On the Nature of Type Ia-CSM Supernovae: Optical and Near-Infrared Spectra of SN 2012ca and SN 2013dn

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ABSTRACT

A growing subset of Type Ia supernovae (SNe Ia) show evidence for unexpected interaction with a dense circumstellar medium (SNe Ia-CSM). The precise nature of the progenitor, however, remains debated owing to spectral ambiguities arising from a strong contribution from the CSM interaction. Late-time spectra offer potential insight if the post-shock cold, dense shell becomes sufficiently thin and/or the ejecta begin to cross the reverse shock. To date, few high-quality spectra of this kind exist. Here we report on the late-time optical and infrared spectra of the SNe Ia-CSM 2012ca and 2013dn. These SNe Ia-CSM spectra exhibit low [Fe III]/[Fe II] ratios and strong [Ca II] at late epochs. Such characteristics are reminiscent of the super-Chandrasekhar-mass (SC) candidate SN 2009dc, for which these features suggested a low-ionisation state due to high densities, although the broad Fe features admittedly show similarities to the blue “quasi-continuum” observed in some core-collapse SNe Ibn and IIn. Neither SN 2012ca nor any of the other SNe Ia-CSM show evidence for broad oxygen, carbon, or magnesium in their spectra. Similar to the interacting Type IIn SN 2005ip, a number of high-ionisation lines are identified in SN 2012ca, including [S III], [Ar III], [Ar X], [Fe VIII], [Fe IX], and possibly [Fe XI]. The total bolometric energy output does not exceed $10^{51}$ erg, but does require a large kinetic-to-radiative conversion efficiency. All of these observations taken together suggest that SNe Ia-CSM are more consistent with a thermonuclear explosion than a core-collapse event, although detailed radiative transfer models are certainly necessary to confirm these results.

Key words: circumstellar matter — supernovae: general — supernovae: individual (SN 1997cy, SN 1988Z, SN 1998S, SN 2002ic, SN 2005gj, SN 2005ip, SN 2006jc, SN 2007gr, SN 2008J, SN 2009dc, SN 2009ip, SN 2010jl, SN 2011hw, PTF11kx, SN 2012ca, SN 2013cj, SN 2013dn, SN 2014J)
1 INTRODUCTION

Type Ia supernovae (SNe Ia; see Filippenko 1997 for a review) are attributed to the thermonuclear explosion of a C/O white dwarf (WD) primary star that approaches the Chandrasekhar limit by accreting material from a companion star. While the nature of the companion remains somewhat ambiguous, recent arguments suggest that a WD companion (i.e., a double-degenerate progenitor) is more commonplace than the single-degenerate scenario (see Maoz et al. 2013 for a review). Given that these highly evolved stars have long since shed their outer envelopes, the surrounding circumstellar medium (CSM) is expected to have a relatively low density. In fact, the lack of a significant CSM is one of the primary reasons SNe Ia can be used as precise cosmological distance indicators (e.g., Phillips 1993).

A growing number of SNe Ia, however, show evidence of interaction with a dense CSM during the first year post-explosion, and sometimes longer (Silverman et al. 2013; and references within). Classified as SNe Ia-CSM, the spectra have Type Ia features (e.g., Si II and Si II absorption lines) near maximum light that are weaker than usual, most likely diluted by a strong continuum (e.g., Leloudas et al. 2013). The spectra also have relatively narrow hydrogen emission lines, which arise from the dense and slowly moving CSM formed by pre-SN mass loss that is more typically associated with core-collapse SNe IIn (Schlegel 1990; Filippenko 1997). These dense environments suggest that either (a) single-degenerate progenitor scenarios are responsible for these explosions, or (b) the exploding star was not a thermonuclear explosion of a white dwarf at all.

The SN Ia-CSM progenitor explosion mechanism (i.e., thermonuclear versus core collapse) remains debated in the literature (e.g., Inserra et al. 2014). For example, the two most well-studied SN Ia-CSM templates (SNe 2002ic and PTF11kx) were classified as SNe Ia at early times, showing a resemblance to the overluminous SN 1991T (Hamuy et al. 2003; Deng et al. 2004; Wood-Vasey et al. 2004; Dilday et al. 2012; Silverman et al. 2013a). Compared to SNe IIn, weaker and narrower He, Hβ, and O lines in SNe Ia-CSM further support arguments for a thermonuclear origin (Silverman et al. 2013a). For this case of a thermonuclear explosion, Hamuy et al. (2003) propose the dense CSM may be attributed to an evolved secondary star (i.e., single-degenerate binary progenitor).

Alternatively, other SNe Ia-CSM show less obvious S or Si at early times (e.g., SNe 1997cy and 2005gj), but are only classified as SNe Ia-CSM because later spectra exhibit iron features and/or match SNe 2002ic and PTF11kx very well (e.g., Germany et al. 2004; Aldering et al. 2006; Benetti et al. 2006) argue for a core-collapse origin instead, given that some SNe Ic features (e.g., SN 2004aw) can be confused for SNe Ia at early phases if considering only similarities of 6300 Å features most often attributed to Si II λ6355. Furthermore, Inserra et al. (2014) make line identifications of intermediate/heavy elements in the spectra of the SN Ia-CSM 2012ca that are consistent with a core-collapse explosion of an evolved massive star. The ambiguity is compounded by the fact that the available catalogs of SN Ia spectra already suggest a number of degeneracies in the spectroscopic classification process (see Parent et al. 2014 for a review). Furthermore, spectroscopic models of thermonuclear SNe with CSM interaction (CSI) have not yet been constructed. Owing to the strong CSI and underlying continuum, even post-photospheric phase spectra may offer little evidence about the ejecta composition to connect with the pre-maximum spectral type and the related progenitor system (Leloudas et al. 2013).

