DOUBLETS AND DOUBLE PEAKS: LATE-TIME [O I] λ6300, 6364 LINE PROFILES OF STRIPPED-ENVELOPE, CORE-COLLAPSE SUPERNOVAE

Dan Milisavljevic 1, Robert A. Fesen 1, Christopher L. Gerardy 2, Robert P. Kirshner 3, and Peter Challis 3

1 6127 Wilder Lab, Department of Physics & Astronomy, Dartmouth College, Hanover, NH 03755, USA
2 Department of Physics, Florida State University, Tallahassee, FL 32306, USA
3 Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA

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ABSTRACT

We present optical spectra of SN 2007gr, SN 2007rz, SN 2007uy, SN 2008ax, and SN 2008bo obtained in the nebular phase when line profiles can lead to information about the velocity distribution of the exploded cores. We compare these to 13 other published spectra of stripped-envelope core-collapse supernovae (Type IIb, Ib, and Ic) to investigate properties of their double-peaked [O I] λ6300, 6364 emission. These 18 supernovae are divided into two empirical line profile types: (1) profiles showing two conspicuous emission peaks nearly symmetrically centered on either side of 6300 Å and spaced ≈64 Å apart, close to the wavelength separation between the [O I] λ6300, 6364 doublet lines, and (2) profiles showing asymmetric [O I] line profiles consisting of a pronounced emission peak near 6300 Å plus one or more blueshifted emission peaks. Examination of these emission profiles, as well as comparison with profiles in the lines of [O I] λ5577, O I λ7774, and Mg I λ4571, leads us to conclude that neither type of [O I] double-peaked profile is necessarily the signature of emission from front and rear faces of ejecta arranged in a toroidal disk or elongated shell geometry as previously suggested. We propose possible alternative interpretations of double-peaked emission for each profile type, test their feasibility with simple line-fitting models, and discuss their strengths and weaknesses. The underlying cause of the observed predominance of blueshifted emission peaks is unclear, but may be due to internal scattering or dust obscuration of emission from far side ejecta.

Key words: supernovae: general – supernovae: individual (SN 2008ax, SN 2008bo, SN 2007uy, SN 2007rz, SN 2007gr)

Online-only material: color figures

1. INTRODUCTION

Analyses of emission-line profiles of ejecta-tracing elements in stripped-envelope, core-collapse supernovae (CCSNe) during the “nebular phase” several months after outburst probe the chemical and kinematic properties of the metal-rich ejecta, thereby yielding clues about CCSN explosion dynamics and geometry. Particular attention has been paid to studying the line profiles of oxygen, magnesium, and calcium as these elements are among the strongest lines 100–200 days post-outburst (Fransson & Chevalier 1989; Filippenko 1997). Stripped-envelope SN lacking strong Hα emission (i.e., Types IIb, Ib, and Ic) can be particularly informative because details of the interior regions are not obscured by the hydrogen envelope surrounding progenitors of Type II SNe.

Late-time spectra of stripped CCSN have shown that double-peaked line profiles in [O I] λ6300, 6364 emission seem to be a relatively common phenomenon, suggesting a possible unifying characteristic across types IIb, Ib, and Ic. Maeda et al. (2008) found double-peaked [O I] λ6300, 6364 profiles in 40% of a sample of 18 stripped CCSNe, while Modjaz et al. (2008a) reported finding double-peaked [O I] profiles in three of eight objects studied. Such spectra show two conspicuous emission peaks, often symmetrically situated around a trough centered near 6300 Å and, when present, persist over the full observing period.

Double-peaked emission-line profiles deviate from the single-peaked profile expected from a spherically symmetric source and this has been interpreted in many cases as evidence for aspherically distributed debris having a torus or disk-like geometry. Maeda et al. (2002) first predicted that double-peaked [O I] line profiles could be associated with a torus of O-rich ejecta. Mazzali et al. (2005) observed a double-peaked [O I] profile in the Type Ic broad-lined SN 2003jd, and interpreted it as emission originating from a torus of O-rich debris perpendicular to a high-velocity jet in a gamma-ray burst (GRB) model. Maeda et al. (2008) reported observing double-peaked profiles in the optical spectra of approximately 7 out of 18 CCSNe and was able to model the profiles using an aspherical, torus-like geometry of O-rich ejecta. They concluded that the observed [O I] emission could be either single- or double-peaked depending on the viewing angle being either perpendicular to or along the torus plane. Modjaz et al. (2008a) also interpreted double-peaked [O I] profiles in several CCSN spectra and found them consistent with a torus-like distribution of SN debris generated by the explosion physics, but not necessarily a GRB-like jet/torus structure.

Here we present observations and analyses to help characterize the [O I] λ6300, 6364 emission profile in late-time optical spectra of stripped-envelope CCSNe. In Sections 2 and 3, we present new low- to moderate-resolution optical spectra of five recent stripped-envelope CCSNe obtained 2–14 months after optical maximum. We then compare the [O I] emission-line profiles of these and 13 other published late-time spectra in Sections 4 and 5. In Section 6, we summarize our findings, concluding in part that double-peaked [O I] line profiles are not necessarily the signature of emission from front and rear faces of O-rich ejecta arranged in a toroidal geometry as previously suggested.

2. OBSERVATIONS

Low-dispersion optical spectra were obtained with the 6.5 m MMT and the 1.5 m FLWO telescopes at Mt. Hopkins in Arizona, and the 2.4 m Hiltner telescope at the MDM.
Observatory on Kitt Peak, Arizona. MMT observations used the Blue Channel spectrograph (Schmidt et al. 1989) employing a 1′′ wide slit and a 300 lines mm$^{-1}$ blaze grating. Spectra typically spanned 3500–8000 Å with a resolution of $\approx 7$ Å. FLWO observations employed the FAST spectrograph (Fabricant et al. 1998) with a 300 lines mm$^{-1}$ grating and a standard slit width of 3′′, yielding spectra covering 4000–7400 Å with 7 Å resolution.

MDM observations used three different spectrographs. A Boller & Chivens CCD spectrograph (CCDS) was used with a north–south 1′′ × 5′′ slit and either a 150 lines mm$^{-1}$ 4700 Å blaze grating yielding $\approx 10$ Å resolution, or a 600 lines mm$^{-1}$ 4700 Å blaze yielding 2 Å resolution. The Modular Spectrograph was used in combination with the SITE 2K Echelle CCD detector with a 1′′ × 5′′ slit and a 600 lines mm$^{-1}$ 5000 Å blaze grating. Resulting spectra spanned 4500–7500 Å with a resolution of 6 Å. The Mark III spectrograph in combination with a SITE 1K CCD detector ("Templeton") was used with a 300 lines mm$^{-1}$ 6400 Å blaze grism yielding spectra of 12 Å resolution. Details of all observations including dates and exposure times are provided in Table 1.

