambda\lambda 3854, 3856, 3863$. This resembles iPTF16abc, except that the same region there is dominated by Si III and Co III rather than Si II (C. J. Aouad et al. 2024; J. Liu et al. 2024), further emphasizing the lower ionization state of SN 2012dn relative to 91T-like events.

Unlike normal and 91T-like SNe Ia, our models require no Ca above 16000 km s^{-1} . A negligible Ca mass fraction (5×10^{-4}) is sufficient at $15000\text{--}16000 \text{ km s}^{-1}$, rising to 0.05 at $12500\text{--}13500 \text{ km s}^{-1}$ to reproduce the photospheric component. The Ca II NIR triplet is weak in the earliest spectra, becoming prominent only by day -7.6 , unlike normal SNe Ia where it is strong from the earliest epochs, but earlier than in 91T-like events where it typically appears about a week after maximum light.

Distinguishing whether the Ca II line behaviour stems from abundance or ionization is challenging (P. A. Mazzali et al.

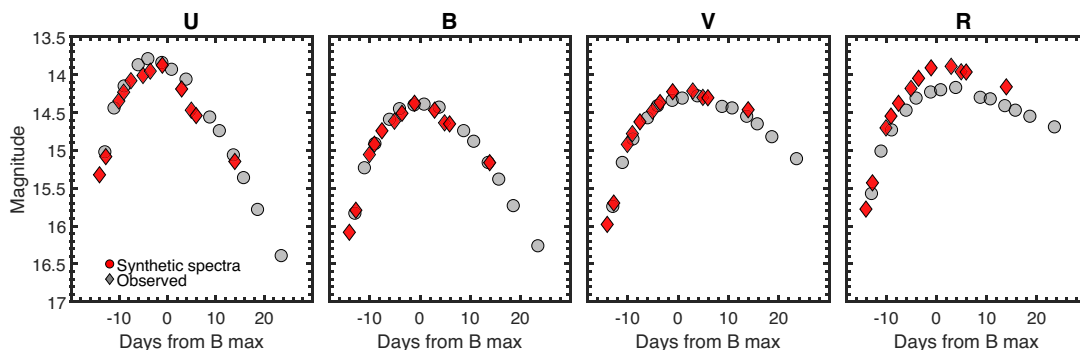


Figure 5. Light curves from the synthetic spectra compared to the light curves from observation. Photometry used from S. Taubenberger (2017).

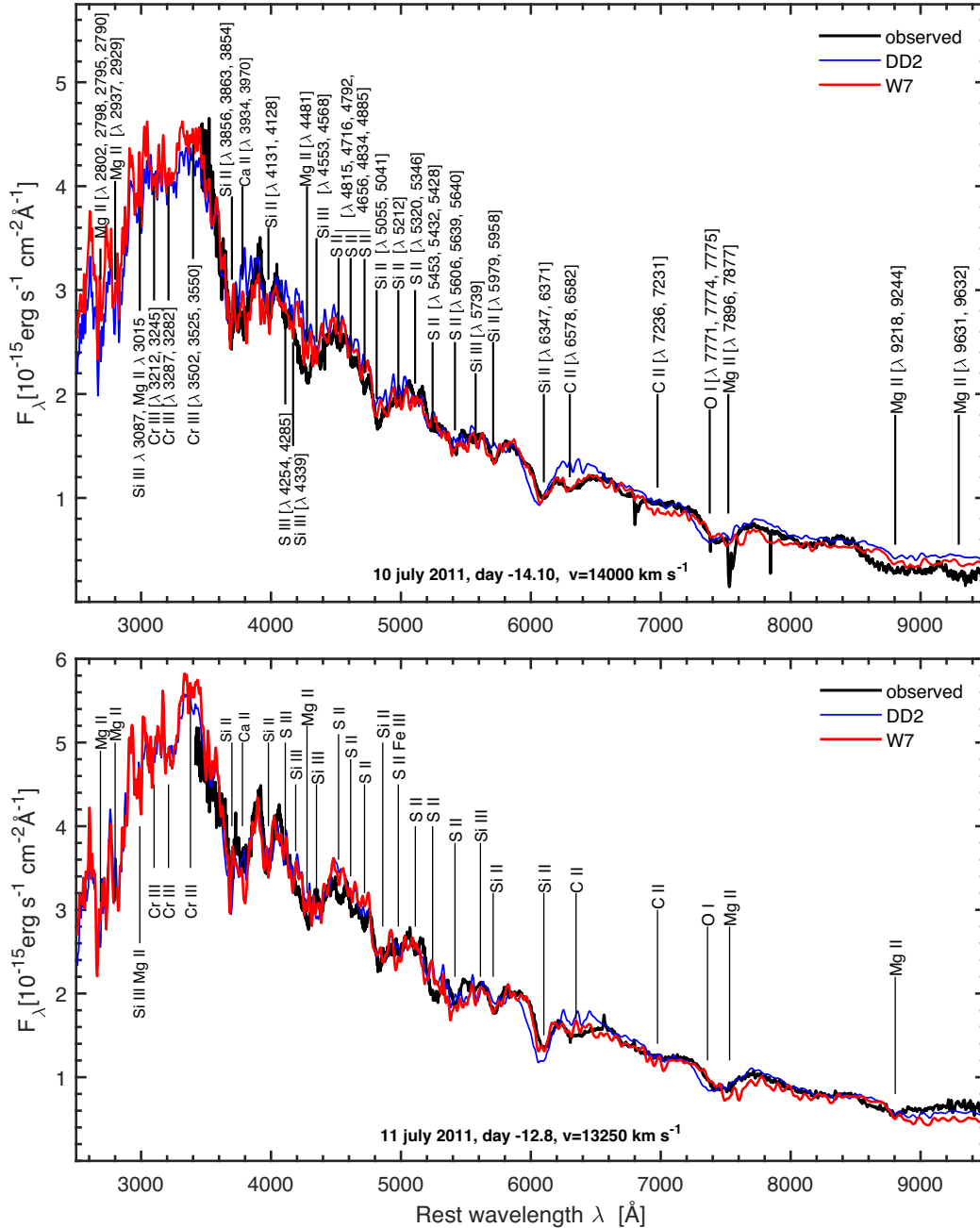


Figure 6. Early-time spectra of SN 2012dn overlaid with the synthetic spectra computed using the W7 and the DD2 density profiles depicted in red and blue, respectively.

2005; C. J. Aouad et al. 2022). However, given the generally low ionization state of SN 2012dn, the absence of high-velocity Ca II H&K features is more likely an abundance effect than an ionization one.

Silicon, Sulphur, Magnesium: The Si II $\lambda\lambda$ 6355 ($\lambda\lambda$ 6347, 6371) and Si II λ 5972 ($\lambda\lambda$ 5958, 5979) lines are clearly visible from the earliest spectrum. The accurate reproduction of their evolving depth ratio, $\mathcal{R}$ Si II, a key ionization indicator (P. Nugent et al. 1995; S. Hachinger et al. 2008), indicates that our models accurately capture the ejecta temperature and ionization structure. The Si II λ 4130 line is notably stronger than in normal and 91T-like SNe during this pre-maximum phase. Si II $\lambda\lambda$ 3856, 3863, 3854 create a deep absorption blueward of the Ca II H&K PV

feature near 3700 Å. A trait absent in both normal and 91T-like events.

The 4850 Å absorption is well reproduced by our models and is dominated by Si II $\lambda\lambda$ 5041, 5056, unlike in normal and 91T-like SNe Ia where it is produced primarily by Fe III $\lambda\lambda$ 5076, 5063. Our models reproduce the Si III $\lambda\lambda$ 4553, 4568 feature near 4400 Å and the absorption around 5600 Å blueward of Si II λ 5972. While S. Taubenberger et al. (2011) suggested the latter, uncommon in normal and 91T-like SNe, may be a Na I D + Si II blend, our models identify it as Si III λ 5739.

The characteristic W-shaped S II feature near 5400 Å, absent at this epoch in hotter 91T-like SNe, as well as the uncommon S II $\lambda\lambda$ 5320, 5346 feature around 5050 Å

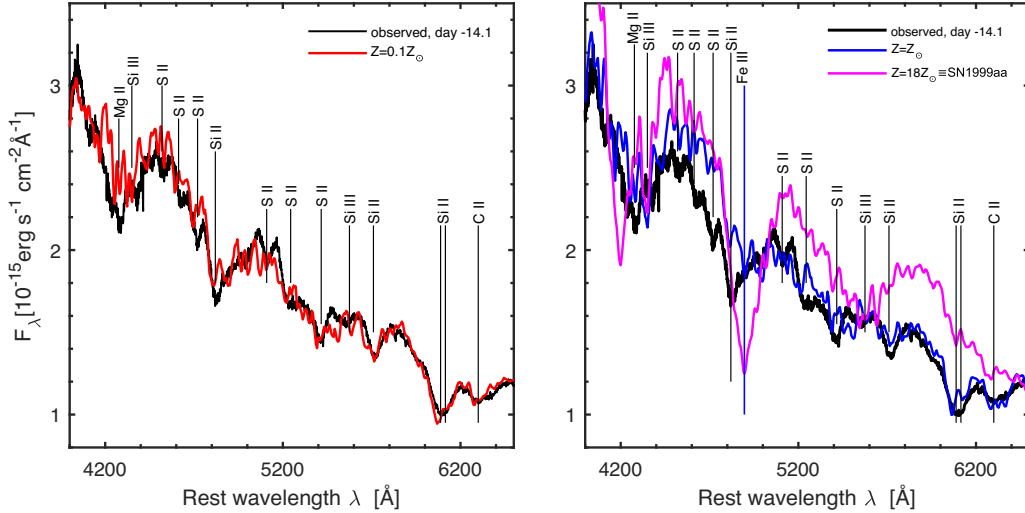


Figure 9. Probing outer-layer iron: Left panel shows the day -14 spectrum with a subsolar model ($Z = 0.1 Z_{\odot}$) at $v > 15000 \text{ km s}^{-1}$. Right panel compares solar (blue) and supersolar (purple; matching SN 1999aa) abundances. Solar and supersolar abundances fail to replicate the observed spectral features.

