INTERACTION BETWEEN THE BROAD-LINED TYPE Ic SUPERNOVA 2012ap
AND CARRIERS OF DIFFUSE INTERSTELLAR BANDS

Dan Milisavljevic[1,†], Raffaella Margutti[1], Kyle N. Crabtree[1], Jonathan B. Foster[2], Alicia M. Soderberg[1],
Robert A. Fesen[3], Jerod T. Parrent[3,4], Nathan E. Sanders[1], Maria R. Drout[1], Atish Kamble[1],
Sayan Chakraborti[1], Timothy E. Pickering[5,6], S. Bradley Cenko[7,8], Jeffrey M. Silverman[9],
Alexei V. Filippenko[8], Robert P. Kirshner[1], Paolo Mazzali[10,11,12], Keiichi Maeda[13,14],
G. H. Marion[9], Jozsef Vinko[9,15], and J. Craig Wheeler[9]

ABSTRACT

The diffuse interstellar bands (DIBs) are absorption features observed in optical and near-infrared spectra that are thought to be associated with carbon-rich polyatomic molecules in interstellar gas. However, because the central wavelengths of these bands do not correspond with electronic transitions of any known atomic or molecular species, their nature has remained uncertain since their discovery almost a century ago. Here we report on unusually strong DIBs in optical spectra of the broad-lined Type Ic supernova SN 2012ap that exhibit changes in equivalent width over short ($\lesssim$ 30 days) timescales. The 4428 Å and 6283 Å DIB features get weaker with time, whereas the 5780 Å feature shows a marginal increase. These nonuniform changes suggest that the supernova is interacting with a nearby source of the DIBs and that the DIB carriers possess high ionization potentials, such as small cations or charged fullerenes. We conclude that moderate-resolution spectra of supernovae with DIB absorptions obtained within weeks of outburst could reveal unique information about the mass-loss environment of their progenitor systems and provide new constraints on the properties of DIB carriers.
Subject headings: astrochemistry — molecular processes — ISM: lines and bands — ISM: molecules — supernovae: general — supernovae: individual (SN 2012ap)

1. INTRODUCTION

One of the long unsolved problems in optical and infrared astronomy is the nature of the diffuse interstellar bands (DIBs). The DIBs represent more than 400 absorption features observed in optical and near-infrared spectra that are typically narrow (full width at half-

[1] Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138
[2] Yale Center for Astronomy and Astrophysics, Yale University, New Haven, CT 06520, USA
[3] Department of Physics & Astronomy, Dartmouth College, 6127 Wilder Lab, Hanover, NH 03755, USA
[4] Las Cumbres Observatory Global Telescope Network, Goleta, CA, USA
[5] Southern African Large Telescope, PO Box 9, Observatory 7935, Cape Town, South Africa
[6] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, Maryland 21218, USA
[7] Astrophysics Science Division, NASA Goddard Space Flight Center, Mail Code 661, Greenbelt, MD 20771, USA
[8] Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
[9] University of Texas at Austin, 1 University Station C1400, Austin, TX, 78712-0259, USA
[10] Astrophysics Research Institute, Liverpool John Moores University, Liverpool L3 5RF, United Kingdom
[11] Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Strasse 1, 85748 Garching, Germany
[12] INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, I-35122, Padova, Italy
[13] Department of Astronomy, Kyoto University Kitashirakawa-Oiwake-cho, Sakyo-ku, Kyoto 606-8502, Japan
[14] Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan
[15] Department of Optics and Quantum Electronics, University of Szeged, Domter 9, 6720, Szeged, Hungary
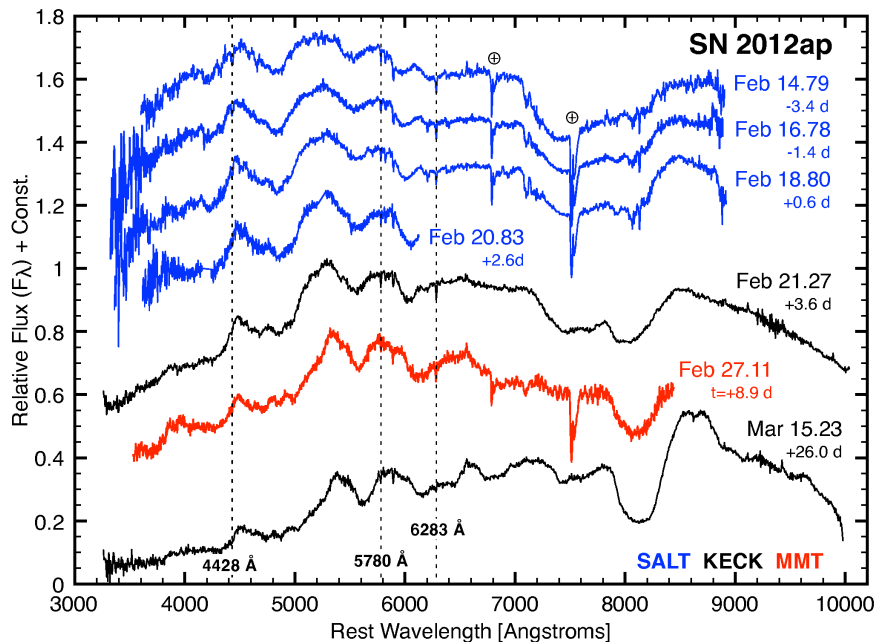[†] email: dmilisav@cfa.harvard.edu