All spectra were reduced and calibrated employing standard techniques in IRAF$^4$ and our own IDL routines (see, e.g., Matheson et al. 2008). Narrow host galaxy emission features, telluric absorptions, and obvious cosmetic defects have been removed from all spectra. All reported wavelengths are in the rest frame of the supernovae (SNe) as determined by the recessional velocity inferred from narrow H$\alpha$ lines observed in local H$\text{II}$ regions. When no such lines were available, host galaxy heliocentric recessional velocities were retrieved on-line from the NASA/IPAC Extragalactic Database (NED).$^5$ Reported epochs are with respect to published dates of maximum optical brightness noted below; otherwise they are estimated with respect to discovery dates.

3. RESULTS

In Figure 1, we present low- to moderate-resolution late-time optical spectra of five stripped-envelope CCSNe observed from 2007–2009 at epochs spanning evolution into the nebular phase when emission is dominated by forbidden transitions. The left panel presents spectra of SN 2008ax, and the right panel spectra of SN 2007gr, SN 2007rz, SN 2007uy, and SN 2008bo. The following is a brief description of these data with particular emphasis on the emission lines of ejecta-tracing elements oxygen, magnesium, and calcium which will be discussed in greater depth in Section 4.

3.1. SN 2008ax

SN 2008ax in NGC 4490 was discovered by Mostardi et al. (2008) on 2008 March 3 and classified spectroscopically as a Type IIb SN (Chornock et al. 2008). Extensive spectra and photometric monitoring of the SN and investigation of pre-explosion Hubble Space Telescope (HST) images show it consistent with the explosion of a young Wolf–Rayet progenitor star of WNL type (Crockett et al. 2008b; Pastorello et al. 2008). The SN reached maximum brightness $m_v = 13.5$ on 2008 March 24 (Pastorello et al. 2008).

Our late-time spectra (Figure 1, left panel) show early P Cygni features attributable to Fe$\text{II}$ lines around 5000 Å, blended He$\text{I}$ λ5876 and Na$\text{I}$ λλ5890, 5896, and He$\text{I}$ λ7065 that decline in strength with time. Emission from forbidden lines [O$\text{I}$]

\[\text{Notes.} \]

$^a$ Recessional velocity inferred from narrow H$\alpha$ line unless otherwise noted.

$^b$ Epoch with respect to discovery date.

$^c$ Presented spectrum smoothed with a 3 pixel boxcar function.

$^d$ No adjacent H$\alpha$ detected; NED recessional velocity of host galaxy used.

$^e$ Presented spectrum is average of two nights of observations, 2009 April 22 and 23.

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\begin{table}[h]
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\begin{tabular}{|l|l|l|l|l|l|l|}
\hline
Supernova/Type & Host Galaxy & Redshift* (km s$^{-1}$) & Observation Date & Epoch (days) & Telescope/Instrument & Spec. Res. (Å) & Exp. Time (s) \\
\hline
SN 2007gr (Ic) & NGC 1058 & 503 & 2007 Dec 21 & 115 & MDM/CCDS & 2 & 3000 × 3 \\
SN 2007rz (Ic) & NGC 1590 & 4023 & 2008 Apr 01 & 111$^b$ & MMT/Blue Channel & 7$^c$ & 600 × 3 \\
SN 2007uy (Ib) & NGC 2770 & 1874 & 2008 Apr 01 & 92$^b$ & MMT/Blue Channel & 7$^c$ & 600 × 4 \\
SN 2008ax (IIb) & NGC 4490 & 565$^d$ & 2008 May 30 & 67 & FLWO/FAST & 10 & 1800 \\
SN 2008bo (IIb) & NGC 6643 & 1484 & 2008 Jun 06 & 74 & MMT/Blue Channel & 7 & 900 \\
SN 2008bx (IIb) & NGC 6643 & 1484 & 2008 Jul 03 & 101 & MDM/CCDS & 11 & 500 \\
SN 2008ax (IIb) & NGC 4490 & 565$^d$ & 2008 Aug 01 & 130 & MDM/Modspec & 6 & 600 \\
SN 2008bo (IIb) & NGC 6643 & 1484 & 2008 Dec 10 & 261 & MDM/CCDS & 11 & 2700 × 2 \\
SN 2008bx (IIb) & NGC 6643 & 1484 & 2008 Jun 22 & 307 & MMT/Blue Channel & 7 & 1800 \\
SN 2008bo (IIb) & NGC 6643 & 1484 & 2009 Apr 22$^e$ & 394 & MDM/CCDS & 11 & 2700 × 4 \\
SN 2008bo (IIb) & NGC 6643 & 1484 & 2009 May 16 & 418 & MDM/CCDS & 11 & 2700 \\
SN 2008ax (IIb) & NGC 4490 & 565$^d$ & 2008 Jun 06 & 52 & MMT/Blue Channel & 7 & 900 \\
SN 2008bo (IIb) & NGC 6643 & 1484 & 2008 Jul 30 & 106 & MMT/Blue Channel & 7 & 900 \\
SN 2008ax (IIb) & NGC 4490 & 565$^d$ & 2008 Sep 24 & 162 & MDM/Mark III & 12 & 2000 × 2 \\
\hline
\end{tabular}
\caption{Summary of Observations}
\end{table}

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\footnote{\textbf{4}} IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\footnote{\textbf{5}} http://nedwww.ipac.caltech.edu/
Figure 1. Left panel: optical spectra of SN 2008ax spanning its evolution into the nebular phase of emission. Asterisks (*) mark artificial features introduced during the reduction process from oversubtracted nebular lines emitted by coincident H II regions. Right panel: optical spectra of SN 2007gr, SN 2007rz, SN 2007uy, and SN 2008bo. See Table 1 for details of all observations.

Figure 2. Velocity line profiles of [O i] λ5577, [O i] λλ6300, 6364, and [Ca ii] λλ7291, 7324. The dashed line marks zero velocity with respect to 5577, 6300, and 7306 Å, respectively. Time progresses from top to bottom. (A color version of this figure is available in the online journal.)

λλ6300, 6364 and [Ca ii] λλ7291,7324 remains strong at all epochs. We interpret the relatively strong emission peaked at 4544 Å observable on days 307, 394, and 418 with Mg i] λ4571. Oxygen emission from [O i] λ5577 and O i λ7774 decline in strength relative to [O i] λλ6300, 6364. Two conspicuous narrow emission peaks around 6260 Å and 6323 Å (−1800 km s⁻¹ and +1200 km s⁻¹, with respect to 6300 Å) are noticeable in the [O i] profile from the earliest spectrum on day 67 and persist until our last observation on day 418.