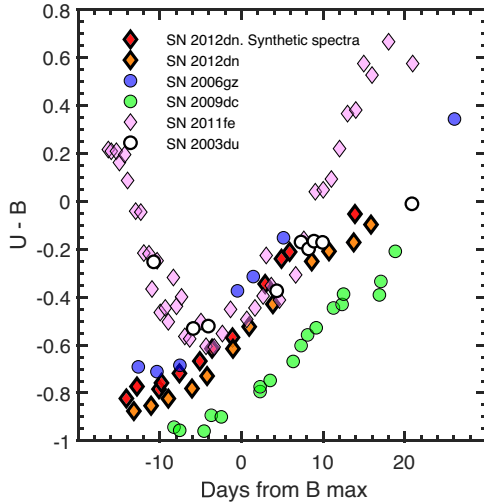


Figure 10. $U-B$ colour evolution of SN 2012dn compared with synthetic spectra and other SNe (S. Taubenberger et al. 2019). The 03fg-like events exhibit notably blue pre-maximum colours, likely due to a lack of Fe-group elements reducing UV line blanketing (P. A. Mazzali et al. 2014). This contributes to the distinct early colour evolution observed in this subclass.

deep HV Ca II H&K at the same epoch. The Ca II NIR becomes stronger and splits into two components, accurately reproduced in our synthetic spectra. Notably, no calcium was required in these layers to achieve these fits.

Silicon, Sulphur, Magnesium: Both Si II λ 6355 and Si II λ 5972 deepen, with their ratio $\mathcal{R}(\text{Si II})$ still being accurately reproduced. The Si III λ 5739 line, located blueward of Si II λ 5972, weakens progressively until it disappears entirely by day $+2.9$.

The region near $4400 \text{ \AA}$, which previously exhibited two distinct components, now shows a single, deep absorption. On the red side, a blend of Fe II and Fe III lines now dominates, replacing the Si III $\lambda\lambda$ 4553, 4568 doublet that characterized the earlier spectra. These iron-group transitions, along with the Mg II/Fe III

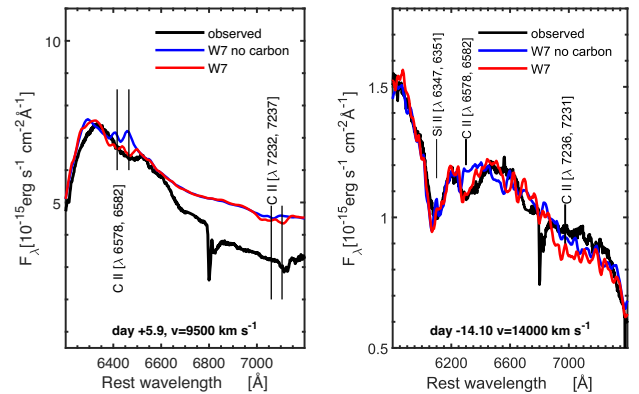


Figure 11. Comparison between a synthetic model excluding carbon (blue) and a model incorporating $0.01 M_{\odot}$ of carbon ($X(\text{C}) = 0.05$) within the velocity range $9100 < v < 10200 \text{ km s}^{-1}$ (red) is shown in the left panel. The right panel displays the results for the outer layers, where the observed C II feature near $6200 \text{ \AA}$ is accurately reproduced by including $0.003 M_{\odot}$ of carbon at $v > 14000 \text{ km s}^{-1}$ (red).

complex on the blue wing, collectively shape this broad and prominent feature.

As in the earlier epochs, the blue component of the $5000 \text{ \AA}$ feature (centred near $4800 \text{ \AA}$) is dominated by a blend of Si II $\lambda\lambda$ 5041, 5055. This narrow absorption is absent in normal or 91T-like SNe at similar epochs; in those events, the region typically exhibits a broad, deep absorption feature formed by blends of Fe II and Fe III lines, as shown in Fig. 14. This distinctive ‘double narrow’ absorption profile is a notable characteristic of SN 2012dn and other 03fg-like SNe (M. Hicken et al. 2007).

The W-shaped Si II feature near $5400 \text{ \AA}$ and the Si II-dominated $4500\text{--}4700 \text{ \AA}$ region remain well reproduced. At this epoch, a blend of Si II λ 8859 and Ca II $\lambda\lambda$ 8927, 8912 flattens the emission peak redward of the Ca II NIR triplet (Fig. 13, day $+2.9$), also reproduced by our models.

Mg II continues to contribute to the absorption feature near $4400 \text{ \AA}$, though the line is increasingly influenced by Fe III at

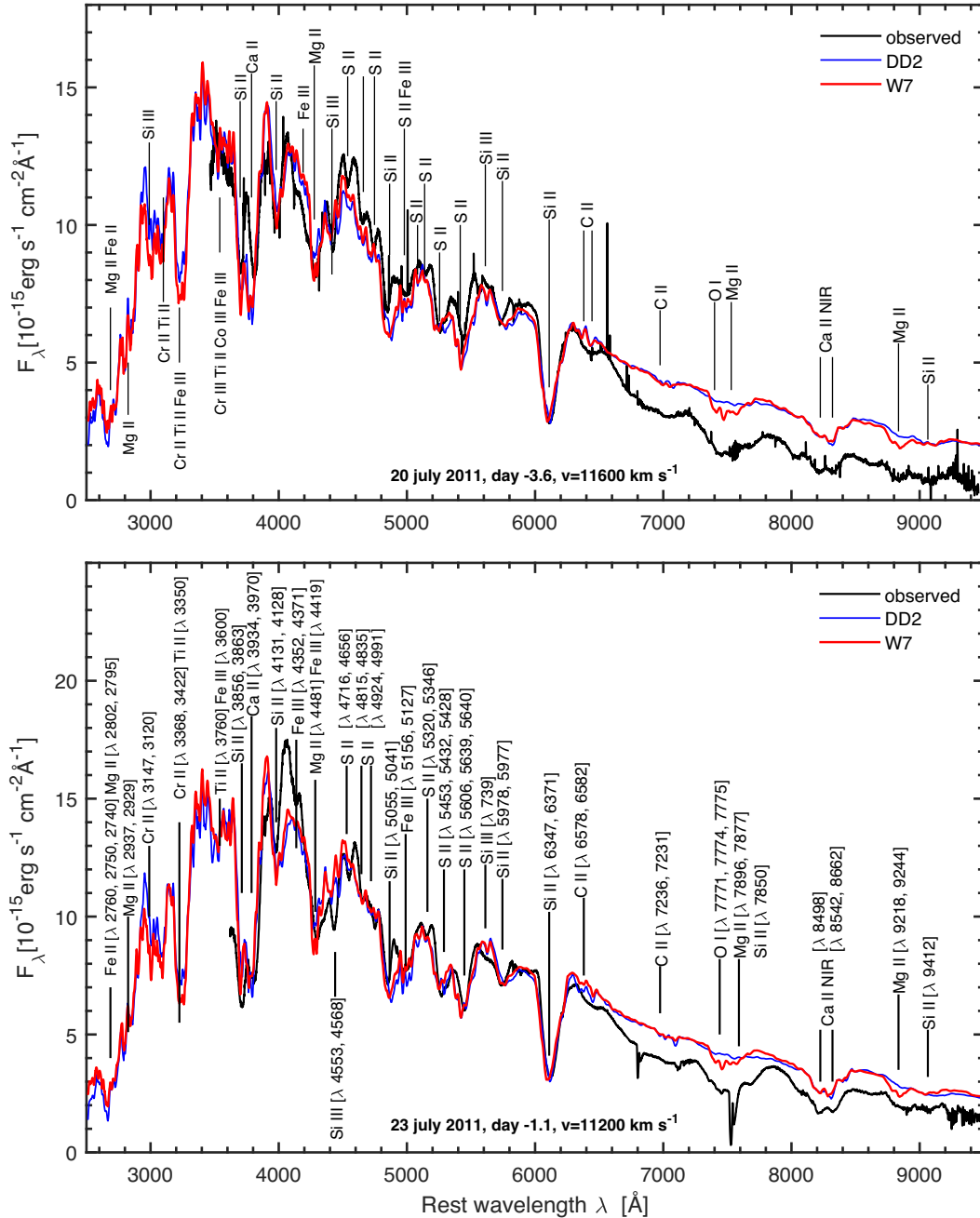


Figure 12. Spectra of SN 2012dn near maximum light overlaid with the synthetic spectra computed using the W7 and the DD2 density profiles depicted in red and blue, respectively.

this epoch. The Mg II features around 7500 and 8800 Å remain accurately replicated. Notably, no magnesium is required in these layers, which is consistent with the chemical composition predicted by the W7 model (K. Nomoto et al. 1984; K. Iwamoto et al. 1999).

