A STUDY OF CARBON FEATURES IN TYPE Ia SUPERNOVA SPECTRA

Jerod T. Parrent1, R. C. Thomas2, Robert A. Fesen1, G. H. Marion3,4, Peter Challis3, Peter M. Garnavich5, Dan Milisavljevic1, József Vinkó6, and J. Craig Wheeler4

1 Department of Physics & Astronomy, 6127 Wilder Laboratory, Dartmouth College, Hanover, NH 03755, USA
2 Physics Division, Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA
3 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
4 Astronomy Department, University of Texas at Austin, Austin, TX 78712, USA
5 Physics Department, University of Notre Dame, Notre Dame, IN 46556, USA
6 Department of Optics & Quantum Electronics, University of Szeged, Dóm tér 9, Szeged H-6720, Hungary

Received 2010 December 1; accepted 2011 February 23; published 2011 April 12

ABSTRACT

One of the major differences between various explosion scenarios of Type Ia supernovae (SNe Ia) is the remaining amount of unburned (C+O) material and its velocity distribution within the expanding ejecta. While oxygen absorption features are not uncommon in the spectra of SNe Ia before maximum light, the presence of strong carbon absorption has been reported only in a minority of objects, typically during the pre-maximum phase. The reported low frequency of carbon detections may be due to low signal-to-noise data, low abundance of unburned material, line blending between C II λ6580 and Si II λ6355, ejecta temperature differences, asymmetrical distribution effects, or a combination of these. However, a survey of published pre-maximum spectra reveals that more SNe Ia than previously thought may exhibit C II λ6580 absorption features and relics of line blending near ~6300 Å. Here we present new SN Ia observations where spectroscopic signatures of C II λ6580 are detected and investigate the presence of C II λ6580 in the optical spectra of 19 SNe Ia using the parameterized spectrum synthesis code, SYN. Most of the objects in our sample that exhibit C II λ6580 absorption features are of the low-velocity gradient subtype. Our study indicates that the morphology of carbon-rich regions is consistent with either a spherical distribution or a hemispheric asymmetry, supporting the recent idea that SN Ia diversity may be a result of off-center ignition coupled with observer line-of-sight effects.

Key words: supernovae: general – supernovae: individual (SN 2010Y, 2010ai, PTF10icb)

Online-only material: color figures

1. INTRODUCTION

The typical pre-maximum Type Ia supernova (SN Ia) spectrum consists of overlapping P-Cygni profiles of intermediate-mass elements (IMEs) and Fe-peak elements (IPEs) that indicate expansion velocities on the order of 10^4 km s^-1 (Filippenko 1997). Photometric properties of the rise, peak, and decline of an SN Ia light curve can be explained by assuming that a substantial amount of 56Ni, synthesized in the explosion, powers the SN luminosity (Colgate & McKee 1969; Arnett 1982). Consequently, results of spectroscopic and photometric studies have supported the idea that SNe Ia are the outcome of a thermonuclear explosion of a C+O white dwarf in a binary system (Hoyle & Fowler 1960; Nomoto et al. 1984, 2003; Elias et al. 1985; Iben 1988; Chen & Li 2009; Howell 2010).

The explosion mechanisms that have been proposed differ by how the thermonuclear flame is propagated through the star’s interior, i.e., a sub-sonic deflagration via thermal conductivity or a super-sonic detonation due to strong shock burning. Pure detonation models appear unlikely since they conflict with observations by producing too much 56Ni, not enough IMEs, and leaving very little unburned material behind (Arnett 1969; Branch & Khokhlov 1995). On the other hand, while pure deflagration models may account for fainter SN Ia events, they are energetically weak, leaving too much material unburned to represent the majority of SNe Ia (Travaglio et al. 2004; Gamezo et al. 2005; Kozma et al. 2005). Thus, a deflagration that transitions into a detonation may be necessary in order to attain the nucleosynthetic yields that are consistent with the observations (Khokhlov 1991; Höflich et al. 1995; Kasen et al. 2009; Maeda et al. 2010).

Additional facets of modeling (e.g., multidimensional considerations) will affect the abundance tomography as well (Woosley et al. 2009). This can make it difficult to distinguish the dominant sources of SN Ia diversity. For certain, however, one similarity between all explosion models is the existence of burned (ash) and unburned material (fuel). By using spectroscopic signatures of C and O at pre-maximum epochs, one can infer the amount and velocity structure of the outer, unburned material.

Some of the unburned material may be subject to a degree of downward mixing toward the inner ejecta when burning becomes turbulent and enters the distributed flame regime (Pope 1987; Niedermayer 1998; Aspdin et al. 2010). As a result, it is not certain whether regions of unburned material are strictly located in the outer layer or mixed within the rest of the ejecta, nor is the mass range of unburned material from these thermonuclear explosions known (Baron et al. 2003). Therefore, the rate of detection of unburned material and its phenomenological details is of great importance for constraining how much material remains unburned in the explosion models.

The most prominent oxygen line in the optical spectra of SNe Ia is O i λ7774. Unfortunately, since oxygen is a product of carbon burning, oxygen absorption lines are likely to be a biased reference for measuring the location of unburned material. Thus, one must look to carbon absorption features as a tracer for unburned material. While it is not uncommon for oxygen to be present in SN Ia spectra (Branch et al. 2006), signatures of
carbon have only been sporadically reported in SN Ia spectra, most often during the pre-maximum phase.

For the typical ejecta temperatures seen in SNe Ia (∼10,000 K), the dominant ionization state of carbon is C ii (Tanaka et al. 2008). At this temperature, the strongest optical line of C ii is that of λ6580 (Hatano et al. 1999b). When seen, this line produces a blueshifted absorption near 6300 Å that sometimes blends with the neighboring emission component of the Si ii λ6355 P-Cygni profile, thus making C ii identifications problematic. There are well-observed SNe Ia where C ii λ6580 is clearly present (Patat et al. 1996; Mazzali 2001; Garavini et al. 2005; Hicken et al. 2007; Thomas et al. 2007; Yamanaka et al. 2009b; Scalzo et al. 2010); however, in general, C ii absorption is often weak and/or blended and therefore not a conspicuous SN Ia feature (Salvo et al. 2001; Branch et al. 2003; Stanishev et al. 2007).

A number of factors intrinsic to the explosion itself may contribute to the strength of C ii λ6580 and whether or not carbon features show up in SN Ia spectra. These include the asymmetrical distribution of carbon, the extent of carbon burning, the temperature of the carbon-rich region, and the possible formation of an envelope of unburned material through a merger of two white dwarfs (Thomas et al. 2007; Tanaka et al. 2008; Scalzo et al. 2010). Low signal-to-noise (S/N) spectra and effects of line formation may also obscure weak C ii λ6580 absorption features, thereby complicating the rate of detection further.

In an attempt to better understand spectroscopic carbon signatures in the pre-maximum optical spectra of SNe Ia, we present a comparative study of 16 SNe Ia where a C ii λ6580 absorption signature is evident, plus three additional cases where it may be present. Then using the spectrum synthesis code, SYNOW, we fit this sample of SN Ia spectra, thereby mapping the velocity distribution of carbon-rich regions that give rise to C ii λ6580 absorption features. To ensure a consistent analysis, we included these in our sample. These data were reduced using standard IRAF procedures, were corrected for host galaxy redshift, and are presented in Figure 1 and Table 1. We used the spectrum-comparison tool, SNID (Blondin & Tonry 2007), to estimate the age of each spectrum relative to maximum light.

The new and archival data used in this study are presented in Section 2. We review SN Ia subtype classifications in Section 3, and in Section 4 we discuss the spectrum fitting methods implemented with the SYNOW model, followed by our results in Section 5. We discuss our results in Section 6 in the context of recent findings on the diversity of SNe Ia and conclude in Section 7 with our results regarding the nature of C ii absorption features.

2. DATA

Low signal-to-noise SN Ia spectra make investigations of any suspected C ii absorption features difficult. Therefore, with the possibility of carbon features being both weak and blended with Si ii λ6355, well-observed multi-epoch confirmations of any suspected C ii λ6580 signatures were preferred for analysis.