In Figure 2, we show these same spectra enlarged around emission lines of interest to better see temporal changes in the observed features. The [O i] λ5577 line (Figure 2, left) shows only a blue peak, with nearly all of the emission profile falling blueward of zero velocity. The weighted center of this emission shifts to smaller velocities with time, until day 261 when no significant [O i] λ5577 emission is detected. On the other hand, the [O i] λλ6300, 6364 lines (middle) show two peaks roughly symmetric about 6300 Å. The relative strengths of the blue and red peaks change noticeably, with the blue peak stronger at early times but gradually becoming weaker at later epochs. The [Ca ii] λλ7291,7324 profile (right) is only modestly blueshifted and shows no change in the weighted line center over time.

Finally, we note that although SN 2008ax shares many spectral features with the SN IIb event SN 1993J, SN 2008ax...
displayed a clear and prominent double-peaked $[O\text{ I}]\lambda\lambda6300, 6364$ emission profile that SN 1993J did not. In Figure 3, we show SN 2008ax’s day 101 and day 307 spectra alongside optical spectra of SN 1993J taken on days 182 and 387, measured from date of maximum brightness. Data for SN 1993J are from Matheson et al. (2000a, 2000b).

### 3.2. SN 2007gr

SN 2007gr in NGC 1058 was discovered on 2007 August 15 by Madison & Li (2007) as part of the Lick Observatory Supernova Search. It was spectroscopically identified as a Type Ib/c by Chornock et al. (2007) and later confirmed as a Type Ic by Valenti et al. (2008a). It reached maximum brightness $m_B = 12.8$ on 2007 August 28 (Valenti et al. 2008a). Pre-explosion HST WFPC2 and ground-based $K$-band images marginally favor a progenitor star from a 7.0 ± 0.5 Myr cluster having a turn-off mass of 28 ± 4 $M_{\odot}$ (Crockett et al. 2008a). Extensive optical and near-infrared observations from days 5 to 415 are presented by Hunter et al. (2009).

Our moderate-resolution spectrum of SN 2007gr on day 115 (Figure 1, right panel) shows broad (HWZI $\gtrsim 6000$ km s$^{-1}$) $[O\text{ I}]\lambda\lambda6300, 6364$ emission strongly peaked around 6300 Å, along with $[Ca\text{ II}]\lambda\lambda7291, 7324$, and $O\text{ I}\lambda\lambda7774$ emission peaked at 7291 and 7770 Å, respectively. A minor emission peak around 6260 Å ($\sim 1900$ km s$^{-1}$) is observed in the $[O\text{ I}]\lambda\lambda6300, 6364$ profile and the high signal-to-noise ratio (S/N) of the spectra ensures that this feature is real. By day 391 $[O\text{ I}]6300, 6364$ emission remains relatively strong and chiefly single-peaked, and the minor blueshifted peak is no longer detected.

### 3.3. SN 2007rz

SN 2007rz in NGC 1590 was discovered on 2007 December 12 by Parisky & Li (2007) as part of the Lick Observatory Supernova Search and classified as a Type Ic by Morrell et al. (2007). Our $\sim 111$ day spectrum of SN 2007rz (Figure 1, right panel) shows weak $[O\text{ I}]$ emission roughly symmetric about 6300 Å with two peaks at 6264 and 6330 Å (approximately $-1700$ and 1400 km s$^{-1}$, respectively). Broad $[Ca\text{ II}]\lambda\lambda7291, 7324$ emission centered around 7305 Å is also observed.

### 3.4. SN 2007uy

SN 2007uy in NGC 2770 was discovered on 2007 December 31 by Y. Hirose (Nakano et al. 2008) and classified as a Type Ib by Blondin & Calkins (2008). The SN has not quite reached a fully nebular phase in our day $\sim 92$ spectrum (Figure 1, right panel) and displays a relatively complex collection of lines with notable emissions of $[O\text{ I}]\lambda5577$, $[O\text{ I}]\lambda\lambda6300, 6364$, $[Ca\text{ II}]\lambda\lambda7291, 7324$, and $O\text{ I}\lambda\lambda7774$. By day $\sim 158$ the SN has entered the nebular phase and the spectra show only $[O\text{ I}]\lambda\lambda6300, 6364$ and $[Ca\text{ II}]\lambda\lambda7291, 7324$. There is a noticeable change in the emission profile of $[O\text{ I}]\lambda\lambda6300, 6364$ emission between the two epochs. On day 92 the profile shows an asymmetric double-peaked profile with one peak near 6300 Å and the other blueshifted around 6243 Å ($\sim 2700$ km s$^{-1}$). However, by day 158 the blueshifted peak has weakened leaving the $[O\text{ I}]\lambda\lambda6300, 6364$ emission single-peaked and centered around 6300 Å.

### 3.5. SN 2008bo

SN 2008bo in NGC 6643 was discovered on 2008 April 22 by Nissinen & Oksanen (2008). Early optical spectra obtained by Navasardyan et al. (2008) showed a close resemblance to SN 2008ax, and they classified it as a Type Ib SN. Later spectra presented here and analyzed with the Supernova Identification code (SNID; Blondin & Tonry 2007) favor a Type Ib classification, which we adopt. Epochs for SN 2008bo follow from an optical maximum on 2008 April 15 estimated from unfiltered photometry retrieved from the SNWeb Web site.

Our spectra from days 52, 106, and 162 (Figure 1, right panel) show SN 2008bo’s entrance into the nebular phase. Blueshifted $[O\text{ I}]\lambda5577$ emission is observed on days 52 and 106 but faded and was not detected on day 162. During this time, emission from the $[O\text{ I}]\lambda\lambda6300, 6364$ lines shows conspicuous evolution. On day 52, two peaks, one centered around 6232 Å and another centered around 6297 Å (approximately $-3200$ and 0 km s$^{-1}$), are seen, with the blueshifted peak stronger than the other. On day 106, the same two peaks are observed, but the blue peak is now weaker than the red one, and evidence of an additional minor peak around 6268 Å is observed. By day 162, the blue peak continues to weaken in strength relative to emission centered around 6300 Å. In contrast, the $[Ca\text{ II}]\lambda\lambda7291, 7324$ lines show little relative change throughout this time period.
Figure 4. Comparing emission-line profiles of [O\textsc{i}] λλ 6300, 6364, [O\textsc{i}] λ 5577, O\textsc{i} λ 7774, [Ca\textsc{ii}] λλ 7291, 7324, and Mg\textsc{i} λ 4571 in SN 2008ax at four epochs. The heavy dashed line marks zero velocity with respect to wavelengths 6300, 5577, 7774, 7306, and 4571 Å, respectively. The fainter dashed line highlights blueshifted peaks around —1800 km s\(^{-1}\) shared across [O\textsc{i}] λλ 6300, 6364, [O\textsc{i}] λ 5577, and Mg\textsc{i} λ 4571.