SN 2012ca stands out as being one of the most nearby SNe Ia-CSM (79 Mpc; see Table 1), allowing for high-resolution data having a high signal-to-noise ratio (S/N), even at late times after the CSI has faded and the ejecta begin to cross the reverse shock. Here we present new optical and infrared (IR) spectra of SN 2012ca, along with a number of other SNe Ia-CSM, SNe IIn, and SNe Ia. We compare the line identifications of Inserra et al. (2014) among the various spectra in our database. In particular, we consider the case of the SN Ia-CSM 2013dn, for which we have well-sampled, high-S/N spectra through day ∼441 post-maximum. Section 2 presents the observations, while 3 concerns the detailed comparison of the spectra to other SN types. In 4 we discuss the implications on the SN Ia-CSM progenitor, and 5 summarises our conclusions.

| Table 1. Summary of Distances to Reported SNe Ia-CSM |
|-----------------|--------------|----------------|
| SN               | Distance (Mpc) | Reference       |
| 2014ab           | 95            | ATel 4076       |
| 2014T            | 375           | CBET 3815       |
| 2014Y            | 162           | CBET 3824       |
| 2013dn           | 233           | CBET 3570       |
| 2013I            | 144           | CBET 3386       |
| 2012ca           | 79            | CBET 3101       |
| CSS120327:110520-015205 | 215    | ATel 4081       |
| 2011dz           | 100           | CBET 2761       |
| 2011jb           | 142           | CBET 2947       |
| PTF11kx          | 194           | Dilday et al. 2012 |
| PTF10htz         | 147           | Silverman et al. 2013b |
| 2009in           | 98            | CBET 1953       |
| 2008J            | 92            | CBET 1218       |

2 OBSERVATIONS

This paper presents new data on SNe Ia-CSM 2012ca and 2013dn and SNe In 2005ip and 2006ip. SN 2012ca was discovered in the late-type spiral galaxy ESO 336-G009 on 2012 Apr. 25.6 (UT dates are used throughout this paper) at redshift z = 0.019 (m_r ≈ 14.8 mag; Drescher et al. 2012; Inserra et al. 2014). The earliest spectrum matches that of SN Ia-CSM 1997cy at an estimated ∼ 60 days post-maximum (Inserra et al. 2013; Valenti et al. 2013), although the peak of SN 1997cy was never observed (Germany et al. 2004; Turatto et al. 2000). Similar to Inserra et al. (2014), we take the light-curve peak to be 2012 Mar. 2.

SN 2013dn was discovered in the galaxy PGC 71942 on 2013 Jun. 14.45 at z = 0.056 (m_r ≈ 16.2 mag; Drake et al. 2013). The earliest spectrum (2013 Jun. 26.13) matches that of SN Ia-CSM 2005gj at 54 days post-explosion (Drake et al. 2014), although at this redshift the derived absolute magnitude (∼ −21.1) is somewhat brighter than that derived for SN 2005gj around maximum light. Given that SN 2005gj peaks ∼ 32 days post-explosion in the r

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Table 2. RATIR Photometry of SN 2013dn

| JD − 2,450,000 | Epoch (days) | r       | i       | Z       | Y       | J       | H       | Log L<sub>opt</sub>/(erg s<sup>−1</sup>) |
|----------------|--------------|---------|---------|---------|---------|---------|---------|----------------------------------------|
| 6510           | 100          | 17.00 (0.02) | 17.01 (0.02) | 16.61 (0.02) | 16.78 (0.03) | 17.16 (0.03) | 17.18 (0.04) | 43.12 |
| 6519           | 115          | 17.25 (0.02) | 17.01 (0.02) | 16.74 (0.02) | 16.92 (0.03) | 17.37 (0.03) | 17.26 (0.04) | 43.39 |
| 6539           | 135          | 17.30 (0.02) | 17.20 (0.02) | 16.93 (0.02) | 17.08 (0.03) | 17.56 (0.06) | 17.44 (0.08) | 43.29 |
| 6546           | 142          | 17.48 (0.02) | 17.40 (0.02) | 17.06 (0.02) | 17.21 (0.03) | 17.67 (0.03) | 17.57 (0.04) | 43.26 |
| 6551           | 147          | 17.42 (0.02) | 17.34 (0.02) | 16.96 (0.02) | 17.25 (0.03) | 17.77 (0.05) | 17.59 (0.08) | 43.23 |
| 6562           | 158          | 17.53 (0.02) | 17.43 (0.02) | 17.03 (0.02) | 17.29 (0.03) | 17.86 (0.05) | 17.75 (0.07) | 43.20 |
| 6579           | 175          | 17.85 (0.02) | 17.61 (0.02) | 17.15 (0.03) | 17.54 (0.04) | 18.13 (0.05) | 17.98 (0.08) | 43.11 |
| 6591           | 187          | 18.04 (0.02) | 17.73 (0.02) | 17.21 (0.02) | 17.72 (0.04) | 18.10 (0.05) | 18.11 (0.08) | 43.09 |
| 6606           | 202          | 17.99 (0.02) | 17.88 (0.02) | 17.34 (0.02) | 17.98 (0.04) | 18.35 (0.06) | 18.44 (0.09) | 43.02 |
| 6612           | 208          | 18.01 (0.02) | 17.90 (0.02) | 17.93 (0.03) | 18.09 (0.04) | 18.30 (0.06) | 18.21 (0.09) | 42.98 |
| 6621           | 217          | 18.11 (0.02) | 18.03 (0.02) | 17.47 (0.03) | 18.18 (0.04) | 18.44 (0.06) | 18.72 (0.09) | 42.95 |
| 6632           | 228          | 18.16 (0.02) | 18.08 (0.02) | 17.51 (0.03) | 18.31 (0.04) | 18.48 (0.06) | 18.77 (0.09) | 42.94 |
| 6638           | 234          | 18.30 (0.02) | 18.21 (0.02) | 17.62 (0.03) | 18.27 (0.04) | 18.60 (0.06) | 18.71 (0.09) | 42.89 |
| 6680           | 276          | 18.57 (0.02) | 18.46 (0.02) | 17.90 (0.03) | 18.59 (0.04) | 18.07 (0.09) | 18.13 (0.19) | 42.81 |
| 6821           | 417          | 19.95 (0.03) | 19.97 (0.04) | 19.49 (0.05) | –       | >19.00   | >18.75   | 42.26 |

**Figure 1.** Optical/IR light curve of SN 2013dn. Black arrows signify epochs at which optical spectra were obtained. The red arrow marks the epoch at which the near-IR spectrum was obtained.