In constructing our data sample, we have included only SNe Ia where at least two consecutive spectra showed the presence of a ∼6300 Å absorption signature, indicating a likely C ii λ6580 absorption feature. In addition, if the C ii feature was not seen before maximum light, then we did not include those SNe in our sample since this region of the spectrum becomes contaminated by neighboring Fe ii lines within a week after maximum light (Branch et al. 2008). The two exceptions are the single-epoch spectra of PTF10icb and the 2002cx-like, SN 2008ha, where the C ii λ6580 signature is evident.

2.1. New Observations

Pre-maximum optical spectra of SN 2010Y, 2010ai, and PTF10icb show absorptions likely due to C ii λ6580 and thus we included these in our sample. These data were reduced using standard IRAF procedures, were corrected for host galaxy redshift, and are presented in Figure 1 and Table 1. We used the spectrum-comparison tool, SNID (Blondin & Tonry 2007), to estimate the age of each spectrum relative to maximum light.

Three spectra for SN 2010Y covering days −7, −6, and −3 with respect to maximum light were obtained using a Boller & Chivens CCD spectrograph (CCDS) on the 2.4 m Hiltner telescope at the MDM Observatory on Kitt Peak, Arizona. These spectra show the emergence of a relatively weak yet persistent 6330 Å absorption feature. Two additional spectra were taken on days −2 and +1 and were acquired with the
9.2 m Hobby–Eberly Telescope (HET; Ramsey et al. 1998) at the McDonald Observatory using the Marcario Low-Resolution Spectrograph (LRS; Hill et al. 1998). By day $-2$, the 6330 Å feature peaked in intensity and began to fade by day $+1$.

Low-resolution optical spectra of SN 2010ai were also obtained with the HET. Spectra were taken well before maximum light on days $-10$ and $-8$. These spectra show signs of a flux depression in the emission component of the $\lambda 6555$ P-Cygni profile, suggesting the presence of $\lambda 6580$ absorption.

Additional data come from the discovery of PTF10icb by The Palomar Transient Factory (Nugent et al. 2010). A low-resolution follow-up spectrum was obtained with the LRS on HET on June 3. The spectrum-comparison tool, SNID, identifies the spectrum of PTF10icb as that of a normal SN Ia near day $-10$. Similar to SN 2010Y and 2010ai, the spectrum of PTF10icb also exhibited a 6330 Å absorption feature.

### 2.2. Archival Data

In Table 2, we list these three recent objects along side 65 SNe Ia found in the literature with pre-maximum or near-maximum light spectra. These 68 SNe Ia have been organized by the subtype scheme of Benetti et al. (2005) and are labeled by the classification subtypes of Branch et al. (2006; see Section 3). Since the progenitor channel and the origin of $\lambda 6580$ absorption features may differ for Super-Chandra SNe Ia, we separate SN 2003fg, 2006gz, 2007if, and 2009dc as possible Super-Chandra candidates. We have also grouped SN 2000cx, 2002bj, 2002cx, 2007qd, and 2008ha as miscellaneous objects since their classifications as SN Ia-like events are still under debate (Valenti et al. 2009; McClelland et al. 2010; Poznanski et al. 2010).

Optical spectra for all but three SNe Ia in our sample were obtained from the Supernova Spectrum Archive (SuSpect)\(^7\) and sources therein. All spectra have been corrected for host galaxy redshift and normalized according to the formula given by Jeffery et al. (2007) in order to remove the underlying continuum since in this study we are only concerned with the position of the $\lambda 6580$ absorption minimum and not absolute flux. The inclusion of SN 2008ha is for comparison purposes only and not meant to contribute to the discussion of carbon-rich regions of normal SNe Ia.

In Figure 2, we present a single pre-maximum spectrum of the 19 SNe Ia in our sample that shows evidence of a $\lambda 6550$ absorption signature. Under the assumption of local thermodynamic equilibrium at 10,000 K, the strongest four optical lines of $\text{C} II$ are $\lambda\lambda 4267, 4745, 6580,$ and 7234, with the 6580 Å line being the strongest. Rest-frame positions of these lines are represented by vertical lines in Figure 2 and the four gray bands at the top indicate Doppler velocities of 1000–20,000 km s$^{-1}$. This corresponds to a region spanning 440 Å wide and blueward of 6580 Å, well within the extent of typical $\text{Si} II \lambda 6545$ P-Cygni profiles.

### 2.3. SNe Ia: SUBTYPE CLASSES

The observed diversity of SNe Ia has been subdivided based on photometric and spectroscopic properties by Benetti et al. (2005) and Branch et al. (2006). Below we briefly describe these classification schemes which will be referred to in our analysis.

Benetti et al. (2005) grouped 26 SNe Ia according to two photometric and three spectroscopic observables, namely (1) $\Delta m_{15}(B)$—the decline in magnitude of the $B$-band 15 days after $B$-band maximum (Phillips 1993), (2) $M_B$—the peak $B$-band magnitude, (3) $\bar{v}_{\text{Si II}}$—the $\text{Si} II$ expansion velocity rate of decrease, (4) $\psi_{\text{Si II}}$—the $\text{Si II}$ expansion velocity of $\text{Si} II \lambda 6550$ 10 days after maximum light, and (5) $R(Si)_{\text{max}}$—the ratio of $\lambda 5972, 6355$ absorption depth measured at maximum light (Nugent et al. 1995; Bongard et al. 2008).

With a sample of 26 SNe Ia, they found that SNe Ia could be organized into three discrete subtypes that were functions of velocity gradient and luminosity, namely (1) high-velocity gradient (HVG), (2) low-velocity gradient (LVG), and (3) FAINT. The subtypes HVG and LVG were mainly distinguished by having $\bar{v}$ values above or below $\sim 70$ km s$^{-1}$ day$^{-1}$, respectively, while the SNe in their sample with $M_B,\text{max}\gtrsim -18.20$ were labeled as FAINT.

Branch et al. (2006) took a purely spectroscopically based approach, classifying 24 SNe Ia (later 65 SNe; see Branch et al. 2009) by the equivalent width of features near 5750 Å and 6100 Å which are usually attributed to $\text{Si II} \lambda\lambda 5972, 6355$, respectively. When SNe Ia are arranged in this manner, the objects can be subdivided roughly into four spectroscopic subtypes: (1) core-normal (CN) SNe Ia consist of objects such as SN 1994D, where from pre-maximum to 1-week

### Table 1

| Supernova Name | Host Galaxy | Redshift ($\text{km s}^{-1}$) | Observation Date | Epoch (days) | Telescope/Instrument |
|----------------|-------------|-------------------------------|------------------|--------------|----------------------|
| SN 2010Y       | NGC 3392    | 3256                          | 2010 Feb 9       | $-7$         | MDM/CCDS            |
|                |             |                               | 2010 Feb 10      | $-6$         | MDM/CCDS            |
|                |             |                               | 2010 Feb 13      | $-3$         | MDM/CCDS            |
|                |             |                               | 2010 Feb 14      | $-2$         | HET/LRS             |
|                |             |                               | 2010 Feb 17      | $+1$         | HET/LRS             |
| SN 2010ai      | SDSS J125925.04+275948.2 | 5507                          | 2010 Mar 11      | $-10$        | HET/LRS             |
| PTF10icb       |             |                               | 2010 Mar 13      | $-8$         | HET/LRS             |
|                |             |                               | 2010 Jun 3       | $-10$        | HET/LRS             |

---

\(^7\) [http://nhn.ou.edu/~suspect](http://nhn.ou.edu/~suspect)
### Table 2

| SN Name | Sub-type | C n? | Epoch (days) | Spectrum Source |
|---------|----------|------|--------------|-----------------|
| SN 1990N<sup>c</sup> | CN | Definite | −14 | M01 |
| SN 1991T<sup>c</sup> | SS | Possible | −13 | F99 |
| SN 1994B<sup>d</sup> | CN | Probable | −11 | F99g |
| SN 1995D | CN | Uncertain | +0 | S96 |
| SN 1996K<sup>e</sup> | CN | Probable | −4 | S01 |
| SN 1997B<sup>e</sup> | SS | No | −9 | L99 |
| SN 1997dt | CN | Uncertain | −10 | M08 |
| SN 1998V | CN | Uncertain | +0.5 | M08 |
| SN 1998ab | SS | No | −7.5 | M08 |
| SN 1998aqc | CN | Probable | −9 | B03 |
| SN 1999bu | CN | Probable | −7 | H00 |
| SN 1999es | SS | No | −10 | M08 |
| SN 1999aa | SS | No | −11 | Gara04 |
| SN 1999ac<sup>e</sup> | SS | Possible | −15 | Gara05 |