Carbon, Oxygen: The C II λ 6580 remains clearly visible near maximum light whereas the λ 7234 feature is less prominent, a behaviour that is faithfully reproduced in our synthetic spectra. The carbon mass fraction is sustained at 0.05 down to $v > 9500$ km s⁻¹ with oxygen also persisting in these layers. Our derived carbon fraction is an order of magnitude higher than the $X_C \approx$

0.002 found in normal SNe Ia (M. Tanaka et al. 2011) and falls within the same range as the carbon required for SN 2009dc (S. Hachinger et al. 2012).

3.4 The spectra post-maximum light

In Fig. 16, we present synthetic spectra for days +5.9 and +13.9, overlaid on the observed spectra. The photospheric velocity decreases from 9500 to 7100 km s⁻¹. At this epoch, the photosphere has receded into the ⁵⁶Ni-dominated region, rendering the assumption of a sharp photospheric boundary inadequate. In re-

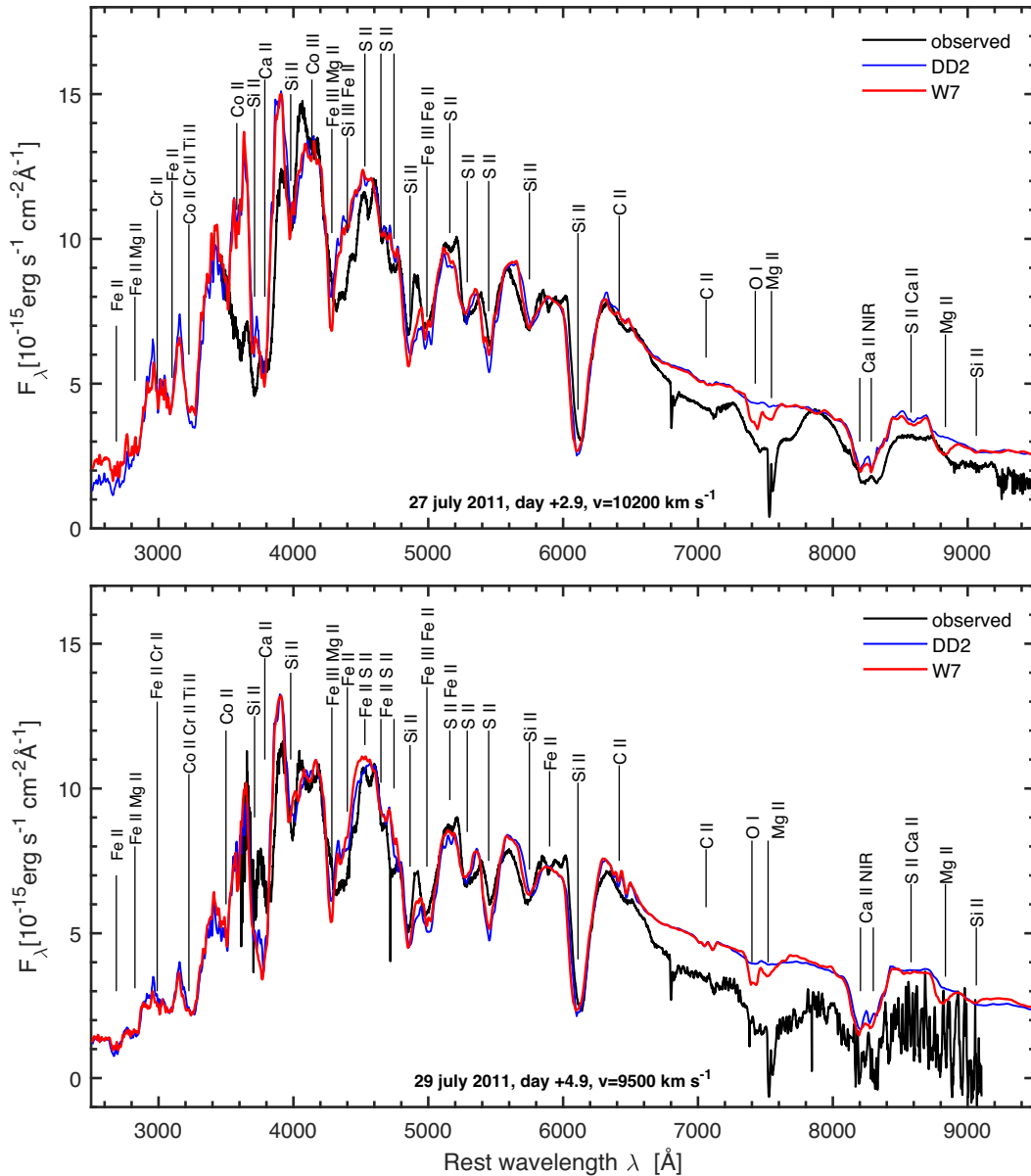


Figure 13. Spectra of SN 2012dn near maximum light overlaid with the synthetic spectra computed using the W7 and the DD2 density profiles depicted in red and blue, respectively.

ality, a significant fraction of the radioactive energy is deposited above the photosphere, a physical effect that is not captured by our model’s assumption of a blackbody-emitting surface located at the photosphere. Consequently, this discrepancy results in a synthetic flux excess at wavelengths beyond 6000 Å. However, this assumption does not impact the formation of the lines, neither the ionization conditions in the ejecta.

Fe-group elements: The feature near 4400 Å becomes increasingly dominated by blended absorptions of Fe II and Fe III, while the influence of Mg II and Si III weakens gradually.

The feature near 5000 Å remains split into two distinct components: The blue wing still shows a contribution from Si II, while the red component is now entirely dominated by Fe III and Fe II. This structure resembles normal SNe Ia (see fig. 3 of M. Tanaka et al. 2011), contrasting with 91T-like events where the feature appears broader and lacks two distinct components. In those

cases, higher ionization levels mean the feature is not influenced by Si II, leading to a different spectral morphology (M. Sasdelli et al. 2014; C. J. Aouad et al. 2022).

By two weeks post-maximum, the absorption feature near 4000 Å initially dominated by Si II becomes increasingly blended with Fe II and Co II transitions (see Fig. 16). Similarly, the emission peak on the red wing of the Ca II NIR triplet evolves to become entirely dominated by a blend of Co II lines by day +14.

The derived ^{56}Ni mass fraction in these layers does not exceed 0.45, while the total iron abundance is ~ 0.27 . At these epochs, approximately half of the iron originates from the decay of ^{56}Ni , with the remainder produced by direct explosive nucleosynthesis.

Calcium: The feature near 3800 Å shows little evolution, remaining dominated by photospheric Ca II in its redder component with a minor Si II contribution on the blue side. Similarly, the Ca II NIR triplet maintains a clear double-component profile.

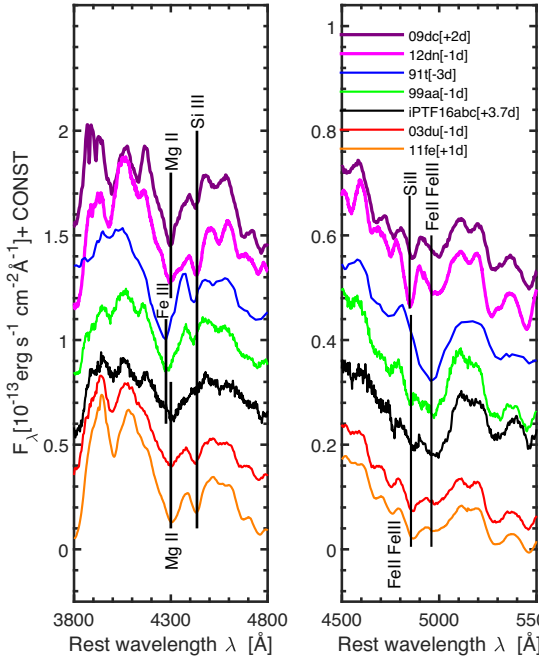


Figure 14. Left: The 4300 Å region shows Fe III absorption characteristic of 91T-like SNe, whereas Mg II dominates this feature in normal and 03fg-like SNe. The Si III contribution remains consistent across all types. Right: The 5000 Å region distinguishes 03fg-like events, where the blue component is driven by Si II $\lambda\lambda$ 5041, 5056, unlike the Fe II/Fe III blend seen in normal and 91T-like objects. This feature serves as a temperature indicator: The two components are well-separated in 03fg-likes but gradually blend as temperature increases, fusing into a single absorption in the hottest SN 1991T.

While these specific layers require no calcium to fit the current absorption (which originates from higher-velocity material), a small abundance (fractional percentage) is necessary in these deeper shells to account for later nebular-phase emission.

Silicon, Sulphur, Magnesium: At this phase, the Si II λ 6355 and λ 5972 lines continue to deepen. The model maintains its accurate reproduction of the $\mathcal{R}(\text{Si})$ ratio, confirming that the ionization balance and temperature structure established in earlier epochs remain consistent as. However, the modelled Si II λ 6355, line velocity could not be fully matched to the observed one, likely due to the development of a blend of emerging Fe II lines on the blue wing of the Si II feature, a behaviour also observed in SN 2009dc (S. Hachinger et al. 2012).

The blue component of the feature near 4800 Å continues to be shaped by a blend of Si II $\lambda\lambda$ 5055, 5041 and Fe II, sustaining the same behaviour observed from pre-maximum epochs through this post-maximum phase.

The absorption near 4000 Å, which was due to Si II λ 4130 in earlier spectra, is now dominated by Fe II and Co II by day +14. Similarly, the characteristic W-shaped Si II feature near 5400 Å remains well-defined at day +6; however, it gradually fades over the following week, and is barely discernible by day +14. Several Fe II lines shape the region 4500–4700 Å formerly shaped by blends of Si II lines.