2.1 Optical and Near-Infrared Photometry

Photometry of SN 2013dn was obtained with the multichannel Reionization And Transients InfraRed camera (RATIR; Butler et al. 2012) mounted on the 1.5-m Johnson telescope at the Mexican Observatorio Astronómico Nacional on Sierra San Pedro Mártir in Baja California, Mexico (Watson et al. 2013). Typical observations include a series of 80-s exposures in the ri bands and 60-s exposures in the ZYJH bands, with dithering between exposures. RATIR’s fixed IR filters cover half of their respective detectors, automatically providing off-target IR sky exposures while the target is observed in the neighbouring filter. Master IR sky frames are created from a median stack of off-target images in each IR filter. No off-target sky frames were obtained on the optical CCDs, but the small galaxy size and sufficient dithering allowed for a sky frame to be created from a median stack of all the images in each filter. Flat-field frames consist of evening sky exposures. Given the lack of a cold shutter in RATIR’s design, IR dark frames are not available. Laboratory testing, however, confirms that the dark current is negligible in both IR detectors (Fox et al. 2012).

The data were reduced, coadded, and analysed using standard CCD and IR processing techniques in IDL and Python, utilizing online astrometry programs SExtractor and SWarp. Calibration was performed using field stars with

1 SExtractor and SWarp can be accessed from [http://www.astromatic.net/software](http://www.astromatic.net/software).
CCD processing and spectrum extraction were completed (e.g., Foley et al. 2003; Silverman et al. 2012b). Routine and 1200 line mm$^{-1}$ Channel (BC) spectrograph (Schmidt et al. 1989). The 300 also obtained from the MMT 6.5-m telescope using the Blue. 

...aligned along the parallactic angle to minimise differential 10-m Keck II telescope. Most observations had the slit... 

Additional spectra were obtained with the Hiltner 2.4 m telescope at MDM Observatory using the Boller & Chivens CCDS spectrograph. The 150 line mm$^{-1}$ grating was used with a 1.2$''$ slit to yield spectra having a full width at half-maximum intensity (FWHM) resolution of 12 Å. Data were also obtained from the MMT 6.5-m telescope using the Blue Channel (BC) spectrograph. The 300 and 1200 line mm$^{-1}$ gratings were used in conjunction with a 1.0$''$ slit to yield spectra having FWHM resolutions of 7 and 2 Å, respectively. 

The spectra were reduced using standard techniques (e.g., Foley et al. 2003; Silverman et al. 2012b). Routine CCD processing and spectrum extraction were completed with IRAF and the data were extracted with the optimal algorithm of Horne (1986). We obtained the wavelength scale from low-order polynomial fits to calibration-lamp spectra. Small wavelength shifts were then applied to the data after cross-correlating a template-sky spectrum to an extracted night-sky spectrum. Using our own IDL routines, we fit a spectrophotometric standard-star spectrum to the data in...
Table 4. Summary of Infrared Spectra

| SN      | JD − 2,450,000 | Epoch (days) | Instrument          |
|--------|----------------|--------------|---------------------|
| 2014J  | 6727           | 36           | TripleSpec (APO)    |
|        | 6766           | 95           | TripleSpec (APO)    |
| 2013dn | 6559           | 133          | TripleSpec (APO)    |
| 2012ca | 6053           | 70           | FIRE                |
|        | 6087           | 104          | FIRE                |
| 2010jl | 5657           | 170          | TripleSpec (APO)    |
|        | 6727           | 1233         | TripleSpec (APO)    |
| 2005ip | 4547           | 884          | TripleSpec (APO)    |
|        | 4580           | 917          | TripleSpec (APO)    |
|        | 6727           | 3064         | TripleSpec (APO)    |
| 2008J  | 4714           | 234          | TripleSpec (APO)    |
| 2007gr | 4376           | 35           | TripleSpec (Palomar)|
|        | 4450           | 109          | FIRE                |

order to flux calibrate the SN and to remove telluric absorption lines (Wade & Horne 1988; Matheson et al. 2000). Other optical spectra used throughout this paper were obtained from both the Berkeley Supernova Database (Silverman et al. 2012) and the Weizmann Interactive Supernova data REPository (WISERep: Yaron & Gal-Yam 2012).

2.3 Near-Infrared Spectroscopy

Table 4 summarises the details concerning new near-IR spectra presented in this paper. Some data were obtained with TripleSpec spectrographs (Wilson et al. 2004; Herter et al. 2008) operating at both the Apache Point Observatory 3-m and the Palomar Observatory 5-m telescopes. TripleSpec observations typically consisted of 300-s exposures, taken at varying locations along the slit and then pair-subtracted to allow for the correction of night-sky emission lines. We extract the spectra with a modified version of the IDL-based SpecTool (Cushing et al. 2004). The underlying galaxy and sky emission are approximated by a polynomial fit and subtracted from the supernova. A-type calibration stars were observed directly after each SN exposure to remove telluric absorption lines using the IDL-based xtellcor package (Vacca et al. 2003). The day +917 of SN 2010jl was previously published by Borish et al. (2014), along with the full near-IR evolution of SN 2005ip from earlier epochs.