### HVG

| SN Name | Sub-type | C n? | Epoch (days) | Spectrum Source |
|---------|----------|------|--------------|-----------------|
| SN 1981B | BL | No | 0 | B83 |
| SN 1984A | BL | No | −7 | B89 |
| SN 1992A | BL | Probable | −6.5 | K93 |
| SN 1997do | BL | No | −11 | M08 |
| SN 1998dh | BL | No | −9 | M08 |
| SN 1998ec | BL | No | −2.5 | M08 |
| SN 1999cc | BL | No | −3 | M08 |
| SN 1999cl | BL | No | −7.5 | M08 |
| SN 1999cj | BL | No | −0.5 | M08 |

### FAINT

| SN Name | Sub-type | C n? | Epoch (days) | Spectrum Source |
|---------|----------|------|--------------|-----------------|
| SN 1986G | CL | Possible | −6 | P87 |
| SN 1989B | CL | Possible | −7 | W94 |
| SN 1991bg | CL | No | +1 | T96 |
| SN 1997cn | CL | No | 0 | T98 |
| SN 1998bp | CL | No | −2.5 | M08 |
| SN 1998de | CL | No | −6.5 | M08 |
| SN 1999by<sup>d</sup> | CL | Possible | −5 | Gara04 |

### SC<sup>c</sup>

| SN Name | Sub-type | C n? | Epoch (days) | Spectrum Source |
|---------|----------|------|--------------|-----------------|
| SN 2003fg | ... | Definite | ... | H06 |
| SN 2007if | ... | Definite | −9 | S10 |
| SN 2000cx | ... | Possible | −3 | L01 |
| SN 2002bj | ... | Definite | +7 | P10 |
| SN 2002cx | ... | Probable | −4 | L03 |

### Misc.

| SN Name | Sub-type | C n? | Epoch (days) | Spectrum Source |
|---------|----------|------|--------------|-----------------|
| SN 2005hk<sup>c</sup> | ... | Possible | −5 | S08 |
| SN 2007qd | ... | Possible | +3 | M10 |
| SN 2008ha | ... | Definite | −1 | F09, F10a |

### Notes.

<sup>a</sup> SN type notation of Branch et al. (2006), where CN: “core normal,” SS: “shallow silicon,” CL: “cool,” and BL: “broad line.” The similar subtypes of Benetti et al. (2005) have been used to separate these SNe Ia into subclasses.

<sup>b</sup> References: (B89) Barbon et al. 1989; (B83) Branch et al. 1983; (B03) Branch et al. 2003; (E-R06) Elias-Rosa et al. 2006; (F99) Fisher et al. 1999; (F09) Foley et al. 2009; (F10a) Foley et al. 2010a; (F10b) Foley et al. 2010b; (Gara04) Garavini et al. 2004; (Gara05) Garavini et al. 2005; (Garn04) Garnavich et al. 2004; (H00) Hernandez et al. 2000; (H07) Hicken et al. 2007; (K93) Kirshner et al. 1993; (K05) Kotak et al. 2005; (L99) Li et al. 1999; (L01) Li et al. 2001; (L03) Li et al. 2003; (M08) Matheson et al. 2008; (Matt05) Mattila et al. 2005; (M10) Mazzali 2010; (M11) Mazzali et al. 2011; (P87) Phillips et al. 1987; (P96) Patat et al. 1996; (P10) Poznanski et al. 2010; (Q06) Quimby et al. 2006; (Q07) Quimby et al. 2007; (S01) Salvo et al. 2001; (S96) Sadakane et al. 1996; (S10) Scalzo et al. 2010; (S05) Stanishev et al. 2005; (T07) Thomas et al. 2007; (T96) Turatto et al. 1996; (T98) Turatto et al. 1998; (V03) Valenti et al. 2003; (W06) Wang et al. 2006; (W09) Wang et al. 2009; (W94) Wells et al. 1994; (Y09) Yamanaka et al. 2009a; (Z10) Zhang et al. 2010.

<sup>c</sup> This work

<sup>d</sup> Objects with both published spectropolarimetry data and C<sub>λ5680</sub> absorption signatures: 1994D, Wang et al. (1996); 1996X, Wang et al. (1997); 1999by, Howell et al. (2001); 2003du, Leonard et al. (2005); 2005hk, Chornock et al. (2006).

<sup>e</sup> SC: Super-Chandra Candidates.
post-maximum spectra are dominated by lines of Ca II, Fe II, Fe III, Mg II, O I, S II, Si II, and Si III; (2) broad-line (BL) SNe Ia are similar to CNs but instead display noticeably broader lines with higher average Doppler velocities; (3) cool (CL) 1991bg-like spectra which exhibit low-ionization energy ions such as Ti II, along with an increased ratio between the 5750 and 6100 Å features; and (4) shallow silicon (SS) 1991T-like spectra display mostly high-ionization energy ions, such as Fe III, in their pre-maximum spectra and are accompanied by weak S II absorption features.

We note that comparing the sample of SNe Ia used in both studies shows that FAINT and HVG objects are equivalent to CL and BL, respectively, and the LVG objects are equivalent to CN and SS subtypes (Branch et al. 2006). Since we are using subtype classes that are mostly based on spectroscopic properties of SNe Ia, our study cannot address issues regarding broadband photometric observations. A systematic study of both the spectroscopic and light-curve properties is difficult because these data can come from multiple sources and not every target we study here have both good spectroscopy and photometry. This type of study is better suited for the Nearby Supernova Factory (Aldering et al. 2002) and the Palomar Transient Factory (Rau et al. 2009), where the data sets are large and have good time-series coverage.
4. SPECTRUM ANALYSIS MODEL: SYNOW

One way to infer the velocity range of unburned material is to measure the absorption minimum of the C ii λ6580 line. The observed minimum of this feature is often located near the strong emission component of Si ii λ6355, and is therefore subject to line blending and any limb-brightening that the Si ii line contributes to the integrated spectrum (Höflich 1990). Consequently, the observed minimum may underestimate the actual expansion velocity of the carbon-rich region. Therefore, in order to accurately estimate the true minimum of a blended line profile, one must take into account the effects of line formation by reconstructing the spectrum via numerical calculation.

While there have been several new and more detailed spectrum synthesis codes presented in the literature since the inception of SYNOW nearly 30 years ago, the SYNOW spectrum synthesis model remains a useful tool for the quick analysis of resonant-scattering line profiles (Baron et al. 1994, 2009; Mazzali 2000; Branch et al. 2007; Kasen et al. 2008). Therefore, we chose the less computationally intensive approach of SYNOW to produce results that were internally consistent when we compared the SNe Ia in our sample.

From a single-epoch optical spectrum, one can reproduce many of the conspicuous features seen in SNe of all subtypes using SYNOW. However, to have greater confidence in the identification of a spectroscopic feature, it is best to have a time series of closely spaced spectra in order to follow the evolution of both the observations and the fit. Because we wish to probe the nature of C ii λ6580 features in SNe Ia, we required fitting all spectra for the duration of time in which the 6300 Å features could be seen.

In SYNOW, one computes a spectrum by specifying the location and optical depth for a given set of ions. This allows one to infer spectral line identifications by directly fitting to a series of observed spectra. While SYNOW does not calculate relative abundances of various elements, it is instructive at reconstructing the complex spectroscopic profiles brought about by multiple line scattering that is inherent to moving media.

The version of the SYNOW model that we used can be described as follows: (1) a spherically symmetric and homologously expanding ejectum is modeled using a \( v \propto r \) law; (2) light is emitted from a sharp photosphere; (3) optical depth, \( \tau \), is a function of velocity as either \( (v/v_{\text{ph}})^{-n} \), \( \exp(-v/v_{\text{ph}}) \), or \( \exp(-\frac{v-v_{\text{min}}}{2\sigma}) \), where each of these functions is characterized by indices \( n \), \( v_{\text{c}} \), and \( \sigma \), respectively; (4) line formation is purely due to resonant scattering and is treated using the Sobolev approximation (Sobolev 1957; Jeffery & Branch 1990); and (5) for a given ion a reference line profile is calculated for a given \( \tau \) and the remaining lines follow from Boltzmann statistics. Input parameters for a SYNOW spectral fit include: (1) a photospheric velocity \( (v_{\text{ph}}) \), (2) reference line \( \tau \) and minimum/maximum velocities for each ion, and (3) excitation temperature, \( T_{\text{exc}} \), to determine LTE level populations with respect to a reference line.