As in normal SNe Ia, Mg II at 4400 Å gradually weakens, being fully replaced by Fe II and Fe III by day +14. However, Mg II remains detectable redward of O I near 7500 Å and in the 8800–9000

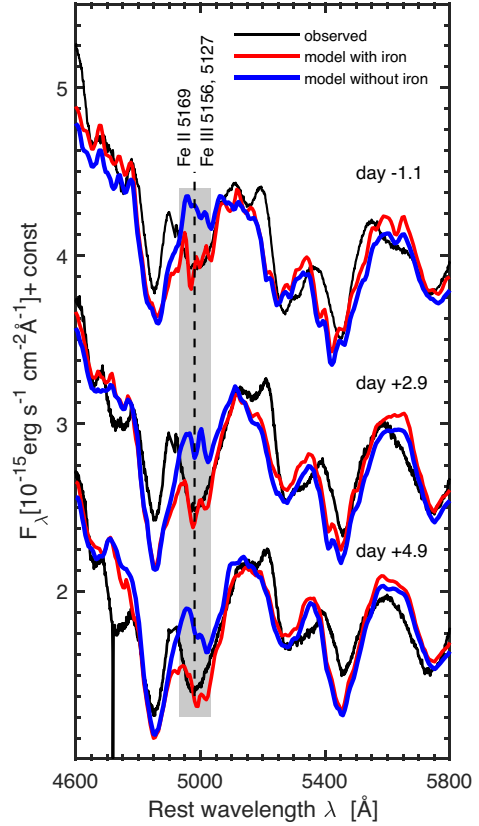


Figure 15. Probing stable iron in the intermediate shells. A stable iron abundance at the 10 per cent level (increasing from 7 per cent to 21 per cent across the shells) is required to reproduce the absorption feature near 5000 Å, which is dominated by a complex of Fe II and Fe III lines.

Å region. This latter feature, positioned redward of the flat-topped 8500 Å profile, is formed by Mg II $\lambda\lambda$ 9218, 9244.

Carbon, Oxygen: Carbon remains necessary ($X_C = 0.05$) between $7100 < v < 9100 \text{ km s}^{-1}$ to replicate the observed C II λ 6580 and λ 7234 features. This is supported by the C II λ 6580 velocity evolution, which drops from $\sim 12\,500 \text{ km s}^{-1}$ to $\sim 5900 \text{ km s}^{-1}$, confirming that unburned material persists at these lower velocities. Oxygen is similarly required in comparable abundances to fit the O I λ 7774 feature.

3.5 Comparison between W7 and DD profiles: density structure and its effect on line formation

Comparing the W7 model with delayed-detonation models (DD1, DD2) reveals differences in IME feature morphology. As shown in Fig. 17, the DD models produce overly broad and blueshifted absorptions because their extended outer density structures lower the ionization at high velocities, shifting line formation outward.

In contrast, W7 better reproduces these profiles. Its density enhancement at $12\,000\text{--}16\,000 \text{ km s}^{-1}$ (Fig. 4) promotes recombination, effectively confining these species to a narrower velocity shell. Ionization analysis (Fig. 18) confirms that the ion fractions of Si II, Mg II, S II, and O I peak sharply within this density bump, resulting in the more accurate, narrower absorption troughs observed in the synthetic spectra, mirroring the behaviour of the observed spectra with remarkable precision.

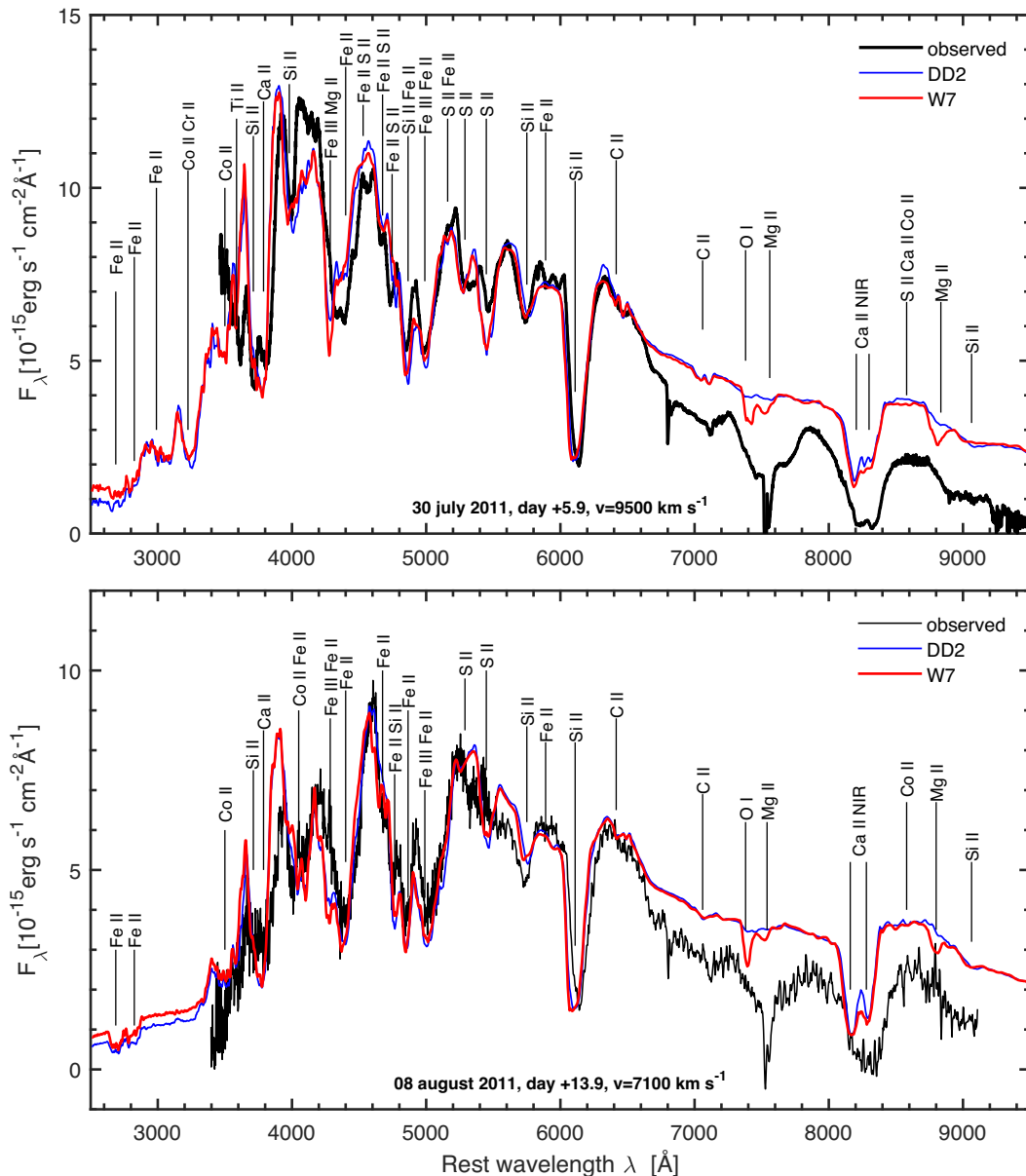


Figure 16. Spectra one week after maximum light of SN 2012dn overlaid with the synthetic spectra computed using the W7 and the DD2 density profiles depicted in red and blue, respectively.

4 THE NEBULAR PHASE

The nebular spectrum of SN 2012dn is unlike most SNe Ia. It is unusual by not showing strong [Fe III] emission, near 4850 Å in particular, but it is even more unusual by showing [O I] $\lambda\lambda$ 6300, 6363, a feature rarely observed in SNe Ia. This comes together with the unexpectedly low luminosity of the SN at late times, a property that SN 2012dn shares with one of the ‘prototypical’ 03fg-like or ‘super-Chandra’ SNe, SN 2009dc (S. Taubenberger et al. 2011).

Despite these issues, we attempted to model the spectrum with our nebular code in order to complete the tomographic description of the ejecta. Our code was described, e.g. in P. A. Mazzali et al. (2020). Starting from a density and abundance distribution, it first computes the emission and diffusion of γ -rays and positrons released by the decay of ^{56}Ni and ^{56}Co . These are as-

sumed to encounter an opacity of 0.027 and 7 g cm^{-2} , respectively, and are diffused using a Monte Carlo scheme (E. Cappellaro et al. 1997). They are assumed to release all of their energy when interacting, which is then transformed into heat, following, e.g. T. S. Axelrod (1980). This heating is then balanced by cooling via mostly emission lines, which gives rise to the observed spectrum. As many strong lines are in the optical domain, the emission line spectrum is typically strongest in the optical. Our model was developed taking into account two pieces of evidence: the [O I] emission at low velocity and the sharp dimming of the light curve after $\sim$ day 100. The first element calls for a small mass of oxygen at $v \lesssim 4000\text{ km s}^{-1}$. Explosion scenarios suggest that low-velocity oxygen may be dragged from a stripped or partially destroyed companion in a double degenerate merging event (R. Pakmor et al. 2010, 2012; M. Kromer et al. 2013). This material would be additional to any SN ejecta.