4. LATE-TIME [O\textsc{i}] EMISSION-LINE PROFILES

Our spectra of five stripped CCSNe show a variety of [O\textsc{i}] λλ 6300, 6364 emission profiles. SN 2008ax and SN 2007rz show double-peaked profiles that are basically symmetric about 6300 Å. SN 2008bo and 2007uy also show double-peaked profiles but ones exhibiting strong asymmetries at early epochs. SN 2007gr, on the other hand, shows principally a single-peaked profile with a minor asymmetric blueshifted emission peak. Despite clear differences between these spectra, some trends emerge in the [O\textsc{i}] emission profiles when compared to other SNe.

Below, we discuss in detail the late-time emission-line profiles of SN 2008ax, which exhibit the sharpest and best-defined [O\textsc{i}] emission peaks compared to many other late-time CCSN spectra, and for which we have the best data set. Following this discussion, we then compare SN 2008ax’s line profiles against other SNe presented in this paper along with others taken from the literature.

4.1. SN 2008ax’s O, Ca, and Mg Emission-line Profiles

In Figure 4, we show SN 2008ax’s [O\textsc{i}] λλ 6300, 6364 line profile plotted in velocity space relative to other emission lines at four epochs. The top two panels show line profiles for the three neutral oxygen lines [O\textsc{i}] λλ 6300, 6364, [O\textsc{i}] λ 5577, and O\textsc{i} λ 7774 from spectra obtained on days 74 and 101. Both the [O\textsc{i}] λ 5577 and [O\textsc{i}] λλ 6300, 6364 profiles show common blueshifted peaks around —1900 km s\(^{-1}\), highlighted in this figure with the light dashed line. The O\textsc{i} λ 7774 profile appears square-topped with evidence for a fairly abrupt rise in emission strength close to the velocity of the [O\textsc{i}] λ 5577 peak and blue [O\textsc{i}] λλ 6300, 6364 peak.

The bottom two panels show line profiles for days 307 and 394. Emission observed at these later times should not suffer as much from radiative transfer effects or line contamination that may affect the earlier epoch observations of the above panels.

Compared to earlier epochs, [O\textsc{i}] λ 5577 and O\textsc{i} λ 7774 emission has faded and is no longer detected. Blueshifted Mg\textsc{i} λ 4571 emission is observed with a sharp emission peak at a velocity closely matching the blueshifted peak of the [O\textsc{i}] λλ 6300, 6364 profile of the same epoch and the blueshifted peak of the [O\textsc{i}] λ 5577 profile of the two earlier epochs. Though of poorer S/N, our day 394 spectrum shows the same blueshifted peak in the Mg\textsc{i} λ 4571 line, with possible additional emission around zero velocity. The profile of [Ca\textsc{ii}] λλ 7291, 7324 shows a slightly blueshifted, broad distribution that remains relatively unchanged at all epochs (see also Figure 2).

In summary, the emission-line profiles of ejecta tracing elements oxygen, calcium, and magnesium in the late-time spectra of SN 2008ax exhibit quite different line profiles. [O\textsc{i}] λλ 6300, 6364 shows an unmistakable double-peaked profile at all epochs observed. In sharp contrast, the [O\textsc{i}] λ 5577 profile shows a prominent single-peaked blueshifted profile with a little redshifted emission, while O\textsc{i} λ 7774 shows a broad profile centered close to zero velocity with no obvious emission peaks. Neither of these lines are observed at the later epochs. The Mg\textsc{i} λ 4571 profile, which is first observed on day 307, is strongly blueshifted with an emission peak at a velocity matching the blueshifted peak seen in the [O\textsc{i}] λλ 6300, 6364 lines.

4.2. SN 2008ax’s Line Profiles Compared to Other SNe

To test if SN 2008ax’s oxygen emission profile behavior is exceptional, we compared its late-time spectra with two of the four other SNe we observed (Table 1, Figure 1), along with four additional CCSNe taken from the literature. This sample is comprised of SN 2004ao (Modjaz et al. 2008a), SN 2004dk (Modjaz et al. 2008a), SN 2006T (Modjaz et al. 2008a), SN 2007uy, SN 2008D (Modjaz et al. 2008b), and SN 2008bo. Selection of these six SNe was based upon the presence of double-peaked [O\textsc{i}] λλ 6300, 6364 line profiles and the availability of high quality late-time [O\textsc{i}] λ 5577, O\textsc{i} λ 7774, and Mg\textsc{i} λ 4571 line profile data.

Figure 5 shows the emission-line profiles of these six SNe. Multiple epochs are shown for SN 2004ao because the [O\textsc{i}] λ 5577 and Mg\textsc{i} λ 4571 lines are seen at different stages of optical evolution. With the exception of SN 2004dk, these emission profiles observed at epochs \( t < 200 \) days may be contaminated by other emission lines and/or radiative transfer effects, but are late enough that these effects should be small.

Like SN 2008ax, all five [O\textsc{i}] λ 5577 profiles that are observed show no appreciable redshifted emission. Moreover, in four of five of these cases, but seen particularly clearly in SN 2006T and SN 2004ao, the [O\textsc{i}] λ 5577 line profile is single-peaked with the velocity of the peak closely matching the blueshifted peak in the [O\textsc{i}] λλ 6300, 6364 line profiles.

Also like SN 2008ax, the O\textsc{i} λ 7774 and Mg\textsc{i} λ 4571 lines of these SNe exhibit profiles noticeably different from [O\textsc{i}]
A recent independent survey of [O\textsc{i}] $\lambda\lambda 6300, 6364$ line profiles exhibited in the optical spectra of Ib/c CCSN by Taubenberger et al. (2009) provides additional examples of Mg\textsc{i} $\lambda 4571$, [O\textsc{i}] $\lambda 5577$, and [O\textsc{i}] $\lambda 7774$ lines to compare. Many SNe in their sample show the same trends in the oxygen and magnesium lines. Examples include the Mg\textsc{i} $\lambda 4571$ profile observed in SN 2006T on day 371 (an epoch much later than our data) and in SN 2006Id on day 280, both of which show single-peaked blueshifted emission at velocities matching blueshifted peaks in the [O\textsc{i}] $\lambda\lambda 6300, 6364$ lines. Similarly, single-peaked [O\textsc{i}] $\lambda 5577$ at a blueshifted velocity matching the Mg\textsc{i} $\lambda 4571$ and [O\textsc{i}] $\lambda\lambda 6300, 6364$ lines is observed in SN 2006ew on day 112.