maximum intensity [FWHM] < 1 Å) and weak (less than 5% below the continuum), with central wavelengths that do not correspond with any known atomic or molecular species (Herbig 1995; Hobbs et al. 2009; Geballe et al. 2011). They were first noticed in stellar spectra by Heger (1922). Merrill (1934) subsequently uncovered a number of DIBs as ubiquitous interstellar features and their nature has been an enduring subject of speculation.

It is now well established that sources (or "carriers") of the DIBs are found in the interstellar medium (ISM). DIB features remain stationary in spectroscopic binaries, and there are rough correlations between extinction and Na I D column density with the intensity of DIB features (Herbig 1995). Searches for DIBs in circumstellar shells have generally reported null detections or results that cannot distinguish whether the absorption arises in circumstellar material or the intervening ISM (Snow & Wallerstein 1972; Luna et al. 2008).

Merrill (1934) was the first to suspect dust grains and/or molecules as possible carriers of the DIBs. After nearly a century of observational, theoretical, and experimental work, these two original suggestions have remained the primary candidates, occasionally swapping in popularity (see Sarre 2006, and references therein). Current research favors multiple carriers produced by a mix of fairly large and complex carbon-based ("organic") polyatomic molecules composed of cosmically abundant elements such as H, C, O, and N. There has been considerable investigation of polycyclic aromatic hydrocarbons (PAHs) as DIB carriers, but as yet no firm associations between PAH species and DIB features have been found (see Cox 2011 for a recent review).

Insights into the chemical and physical properties of DIB carriers has come from study of their behavior in dif-

Figure 1. Optical spectra of the broad-lined Type Ic SN 2012ap during its first ~ 40 d after explosion. Three prominent DIBs around 4428 Å, 5780 Å, and 6283 Å are highlighted with dashed lines. SALT and Keck data have a 4–6 Å FWHM resolution. MMT data have 7 Å FWHM. Symbols show telluric absorptions in the SALT spectra that have not been corrected. Spectra have been corrected for a redshift of z = 0.0121 measured from narrow H II region lines of [O III] $\lambda\lambda4959$, 5007, Hα, and [N II] $\lambda\lambda6548$, 6583 observed near the location of the supernova.

ferent interstellar environments, especially extragalactic ones. Most studies have focused on nearby star systems including the Magellanic Clouds and M31 (Cox et al. 2007; Cordiner et al. 2008). Outside of limited work with quasars (e.g., Ellison et al. 2008), only supernovae (SN) have been bright enough to probe DIBs beyond the Local Group (see, e.g., Cox & Patat 2008). In general, extragalactic studies have shown that DIB carrier abundances can be similar to Galactic values, though systematic differences sometimes exist.

In this *Letter* we report on recent observations of a broad-lined Type Ic SN that exhibits some of the strongest DIBs ever detected in an extragalactic source. These absorptions undergo changes in intensity over relatively short timescales in a manner that suggests that the SN explosion interacted with local carriers of DIBs. We conclude that moderate-resolution spectra of SN obtained shortly after outburst may provide a new and powerful probe of DIBs and offer clues about the progenitor systems of these explosions.

2. RESULTS

2.1. *Discovery and Classification*

SN 2012ap was first detected by the Lick Observatory Supernova Search at coordinates $\alpha(2000.0) = 05^h00^m13\overset{s}{.}72$ and $\delta(2000.0) = -03°20'51\overset{''}{.}2$ in the face-on galaxy NGC 1729 ($d \approx 43.1$ Mpc; Springob et al. 2009) on Feb. 10.23 UT (Jewett et al. 2012). The SN is located in the outskirts of the host galaxy some 7.1 kpc in projection from the nucleus in a region with no obvious star formation.