As was done in the SN Ia comparative study of Branch et al. (2005), for our investigation we too left the excitation temperature at 10,000 K for each ion. We also chose to use the exponential form of the optical depth profile with \( v_{\text{c}} = 1000 \text{ km s}^{-1} \). This aided in limiting the number of free parameters for a spectral fit.

Because SYNOW assumes spherical symmetry, we are limited when investigating the possible asymmetrical distributions of unburned material. If the distribution is that of a spherical layer, as is the case for the W7 model (Nomoto et al. 1984; Thielemann et al. 1986), then it is straightforward to make SYNOW model fits to compare with observations. In this case, the unburned material resides above the burned material in a spherical shell where the thickness depends on the extent of the burning. For W7, this boundary is roughly at 14,000 km s\(^{-1}\) with a stratified composition of IMEs and IPes below.

Recent multidimensional models of delayed detonations suggest that the unburned material may be left behind in clumps throughout the ejecta (Gamezo et al. 2004). For the situation where the unburned material is heavily concentrated to a single clump structure, we can only utilize SYNOW in certain cases (see Section 6.2.1).

Observations have shown that there often exist higher velocity regions of line formation, namely Ca ii and Si ii (Hatano et al. 1999; Kasen et al. 2003; Tanaka et al. 2010). Such regions are said to be detached from the photosphere. A noticeable facet that arises when fitting Si ii λ6355 profiles during the earliest epochs is that the absorption width, the slow rise of the blue wing, and the sharp rise of the red wing require two separate velocity components of Si ii to achieve a good match to observations. At best, a single-component of Si ii with an increased value of the optical depth profile indices can only properly fit the red wing of the 6355 Å absorption feature.

G. H. Marion et al. (2011, in preparation) discuss recent observations of the Type Ia event, SN 2009ig, where there is clear evidence for both a photospheric region and a high-velocity region of Si ii. In their SYNOW analysis, they used the two-component approach in following the evolution of the Si ii λ6355 feature, which produced a better fit overall. Similarly, we too have adopted a procedure of using two components of Si ii that are separated by \( \sim 4000–6000 \text{ km s}^{-1} \) when necessary.

One consequence that detached ions have on the line profile is that the emission component of the line is flat-topped. Some of our spectroscopic fits in Section 5.3 detach Si ii to better fit the absorption component, while forfeiting a comparable fit to the full emission component, e.g., our fit for SN 1999ac. The impact that detaching has toward blending with C ii λ6580 is minimal and only one of offsetting the prescribed value of \( \tau \) for C ii in the fit.

5. RESULTS

In terms of the spectroscopic diversity of SNe Ia, many of the differences are seen immediately after the explosion as the photosphere maps out the distribution of the outermost ejected material, with an increase toward spectroscopic conformity at later epochs (Branch et al. 2008). Unfortunately, as shown in Figure 3, SN Ia spectroscopic observations during the two weeks prior to maximum light are underrepresented compared to those taken near maximum light or at later times. In addition, absorption features attributed to C ii λ6580 are generally weak. As a result, they can be easily missed and thus go unreported or are not securely verifiable due to low S/N and/or line blending.

5.1. Frequency of C ii Absorption Features

Our search of the literature revealed that \( \sim 30\% \) of SNe Ia with moderate to high S/N, pre-maximum spectra taken since 1983 January 1 show a feature near 6300 Å that may be associated with C ii λ6580 absorption (see Table 2: Definite + Probable). Because of the sparsity of optical spectra before peak brightness, this percentage may not represent the actual fraction of SNe Ia that exhibit C ii λ6580 signatures during the pre-maximum
Figure 3. Shaded in gray are the number of SNe Ia discovered between 2006 January 1 and 2009 December 1 plotted against the epoch at which they were identified as being Type Ia supernovae. Shaded in black are the number of SNe Ia that show \( \sim 6300 \) absorption features in their pre-maximum spectra at the time when the feature was first seen. Data were taken from Central Bureau Electronic Telegrams (CBET) and Astronomical Telegrams (ATEL). Estimates for the age of each supernova were obtained by one of several publicly available spectrum-comparison tools (PASSparToo, Harutyunyan et al. 2005; Superfit, Howell et al. 2005; SNID, Blondin \\& Tonry 2007; GELATO, Harutyunyan et al. 2008). The cited epoch for each SN Ia in this plot was taken as reported in the telegrams. The numbers above are not a strict sampling of all objects during the four-year period, given that some of the age estimates were too vague to be included. This explains the peaks at days \(-7, 0, +7, \) and \(+14\) relative to maximum light. Because the spectral identification programs determine age with several days of error, we binned the data sample at days \(-13 \pm 1, -10 \pm 1, -7 \pm 1, -4 \pm 1, 0 \pm 2, +4 \pm 1, +7 \pm 1, +10 \pm 1, \) and \(+13 \pm 1\). Both histograms show, on average, that observations before 1 week pre-maximum phase are not well represented compared to observations near maximum light or later.

5.2. SNe Ia C II Features: Conspicuous to Weak

Like most features in the spectra of SNe Ia, the degree of adjacent line blending that C II \( \lambda 6580 \) absorption signatures
undergo can obscure the full extent of a line profile. More often than not, the minimum of the C II λ6580 line is blended with the P-Cygni emission component of the Si II λ6355 line. The day −5 spectrum of SN 1999by is a good example of when this takes place (see Figure 2).

When the C II λ6580 absorption feature is weak, there is also often no obvious C II λ7234 signature. However, when the C II λ6580 feature is strong, a corresponding C II λ7234 feature does begin to appear as the excited level of the 7234 Å line becomes more populated. There are several cases, such as SN 2006gz and 2007if, where C II becomes more populated. There are several cases, such as SN 2006gz, 2007if, and 2009dc, where the C II lines are the best means by which to securely identify whether carbon is present in the early-epoch SN Ia spectra.

In Figure 5, we plot two spectral regions of four SNe Ia in Figure 2 that highlight cases when both of these C II lines are present. For each SN, the red and blue lines denote λλ 6580, 7234 Doppler velocity-scaled spectra, respectively. The absorption minima overlap nicely (see dashed vertical lines) and the symmetry about the minima is indicative of a match between the spectral signatures of the same ion. We interpret this to mean that the 7234 Å line is indeed present when the 6580 Å line is strong. Currently, these two C II lines are the best means by which to securely identify whether carbon is present in the early-epoch SN Ia spectra.

The C II lines that appear further in the blue have also been suggested to be present as well (Thomas et al. 2007). However, this region is crowded by lines of IPEs, making it more difficult to securely identify C II λ4267, 4745 and use for determining accurate Doppler velocities. This appears to be the case even for SN 2006gz, 2007if, and 2009dc, where the C II λ6580 absorption is strong (Hicken et al. 2007; Scalzo et al. 2010; Taubenberger et al. 2011).

5.3. SYNOW Model Fitting

For each of the 19 SNe Ia in our C II sample, we produced a time series of synthetic optical spectra that covered the observed extent of the C II λ6580 feature’s presence as well as the observed wavelength coverage of the data (≈3500–9000 Å). Our initial fits included the canonical set of IMEs and IPEs that are prevalent in pre-maximum SN Ia spectra, whereby afterward we included C II and adjusted the optical depth and detachment velocity until a match to observation was made. The goodness-of-fit to the observed Si II λ6355 − C II λ6580 blended profiles did not change with the full set of IMEs and IPEs removed. Thus, for each SN in Table 3, we only list the relevant parameters for C II and Si II.

As discussed in Section 4, some of the observed Si II λ6355 profiles required two separate components of Si II in order to fit the full width of the absorption. We indicate which SNe Ia in our sample required this fitting procedure by appending the inferred Doppler velocities and optical depths with “>” in Table 3.