A caveat to the trends noted above is a possible uncertainty in identifying the emission feature near 5500 Å with [O\textsc{i}] $\lambda 5577$. For example, early analysis of blueshifted emission around 5500 Å in SN 1993J was identified as $\text{[O\textsc{i}] } \lambda 5577$ (Sromilin et al. 1994, Filippenko et al. 1994; Wang & Hu 1994), but later analysis appeared to favor [O\textsc{i}] $\lambda 5577$ emission blended with [Fe\textsc{ii}] $\lambda 5536$ and [Co\textsc{ii}] $\lambda 5526$, the combination of which falsely gave the impression of blueshifted emission (Houck & Fransson 1996). However, because of the correspondence between the blueshifted peaks in the Mg\textsc{i} $\lambda 4571$, [O\textsc{i}] $\lambda 5577$, and [O\textsc{i}] $\lambda\lambda 6300, 6364$ line profiles, we examined a larger set of stripped-envelope CCSN spectra but this time not restricted to the availability of high quality late-time [O\textsc{i}] $\lambda 5577$, O\textsc{i} $\lambda\lambda 7774$ or Mg\textsc{i} $\lambda 4571$ line profile data. In Figure 6, we show a comparison of [O\textsc{i}] $\lambda\lambda 6300, 6364$ emission-line profiles for a sample of 18 SNe comprised of our five SNe plus an additional 13 taken from the literature. Table 2 references the sources, observing details, and estimated epochs of all spectra. These 18 objects have been divided into two main types: nine profiles that exhibit two prominent [O\textsc{i}] emission peaks positioned approximately symmetric about zero velocity, and nine asymmetric profiles with one peak lying near 6300 Å and additional peaks at blueshifted velocities.

4.3. A Wider Survey of [O\textsc{i}] $\lambda\lambda 6300, 6364$ Profiles

To broaden our investigation of [O\textsc{i}] $\lambda\lambda 6300, 6364$ line profiles, we examined a larger set of stripped-envelope CCSN spectra but this time not restricted to the availability of high quality late-time [O\textsc{i}] $\lambda 5577$, O\textsc{i} $\lambda\lambda 7774$ or Mg\textsc{i} $\lambda 4571$ line profile data. In Figure 6, we show a comparison of [O\textsc{i}] $\lambda\lambda 6300, 6364$ emission-line profiles for a sample of 18 SNe comprised of our five SNe plus an additional 13 taken from the literature. Table 2 references the sources, observing details, and estimated epochs of all spectra. These 18 objects have been divided into two main types: nine profiles that exhibit two prominent [O\textsc{i}] emission peaks positioned approximately symmetrically about 6300 Å (left panel), and nine asymmetric profiles with one peak lying near 6300 Å and additional peaks at blueshifted velocities (right panel).

4.4. Symmetric [O\textsc{i}] Profiles

The nine [O\textsc{i}] $\lambda\lambda 6300, 6364$ emission-line profiles shown in the left panel of Figure 6 share the property of exhibiting two conspicuous emission peaks positioned roughly on either side of 6300 Å. The velocity of the blueshifted emission peak ranges from $\approx -1000$ to $-2600$ km s$^{-1}$ assuming it to be due to the [O\textsc{i}] $\lambda\lambda 6300$ line. While the peaks can be narrow as in the case of 08ax or broad as in 03jd, the presence of these two emissions peaks dominates the overall appearance of the [O\textsc{i}] line profiles.

We subdivided these nine objects into three subgroups. Sometimes a third, weaker emission peak near zero velocity
is seen in the [O I] λλ6300, 6364 profile and this is highlighted in the figure for three SNe 05kl, 04ao, and 07rz (left panel, upper middle). Contaminating [O I] emission from an underlying H II region is a possible but unlikely origin for this feature (see Tanaka et al. 2009). The broad-lined Type Ic SN, 03jd, plotted at the top of the figure in its own subgroup, also shows a weak central trough between peaks with no obvious central emission peak (left panel, bottom).

Although the relative strengths of the blueshifted and redshifted peaks vary across these subgroups, in most cases the spacing between the two peaks is close to 3000 km s$^{-1}$ (i.e., $\approx 64 \, \text{Å}$). The two lines of the [O I] λλ6300, 6364 doublet (more precisely at 6300.30 and 6363.78 Å) are suspiciously close to their transition probabilities when the lines are optically thin. This is perhaps unexpected, but not without precedent, as some SNe have shown similar ratios smaller than the nebular 3:1 value. Optical spectra of SN 1987A (Spyromilio et al. 1991; Li & McCray 1992) and 1988A (Spyromilio 1991) showed [O I] 6300:6364 line ratios close to 1 in spectra taken at epochs $t \sim 200$ days post-outburst. Though likely originating from different physical conditions, [O I] 6300:6364 flux ratios around 2 and smaller are also routinely observed in novae at similar times (Williams 1994). Deviations from the 3:1 nebular value are attributed to optically thick line emission with $\tau \gtrsim 1$ (see Li & McCray 1992 and Williams 1994). We investigate other possible interpretations of these non-nebular ratios in Section 5.

**4.5. Asymmetric [O I] Profiles**

The nine [O I] λλ6300, 6364 emission-line profiles shown in the right panel of Figure 6 exhibit two or more emission peaks, where one peak is located close to 6300 Å, and the other(s) blueshifted with respect to 6300 Å producing an asymmetrical-looking line profile. As was done for the symmetric profile SNe, we subdivided these asymmetric profiles into three groups. SN 2004dk, showing a relatively broad [O I] profile, forms the top grouping, while SNe showing emission-line profiles that are multi-peaked or double-peaked form the middle and bottom groupings, respectively.

Much like that found for many of the symmetric [O I] profiles shown in the left panel, a few asymmetric profiles (90B, 07uy, and 08bo; middle grouping) exhibit emission peaks separated...
by \( \sim 3000 \) km s\(^{-1} \), i.e., close to the 64 Å separation of the \([\text{O} \text{I}] \lambda \lambda 6300, 6364\) doublet. However, most show separations between peaks larger or smaller than this (top and bottom groupings) with velocities of the blueshifted emission peak ranging from \(-1500\) km s\(^{-1}\) (SN 1996cb) to \(-3300\) km s\(^{-1}\) (SN 2004dk). Also unlike the symmetric profiles plotted in the left panel, most asymmetric profiles show no conspicuous redshifted emission peaks. The one apparent exception is 1990B, although the red emission feature observed around 3000 km s\(^{-1}\) is likely the \( \lambda 6364 \) line of \([\text{O} \text{I}] \) (see Taubenberger et al. 2009).

### 4.6. The Persistence of Blueshifted Emission Peaks

An important caveat to Figures 6 and 7 is that the \([\text{O} \text{I}] \lambda \lambda 6300, 6364\) profiles are snapshots of emission profiles at single epochs and thereby do not address possible evolutionary changes. From the handful of examples having multi-epoch observations, symmetric profiles show blueshifted emission peaks that slowly weaken in strength relative to their redshifted companions. For example, SN 2008ax (Figure 2), SN 2004ao (Modjaz 2007), and SN 2006T (compare day 106 of Modjaz et al. 2008a with day 371 of Taubenberger et al. 2009) all exhibit slow but measurable evolution in their double-peaked \([\text{O} \text{I}] \lambda \lambda 6300, 6364\) line profiles. Notably, the emission peaks maintain their blueshifted/redshifted velocities in all cases.