Other IR spectra were obtained with the Folded-port InfraRed Echellette (FIRE) spectrograph at the Magellan 6.5-m telescope (Simcoe et al. 2008). The FIRE spectra were obtained in the high-throughput prism mode with a 0′′6 slit. This configuration yields a continuous wavelength coverage from 0.8 to 2.5 μm with a resolution of R ≈ 500 in the J band. When acquiring the supernova, the slit was oriented at the parallactic angle to minimise the effect of atmospheric dispersion (Filippenko 1982). At each epoch, several frames were obtained using the conventional ABBA “nod-along-the-slit” technique and the “sampling-up-the-ramp” read-out mode. The per-frame exposure time was between 95.1 and 158.5 s, depending on the brightness of the supernova.

These exposure times were chosen such that adequate signal was obtained in each frame without saturating the bright night-sky lines in the K band. At each epoch, an A0V star was observed close to the science observations in time, angular distance, and airmass for telluric correction, as per the method described by Vacca et al. (2003).

The data were reduced using the IDL pipeline firehose, specifically designed for the reduction of FIRE data. The pipeline performed steps of flat fielding, wavelength calibration, sky subtraction, spectral tracing, and spectral extraction. The sky flux was modeled using off-source pixels as described by Kelson (2003) and subtracted from each frame. Next, the spectral extraction was performed using the optimal technique (Horne 1986), a weighting scheme that delivers the maximum S/N while preserving spectrophotometric accuracy. Individual spectra were then combined with sigma clipping to reject spurious pixels. Corrections for telluric absorption were performed using the IDL tool xtellcor developed by Vacca et al. (2003). To construct a telluric correction spectrum free of stellar absorption features, a model spectrum of Vega was used to match and remove the hydrogen lines of the Paschen and Brackett series from the A0V telluric standard. The resulting telluric correction spectrum was also used for flux calibration.
3 ANALYSIS OF THE SPECTRA

3.1 Early-Time Optical Spectra

Figure 4 illustrates the early-time evolution of several SNe ranging from days +9 to 56, including the SNe Ia-CSM 2013dn (orange), 2008J (green), and PTF11kx (dark blue), and the overluminous SN Ia 1991T (light blue). Owing to difficulties in identifying and removing the continuum, we instead apply a minimal degree of artificial reddening or dereddening for plotting purposes in Figure 4. This reddening/dereddening does not change the presence of any spectral lines and is not applied during the analysis of the spectra elsewhere in the article (although we deredden SN 2008J throughout the paper by a factor consistent with measurements of Taddia et al. 2012). Vertical grey bars highlight several of the more prominent narrow features, solid grey vertical bars mark a few of the broader features, and solid blue vertical bars show some of the more prominent P Cygni features. Not all lines appear in all spectra. Also note that the 6500 Å feature in SN 1991T is a blend of [Fe II] and Co, not Ha.

3.2 Late-Time Optical Spectra

Figure 5 compares the SNe Ia-CSM at later epochs, ranging from days +202 to 282. We also consider the Type Ia SN 1991T (light blue) and the broad-lined Type Ic SN 1998bw (red) given their widespread use in other papers (e.g., Inserra et al. 2014). The reader should be aware, however, of several conditions that make a direct comparison difficult. First, strong circumstellar lines and an underlying continuum dominate the spectra of the interacting SNe, but are not necessarily associated with the exploding star or ejecta. A cold, dense shell (CDS) can form between the forward and reverse shocks that, if optically thick, may further obscure the underlying ejecta. Second, the continuum levels are difficult to identify since the blue flux shortward of 5500 Å in the SNe Ia-CSM may arise from a “quasi-continuum” produced by many overlapping permitted and forbidden lines of iron-group elements (e.g., Deng et al. 2004, Bowers et al. 1997, Branch et al. 2008, Silverman et al. 2013b). Third, the nebular spectra of SNe Ia do not have many unique or unambiguous characteristic features among various SN Ia subtypes (see Fig. 13 of Parent et al. 2014). We discuss the implications of these effects on our interpretation in §4.

Figure 6 compares different SN types on a linear scale over different epochs at late-times. The linear scale highlights the relative line intensities more clearly than the log scale in Figure 4. All spectra are scaled by a multiplicative factor to highlight features relative to the likely continuum, which we identify as being just redward of Hα (~6800 Å) and just blueward of He I λ5876. The SNe Ia-CSM have three distinguishing traits: (1) a low [Fe III] λ4700/[Fe II]
Figure 6. (top) Comparison of SN 2012ca (black) at later epochs to the Type Ia SN 199T (light blue), the super-Chandrasekhar-mass (CS) candidate Type Ia SN 2009dc (pink), and the Type Ibn SN 2006jc (green). (bottom) Comparison of SN 2013dn (orange) at ∼200 days to the CS candidate Type Ia SN 2009dc (pink), the Type IIn SN 2009ip (brown), the Type Ibn SN 2006jc (green), and the broad-lined Type Ic SN 1998bw (red). Dashed vertical lines highlight several of the more prominent narrow features, while solid grey vertical bars mark a few of the broader iron features. Unlabeled dotted black lines correspond to [Fe III].
Figure 7. Comparison of late-time spectra, including the Type Ia-CSM SN 2013dn (orange), the Type Ia-CSM SN 2012ca (black), the Type IIn SN 2009ip (brown), and the Type IIn SN 2006ip (pink). Inserra et al. (2014) identify oxygen and carbon in the spectrum of SN 2012ca, all blueshifted by $\sim 2500$ km s$^{-1}$. Dashed vertical lines highlight the positions of these spectral lines at rest (grey) and blueshifted (dark blue). Surprisingly, these spectral lines also appear in SNe 2005ip, 2013dn, and 2008J at the same blueshift. Unlikely to be a coincidence, in the text we argue alternative line identifications.