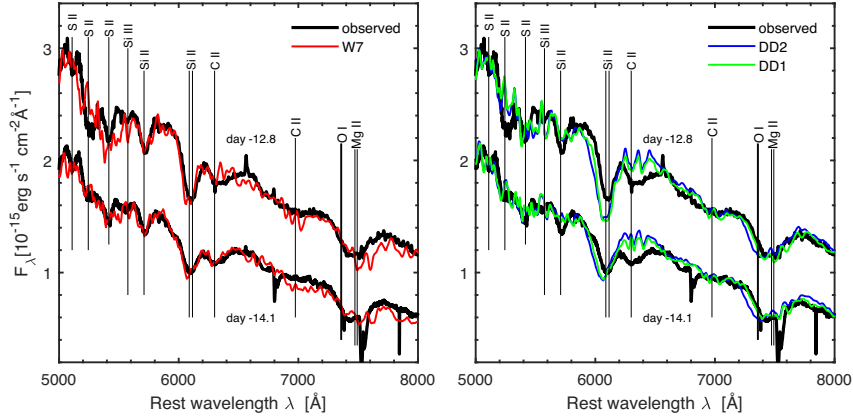


Figure 17. Comparison of observed and synthetic spectra at days -14 and -13 is presented. The W7 model successfully reproduces the narrow Si II feature near $6000 \text{ \AA}$, the Mg II O I blend near $7400 \text{ \AA}$, and the Si II feature near $5800 \text{ \AA}$, which the DD models fail to capture.

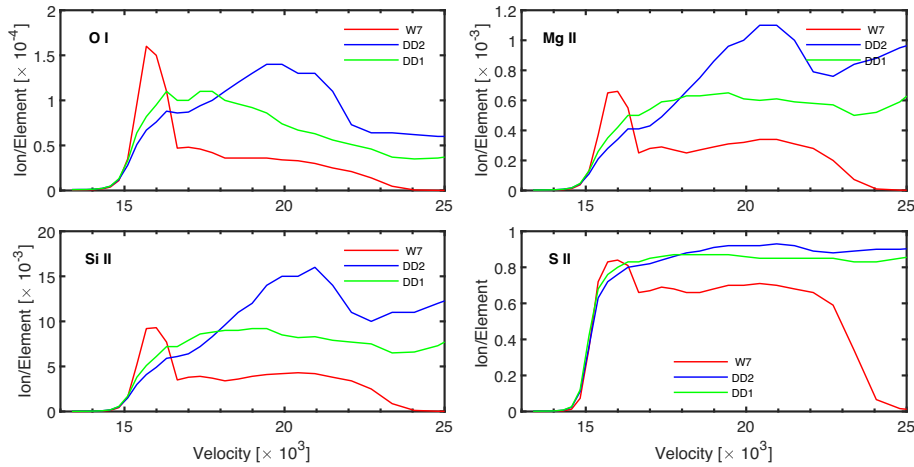


Figure 18. Ionization conditions in the ejecta at day -13 . In the W7 model, the density bump enhances recombination and lowers the overall ionization level, confining singly ionized Mg, Si, and S, as well as neutral O, within a narrow velocity region around $\sim 16,000 \text{ km s}^{-1}$. In contrast, the DD1 and DD2 profiles distribute these ions over a broader velocity range, causing line formation to occur across a more extended region of the ejecta and producing correspondingly bluer line wings (see Fig. 17).

The observed dimming appears roughly constant across all photometric bands, consistent with wavelength-independent (grey) extinction. We quantify this effect using two distinct methods: first, by comparing the weighted flux attenuation for each individual band relative to the normal SN 2003du at day 290 (see Fig. 3), and secondly, by independently evaluating the late-time bolometric light-curve trends (see also fig. 4 of S. Taubenberger et al. 2019). Both approaches yield a consistent dimming factor between 4 and 5, the detailed derivation of which is provided in Appendix A. If this grey attenuation is indeed caused by dust, asymmetric nebular emission-line profiles, with the red side appearing weaker than the blue, might be expected. The absence of such pronounced asymmetries in SN 2012dn, however, does not by itself rule out dust formation, as they are primarily expected for dust distributed throughout the inner ejecta, whereas dust confined to a shell or optically thick clumps may produce little or no line-profile asymmetry (L. B. Lucy et al. 1991; A. Bevan & M. J. Barlow 2016).

We therefore constructed two models with a ^{56}Ni mass four, and five times what is necessary to fit the observed nebular spectrum. The resulting spectra were then scaled down by these factors. Additionally, some mass ($0.3 M_{\odot}$) was added at low velocities

below 7000 km s^{-1} . The total mass is now $1.66 M_{\odot}$. Oxygen is ~ 20 per cent of the material that was added, ^{56}Ni is about 30 per cent, the rest being composed of IMEs which were necessary to preserve the overall look of the synthetic spectrum. The total ^{56}Ni mass in this model is $0.45\text{--}0.49 M_{\odot}$. The result using a factor of four is shown in Fig. 19. The model using a factor of five is indistinguishable.

Another SN Ia which is known to have shown [O I] emission at late times is SN 2010lp (S. Taubenberger et al. 2013a). This was a low-luminosity, SN 1991bg-like SN at early times. The nebular spectra could be best reproduced with a two-component model containing $\approx 0.18 M_{\odot}$ of ^{56}Ni , consistent with the low peak luminosity (P. A. Mazzali et al. 2022). The ejecta were consistent with a sub-Chandrasekhar mass. A low-mass progenitor white dwarf would have low central density and would not synthesize neutron-rich iron-group elements. Oxygen was located at low velocities, and an oxygen mass of $0.04 M_{\odot}$ was sufficient to match the observed [O I] 6300, 6363 $\text{\AA}$ emission line. This may be surviving oxygen from a double-degenerate white dwarf (WD) merger episode, although detailed models of a massive merger suggest a larger mass (M. Kromer et al. 2013). Interestingly, SN 2010lp

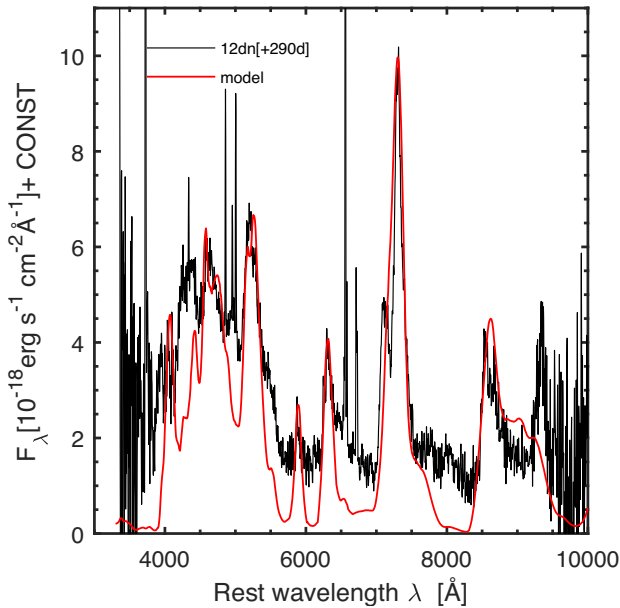


Figure 19. Nebular spectrum at 290 d after B maximum light. The red line is the model.

showed distinctly multiple emission peaks, supporting a DD origin for the event. Such multiple profiles are not observed in SN 2012dn, but the amount of oxygen is consistent with the high-mass DD model of M. Kromer et al. (2013). Other instances of [O I] emission include ASASSN-20jq, attributed to an off-centre delayed detonation in a M_{Ch} WD (P. Heflich et al. 2021; S. Bose et al. 2025), iPTF14atg (M. Kromer et al. 2016), and within the 03fg-like sub-group, SN 2022pul (M. R. Siebert et al. 2023b) and SN 2021zny (G. Dimitriadis et al. 2023).

5 ABUNDANCE TOMOGRAPHY

The yields derived from our modelling are summarized in Table 2 and shown in Fig. 20. The distribution of abundances is not very different from a normal SN Ia but it exhibits large-scale mixing. Oxygen extends deep into the core, reaching a total mass of $\sim 0.33 M_{\odot}$, with approximately $0.1 M_{\odot}$ located below 3000 km s^{-1} , a feature essential for reproducing the [O I] $\lambda\lambda$ 6300, 6364 emission in our nebular spectra. Carbon similarly persists down to $v \approx 6000 \text{ km s}^{-1}$ with a mass of $0.03 M_{\odot}$. Neutron-rich stable Fe-group elements, including ^{54}Fe and ^{58}Ni , are absent from the core. Stable iron ($0.11 M_{\odot}$) is additionally absent from the outermost layers, being instead confined to a shell between $6000 < v < 13000 \text{ km s}^{-1}$. While ^{56}Ni extends into deeper layers, it remains relatively poor in the core (at ≈ 30 per cent) and peaks within the same shell as the stable iron. In contrast, silicon ($0.54 M_{\odot}$) and sulfur ($0.14 M_{\odot}$) span the entire ejecta. The total burned mass is $\sim 1.25 M_{\odot}$, only about 10 per cent higher than in normal SNe Ia (P. A. Mazzali et al. 2007), with a total kinetic energy of $\approx 1.4 \times 10^{51} \text{ erg}$. A comparison with SN 2003du (M. Tanaka et al. 2011) is given in Fig. 20.