In Figure 6, we compare fits to a single observed spectrum for each of the SNe Ia in our sample. The black lines represent the observed spectra, the red lines are SYNOW fits where C II has been included, and the blue lines are the same fits without C II. The synthetic spectra match fairly well to a variety of Si II λ6355 − C II λ6580 blended profiles, and the interpretation that the 6300 Å feature is due to C II λ6580 is in agreement with that of previous authors (see references in Table 2).

In this study, we also offer new and revised expansion velocity estimates of C II for a couple of SNe Ia, particularly SN 1990N and 1999by. It was suggested by Fisher et al. (1997) that the overly broadened 6040 Å absorption in the day −14 spectrum of SN 1990N was due to a two-component blend composed of Si II at ~20,000 km s⁻¹ and C II at ~26,000 km s⁻¹. Similarly, Mazzali (2001) suggested that this feature is predominantly due to Si II λ6355 but also requires an outer zone of high-velocity carbon between 19,000 and 30,000 km s⁻¹. If this interpretation is correct, then other SNe Ia like SN 1990N would also require a similar zone of carbon to reproduce their early-epoch spectra. However, our fit for SN 1990N uses two components of Si II to fill the 6040 Å feature while C II is only at 16,000 km s⁻¹ to account for the 6300 Å feature.

In the case of the sub-luminous SN 1999by, C II λ6580 was not reported by Garnavich et al. (2004). However, our fit in Figure 6 is fairly convincing when C II is included as a detached layer 2000 km s⁻¹ above the photosphere for the day −5 spectrum. In fact, almost 80% of the SNe in our sample suggest at least a mildly detached layer of C II during some point along the evolution of the absorption feature. For example, we modeled the C II in SN 1994D initially at 14,000 km s⁻¹ coincident with vphot at day −11, after which it remains at this velocity as the photosphere recedes to 12,000 km s⁻¹ by day −5.

6. DISCUSSION

The strength and velocity range of carbon in pre-maximum SNe Ia spectra can provide a valuable tool to investigate various explosion models. The W7 deflagration model, for instance, contains a ~0.07 M⊙ layer of unburned material above 14,000 km s⁻¹. Using the spectrum synthesis and model atmosphere code, PHOENIX, Lentz et al. (2001) compared calculated non-LTE spectra to spectroscopic observations of the normal Ia event, SN 1994D. Despite the outer layer of unburned material in W7, none of their synthetic spectra were
Table 3
SYNOW Fit Parameters

| Supernova Name | Epoch (days) | \(v_{\text{phot}}\) (km s\(^{-1}\)) | C\(\text{ii}\) Velocity | Si\(\text{ii}\) Velocity | \(\tau\) |
|----------------|-------------|---------------------------------|-------------------------|-------------------------|--------|
| SN 1990N       | -14         | 13,000                          | 16,000                  | 0.60                    | >14,000 |
|                | -8          | 11,000                          | 14,000                  | 0.25                    | 11,000  |
|                | -2          | 11,000                          | 14,000                  | 0.15                    | 11,000  |
|                | 2           | 11,000                          | 14,000                  | 0.35                    | 11,000  |
| SN 1994D       | -11         | 14,000                          | 14,000                  | 1.30                    | >14,000 |
|                | -10         | 13,000                          | 14,000                  | 0.45                    | >13,000 |
|                | -8          | 13,000                          | 14,000                  | 0.45                    | >13,000 |
|                | -5          | 12,000                          | 14,000                  | 0.20                    | >12,000 |
| SN 1996X       | -4          | 13,500                          | 13,500                  | 0.60                    | 13,500  |
|                | -2          | 13,000                          | 13,000                  | 0.40                    | 13,000  |
|                | -1          | 12,000                          | 13,000                  | 0.04                    | 13,000  |
| SN 1998aq      | -9          | 12,000                          | 15,000                  | 0.20                    | 13,000  |
|                | -8          | 12,000                          | 14,000                  | 0.20                    | 13,000  |
|                | 10          | 12,000                          | 13,500                  | 0.60                    | 12,000  |
| SN 1999ac      | -15         | 13,000                          | 17,000                  | 0.40                    | 15,000  |
|                | -9          | 14,000                          | 17,500                  | 0.30                    | 14,000  |
| SN 1999by      | -5          | 12,000                          | 14,500                  | 0.50                    | 12,000  |
|                | -4          | 12,000                          | 14,500                  | 0.30                    | 12,000  |
|                | 13          | 12,000                          | 14,500                  | 0.30                    | 12,000  |
| SN 2001V       | -7          | 8000                            | 12,000                  | 0.15                    | 8000    |
|                | -6          | 8000                            | 12,000                  | 0.15                    | 8000    |
|                | -4          | 8000                            | 12,000                  | 0.15                    | 8000    |
| SN 2003du      | -13         | 14,000                          | 14,000                  | 0.60                    | >14,000 |
|                | -11         | 12,000                          | 14,000                  | 0.60                    | >12,000 |
| SN 2005hk      | -5          | 6000                            | 7500                    | 0.07                    | 7000    |
|                | 0           | 6000                            | 7500                    | 0.14                    | 7000    |
| SN 2006D       | -7          | 11,000                          | 14,500                  | 0.30                    | 13,000  |
|                | -5          | 11,000                          | 14,500                  | 0.20                    | 13,000  |
| SN 2006bt      | -4          | 6500                            | 6500                    | 0.30                    | >11,000 |
|                | -3          | 6500                            | 6500                    | 0.25                    | >11,000 |
| SN 2006gz      | -14         | 12,000                          | 18,500                  | 0.50                    | 16,500  |
|                | -12         | 12,000                          | 18,500                  | 0.40                    | 16,500  |
|                | -10         | 12,000                          | 17,500                  | 0.30                    | 16,000  |
| SN 2007if      | -9          | 8500                            | 9500                    | 0.25                    | 8500    |
| SN 2008ha      | -1          | 1000                            | 1000                    | 1.00                    | 2500    |
| SN 2009dc      | -8          | 8000                            | 11,000                  | 0.50                    | 10,000  |
|                | -7          | 8000                            | 10,000                  | 0.30                    | 9500    |
|                | -6          | 8000                            | 10,000                  | 0.30                    | 9500    |
|                | -5          | 7000                            | 9500                    | 0.30                    | 9000    |
|                | -3          | 7000                            | 9500                    | 0.30                    | 8500    |
|                | -2          | 6500                            | 9000                    | 0.30                    | 8000    |
|                | -1          | 6500                            | 9000                    | 0.30                    | 8000    |
|                | 0           | 6500                            | 8500                    | 0.40                    | 8500    |
|                | 2           | 6500                            | 8500                    | 0.30                    | 8000    |
|                | 3           | 6000                            | 7500                    | 0.30                    | 7500    |
|                | 4           | 6000                            | 7500                    | 0.30                    | 7500    |
|                | 5           | 6000                            | 7500                    | 0.30                    | 7500    |
|                | 6           | 5500                            | 7500                    | 0.30                    | 7000    |
|                | 7           | 5500                            | 7500                    | 0.30                    | 6500    |
|                | 8           | 6000                            | 7500                    | 0.30                    | 7000    |
|                | 9           | 5000                            | 6000                    | 0.20                    | 7000    |
|                | 15          | 5000                            | 5000                    | 0.20                    | 6500    |
| SN 2009ig      | -14         | 16,000                          | 16,000                  | 1.00                    | >16,000 |
|                | -13         | 16,000                          | 16,000                  | 0.50                    | >16,000 |
| SN 2010Y       | -7          | 12,000                          | 15,000                  | 0.50                    | 14,000  |
|                | -6          | 12,000                          | 15,000                  | 0.50                    | 14,000  |
|                | -3          | 12,000                          | 14,500                  | 0.50                    | 13,000  |
|                | -2          | 11,500                          | 14,000                  | 0.50                    | 12,500  |
|                | 1           | 11,000                          | 14,000                  | 0.30                    | 12,000  |
| SN 2010ai      | -10         | 13,500                          | 14,000                  | 1.00                    | 13,500  |
|                | -8          | 12,500                          | 14,000                  | 1.00                    | 12,500  |
| PTF10icb       | -10         | 11,000                          | 14,500                  | 0.10                    | >12,000 |

Notes.

a Fits made with \(T_{\text{esc}} \approx 10,000\) K and \(v_e \approx 1000\) km s\(^{-1}\).

b Used two components of Si\(\text{ii}\) to fit broad Si\(\text{ii}\) 6355 P-Cygni profiles.

c See Valenti et al. (2009) for an alternate SYNOW fit where the origin of explosion is interpreted to be a core-collapse supernova.