$\lambda 5200$ ratio, (2) weak [O I] $\lambda 6300$, and (3) weak Mg I $\lambda 4570$. The lack of obvious iron (thermonuclear) and/or intermediate mass (core-collapse) signatures is the very characteristic that led to the ambiguity surrounding the SNe Ia-CSM in the first place.

3.2.1 Low [Fe III]/[Fe II] ratio

Inserra et al. (2014) point out, in favour of their core-collapse progenitor argument, that the dominant [Fe III] features observed in most nebular SNe Ia (e.g., SN 1991T and even PTF11kx) are not observed in SN 2012ca, even after accounting for dilution by a continuum. Figure 6 highlights blended [Fe III] lines at $\sim 4700$ Å, which Resen & Hurford (1996) decompose into a number of individual components at 4658.10, 4701.62, 4733.93, 4754.83, 4769.60, and 4777.88 Å. Another iron blend, composed primarily of [Fe II], is centered at $\sim 5200$ Å. Indeed, the [Fe III]/[Fe II] ratio in SNe 2012ca and 2013dn is significantly lower than that in SN Ia 1991T. The ratio is similarly low, however, in the SC candidate SN 2009dc, the SN Iin 2006jc, and the SN IIn 2009ip, although the strengths of the features do vary. We further discuss these comparisons in § 4.

3.2.2 No Oxygen or Carbon Detected

Inserra et al. (2014) further argue for a core-collapse origin of SN 2012ca based on the identification of (1) oxygen, (2) carbon, (3) magnesium, and (4) helium. We examine the oxygen and carbon lines here in more detail, and discuss magnesium and helium below in § 3.3. Figure 7 plots SN 2012ca (black) alongside the SN Ia-CSM 2013dn (orange) and SNe IIn 2005ip (pink) and 2009ip (brown). Note that the late-time spectra of SNe 2009ip and 2012ca (> 400 days) likely reflect the nebular phase during which the emission lines are generated primarily by the ejecta. In this case, we believe the emission lines are less dominated by CSI and more representative of the SN ejecta.

Oxygen: Inserra et al. (2014) specifically identify the O I $\lambda 7774$, [O I] $\lambda 6300$, 6364, and [O II] $\lambda\lambda 7254$ lines, all blueshifted by $\sim 2500$ km s$^{-1}$. Blueshifted lines can be expected in late-time spectra as absorption from the dense ejecta obscures emission from the receding SN hemisphere. Milisavljevic et al. (2012) observe this effect in a number of late-time core-collapse SN spectra, but the blueshifted velocities range from 500 km s$^{-1}$ up to $> 3000$ km s$^{-1}$. Silverman et al. (2013b) point out that these lines are indeed lacking from their SN Ia-CSM sample (although they do concede that part of the very broad emission feature around 7400 Å may be a blend of [O II] $\lambda\lambda 7319, 7330$ and [Ca II] $\lambda\lambda 7291, 7324$).

Vertical dashed lines in Figure 7 mark these oxygen lines both in the rest frame (grey) and blueshifted (blue), while Figure 8 plots the corresponding velocity profiles. Taken on its own, SN 2012ca does exhibit strong lines that could be considered consistent with blueshifted oxygen, but we identify the $\lambda 7774$ and $\lambda 6300$, 6364 lines at the exact same blueshift in SNe 2005ip, 2013dn, 2008J, 2006ip, and 1998S. The lack of any velocity spread between the SNe is curious, especially considering that the [O II] $\lambda 7254$ line is missing in SNe 2013dn and 2008J. We suggest the lines that appear to
be consistent with blueshifted oxygen actually corresponding to blueshifts of ~ 2500 km s\(^{-1}\), a line consistent with Ca II exists. This line, in fact, is the dominant line identified in the spectra presented by Inserra et al. (2014). Some carbon does exist, however, in SNe 2013dn and 2012ca, but not in the Type II SN 2005ip.

Figure 9. Velocity profiles of spectra plotted in Figure 8 plus the Type IIn/Ia-CSM SN 2008J (green). Vertical grey dashed lines mark the primary carbon line at rest velocity. At a blueshift of ~ 2500 km s\(^{-1}\), a line consistent with Ca II exists. This line, in fact, is the dominant line identified in the spectra presented by Inserra et al. (2014). Some carbon does exist, however, in SNe 2013dn and 2012ca, but not in the Type II SN 2005ip.

3.2.3 High-Ionisation Coronal Lines

Section 3.2.2 suggests alternate line identifications for the blueshifted oxygen. Compared to SN 2005ip (Smith et al. 2009), Figure 8 shows that [Fe II] emission corresponds to the strongest coronal lines in SN 2005ip, although all lines are not quite as prominent in the Type Ia-CSM as they are in SN 2005ip. The lines we detect generally correspond to the strongest coronal lines in SN 2005ip, since the underlying continuum likely overwhelms the presence of the weaker lines.

Smith et al. (2009) attribute the narrow (~ 120–240 km s\(^{-1}\)) coronal lines in SN 2005ip to pre-shock ionisation of the CSM by sustained X-ray emission from ongoing CSI. The ionisation potentials imply high temperatures up to ~ 2 x 10\(^6\) K. Smith et al. (2009) go on to explain the lack of any higher-velocity components in these lines with a clumpy or asymmetric CSM, which can arise from various progenitor systems with evolved stars and do not necessarily distinguish between a core-collapse and thermonuclear explosion. Dense clumps can accelerate the forward shock, giving rise to intermediate-width H\(_\alpha\) lines, but also leading to efficient cooling and suppression of coronal lines in the post-shock cooling region. At the same time, the X-rays generated by the CSI can escape along paths without clumps to ionise the pre-shock CSM.