6 BOLOMETRIC LIGHT CURVE

We construct a pseudo-bolometric light curve in the 3000–10 000 Å range using photometry data from S. Taubenberger et al. (2019) in the *U*, *B*, *V*, *R*, *I* bands. Magnitudes are converted to flux us-

ing the flux zero points from M. Fukugita, K. Shimasaku & T. Ichikawa (1995), and dereddened with the extinction curve of J. A. Cardelli, G. C. Clayton & J. S. Mathis (1989), assuming a reddening value of 0.09 (see Section 2). The flux for each epoch is calculated using trapezoidal integration between the central wavelengths of each band. Beyond the *U* and *I* bands, the flux is extended to 3000 Å and 10 000 Å using a flat function similar to C. J. Aouad et al. (2022). Bolometric luminosities are then derived using a distance modulus of $\mu = 33.26 \pm 0.20 \text{ mag}$ (S. Taubenberger et al. 2019). However, 03fg-like SNe are known to exhibit enhanced NIR emission relative to the optical. Therefore, the *UBVRI* pseudo-bolometric light curve should be regarded as a lower limit to the true bolometric luminosity (C. Ashall et al. 2021).

The SN reaches a rest-frame peak luminosity of $L_{\text{peak}} = 1.35^{+0.27}_{-0.22} \times 10^{43} \text{ erg s}^{-1}$ with a rise time of 18.44 d. This peak is in the same range as the transitional SN 1999aa (C. J. Aouad et al. 2022) and the normal SN 2003du. Even assuming the maximum literature reddening of $E(B - V) = 0.18$; (N. K. Chakradhari et al. 2014), the resulting peak of $1.78^{+0.27}_{-0.22} \times 10^{43} \text{ erg s}^{-1}$ remains significantly fainter than extreme 03fg-like events like SN 2007if and SN 2009dc, which reach peak luminosities nearly twice that of SN 2012dn (S. Taubenberger et al. 2013a; C. Ashall et al. 2021). By day +60, the bolometric decline of SN 2012dn begins to deviate from that of normal SNe Ia, which typically follow a slope slightly steeper than the ^{56}Co decay rate. Notably, while SN 2009dc exhibits a similar decline, it does not do so until day +200. Comparisons with other SNe Ia are provided in Fig. 21, and various literature reports for the peak bolometric luminosity of SN 2012dn are summarized in Table 3.

Using our abundance results, we construct a synthetic bolometric light curve using a Monte Carlo radiative transfer code (E. Cappellaro et al. 1997; P. A. Mazzali et al. 2001). The code computes γ -ray and positron deposition from ^{56}Ni decay (T. S. Axelrod 1980) and follows the diffusion of optical packets through the ejecta. Opacity is dominated by line transitions, parametrized by local Fe-group abundances and temperature (A. W. A. Pauldrach et al. 1996; P. A. Mazzali & P. Podsiadlowski 2006). As expected, the model fails to reach the observed peak luminosity (Fig. 22). This discrepancy suggests that an additional energy source may be at play. For comparison, we plot the light-curve model of SN 2003du (V. Stanishev et al. 2007) normalized to our model peak. The two light curves exhibit nearly identical behaviour, with the primary difference being the broader width of SN 2012dn. This increased width, a direct consequence of the larger ejecta mass ($1.66 M_{\odot}$), provides a better fit to the observed evolution than a standard Chandrasekhar-mass profile.

7 VIABLE PROGENITOR-EXPLOSION CHANNELS

To power the peak of SN 2012dn via radioactive decay alone, $\sim 0.65 M_{\odot}$ of ^{56}Ni is required, based on its peak luminosity similarity to SN 1999aa and SN 2003du (M. Tanaka et al. 2011; C. J. Aouad et al. 2022). Our nebular model initially yields $0.45\text{--}0.49 M_{\odot}$ of ^{56}Ni , a range dictated by the uncertainty of the late-time grey-extinction factor. Allowing for a modest additional $\sim 0.05 M_{\odot}$ to account for residual continuum discrepancies between the observed and synthetic spectra (Fig. 19) raises the total to $\approx 0.54 M_{\odot}$, still below the value required to explain the peak luminosity. Even when adopting the upper limit of the inferred ^{56}Ni mass

Table 2. Nucleosynthetic yields and kinetic energies from the modelling compared to the original hydrodynamic models. Results from other SNe are also shown.

	^{56}Ni ($M_{\odot}$)	Fe ^a ($M_{\odot}$)	Ni _{stable} ($M_{\odot}$)	IME ^b ($M_{\odot}$)	O ($M_{\odot}$)	IME/Fe ^c	E_k (10^{51} erg)
2012dn	0.45	0.11	0.000	0.68	0.33	1.21	1.4
Original W7	0.59	0.16	0.1220	0.24	0.143	0.27	1.30
Original DD2	0.69	0.10	0.0540	0.33	0.066	0.39	1.40
Original DD3	0.77	0.10	0.0664	0.25	0.056	0.27	1.43
iPTF16abc ^d (DD2)	0.76	0.20	0.0060	0.19	0.21	0.20	1.32
1991T ^e (DD3)	0.78	0.15	0.0006	0.18	0.29	0.19	1.24
1999aa ^f (DD2)	0.65	0.29	0.0060	0.20	0.22	0.21	1.32
2003du ^g (W7)	0.62	0.18	0.0240	0.26	0.23	0.32	1.25
2002bo ^h (W7)	0.49	0.27	0.0001	0.28	0.11	0.37	1.24
2004eo ⁱ (W7)	0.32	0.29	0.0005	0.43	0.30	0.70	1.10

Notes. ^aStable isotopes excluding ^{56}Fe , ^{28}Si + ^{32}S , ^c ^{56}Ni + ^{54}Fe + ^{58}Ni ,

^dC. J. Aouad et al. (2024), ^eM. Sasdelli et al. (2014), ^fC. J. Aouad et al. (2022),

^gM. Tanaka et al. (2011), ^hM. Stehle et al. (2005), ⁱP. A. Mazzali et al. (2008).

range, a deficit persists relative to that required to power the peak. This suggests that even within the most flexible range of our abundance tomography, an additional energy source is required to bridge the remaining gap. This shortfall is likely reconciled by a supplemental energy contribution from ejecta interaction with a carbon- and oxygen-rich circumstellar material (CSM). Such a scenario is frequently invoked for 03fg-like events to explain their enhanced luminosity, persistent carbon features, and low ionization states (S. Hachinger et al. 2012; U. M. Noebauer et al. 2016; C. Ashall et al. 2021).

Following the methodology of S. Hachinger et al. (2012), we simulated this effect by reducing the radioactive luminosity in our models and compensating for the flux deficit with a black-body component. Our analysis at two distinct phases reveals that interaction can account for up to 25 per cent of the total flux at the early epoch, decreasing to 20 per cent near maximum light. Importantly, the inclusion of this component maintains the high quality of the spectral fits (see Fig. 23). This requirement is notably less extreme than the 50 per cent early-time contribution necessitated by SN 2009dc (S. Hachinger et al. 2012). Nevertheless, such a contribution comfortably bridges the gap between our derived ^{56}Ni mass and the observed peak luminosity. These findings suggest a shared physical origin for 03fg-like events, where CSM interaction provides a fundamental, yet highly variable, power source across the class regardless of the specific peak magnitude.

Such an interaction is a plausible consequence of a double-degenerate (DD) merger, a scenario that simultaneously accounts for both the central oxygen core and the circumstellar environment required for SN 2012dn. Similar observational characteristics have recently been reported for SNe 2021zny (G. Dimitriadis et al. 2023) and 2022pul (M. R. Siebert et al. 2023b), including an early-time flux excess consistent with ejecta-CSM interaction, persistent carbon features, low late-time ionization, reduced stable Fe-group elements abundances, and nebular [O I] emission, further supporting a double white dwarf merger origin (see also G. Dimitriadis et al. 2022; A. Dutta et al. 2022; J. Liu et al. 2026). Interestingly, *James Web Space Telescope* observations of SN 2022pul provide direct evidence for dust emission (M. R. Siebert et al. 2023b), demonstrating that dust formation can occur in 03fg-like SNe Ia. However, despite being only ~ 0.3 mag fainter than SN 2012dn in peak absolute *B*-band magnitude, SN 2022pul remained substantially brighter at late epochs. The substantially larger late-time luminosity deficit observed in SN 2012dn there-

fore demonstrates further that the strength of this effect varies significantly among members of the subclass.

Remarkably, our results resemble the 3D hydrodynamic simulations of a $1.1 + 0.9 M_{\odot}$ CO–CO white dwarf merger by R. Pakmor et al. (2012) to a high degree (see their fig. 2). Despite the 1D nature of our reconstruction compared to their 3D asymmetric models, the general abundance trends are remarkably consistent: Oxygen dominates the core and is surrounded by a shell of stable iron. Silicon extends from the outermost layers deep into the centre, ^{56}Ni abundance remains poor (≈ 30 per cent) in the innermost layers while carbon persists to intermediate shells. In their simulations, the primary white dwarf’s ashes expand and sweep around the secondary during the burning phase. Because this expansion occurs before the secondary completes its own nucleosynthesis, the secondary’s unburned material eventually dominates the inner ejecta. Although the lower-mass merger model of $0.9 + 0.76 M_{\odot}$ of M. Kromer et al. (2013), predicts nebular oxygen line, it synthesizes a ^{56}Ni mass far too low to account for the peak luminosity of SN 2012dn.

However, a discrepancy arises in the innermost composition: Our modelling suggests the absence of neutron-rich isotopes such as ^{58}Ni and ^{54}Fe in the core, whereas the merger models discussed above, predict measurable ^{58}Ni under solar-metallicity conditions, as also seen in the equal-mass $0.9 + 0.9 M_{\odot}$ model of R. Pakmor et al. 2010. However, low neutronization may reflect not only lower densities (and thus progenitor mass) but also low metallicity (W. D. Arnett 1982). The absence of neutron-rich ions in the core of SN 2012dn therefore suggests that both effects act to suppress their synthesis, consistent with our inferred low-metallicity progenitor.