Asymmetric profiles, on the other hand, show a variety of evolutionary timescales in their emission peaks. As demonstrated by the persistent blueshifted peaks of SN 2004dk and SN 2005bf in Figure 6, and recent observations of SN 2008D observed on day 363 that show little change from day 91 (Modjaz et al. 2008b; Tanaka et al. 2009), some asymmetric profiles exhibit blueshifted peaks lasting hundreds of days. However, emission profiles like those seen in SN 2007uy and SN 2008bo are examples of asymmetric \([\text{O} \text{I}] \lambda \lambda 6300, 6364\) line profiles exhibiting blueshifted emission peaks at early epochs (\( t < 90 \) days) that diminish in strength at later times.

Although features observed at epochs \( t < 200 \) days may be due to contributions from other emission lines, the fact that these blueshifted features are routinely accompanied by blueshifted peaks in other oxygen and magnesium lines at matching velocities (Figure 5) makes contamination an unlikely source. As observed in symmetric profiles, the wavelength of blueshifted emission peaks in all asymmetric profiles does not change with time, and their strength relative to emission near zero velocity tends to weaken.

### 5. The Nature of \([\text{O} \text{I}] \lambda \lambda 6300, 6364\) Line Profiles

#### 5.1. A Torus-like Distribution of O-rich Ejecta?

Several authors have proposed that double-peaked \([\text{O} \text{I}] \lambda \lambda 6300, 6364\) emission-line profiles are consistent with emission originating from a torus or disk of O-rich material, possibly oriented perpendicular to a rapidly expanding jet (Maeda et al. 2002; Mazzali et al. 2005; Maeda et al. 2006, 2008; Modjaz et al. 2008a; Tanaka et al. 2009). In this model, an object’s double-peaked \([\text{O} \text{I}] \) profile reflects the observer’s fortunate orientation close to the plane of an expanding torus/disk of O-rich ejecta leading to blueshifted and redshifted emission peaks associated with the approaching and receding portions. Alternatively, viewing the torus perpendicular to the plane of expansion would result in a sharp, single-peaked \([\text{O} \text{I}] \) line profile.

Some of the observational trends noted above in Section 4, however, signal warnings about adopting a torus/disk interpretation for some double-peaked \([\text{O} \text{I}] \lambda \lambda 6300, 6364\) profiles. Most apparent is that the separation of the two prominent peaks in symmetric \([\text{O} \text{I}] \) profiles is often very close to 64 Å, i.e., the separation of the \([\text{O} \text{I}] \lambda \lambda 6300, 6364\) doublet...
Double emission peaks seen in asymmetric profiles with separations larger or smaller than the doublet spacing (e.g., SN 2004dk and 2005bf) do not share this problem. However, the preferentially blueshifted emission profiles of Figure 6 illustrate the point that asymmetric profiles rarely show prominent peaks at wavelengths significantly longward of 6300 Å. If the two observed emission peaks are attributed solely to the 6300 Å line of [O i] originating from a toroidal geometry of ejecta, then one must interpret the tori to have centers of expansion having velocities blueshifted toward the observer, with the most redshifted portion of the expanding ring/torus at a velocity close to zero.

An example of a double-peaked [O i] λλ6300, 6364 profile interpreted this way was SN 2005bf (refer to Figure 6). Maeda et al. (2007) modeled the blueshifted profile as emission originating from a layered blob of Fe, Ca, O material either (1) unipolar and moving at a center-of-mass velocity \( \nu \sim 2000-5000 \text{ km s}^{-1} \), or (2) suffering from self-absorption within the ejecta. In this case, the blueshifted double-peaked [O i] λλ6300, 6364 line profile was thought to be unique, and thus explanation (1) involving an extremely elongated shell of O-rich material, though unusual, was not viewed as improbable especially in light of good model agreement.

However, Figure 6 suggests that asymmetric profiles like SN 2005bf are not unique. While blobs of ejecta moving at thousands of km s\(^{-1}\) may represent one possible scenario (e.g., unipolar explosion models; see Hungerford et al. 2005), the frequent need for the centers of expansion of these blobs to be at velocities systematically directed toward the observer seems problematic.

### 5.2. Other Models

Complications with a torus/disk model raised by our observations prompted us to investigate two alternative interpretations of the double-peaked [O i] λλ6300, 6364 emission-line profiles. In light of mounting evidence that CCSNe are intrinsically aspherical, a torus geometry might still be correct but with considerable internal extinction. In cases like SN 2003jd where the expansion velocity is especially high and extinction is minimal, one may be truly seeing both blue and red sides of a shell or torus (Mazzali et al. 2005). However, in other cases where velocities are smaller and extinction is higher, the rear side of the ejecta and its emission might be hidden, even at epochs \( t > 200 \text{ days} \).

On the other hand, different line profiles observed in the oxygen and magnesium lines noted in Section 4 may originate from different regions of the SN. Line formation differences attributable to density, temperature, and energy potential dependences may be introducing pronounced emission discrepancies between elements and species. Hence, the blueshifted, narrow profiles observed in [O i] λλ5577 and the zero velocity, broad profiles observed in O i λ7774 may originate from two different regions of the SN: (1) a central, pseudo-spherically symmetric distribution of O-rich ejecta, and (2) a clump or shell of O-rich material traveling at a moderate velocity (\(-2000 \text{ to } -4000 \text{ km s}^{-1}\)) in the front-facing hemisphere.

We explored both of these scenarios in simple line-fitting models. Below, we briefly discuss the results of these models, comment on their interpretations, and highlight their own associated difficulties.

#### 5.2.1. A Single Blueshifted Emission Component?

The [O i] λλ6300, 6364 emission-line profile that would follow from a single preferentially blueshifted emission source was investigated first. This configuration mimics emission originating from a blueshifted, optically thick, and high density region (possibly the front side of a ring, torus, or hollow shell with densities upward of \(10^{10} \text{ cm}^{-3} \)) where the 6300:6364 flux ratio could approach unity and the lack of a corresponding redshifted emission peak might be due to significant internal extinction in the ejecta.

Both observed [O i] λλ5577 and Mg i] λ4571 emission-line profiles were used as templates for the [O i] λλ6300, 6364 lines. The [O i] λλ5577 profiles were used for earlier epochs \( t \lesssim 100 \text{ days} \) and the Mg i] λ4571 at later ones \( t \gtrsim 200 \text{ days} \), as these epochs represent when the lines are best observed. The template profiles were separated by 3000 km s\(^{-1}\) in velocity, added, and the result scaled to match the amplitude of the observed [O i] λλ6300, 6364 profile of the same epoch. The SNe having the best time coverage of our data set (SN 2008ax and SN 2004ao) were modeled at two epochs, while two other objects displaying these lines with adequate S/N were modeled at one epoch (SN 2004dk and SN 2006T).