Figure 6. SYNOW fits of the 19 SNe Ia in our sample presented in two panels. The red and blue lines denote a synthetic fit to the spectrum of an SN Ia with and without C\(\text{ii}\), respectively. The contrast between both fits suggests the presence of C\(\text{ii}\) with varying strength in these objects. See Table 2 for fitting parameters. (A color version of this figure is available in the online journal.)
upper mass limit of unburned material below 10,000 km s\(^{-1}\) to be \(\sim 0.07 M_\odot\). Other estimates for the mass of unburned material have been made using delayed detonations (Höflich et al. 2002) and other modeling, e.g., lower limit of 0.014 \(M_\odot\) of unburned material between 10,000 and 14,000 km s\(^{-1}\) for SN 2006D (Thomas et al. 2007). However, since each estimate is obtained by different means, a comparison of such results does not advance the discussion on the nature of C \(\lambda\lambda 6580\) absorption features.

In order to utilize C \(\lambda\lambda 6580\) absorption features for estimating the mass of unburned material, the effects of temperature and geometry of the carbon-rich regions as well as the influence of radiative transfer effects must be explored. Our SYNOW modeling begins this process by mapping the observed velocity distribution for a sample of 19 SNe Ia. Below, we discuss our interpretation of the observed frequency of C \(\lambda\lambda 6580\) absorption features and how they relate to the properties of carbon-rich regions and SN Ia diversity.

6.1. Temperature Effects on Carbon Features

The temperature of the carbon-rich region will influence whether or not C \(\Pi\) is the dominant ionization species and will therefore dictate the strength of C \(\lambda\lambda 6580\) absorption features. Using non-LTE calculated spectra, Nugent et al. (1995) pointed out that the spectroscopic sequence observed among various SNe Ia could be explained by a continuous change in the effective temperature of the ejecta \((7400–11,000 \, K)\), from cool 1991bg-like to the hotter 1991T-like spectra (see their Figure 1).

While the ejecta of SNe Ia are an environment with non-LTE processes, under the assumption of a C+O-rich composition the Sah–Boltzmann equation indicates that carbon will mostly be in the form of C \(\Pi\) between 6000 and 12,000 K.

Of the 68 SNe Ia listed in Table 2, 10 out of the 14 CNs and 5 out of the 13 CLs exhibit C \(\lambda\lambda 6580\) absorption features. From a nearly equal sampling of SN Ia subtypes, the fact that two CNs for every one CL SN Ia exhibit C \(\lambda\lambda 6580\) absorption lines suggests that the presence of C \(\Pi\) absorption features depends on the effective temperature to some degree. This point is also consistent with the fact that only 2 of 13 SSS show signs of C \(\lambda\lambda 6580\) absorption features in their spectra.

We note that C \(\Pi\) absorption features are not often detected in SN Ia spectra. Marion et al. (2006) presented NIR spectra of three normal SNe Ia and discussed the lack of C \(\Pi\) absorption signatures due to the absence of the strongest C \(\Pi\) NIR lines, namely C \(\Pi\lambda\lambda 9093, 10691\). A more extensive study of 41 SN Ia NIR spectra spanning two weeks before and after maximum light was discussed by Marion et al. (2009) and they too reported a lack of C \(\Pi\) signatures. Because spectral signatures of carbon burning products were observed to occupy the same region of ejecta \((\text{Mg} \Pi \text{ and O} \Pi)\), Marion et al. (2006) concluded that nuclear burning had been complete out to at least 18,000 km s\(^{-1}\) in their objects.

It is perhaps not surprising that many NIR spectra of SNe Ia do not show lines from C \(\Pi\), given that (1) the abundance of carbon may be only \(\sim 1\%–10\%\) of the total ejected mass, and (2) if there is carbon present in the outer layers then it is mostly once ionized. Interestingly, however, Höflich et al. (2002) reported a conspicuous C \(\Pi\lambda\lambda 6091\) absorption feature in the day \(-4\) NIR spectrum of SN 1999by. They were able to reproduce many features of the observed optical and NIR spectra using a series of sub-luminous delayed-detonation models with a range of transition densities, \(\rho tr\), between 8 and \(27 \times 10^6 \, \text{g cm}^{-3}\).

The appearance of the C \(\Pi\lambda\lambda 10691\) line was seen concurrently with the optical C \(\lambda\lambda 6580\) absorption feature, as reported in Section 5.3. Both the C \(\Pi\) and C \(\Pi\) spectral signatures indicated that the carbon-rich region was above the 12,000 km s\(^{-1}\) photosphere, i.e., the minimum of the C \(\Pi\lambda\lambda 10691\) absorption corresponds to \(\sim 13,000 \, \text{km s}^{-1}\) while our SYNOW fits for this object place C \(\Pi\) at 14,500 km s\(^{-1}\). At least for this cool subluminous SN Ia, the influence of temperature on the ionization state of the carbon-rich region is apparent from the simultaneous appearance of C \(\Pi\) and C \(\Pi\) absorption features.

Additional evidence that ejecta temperature plays a role in the detection of carbon in SN Ia spectra would be if C \(\Pi\) were clearly detected in a hotter SN Ia subtype, such as SN 1991T or SN 1997br. The similarity between the ionization potentials of C \(\Pi\) \((24.4 \, \text{eV})\) and S \(\Pi\) \((23.3 \, \text{eV})\) suggests that the presence of C \(\Pi\) absorption features may be concurrent with spectroscopic signatures of S \(\Pi\). Fortunately, we can examine optical spectra to check for the simultaneous presence of C \(\Pi\) \(\lambda\lambda 4649\) and S \(\Pi\) \(\lambda\lambda 4254\) absorption features.

In Figure 7, we plot and compare SYNOW fits for SN 1991T and 1997br where we have included C \(\Pi\) and S \(\Pi\). The identification of the 4500 Å feature of SN 1991T has been discussed before by Hatano et al. (2002), and similarly in other SNe Ia (Garavini et al. 2004; Chornock et al. 2006). While it was argued by Hatano et al. (2002) that including C \(\Pi\) in the fit produced a mismatch with the observed spectrum (too blue overall), our synthetic spectra (red lines) are in fair agreement with observations near 4500 Å for both SN 1991T and 1997br.

In addition, a better fit to the 4250 Å absorption feature is obtained with the inclusion of S \(\Pi\). The 4250 Å feature is predominately due to the Fe \(\Pi\lambda 4404\) multiplet. However, by adding S \(\Pi\) to the fit we were able to fill in the blue wing of this absorption feature for both objects. Therefore, our identification for the 4500 Å absorption feature as being that of C \(\Pi\) \(\lambda\lambda 4649\) is more likely, though the evidence is circumstantial. If the C \(\Pi\) \(\lambda\lambda 4649\) identification is correct, then this may indicate that a lack of C \(\Pi\) \((\text{or C} \Pi)\) spectroscopic features does not necessarily imply the complete burning of carbon in the hotter subtype events.

6.2. Interpreting C \(\Pi\lambda\lambda 6580\) Doppler Velocities

In this paper, our attention has been primarily focused on carbon-rich regions in the outermost ejecta. The wide range of observed C \(\Pi\) Doppler velocities among different SNe Ia suggests a large variation in the extent of carbon burning, with some objects exhibiting high-velocity carbon while in others the carbon is present at low velocities (see Table 3). How high or low is usually in reference to the position of the carbon cutoff seen in the W7 model \((\sim 14,000 \, \text{km s}^{-1})\) instead of the kinetic energy of the supernova itself.

6.2.1. Extent of Burning via C \(\Pi\lambda\lambda 6580\)

Given that the characteristic ejecta velocity is proportional to \((E_{\text{kin}}/M_\odot)^{1/2}\) (Arnett 1982), a standardized way of looking at the extent of burning is a more appropriate measure for interpreting the range of observed carbon velocities. The 6355 Å line of Si \(\Pi\) has been used as an indicator of the photospheric velocity at early epochs (Jeffery & Branch 1990; Patat et al. 1996). Choosing Si \(\Pi\lambda 6355\) over other lines alleviates any difficulty in obtaining Doppler velocities amid too much line blending and allows for consistent time coverage. This makes the absorption minimum of Si \(\Pi\lambda 6355\) a good point of reference.
for investigating the extent of burning via C II λ6580 absorption features before maximum light.