Constraining the white dwarf mass ratio therefore requires hydrodynamical simulations and remains further complicated by the possible degeneracy with progenitor metallicity; nevertheless the CO–CO merger framework remains the most consistent explanation for the multifaceted properties of SN 2012dn.

8 CONCLUSIONS

We have presented our abundance tomography analysis of the 03fg-like SN 2012dn. This event is highly peculiar, exhibiting a peak luminosity comparable to normal SNe Ia while retaining 03fg-like spectroscopic hallmarks, such as narrow IME features, weak Fe III lines, and persistent carbon. Notably, in the neb-

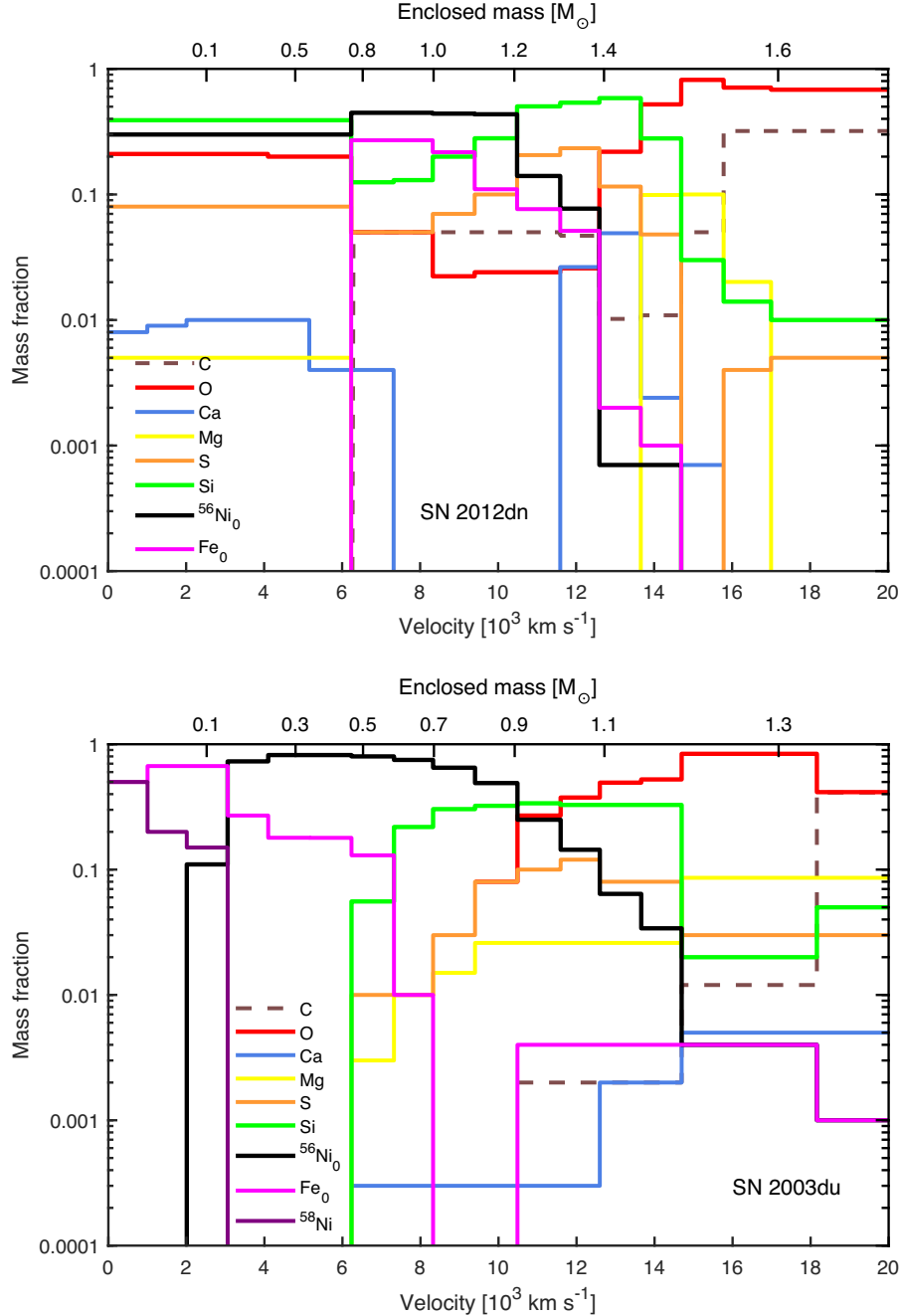


Figure 20. Abundance distributions of SN 2012dn (upper panel) compared to the normal SN 2003du. The two events show strikingly different core compositions: While the innermost layers of SN 2003du are dominated by neutron-rich iron-group elements and are entirely depleted of oxygen, SN 2012dn features a central oxygen reservoir. In this model, oxygen extends to the core, intermixed with silicon and sulfur, alongside a notably low ^{56}Ni abundance.

ular phase, SN 2012dn does not show strong [Fe III] emission, near 4850 Å and displays [O I] emission, rare among type Ia SNe and detected for the first time in this subclass. Furthermore, SN 2012dn exhibits an unusual wavelength-independent dimming starting ~ 60 d post-maximum, likely due to grey or clumpy dust formation. Our results can be summarized as follows:

(i) The photospheric phase is remarkably well-reproduced by a standard W7 Chandrasekhar-mass density profile. The W7 model outperforms delayed-detonation models (e.g. DD1, DD2) by accurately replicating the narrow absorption troughs. The density

enhancement in W7 at 12 000–16 000 km s^{-1} confines singly ionized species within a narrow velocity shell, preventing the overly broad, blueshifted features produced by DD models.

(ii) Modelling the nebular phase is inconsistent with a Chandrasekhar-mass model. Reproducing the [O I] emission necessitates a low-velocity mass component that brings the total inferred ejecta mass to $1.66 M_{\odot}$. This total includes $0.33 M_{\odot}$ of oxygen (of which $0.1 M_{\odot}$ is concentrated in the core). This oxygen-rich core is largely devoid of stable iron, which instead resides in a surrounding shell. The total ^{56}Ni mass, estimated in the range

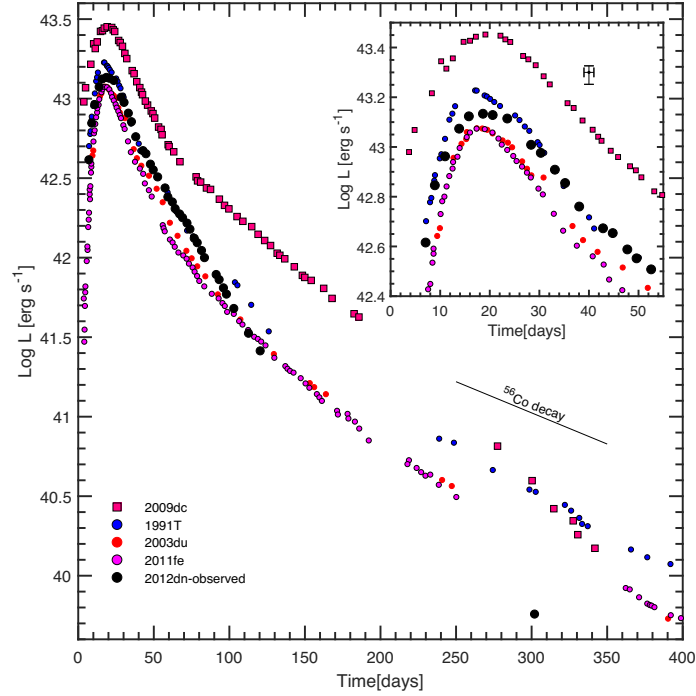


Figure 21. *UBVR* pseudo-bolometric light curve of SN 2012dn compared with SNe 1991T, 2003du, 2011fe, and 2009dc (V. Stanishev et al. 2007; S. Taubenberger et al. 2011; M. Sasdelli et al. 2014; K. Zhang et al. 2016). By ~ 60 d post-maximum, SN 2012dn undergoes a sharp decline, becoming significantly less luminous than the rest of the sample by day 300. SN 2009dc exhibits a similar drop ~ 100 d later; notably, both events follow a nearly identical, steep decline slope. The vertical error bar reflects the peak luminosity range of SN 2012dn based on the minimum and maximum distance moduli in the literature.

Table 3. Bolometric luminosity of SN 2012dn in the *U, B, V, R, I*.

Author	$\log L_{\text{peak}}$ (erg s^{-1})	Distance modulus	$E(B - V)$
S. Taubenberger et al. (2019)	43.075	33.26	0.10
N. K. Chakradhari et al. (2014)	43.17	33.15	0.18
This paper	43.12	33.26	0.09

($0.45\text{--}0.54 M_{\odot}$) is modulated by the bolometric factor required to account for the exceptionally low nebular-phase flux caused by grey or clumpy dust extinction. Carbon persists down to $v \approx 6000 \text{ km s}^{-1}$, while silicon and sulfur extend from the interior to the surface.

(iii) The derived ^{56}Ni yield is insufficient alone to power the peak luminosity. Regardless of the specific mass within our derived range, an additional energy source is required to bridge the remaining deficit. This shortfall in radioactive heating is reconciled by supplemental energy from ejecta-CSM interaction, which we model as a thermal blackbody component. By incorporating this component—accounting for up to 20 per cent of the maximum-light luminosity – we achieve a high-quality fit that compensates for the nickel mass discrepancy.