The first reports of optical spectra of SN 2012ap classified it as a Type Ib/c SN similar to SN 2008D not long after explosion (Xu et al. 2012). This prompted extensive follow-up observations by our group that included optical

spectra obtained with the 10 m Southern African Large Telescope (SALT) using the Robert Stobie Spectrograph (RSS; Burgh et al. 2003), the 10 m Keck-I telescope using the Low Resolution Imaging Spectrometer (LRIS; Oke et al. 1995), and the MMT 6.5 m telescope using the Blue Channel spectrograph (Schmidt et al. 1989). The spectra shown in Figure 1 are part of a larger dataset (Milisavljevic et al., in prep.).

Unlike SN 2008D, which transitioned to a Type Ib SN exhibiting conspicuous He I, spectra of SN 2012ap obtained weeks later continued to show broad features associated with ejecta traveling $\sim 2 \times 10^4$ km s^{-1}. Milisavljevic et al. (2012) reported that these later spectra were similar to those observed in broad-lined SN Ic such as SN 1998bw and SN 2002ap $\sim$ 1–2 weeks after maximum light (see Fig. 1). Further examination shows that the later spectra of SN 2012ap also resemble those of SN 2009bb, a SN Ib/c that had a substantial relativistic outflow powered by a central engine (Soderberg et al. 2010; Pignata et al. 2011).

2.2. *Strong DIB Features*

Superimposed on the broad-lined Type Ic features of SN 2012ap are conspicuous absorptions with equivalent widths (EWs) $\gtrsim 1$ Å associated with DIBs at the rest wavelength of the host galaxy. The DIB features are strongest at 4428 Å, 5780 Å, and 6283 Å, which are the wavelengths of well-known DIBs typically seen in stellar spectra (Herbig 1995). In Figure 2 we display enlarged regions around these features. Not shown is another possible DIB detection near 6203 Å that may be contaminated by an OH telluric line at an observed wavelength of 6280 Å.

The central wavelengths of these DIBs do not change with time, but the intensities do exhibit measurable
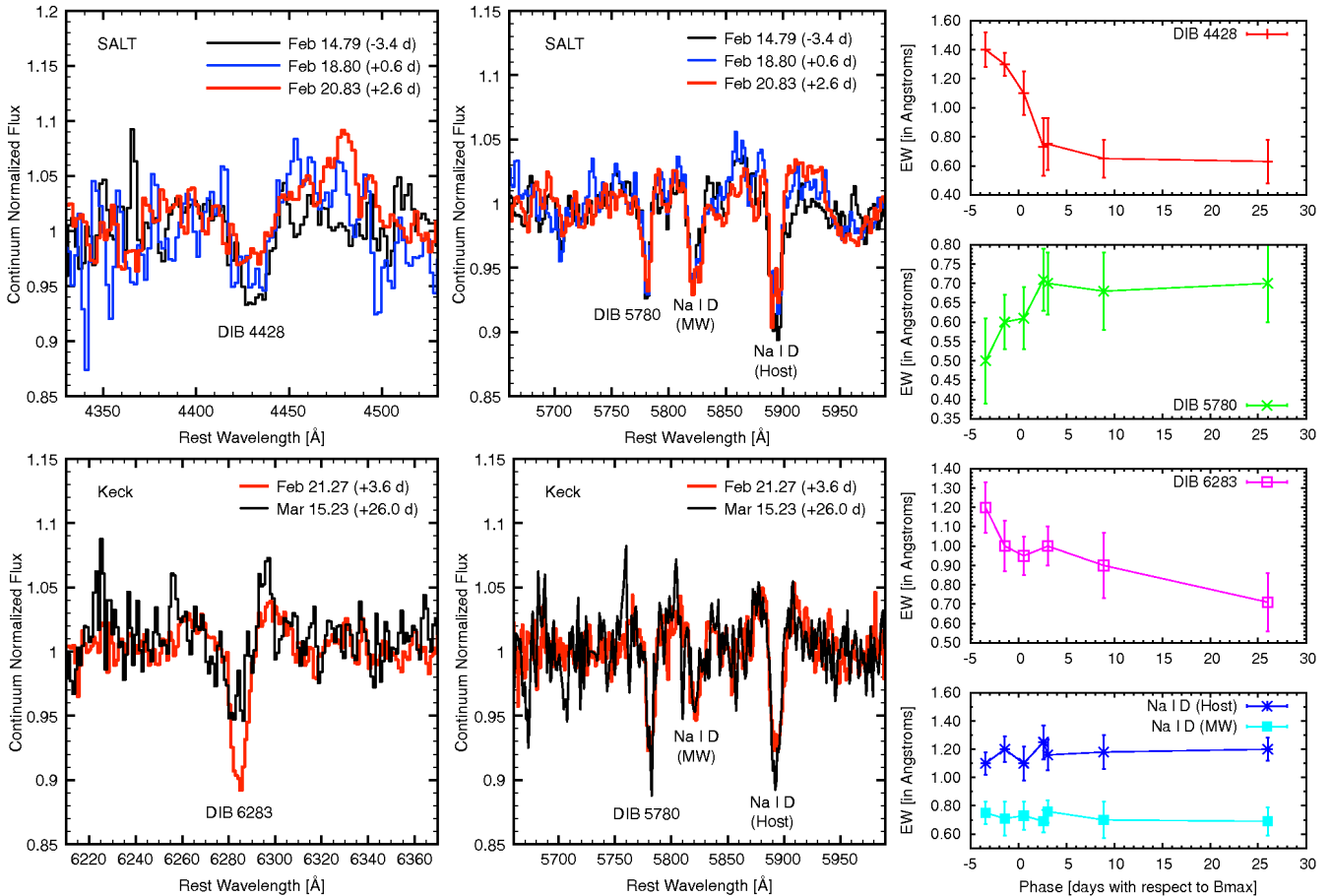
Figure 2. Enlarged DIB absorption features of SN 2012ap. The left and middle columns show select epochs to illustrate possible changes in EW, and the right column shows all EW measurements of narrow absorptions. Phase is with respect to B-band maximum on Feb 18.2 UT. We removed the global shape of the underlying continuum by smoothing the spectra with a running boxcar of width 50 Å and then subtracting the smoothed version. The EW of the Na I D lines of the host galaxy shows no measurable change. To further illustrate that the changes are not related to instrumental setups, spectra from the same the spectrograph using identical configurations are plotted.