Figure 8 shows a comparison between the line-fitting models and observed [O i] λλ6300, 6364 profiles. The top panels show our results with the [O i] λ5577 template. The best fits were obtained using a 6300:6364 flux ratio of 1:1 in all three cases. Noticeable disagreement on the red side might be due to less reddening/extinction around 6300 Å as compared to around 5577 Å, and/or contributions from other lines to the red of the oxygen emission as evidenced by the moderate strength of the lines. The agreement is good for SN 2008ax and 2004ao, but rather poor in SN 2006T where peak height is adequately matched but position and width is not.

The bottom panels of Figure 8 present [O i] line models using the Mg i] λ4571 line template. Both SN 2004ao and 2004dk show good agreement and were best fit with templates added in a 3:1 ratio. However, SN 2008ax was best fit with a ratio of 1:1.2:1:0 and showed an overall reasonable fit but with noticeable disparity between the line model and observation around zero velocity.

The results with our single-component line-fitting models corroborate observations made in the Taubenberger et al. (2009) survey of [O i] λλ6300, 6364 lines at 200 days, but rather poor in SN 2006T where peak height is adequately matched but position and width is not.

On the other hand, different line profiles observed in the oxygen and magnesium lines noted in Section 4 may originate from different regions of the SN. Line formation differences attributable to density, temperature, and energy potential dependences may be introducing pronounced emission discrepancies between elements and species. Hence, the blueshifted, narrow profiles observed in [O i] λλ5577 and the zero velocity, broad profiles observed in O i λ7774 may originate from two different regions of the SN: (1) a central, pseudo-spherically symmetric distribution of O-rich ejecta, and (2) a clump or shell of O-rich material traveling at a moderate velocity (\(-2000 \text{ to } -4000 \text{ km s}^{-1}\)) in the front-facing hemisphere.

Although the one-component line-fitting models are encouraging in five out of six profiles presented here, attributing double-peaked [O i] emission to the two doublet lines has problems. The most serious problem is the origin of the preferentially blueshifted emission. Expansion of SN ejecta should lower density significantly such that emitted optical photons have minimal interaction with the gas at nebular epochs (Maeda et al. 2008), but the \( \sim 1:1 \) flux ratio of the SN 2004ao and 2008ax [O i] λλ6300, 6364 line models and the lack of redshifted emission...
imply a significantly high optical depth even at epochs of day ∼100 and greater.

Another potential problem for the single-component model is the evolution of the blue/red peak height ratio. As seen in Figure 2, the blueshifted peak decreases in strength relative to the redshifted peak with time. The opposite evolution is expected, however, if the two peaks are associated with the [O\textsc{i}] λλ6300, 6364 doublet lines, since expansion of the SN should drive the blue/red peak height ratio toward the nebular 3:1 ratio.

A similar blue/red peak evolution away from the nebular 3:1 ratio in the [O\textsc{i}] λλ6300, 6364 profile of SN 2004ao led Modjaz et al. (2008a) to conclude that the doublet lines were likely not corrected for the discrepancy in the blue/red peak ratio using the IRAF package SPECFIT (Kriss 1994). Each profile fit consisted of five sources: (1) a linear continuum, (2) a broad (FWHM ∼ 6000 km s\(^{-1}\)) Gaussian centered at 6300 ± 10 Å, (3) another Gaussian shifted 64 Å to the red fixed with the same FWHM but one third its strength, (4) a narrow (FWHM ∼ 1000 km s\(^{-1}\)) Gaussian at a blueshifted wavelength, and (5) another narrow Gaussian 64 Å to the red fixed with the same FWHM and one third its strength. The free parameters were the strength of the linear continuum, and the position, FWHMs, and relative strengths of the pairs of peaks.

The line profile model was tested with four SNe (SN 2007gr, SN 2008ax, SN 2008bo, and SN 2004ao from Modjaz et al. 2008a) showing symmetric and asymmetric profiles.

In Figure 9, we present the results of these reconstructed emission-line profiles. The top panels show fits for symmetric profiles. The agreement between our model profiles and the observational data for SN 2008ax and SN 2004ao is good. SN 2006T, on the other hand, shows considerable disagreement. The blue/red peak ratio is not matched, and there is considerable emission at wavelengths longward of 6300 Å. We attempted to correct for the discrepancy in the blue/red peak ratio using non-nebular 6300:6364 flux ratios (see the inset of Figure 9). The model’s agreement with the observed data for SN 2006T improved as a result, although continued disagreement in the peak separation and individual width was evident.

The bottom panels of Figure 9 present our line-fitting results for asymmetric profiles. In all cases the agreement is good, although agreement is relatively poor in SN 2007gr near the zero velocity peak. This discrepancy, as well discrepancies in components. line-fitting models of [O\textsc{i}] λλ6300, 6364 emissions were constructed using the IRAF package SPECFIT (Kriss 1994).

5.2. Broad Emission Plus a Blueshifted Emission Component?

We next investigated the [O\textsc{i}] λλ6300, 6364 line profile that would follow from the contribution of two emission components. line-fitting models of [O\textsc{i}] λλ6300, 6364 emissions were constructed using the IRAF package SPECFIT (Kriss 1994). Each profile fit consisted of five sources: (1) a linear continuum, (2) a broad (FWHM ∼ 6000 km s\(^{-1}\)) Gaussian centered at 6300 ± 10 Å, (3) another Gaussian shifted 64 Å to the red fixed with the same FWHM but one third its strength, (4) a narrow (FWHM ∼ 1000 km s\(^{-1}\)) Gaussian at a blueshifted wavelength, and (5) another narrow Gaussian 64 Å to the red fixed with the same FWHM and one third its strength. The free parameters were the strength of the linear continuum, and the position, FWHMs, and relative strengths of the pairs of peaks.

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other line models, may in part be a reflection of the inadequate use of Gaussian distributions to model the emission. The fixed 3:1 ratio used for the two components would seem to run counter to the evolution of the blue/red peak height ratio observed in symmetric profiles. However, Taubenberger et al. (2009) recently concluded that the line centroids of the bulk of [O I] emission at phases earlier than day ~200 were blueshifted ~20 Å, after which they drift close to zero velocity. This phenomenon offers an explanation for the apparent 6300:6364 ratio ∼20 Å, after which they drift close to zero velocity. This phenomenon offers an explanation for the apparent 6300:6364 ratio decrease over observed epochs. Assuming a broad/central + narrow/blueshifted interpretation, a gradual shift toward zero velocity of the broad component would cause the blueshifted λ6300 line of the narrow component to weaken in strength relative to the λ6364 companion line. We illustrate this possibility in Figure 10 for SN 2004ao and SN 2008ax.

While these profile fits are encouraging, two-component line-fitting models have notable shortcomings. First, unlike the single-component scenario which used genuine emission profiles of the SNe, these line models assume Gaussian expansion profiles for both the broad and narrow components. This assumption along with the number of free variables used to replicate the observed profiles and the possible redundancy in the reconstructions introduces considerable uncertainty in the veracity of the model fits.