(iv) The derived abundance distribution resembles the outcomes of hydrodynamical models of DD mergers. In this scenario, unburned material from the secondary WD is dragged into the centre, creating an innermost volume dominated by unburned fuel rather than products of complete nucleosynthesis.

(v) The absence of stable iron in the outermost layers of the ejecta constrains the progenitor to subsolar metallicity. This provides a physical explanation for the unusually blue pre-maximum colours of SN 2012dn and supports the consensus that 03fg-like

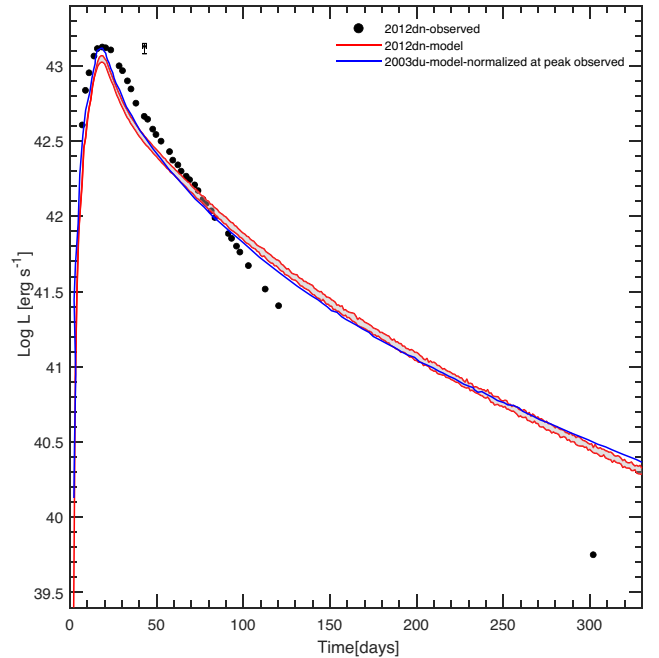


Figure 22. Observed *UBVR* pseudo-bolometric light curve of SN 2012dn (black dots) versus synthetic models (red lines) for $M(^{56}\text{Ni}) = 0.45\text{--}0.49 M_{\odot}$. The normal SN 2003du model (M. Tanaka et al. 2011), scaled to the observed peak (dashed blue), reveals an extinction of ~ 0.7 dex by day +300, highlighting significant late-time luminosity deviation of SN 2012dn. Despite their shared morphology, the model for SN 2012dn is broader than that for SN 2003du, reflecting its larger total ejecta mass.

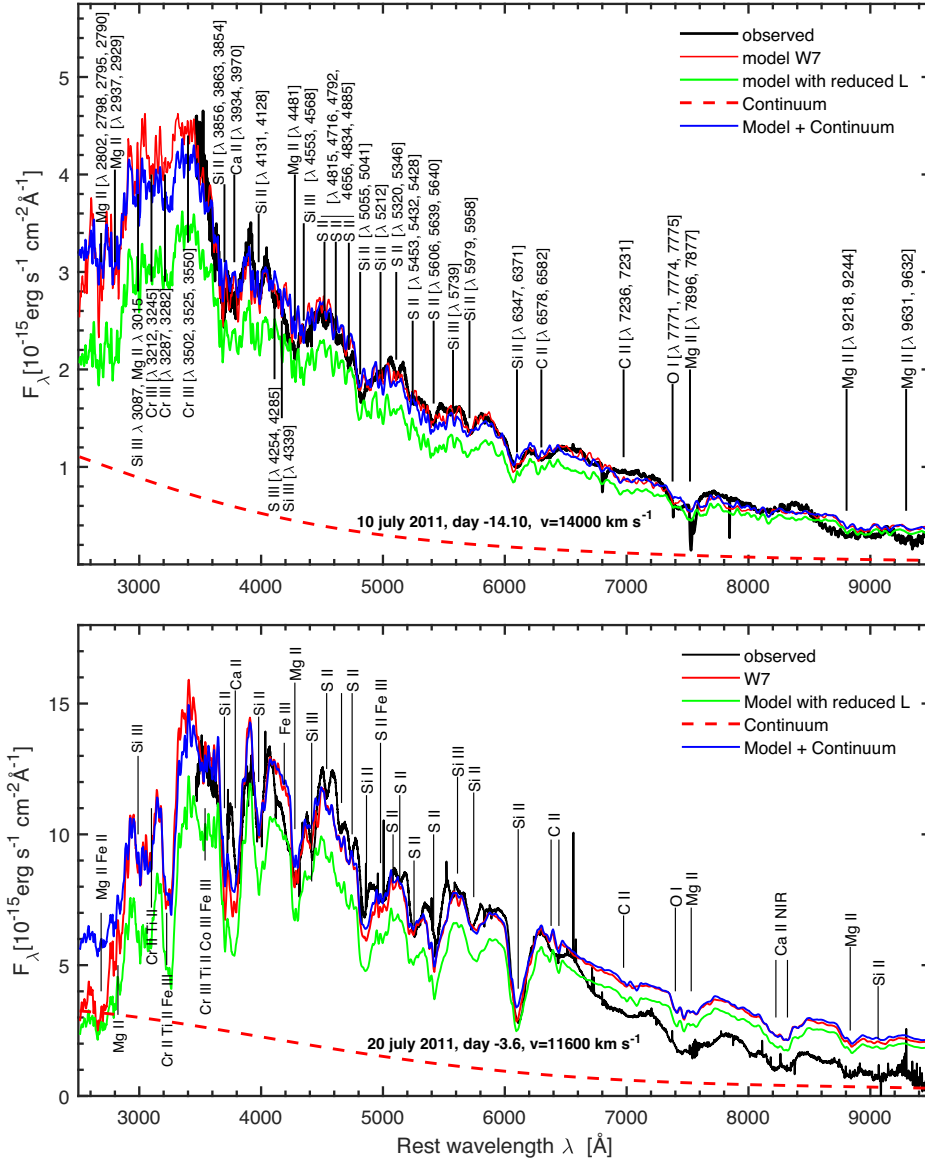


Figure 23. Comparison of observed and modelled spectra incorporating a blackbody (BB) component at two epochs (early and near-maximum light). The observed spectra are shown in black. The initial models are represented by red solid lines, while the models with reduced radioactive luminosity are shown in green. In these final models, the input luminosity was reduced by 25 percent for the early spectrum and 20 percent for the near-maximum spectrum. The red dashed lines represent the additional BB component required to account for the total luminosity, with temperatures of 14 000 and 11 000 K for the early and near-maximum epochs, respectively. The blue solid lines represent the total synthetic flux (the sum of the green model and the BB component).

events originate in metal-poor environments. This may imply that these events may be more common at higher redshift. Given their significant Hubble residuals, they remain a potential source of contamination in future high-redshift cosmological SN surveys.

(vi) This study highlights the necessity of late-time IR observations to recover the full bolometric budget in 03fg-like transients.

(vii) Hydrodynamic simulations of DD mergers involving varying white dwarf mass ratios are required to fully explain the peculiarities observed in SN 2012dn. Currently, the DD merger remains the most cohesive framework for this event; this progenitor channel not only provides the necessary structure for an oxygen-rich, iron-poor core, but also establishes the environments required for dust formation and ejecta-CSM interaction. Ultimately,

the variability in both ^{56}Ni production and strength of the supplemental CSM interaction may offer a consistent explanation for the wide range of peak luminosities observed across this class of objects.

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DATA AVAILABILITY

The spectroscopic data underlying this article are available at the WISEREP (O. Yaron & A. Gal-Yam 2012).

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APPENDIX A: ESTIMATING THE BOLOMETRIC DIMMING FACTOR

The bolometric extinction was estimated by comparing the observed *UBVRI* light curves of SN 2012dn to those of the normal SN Ia 2003du. After normalizing both data sets at peak brightness (see Fig. 4), the systematic offset between the two was interpreted as additional extinction. To determine the total bolometric effect, the extinction in each individual band was first converted into its corresponding transmitted flux fraction. These transmitted fractions were then weighted by the spectral energy distribution (SED) of the *UBVRI* bands, representing the fractional contribution of each photometric band to the total bolometric flux; the specific values adopted for this calculation are summarized in Table A1. Summing the weighted transmitted fluxes yields an observed bolometric flux of approximately 23 per cent of the intrinsic value, corresponding to a dimming factor of 4.5 ± 0.5 , given the inherent uncertainties in the photometric data. As an independent validation, the nebular-phase bolometric luminosity of SN 2012dn was compared with that of the normal Type Ia SN 2003du (normalized at peak). This comparison utilized the light curve from S. Taubenberger et al. (2019) (see their fig. 4), which suggests an attenuation factor of approximately 0.6 dex, as well as the pseudo-bolometric light curve computed in this work (Fig. 22), which yields approximately 0.7 dex. Both independent approaches provide a consistent attenuation factor range of 4–5.

Table A1. Band-dependent extinction values, corresponding flux transmission factors, SED fractions, and weighted transmitted flux contributions used to estimate the bolometric attenuation.

	<i>U</i>	<i>B</i>	<i>V</i>	<i>R</i>	<i>I</i>	Sum
Extinction (mag)	0.78	1.68	2.10	1.07	1.60	
Transmitted fraction a	0.49	0.21	0.14	0.37	0.23	
Bolometric weight b	0.02	0.45	0.24	0.15	0.14	1.00
Weighted transmission $(a \times b)$	0.01	0.10	0.03	0.06	0.03	0.23

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