In Figure 8, we have the ratio of Doppler velocities, \( \frac{v(\text{C II} \lambda 6580)}{v(\text{Si II} \lambda 6355)} \), derived from our SYNOW fits plotted versus days relative to maximum light. This shows that (1) for an individual SN, the ratio remains at a fairly sustained value over time and (2) the different velocity ratios among the SNe lie roughly within the same region and are similar to within ±10%. We have ignored the three outliers because one is in a region of the plot where line blending obscures the supposed C II λ6580 detection (SN 2001V; see Section 6.2.2) and the other two objects suggest that the carbon is clumpy and not along the line of sight of the observer (SN 2006bt and SN 2008ha).

The notion of an optically thick photosphere in SNe is generally a good assumption, even though the line forming region may extend 500 km s\(^{-1}\) in either direction. Therefore, for a given spectrum, any velocities of an ion that are measured to be fairly below that of the photospheric velocity, \( v_{\text{phot}} \), may indicate ejecta asymmetries. That is, any observed discrepancy between \( v_{\text{phot}} \) and \( v_{\text{C II}} \) could be explained if the actual velocity of C II is the same as \( v_{\text{phot}} \) but instead of forming in a shell at the observed velocity, the carbon is in a clump at \( v_{\text{phot}} \) and offset by an angle, \( \theta \), from the line of sight. In particular, we can estimate this projection angle if \( v_{\text{C II}} < v_{\text{phot}} \). For SN 2006bt and SN 2008ha we calculate this projection angle to be \( \sim 50^\circ \) and \( 60^\circ \), respectively, where our result for SN 2006bt is in agreement with Foley et al. (2010b).

If the dominant C II behavior is due to asymmetrical distributions of a single localized clump of unburned material, one could expect there to be more scatter below the mean that is presented in Figure 8 since an arbitrary orientation of the clump relative to the observer ought to lead to more cases where \( \frac{v(\text{C II} \lambda 6580)}{v(\text{Si II} \lambda 6355)} < 1 \) (like SN 2006bt). Instead, what we find for the SNe in our sample is that the distribution of carbon-rich material is consistent with a layered or hemispheric geometry.

Another surprising aspect of Figure 8 is that the candidate Super-Chandra SNe Ia resides in the same region of the plot as the other objects. Scalzo et al. (2010) suggested that the large C II λ6580 feature, concurrent with low velocities, could be explained by invoking a pre-explosion envelope of progenitor material originating from the merger of two white dwarfs. In this scenario, the explosion is inhibited by and loses kinetic energy to the envelope, ionizing the shell of surrounding carbon. Whatever the nature of carbon-rich regions in these three SNe Ia, it is also constrained by the value of \( \frac{v(\text{C II} \lambda 6580)}{v(\text{Si II} \lambda 6355)} \).

6.2.2. Consequences of Line Blending

Toward the uppermost region of Figure 8, there is a noticeable lack of highly detached C II objects with time-series coverage that exhibit pre-maximum C II λ6580 absorption features. This does not necessarily imply that carbon-rich regions in SNe Ia are absent above a particular velocity. Rather, the “missing” subset of objects may be a result of SNe Ia with lower density carbon-rich regions further out and/or radiative transfer selection effects, e.g., line blending.

Most of the SNe Ia in our sample that exhibit C II λ6580 absorption features are of the LVG subtype, while only one is an HVG event (SN 2009ig). This is either a real trend of C II λ6580 absorption features and therefore a diagnostic of SN Ia diversity, or a result of line blending due to very high velocities of carbon-rich regions. In regard to the latter cause, some SNe Ia might contain a C II λ6580 absorption feature in their spectra but its presence is obscured by the Si II λ6355 absorption trough, particularly for HVGs.

Assuming that the scatter of \( \frac{v(\text{C II} \lambda 6580)}{v(\text{Si II} \lambda 6355)} \) values in Figure 8 is the same for both HVG and LVG subtypes, and assuming that HVGs span a \( v_{\text{phot}} \)-space from 14,000 to 16,000 km s\(^{-1}\), then the minimum of any C II λ6580 signature would be between 6120 and 6280 Å. If weak and blueshifted to these wavelengths, the C II λ6580 absorption would most likely go undetected. If the C II optical depth were large enough, then the most direct evidence for hidden C II λ6580 would be whether or not an associated absorption from C II λ7234 could be seen between 6730 and 6900 Å.
This raises the question: at what velocity will C\textsc{ii}\,$\lambda$6580 completely blend with Si\textsc{ii}\,$\lambda$6580? In Figure 6, we presented observed C\textsc{ii}\,$\lambda$6580 blending scenarios where the signature is weak and nearly hidden, such as possibly observed in SN 2001V and 2009ig. These objects suggest that C\textsc{ii}\,$\lambda$6580 absorption features can in some cases be obscured via line blending. Such a “hidden” C\textsc{ii} signature would be seen in the form of an absorption on the shoulder on the blue wing of the Si\textsc{ii}\,$\lambda$6580 emission component.

A series of synthetic spectra that include only blends of Si\textsc{ii}\,$\lambda$6355 and C\textsc{ii}\,$\lambda$6580 line profiles are shown in Figure 9 (top panel). For these SYNOW spectra, the velocity of Si\textsc{ii} was fixed at 10,000 km s\(^{-1}\) while the velocity of C\textsc{ii} was increased from this 10,000 km s\(^{-1}\) by 1000 km s\(^{-1}\) increments up to a velocity of 15,000 km s\(^{-1}\). We simultaneously decreased the optical depth for consistency with the observed profile shapes. At a velocity of 15,000 km s\(^{-1}\), C\textsc{ii}\,$\lambda$6580 loses its discernibility as a feature and remains hidden until C\textsc{ii} reaches a velocity of 27,000 km s\(^{-1}\). At present, there are no observations reporting a C\textsc{ii}\,$\lambda$6580 feature appearing bluward of the Si\textsc{ii}\,$\lambda$6355 absorption.

Aside from being able to account for the observed variety of C\textsc{ii} absorption profile shapes and velocities with respect to Si\textsc{ii}\,$\lambda$6355, in Figure 9 we also show that the shoulder effect can be reproduced when C\textsc{ii} is detached with a velocity \(\sim 4000\) km s\(^{-1}\) greater than that of Si\textsc{ii}. This is consistent with our fit for SN 2001V where we have C\textsc{ii} and Si\textsc{ii} at 12,000 and 8000 km s\(^{-1}\), respectively.

In Figure 9 (bottom panel), we show a series of synthetic spectra where C\textsc{ii} and Si\textsc{ii} are placed at the same velocity and increased in sequence from 10,000 to 18,000 km s\(^{-1}\). We modeled the Si\textsc{ii} profiles using the two-component method so as to reproduce HVG-like properties. As can be seen, the C\textsc{ii}\,$\lambda$6580 absorption feature can be easily obscured at higher velocities. The proposed weak C\textsc{ii}\,$\lambda$6580 feature for SN 2009ig lies atop the emission component of Si\textsc{ii}\,$\lambda$6355 and is consistent with this series of synthetic spectra.

It is generally thought that the infrequent number of HVGs where C\textsc{ii}\,$\lambda$6580 is detected suggests an environment of sparse carbon-rich regions (Pignata et al. 2008). However, if the proposed C\textsc{ii}\,$\lambda$6580 signature in SN 2009ig is correct, then our fits suggest that the feature could be weak based on line blending, and not necessarily due to a low carbon abundance (or lower than that of LVGs) alone.

6.3. Asymmetries in the Distribution of C\textsc{ii} Regions

Because the ejected material follows a homologous expansion law \((v \propto r)\), the degree to which electron scattering will polarize emergent light across a spectral line can provide geometrical information on the material between the observer and the photosphere (Shapiro & Sutherland 1982; Wang & Wheeler 2008). Spectropolarimetry of some SNe Ia has revealed that the distribution of the outermost ejected material has an overall deviation from spherical symmetry of up to \(\sim 10\%\) (H"oflich 1991; Wang et al. 1997). Specifically, optical Si\textsc{ii} P-Cygni profiles are observed to have peak polarization values of \(0.3\%–2.0\%\), five days before maximum light (Wang et al. 2007). Other absorption features, such as the Ca\textsc{ii} IR triplet, have also been observed to be strongly polarized (Wang et al. 2003; Kasen et al. 2003).