3.3 Near-Infrared Line Identifications

Figure 10 compares SNe Ia-CSM 2012ca and 2013dn (orange) to SNe IIn 2005ip (pink) and 2009ip (brown). Using line lists made for SN 2005ip (Smith et al. 2009) and nearby supernova remnants (Fesen & Hurford 1990), we identify a number of high-ionisation lines in SNe 2012ca and 2009ip (also see Table 5), including [S III], [Ar III], [Ar X], [Fe VIII], [Fe X], and possibly [Fe XI], although all lines are not quite as prominent in the Type Ia-CSM as they are in SN 2005ip. The lines we detect generally correspond to the strongest coronal lines in SN 2005ip, since the underlying continuum likely overwhelms the presence of the weaker lines.

Smith et al. (2009) attribute the narrow (~ 120–240 km s\(^{-1}\)) coronal lines in SN 2005ip to pre-shock ionisation of the CSM by sustained X-ray emission from ongoing CSI. The ionisation potentials imply high temperatures up to ~ 2 x 10\(^6\) K. Smith et al. (2009) go on to explain the lack of any higher-velocity components in these lines with a clumpy or asymmetric CSM, which can arise from various progenitor systems with evolved stars and do not necessarily distinguish between a core-collapse and thermonuclear explosion. Dense clumps can accelerate the forward shock, giving rise to intermediate-width H\(_\alpha\) lines, but also leading to efficient cooling and suppression of coronal lines in the post-shock cooling region. At the same time, the X-rays generated by the CSI can escape along paths without clumps to ionise the pre-shock CSM.
the line is heavily blended with Paγ, and the red wing of the feature bleeds into the blue wing of O I (Borish et al. 2014).

A more clearly defined He line is at 2.0589 µm (Modjaz et al. 2009). A broad line at this wavelength is also detected in SNe 2013dn, 2008J, 2012ca, 2010jl, and 2005ip, but not in SN 2007gr. In fact, He is also detected in the optical spectra at 7065 Å. Although Silverman et al. (2013) note little or no He I emission in their SN Ia-CSM sample, their spectra were obtained at earlier epochs when still dominated by an underlying continuum. Regardless, we see no reason for He to distinguish between a thermonuclear or core-collapse event. The He, which has similar velocities as the H lines, likely originated in the progenitor system’s wind and was accelerated by the forward shock. A number of scenarios can produce a He wind in the years leading up to the white dwarf explosion (e.g., Lundqvist et al. 2013).

Mg I: Inserra et al. (2014) identify Mg I λλ11,300, 15,024, which they use to argue for a core-collapse explosion. Indeed, these lines (along with Mg I λ17,109) are prominent in the Type Ic SN 2007gr. However, the Mg I λ15,024, 17,109 lines are not detected in any of the SNe Ia-CSM or SN 2010jl, and the Mg I λ11,300 line is relatively weak, if detected at all. Furthermore, the 1.1300 µm line identification can be easily confused with O I λ1.1287 µm, which we find is more precisely aligned with the features apparent in SNe 2012ca and 2008J. Compared to Type II SNe 2010jl and 2005ip, these lines are more narrow, which likely suggest that they do not originate in the ejecta. Weakening of the apparent line strength by a strong, underlying continuum must be considered, but the Mg I lines are some of the strongest lines observed in the Type Ic SN 2007gr and should still be observed in the interacting SNe if present. Furthermore, Figure 4 (bottom) shows a clear detection of Mg I λ λ4570 in the nebular spectra of SN 1998bw, but not in the SNe Ia-CSM. Broad emission features near this wavelength may be confused with Mg, but are more likely the suppressed [Fe III] discussed in §3.1.

**Oxygen:** Several oxygen lines also reside in the near-IR, including O I λλ11,287, 13,165 and O II λλ21,085. As

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**Table 5. Optical Line Identifications**

| λ (Å)   | Line   | λ (Å)   | Line   |
|--------|--------|--------|--------|
| 4733.93 | [Fe III] | 7065.19 | He I   |
| 4813.9 | [Fe III] | 7135.80 | [Ar III] |
| 4861.36 | Hβ   | 7155.14 | [Fe II] |
| 4921.93 | He I | 7281.35 | He I   |
| 5039.10 | [Fe II] | 1323.88 | [Ca II] |
| 5526  | [Ar X] | 1377.83 | [Ni II] |
| 5754.59 | [Ni II] | 7719.9  | [Fe II] |
| 5876  | blend He I | 7751.06 | [Ar III] |
| 6087.90 | [Fe VIII] | 7774 blend | O I |
| 6155  | Si I | 7891.80 | [Fe XI] |
| 6247.56 | Fe II | 8498.02 | Ca II |
| 6374.51 | [Fe X] | 8542.09 | Ca II |
| 6456.38 | Fe II | 8662.14 | Ca II |
| 6560  | Hα   | 9020   | Paγ    |
| 6678.15 | He I | 9069.00 | [S III] |
| 6723  | [S II] | 9230   | Paζ    |

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**Figure 10.** Comparison of late-time spectra, including the Type IIn/Ia-CSM SN 2008J (green), the Type Ia-CSM SN 2013dn (orange), the Type Ia-CSM SN 2012ca (black), the Type IIn SN 2009ip (brown), and the Type IIn SN 2005ip (pink). Some of high-ionisation coronal lines originally identified in SN 2005ip are seen in a number of SNe Ia-CSM and listed in Table 5.