changes that are not uniform across different features (Fig. 2, right column). The EW of DIB $\lambda4428$ decreased by 0.77 ± 0.25 Å over ~ 10 days and DIB $\lambda6283$ decreased by 0.49 ± 0.28 Å over ~ 30 days. The DIB $\lambda5780$ feature, on the other hand, shows a weak but measurable increase of $\lesssim 0.2$ Å over ~ 10 days. The Na I D line at rest with respect to the host shows negligible change. The Na I D line associated with foreground Milky Way extinction shows no change, as expected.

3. DISCUSSION

3.1. *SN Interaction with DIB Carriers*

The DIB absorptions seen in the spectra of SN 2012ap are among the strongest extragalactic detections ever reported. Detections of extragalactic DIBs at this distance are rare and thus interesting as they allow one to compare Galactic ISM chemical properties with extragalactic ones. However, what is unique and most informative about the spectra of SN 2012ap is that the DIB absorption strengths *change with time* and that *the changes are not uniform across different DIB features* (see Fig. 2).

Various types of interaction between the SN and DIB carrier material may explain the observed changes (see, e.g., Patat et al. 2010). We favor the scenario that the carrier material is nearby and the SN is actively interacting with it. This interaction can take many forms.

Photons may modify or destroy carrier material via ionization and/or dissociation. If extremely nearby, the forward blast wave initiated by the explosion and traveling with velocity $\sim 0.4c$ (Chakraborti et al., in prep.) will disrupt molecules and dust grains within a ~ 0.01 pc radius in the first 30 days.

3.2. *Physical Constraints on the DIB Carriers*

SN 2012ap peaked in the B band on Feb 18.2 UT (Milisavljevic et al., in prep.), implying that the SN flux increased and then decreased at optical wavelengths as the intensities of DIB $\lambda4428$ and $\lambda6283$ became weaker and DIB $\lambda5780$ became slightly stronger. This behavior is consistent with active interaction wherein separate DIB carriers differing in robustness and/or location are affected by the SN independently.