Of the 19 SNe Ia in our sample, only SN 1994D, 1999by, and 2005hk have nearly simultaneous spectroscopic and polarization data during the presence of a C\textsc{ii}\,$\lambda$6580 absorption feature. Polarization levels for these objects across Si\textsc{ii}\,$\lambda$6355 were reported as insignificant (\(< 0.3\%\) for SN 1994D, Wang et al. 1996; \(< 0.4\%\) for SN 1999by, Howell et al. 2001; \(< 0.4\%\) for SN 2005hk, Chornock et al. 2006), whereas the degree of polarization was even less in the region of the C\textsc{ii}\,$\lambda$6580 signature.

Regarding SN 1999by, the three spectropolarimetric observations of Howell et al. (2001) were combined from data taken on days \(-2, -1,\) and 0 in order to increase the S/N (see their Figure 2). The resultant spectrum exhibited the same 6300 Å absorption feature that we attributed to C\textsc{ii}\,$\lambda$6580 in the day \(-5, -4,\) and \(-3\) spectra of Garnavich et al. (2004), but the concurrent polarimetry data of Howell et al. (2001) did not show any significant amount of polarization near the feature. This would suggest that the C\textsc{ii} regions are roughly spherical in at least these objects. However, because spectropolarimetric observations are
Figure 9. Top: a series of synthetic spectra show an evolution of blending scenarios between C II $\lambda$6580 and Si II $\lambda$6355 as the velocity of C II is increased from 10,000 to 15,000 km s$^{-1}$. The two spectra at the bottom represent a case where the CII is present at high velocities. Note that even if the 6580 line is obscured, the 7234 line is blueshifted to the rest-frame position of the 6580 line. Three high-velocity scenarios are also shown to note the velocity at which CII $\lambda$6580 emerges from the blue wing of Si II $\lambda$6355. Bottom: like the top figure, but instead CII and Si II are at the same velocity and increased in sequence together while holding r fixed. The Si II profiles are made from two components of Si separated by 4000 km s$^{-1}$. The day $-$14 spectrum of SN 2009ig is shown for comparison.

In this model, LVGs correspond to viewing the hemisphere of ejecta that coincides with the off-center ignition, whereas HVGs are the contrary with an opening angle of $\sim$70°$-$75°. Since we do not see a predominate number of HVGs with conspicuous C II $\lambda$6580 features in our sample, this is consistent with the above model, owing to the fact that detonation waves ought to leave little unburned material behind on the HVG side. If Maeda et al. (2010) is correct, and if our sample of SNe Ia that exhibit CII $\lambda$6580 is representative, then this suggests that the filling factor of carbon in the LVG hemisphere is less than unity.

7. CONCLUSIONS

In an effort to better understand the frequency and general properties of CII absorption features, we examined CII $\lambda$6580 signatures in the pre-maximum spectra of 19 SNe Ia, of which included 14 “normal” SNe Ia, three possible Super-Chandra SNe Ia, and two 2002cx-like events. Using SYNOW to produce synthetic spectra, we modeled observed $\sim$6300 Å absorption features as a C II $\lambda$6580 P-Cygni profile blended with that of Si II $\lambda$6355. Through our SYNOW model fits we estimated the CII expansion velocities for a variety of objects. Below is a summary of our major findings.

1. A survey of the optical spectra of 68 objects published in the literature since 1983 January 1 indicates that up to $\sim$30% of SNe Ia display an absorption feature near 6300 Å that can be attributed to CII $\lambda$6580. While this percentage is likely biased, it does suggest that CII $\lambda$6580 absorption features are more common than was previously suspected (Thomas et al. 2007). If spectroscopic observations of SNe Ia are obtained more than $\sim$1 week before maximum light, we suspect that an even larger fraction of SNe Ia of all subtypes may show identifiable CII absorption signatures.

2. A greater frequency of CII $\lambda$6580 absorption features appears in the LVG subtypes compared to HVG events. This is in line with the interpretation of Maeda et al. (2010), supporting the idea that part of SN Ia diversity can be accounted for by viewing angle and off-center ignition effects.

3. The influence of the temperature of the carbon-rich region on the incidence of CII $\lambda$6580 signatures is most evident for the 14 “normal” SNe Ia in our survey. The frequency of CII $\lambda$6580 signatures peaks with the CN SNe Ia, while the CL and SS subtypes exhibit fewer CII $\lambda$6580 detections. This result is consistent with the effective temperature sequence of Nugent et al. (1995).

4. We find that the values of $\nu$(CII $\lambda$6580)/$\nu$(Si II $\lambda$6355) among 16 of the SNe Ia in our CII sample are similar to within $\pm$10%. Assuming that the minima of Si II $\lambda$6355 absorption features are an appropriate measure of photospheric velocities prior to maximum light, the small number of cases where $\nu$(CII $\lambda$6580)/$\nu$(Si II $\lambda$6355) $< 1$ could be indicative of either a layered distribution or multiple clumps with a comparable filling factor.

One of the most interesting results of this study is that CII $\lambda$6580 absorption features might be in many, if not most, early-epoch SN Ia spectra. We initially set out to investigate material in the lower density regions and is effectively screened by some of the deflagration ash. What remains is a lopsided distribution of burning products, resulting in a hemispheric asymmetry of the ejecta. Similarly, Maund et al. (2010) reached the same conclusion regarding SN Ia diversity after examining a possible relationship between HVG/LVG subtypes and the possible asymmetrical distribution of photospheric Si II.

Recently, Maeda et al. (2010b) discussed SN Ia diversity in the context of global asymmetries of ejected material. They argued that the HVG and LVG subtypes constitute a picture of SNe Ia in terms of an off-center delayed-detonation at different viewing angles. In this scenario, an off-center ignition is followed by the propagation of a sub-sonic deflagration flame that imprints an offset distribution of high density ash. Once the transition to detonation occurs, a super-sonic flame only successfully burns off-center delayed-detonation at different viewing angles. In this scenario, an off-center delayed-detonation at different viewing angles. In this scenario, an off-center delayed-detonation at different viewing angles. In this scenario, an off-center delayed-detonation at different viewing angles.
One way to test for a high frequency of C II λ6580 features in pre-maximum SNe Ia spectra would be to obtain high S/N observations of the region between 6700 and 7200 Å in order to look for the relatively weaker C II λ7234 line that should also be present. In addition, a data set of C II λ6580 observations with wavelength coverage that encompasses the O I λ7774 absorption feature would allow for investigating any correlations between C and O spectral line properties.

Understanding the presence of C II in SN Ia spectra may prove to be a valuable diagnostic of SN Ia diversity and therefore a possible means by which to probe the underlying explosion mechanism. Utilizing the absolute strength of the C II λ6580 line in order to extract abundance information will require comparison to synthetic spectra calculations based on hydrodynamical modeling. A detailed comparative study that can extract C abundance information, derived from C II λ6580 absorption features, promises to promote a wealth of insight regarding carbon-rich regions, and therefore constrain the parameter space of hydrodynamical modeling.

We are grateful to Laura Kay for obtaining some of the spectra of SN 2010Y and thank Eddie Baron, David Branch, and Andy Howell for helpful comments on an earlier draft of this paper. J.V. has received support from NSF Grant AST-0707669, Texas Advanced Research Program grant ASTRO-ARP-0094, and Hungarian OTKA Grant K76816.

REFERENCES

Aldering, G., et al. 2002, Proc. SPIE, 4836, 61
Arnett, W. D. 1969, Ap&SS, 5, 180
Arnett, W. D. 1982, ApJ, 253, 785
Baron, E., Hauschildt, P. H., & Branch, D. 1994, ApJ, 426, 334
Baron, E., Chen, B., & Hauschildt, P. H. 2009, AIP Conf. Proc., 1171, 148
Baron, E., Khokhlov, A. M. 1991, A&A, 245, 114
Baron, E., Lentz, E. J., & Hauschildt, P. H. 2005, ApJ, 687, L55
Baron, E., Parrent, J., Troxel, M. A., Casebeer, D., Jeffery, D. J., Branch, D., Khokhlov, A. M. 1995, Phys. Rep., 256, 53