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expected, these lines are prominently detected in SN 2007gr. If the 1.1287 μm line is O I (as we suggest above), it is significantly weaker in SN 2012ca, 2008J, and 2013dn than in SN 2007gr. This line, however, most likely has contributions from other elements anyway. A small detection at 1.3165 μm is observed in the day +66 spectrum of SN 2012ca, but this might be from the surrounding CSM and is certainly not persistent. No O I λ13,165 or O II λ21,085 is detected in SNe 2012ca, 2008J, 2013dn, or even 2010jl. Furthermore, none of these lines requires a blueshift like that described for the optical spectra of SN 2012ca. Nonetheless, it should be noted that these near-IR spectra are still dominated by shock-related emission and do not adequately probe nebular lines from the ejecta. The spectrum of SN 2005ip on day +3064, which clearly shows the emergence of broad nebular oxygen lines, underscores this point.

| Table 6. Infrared Line Identifications |
|--------------------------------------|
| λ (μm)   | Line   | λ (μm)   | Line          |
|----------|--------|----------|---------------|
| 0.92315  | Pa 9-3 | 1.5053   | Mg I          |
| 0.95486  | Pa 8-3 | 1.5705   | Br 15-4       |
| 1.0049   | He I   | 1.6114   | Br 13-4       |
| 1.0830   | Pγ     | 1.6412   | Br 12-4       |
| 1.1287   | O I    | 1.6811   | Br 11-4       |
| 1.1828   | Mg I   | 1.7109   | Mg I          |
| 1.2047   | Mg I   | 1.7367   | Br 10-4       |
| 1.2818   | Pβ     | 1.9451   | Brδ           |
| 1.3165   | O I    | 2.1661   | Brγ           |

4 DISCUSSION

4.1 Source of the Emission at Late Times

To interpret the spectra first requires identification of the spectral line origins in the physical SN environment. Figure 6 shows that some of the SNe Ia-CSM and SNe IIn can be a factor of 100 more luminous than even SN 1991T at late times. The normal radioactively powered nebular phase of the underlying thermonuclear explosion can therefore only contribute < 5% of the total flux at these epochs. The majority of the luminosity is instead powered by CSI (and so using the word “nebular” is not quite appropriate even at these late epochs).

While the luminosity may be dominated by CSI, the ejecta need not be completely obscured by an opaque shell. The CSM in many of these systems is likely asymmetric (e.g., Mauerhan et al. 2014). The CDS also continues to expand and can become optically thin over time. Reprocessing of X-rays and ultraviolet (UV) light generated by the shock interaction can illuminate the ejecta to observable levels. Furthermore, the ejecta will be excited as they cross the reverse shock at late epochs (e.g., Mauerhan & Smith 2012).

Any differences between the spectral lines of normal SNe Ia and SNe Ia-CSM/IIn may therefore be caused by any combination of the following reasons. (1) Stratification of the composition and/or ionisation of the ejecta, since they are illuminated from the outside-in, not from the inside-out. (2) The source of heat is thermalised UV and X-rays or the crossing of the reverse shock, but not gamma rays from radioactivity, which could also have a strong impact on the ionisation stratification of the ejectal. (3) Inherent differences in the explosion type and ejecta composition. Radiative transfer models can provide a more definitive answer, but they are beyond the scope of this paper.

4.2 [Fe III] and the Blue “Quasi-Continuum”

The broad [Fe III] and [Fe II] highlighted in Figure 6 often referred to as a blue “quasi-continuum,” is composed of blended iron-group elements (e.g., Foley et al. 2007; Smith et al. 2009, 2012; Silverman et al. 2013). They point to this quasi-continuum in favour of a thermonuclear origin despite weak [Fe III] when compared to most nebular SNe Ia (e.g., SN 1991T). We note, however, that weak [Fe III] has been observed previously in other SNe Ia. Here we refer to the case of SC candidate SN 2009dc, which was believed to have resulted from the explosion of a WD exceeding the
Chandrasekhar limit due to high rotation velocities (and also modeled as a “tamped detonation” due to merging white dwarfs by Raskin et al. 2014). SN 2009dc showed suppressed [Fe III].

Figure 6 highlights the similarities SN 2009dc (pink) shares with the SNe Ia-CSM (aside from Hα (2013) go on to show that the low-ionisation state would decelerated ejecta by the dense CSM. Taubenberger et al. for the SNe Ia-CSM the high densities likely result from Silverman et al. 2011; Taubenberger et al. 2011), whereas the low ejecta expansion velocities observed in SC SNe (e.g., of SN 2009dc, these high densities may be a result of the decelerated ejecta by the dense CSM. Taubenberger et al. (2013) attribute the smaller [Fe II] lines in SN 2009dc to a low-ionisation state during the nebular phase owing to high central ejecta densities (and therefore, enhanced recombination). In the case of SN 2009dc, these high densities may be a result of the low ejecta expansion velocities observed in SC SNe (e.g., Silverman et al. 2011; Taubenberger et al. 2011), whereas for the SNe Ia-CSM the high densities likely result from decelerated ejecta by the dense CSM. Taubenberger et al. 2013) go on to show that the low-ionisation state would also be consistent with the detection of [Ca II] λλ 7291, 7324, since the first and second ionisation potentials of Ca are lower than those of iron. Indeed, Figure 6 shows that [Ca II] is detected in both the SC and SNe Ia-CSM.

Admittedly, such a blue “quasi-continuum” has also been observed in other interacting SNe, including the SNe Ibn 2006jc (Foley et al. 2007) and 2011bw (Smith et al. 2012), and the SN Ibn 2005ip (Smith et al. 2009). As described for the cases of SNe Ibn 2006jc and 2011bw (Smith et al. 2012), which have lost a majority of their H envelopes, a low H abundance will place the burden of the radiative cooling from the CSI on the Fe emission lines. In other words, the Fe lines may very well originate in the ejecta, but the strength of the lines may be an indicator of the H, rather than the Fe, abundance.