Aside from these modeling concerns, there is also the question of why clumps are mainly visible on the forward facing hemisphere, and rarely from the rear side. If clumps were randomly distributed, a variety of blueshifted and redshifted emission peaks would be expected. Any explanation in which a preferential visibility of blueshifted peaks might be caused by high internal extinction is complicated by the fact that considerable broad emission is seen at both higher blueshifted and redshifted velocities.

6. DISCUSSION AND CONCLUSIONS

Double-peaked [O I] λλ6300, 6364 emission-line profiles are not uncommon in the late-time spectra of stripped-envelope CCSNe and have been interpreted as possibly originating from ejecta arranged in a torus or disk-like geometry. As part of an investigation into this phenomenon, we obtained optical spectra of five SNe (SN 2007gr, SN 2007rz, SN 2007uy, SN 2008ax, and SN 2008bo) and examined the emission-line profiles of [O I] λ5577, [O I] λλ6300, 6364, O I λ7774, and Mg I λ4571. Because our spectra of SN 2008ax covered the broadest time interval (day 67 to 418) and showed strong, sharp, and well-defined [O I] emission peaks, we used SN 2008ax to help guide the investigation. We also examined the late-time [O I] λλ6300, 6364 line profiles of 13 other stripped-envelope CCSNe taken from the literature.

6.1. Empirical Results of Our Study

Our investigation into the properties of late-time [O I] λλ6300, 6364 line profiles of stripped CCSN exhibiting double-peaked line profiles showed the following:

1. Doubled-peaked line profiles are primarily in [O I] λλ6300, 6364 emission (Figures 4 and 5) and can be categorized into two types. One type shows conspicuous symmetric
emission peaks positioned about 6300 Å that are persistent across the entire observing period. The other type shows asymmetric emission profiles with one emission peak near zero velocity (i.e., 6300 Å) plus one or more peaks at blueshifted velocities that sometimes persist hundreds of days post-outburst or evolve over short (t < 2 months) timescales.

2. Emission peaks in symmetric double-peaked [O I] λλ 6300, 6364 line profiles are often close to 3000 km s⁻¹ apart (i.e., 64 Å; Figure 7), nearly the 63.5 Å wavelength spacing of the [O I] doublet, suggesting the double peaks are simply reflecting the doublet nature of the [O I] line emission. Over time, the velocities of the two peaks do not change, but the blue/red peak intensity ratio slowly decreases.

3. Conspicuous redshifted emission peaks are not observed in asymmetric profile cases. As seen for symmetric profiles, the position of blueshifted peaks does not change between observed epochs, but their strength relative to emission near zero velocity tends to weaken with time.

4. When double-peaked [O I] profiles are present, single-peaked emission peaks at blueshifted velocities matching blueshifted peaks in [O I] λλ 6300, 6364 are often seen for [O I] λ 5577. The Mg I λ 4571 and O I λ 7774 lines generally show more blueshifted emission than redshifted emission and sometimes evidence of peaks at velocities matching blueshifted and/or zero-velocity peaks in the [O I] λλ 6300, 6364 lines.

6.2. Results of Double-peaked [O I] Line Profile Fits

The high incidence of ≈64 Å separation between emission peaks of symmetric profiles plus the lack of redshifted emission peaks in asymmetric profiles suggests that emission from the rear of the SN may be suppressed. This leads us to conclude that double-peaked [O I] λλ 6300, 6364 line profiles of some stripped-envelope, core-collapse SNe are not necessarily signatures of emission from the front and rear faces of a torus or elongated shell of O-rich ejecta as has been proposed.

Alternative interpretations for the observed [O I] λλ 6300, 6364 profiles were investigated through line-fitting models. Two models were explored: Model 1 where the [O I] profile arises from preferentially blueshifted emission, and Model 2 where the [O I] profile consists of two separate emission components, a broad emission source centered around zero velocity and a narrow, blueshifted source. Both line-fitting models...
reproduced observed [O I] $\lambda\lambda$6300, 6364 profiles in the majority of test cases. Model 2 showed better overall agreement to the data for all six cases of symmetric and asymmetric profiles across all epochs investigated, but Model 1 had fewer parameters and convincing results in a subset of the symmetric profiles. Similar line-fitting results have been reported in Taubenberger et al. (2009).

It should be noted that a torus or elongated shell model is still viable despite the concerns raised above if the rear portion of an O-rich torus or shell is somehow hidden by scattering or dust. Moreover, two of the 18 SNe studied in this sample, SN 2003jd and 2006T, exhibited both blueshifted and redshifted emission peaks with separations and widths that could not be modeled under the alternative interpretations offered here. Hence, these objects represent notable exceptions to the concerns raised in this paper and remain strong candidates for a torus geometry of the ejecta as previously proposed.

6.3. Outstanding Questions

Two questions follow from our observations and findings: Why do these emission-line profiles lack redshifted emission peaks? The predominance of blueshifted emission features in the profiles studied is unclear but internal scattering or dust obscuration of emission from far side ejecta are the most likely scenarios. Taubenberger et al. (2009), who also found predominantly blueshifted peaks in [O I] $\lambda\lambda$6300, 6364 emission-line profiles in a sample of 39 Type Ib/c SNe, favored an opaque inner ejecta scenario, citing that other explanations such as ejecta geometry, dust formation, and contamination from other lines, could not account for all observed trends. What is the physical nature of these blueshifted features? The variety and strength of the emission peaks are suggestive of asphericity in the ejecta. But whether these features can be conclusively associated with cones, jets, or tori of unipolar/bipolar explosions is uncertain and beyond the scope of this paper. We note that the difference between symmetric and asymmetric profiles in our two-component line-fitting models is a consequence of the parameters adopted for the narrow, blueshifted component (i.e., FWHM, central velocity, strength relative to the broad component near zero velocity, and 6300:6364 flux ratio). Sophisticated models incorporating radiative transfer effects could explore how these line-fitting parameters may be related to physical quantities such as mass, velocity, size, and density of the O-rich material, as well as changes with viewing angle. Such models could also investigate specific extinction mechanisms of the suspected opaque inner region.

6.4. Future Observations

Much more robust tests of line-fitting models are possible with spectra of improved time coverage, spectral resolution, and S/N for those CCSNe displaying double-peaked [O I] $\lambda\lambda$6300, 6364 profiles. Moreover, observations optimized around the lines of Mg I $\lambda$4571, [O I] $\lambda\lambda$5577, and O I $\lambda\lambda$7774 at late epochs starting from 50 days past maximum light could greatly help test the trends observed in our sample and help eliminate one of the two line models (single or two component) discussed here. Infrared observations might also place constraints on the cause of the suspected internal extinction. While an opaque inner region appears to best explain the lack of redshifted features, late-time infrared studies of other stripped-envelope CCSNe could characterize the presence of internal molecules and dust as a test of one source of extinction at the epochs studied here.

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