Figure 6 compares the SNe Ia-CSM 2013dn (orange) and 2012ca (black) to the SN Ibn 2006jc (green), the SN Ibn 2009ip (brown), and the SN Ibn 2005ip (pink). While there are some similarities in the shapes of the “quasi-continuum,” there are several important differences to the overall spectra. First, the hydrogen features in SNe 2013dn and 2012ca are significantly less strong than those in SN 2006jc, suggesting that the H abundance is not particularly low in the SNe Ia-CSM. The H line strength may not directly indicate the total gas mass, but the light curves in Figure 6 show that the luminosity from CSM interaction is significantly stronger and more extended in SNe 2012ca and 2013dn than in either SN 2006jc or SN 2005ip. The total gas mass, composed primarily of H, is therefore larger in these SNe Ia-CSM. Second, the [Fe III] lines are present in SNe 2013dn and 2009dc, and even identifiable in SN 2012ca, but seemingly absent in SN 2006jc. Third, the Mg I] λ4570 feature in SN 1998bw is detected in SN 2006jc, but not in SNe 2009dc, 2013dn, or 2012ca. We are surely limited by the epochs of data we have to compare SN 2000dc to SN 2012ca since the [Fe III] becomes only more suppressed over time in SN 2009dc.

4.3 The Nature of the Type Ia-CSM Progenitor

Inserra et al. (2014) suggest the SNe Ia-CSM match well with SN 1998bw, but we find this comparison difficult to reconcile with our data. Namely, [O I] λλ 6300 in SN 1998bw is too strong (as is [Ca II]), particularly considering we do not detect any significant oxygen in our SN Ia-CSM spectra (see §3.2.2). We also do not detect any carbon or magnesium. The SNe Ia CSM feature at ~ 4600–4700 Å is more likely suppressed [Fe III] than the Mg I] found in SN 1998bw. The weak [Fe III] and strong [Ca II] in the nebular spectra of the SNe Ia-CSM are most similar to the SC SN 2009dc, which was modeled by a low-ionisation state owing to high densities that we would also expect in the SNe Ia-CSM.

Furthermore, Figure 2 shows the bolometric light curve of several SNe Ia-CSM. All SN Ia-CSM peak magnitudes are > −19, and the total integrated radiated luminosity output is a few ×10^{50} erg, which is still consistent with a thermonuclear explosion of a white dwarf (~ 10^{31} erg) but requires a high conversion efficiency of kinetic energy into radiation (ε ≈ 0.5). While such conversion efficiencies are quite high, they are certainly possible (e.g., van Marle et al. 2010). The Type Ia IR signatures are less apparent.

With a thermonuclear progenitor in mind, we reconsider Figure 10, which highlights strong iron lines (e.g., λλ 6248, 7155, 7720) in the spectra of SNe 2012ca, 2009ip, 2013dn, and 2008J. Figures 3 plots the velocity profiles for these iron lines. Compared to SN 2005ip, both the SNe Ia-CSM and the SN Ib 2009ip have broader line profiles (> 1000 km s^{-1}). If associated with the pre-shock wind, as suggested in the case of SN 2005ip, the higher velocities could potentially imply progenitor scenarios that differ from the massive-star progenitors with low speed winds (i.e., LBVs) proposed for most SNe II. These velocities, however, are not consistent with the more narrow hydrogen and helium (≤ 1000 km s^{-1}; see Figure 13), which are associated with the pre-shock CSM. Instead, these broad iron lines more likely originate in the post-shock cooling region or in the ejecta, which would be more consistent with SNe Ia.

The broad iron lines in SN 2009ip may be surprising given it has a progenitor that has most certainly been identified as a massive star (i.e., core collapse; see §2). Of course, X-rays produced by the CSI may excite even solar abundances of iron in post-shock CSM. In this case, these iron features would not be a useful discriminator. Furthermore, Figure 6 (bottom) compares a day +260 spectrum of the interacting Type IIn SN 2009ip (brown) to the SNe Ia-CSM. While SN 2009ip does exhibit some evidence for iron emission shortward of 5500 Å, it is significantly weaker than the other thermonuclear events. This fact alone is an important differentiator between the SNe IIn and SNe Ia-CSM in our sample.

Despite our discussion about the oxygen misidentifications in §3.2.2, we note that we do detect some oxygen λλ 5007, 6300, 8446 in the nebular spectra of both SNe Ia-CSM 2013dn, 2012ca and SNe Ib 2009ip, 2005ip. The oxygen emission, however, is relatively weak and narrow, and the broader lines at 8446 Å are more likely a result of Lyα pumping (which scales linearly with density) and not recombination. In this case, the lack of intermediate-mass elements in SN 2009ip and 2005ip may be more of the surprise. These results have been used to argue against a terminal core collapse in SN 2009ip already (Fraser et al. 2013b), but Smith et al. (2014) point out that even their late-time spectra were dominated by CSI. Even if the ejecta are illuminated, the illumination comes from the outside shocks and the intermediate-mass elements may be hidden deep in the ejecta or the lines may be weak. Indeed, the lack of nu-
5 CONCLUSIONS AND FUTURE WORK

We find the SN Ia-CSM subclass to be more consistent with a thermonuclear explosion than a core-collapse event. Specifically, the spectra do not showing evidence for intermediate-mass elements and do exhibit broad iron lines, although it should be noted that not all lines appear in all spectra.

closestwicly, the SN II-n in a common trait (e.g., SNe 2005ip and 1998SS) that results from the formation of an optically thick shell from CSI that obscures emission from the ejecta (Mauerhan & Smith 2012). Late-time spectra of SNe II-n only begin to show evidence for broad oxygen emission if the ejecta are still bright enough once the CSI sufficiently fades and/or the ejecta begin to cross the reverse shock. Therefore, this comparison may be less relevant than previously suggested.

The case for a thermonuclear origin appears to have gained a more robust foothold, the companion’s properties still remain relatively unknown. Furthermore, the ability for the companion to undergo such high mass loss (i.e., $> 10^{-3} M_\odot$; see Silverman et al. (2013) and references therein) remains poorly understood, although the presence of a binary likely has a role (e.g., Smith & Tombleson 2014). Future multi-wavelength observations will be needed to probe the CSM characteristics, trace the CSI, constrain the progenitor mass-loss history, and identify late-time heating mechanisms of warm dust.
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