Using the time evolution of the blackbody temperature and total luminosity derived from photometry data (Milisavljevic et al., in prep.), we estimated the UV flux in the 5–50 eV spectral range as a function of distance and time from SN 2012ap. To estimate the lifetimes of molecular material in this radiation field, we approximated the photoabsorption cross sections in this frequency range for small neutral molecules (Gallagher et al. 1988) and PAHs (Verstraete et al. 1990; Jochims et al. 1996), calculated the photoabsorption rate, and assumed that all
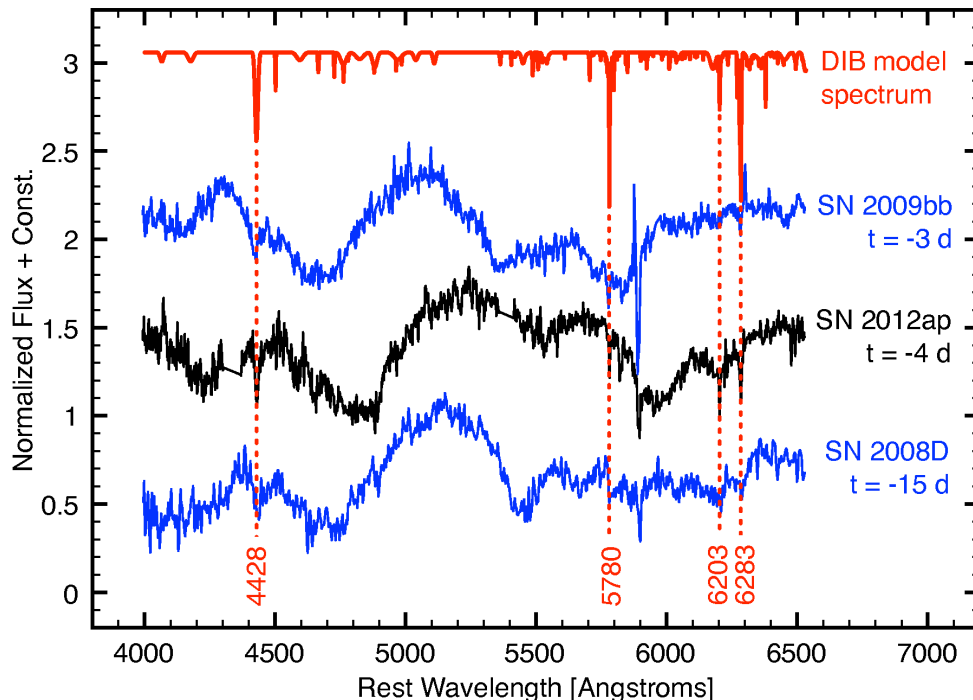
Figure 3. Model spectrum of known DIB absorption features compared to early-time spectra of SN 2012ap, SN 2009bb (Pignata et al. 2011), and SN 2008D (Modjaz et al. 2009). SN 2009bb and SN 2008D have been corrected for redshifts of z = 0.010 and z = 0.007, respectively. All SN exhibit conspicuous absorptions having central wavelengths of well-known DIBs highlighted with vertical dashed lines. Time is with respect to maximum light. The model DIB spectrum was created from a catalog retrieved online at http://leonid.arc.nasa.gov/DIBcatalog.html.

absorption events lead to ionization or dissociation. Because these frequencies are above the peak of the blackbody curve, the absorption rates are highly sensitive to the ionization potential (IP) of a molecule, and the shape and size of its cross section.

The inferred lifetimes vary by several orders of magnitude, but within a distance of $\sim 0.01\,\mathrm{pc}$, at peak luminosity all but the smallest neutral molecules are expected to have lifetimes much less than one day. Within this distance, the population of most neutral species will be rapidly depleted unless their formation from the breakdown of larger material is even more rapid. Cations, owing to their higher IPs, are estimated to have lifetimes on the order of days under the same conditions.

In this context, it is interesting to note that the timescale for the increase in DIB $\lambda 5780$ is comparable to that of the decay in DIB $\lambda 4428$, possibly suggesting that the DIB $\lambda 5780$ carrier is a photoproduct of the DIB $\lambda 4428$ carrier. In constrast, the decay in DIB $\lambda 6283$ occurs over a longer timescale, suggesting the carrier is either more photostable or is more extended. The ratio of the strength of DIB $\lambda 5780$ to DIB $\lambda 5797$ (the latter is not detected toward SN 2012ap) is positively correlated with increasing UV radiation environments (Vos et al. 2011). The increase in strength of DIB $\lambda 5780$ in these observations suggests that this trend continues to very extreme UV environments.

Fullerenes have been proposed as DIB carriers, and are significantly more stable against dissociation by UV radiation than smaller molecules, typically requiring energies of more than $10\,\mathrm{eV}$ for dissociation (Diaz-Tendero et al. 2003). This increased dissociation energy might allow fullerenes to survive longer in the radiation environment

around SN 2012ap. Using the photoabsorption cross section of C_{60} as a representative case (Berkowitz 1999), we estimate that neutral fullerenes (IP $\approx 7\,\mathrm{eV}$) near SN 2012ap will be rapidly ionized, but fullerene cations (IP $\sim 11\,\mathrm{eV}$) should have lifetimes of order days. The fact that the observed changes in EW of these DIB features occur on the timescale of days in such an intense UV field suggests the carriers are fairly robust to ionization and dissociation (particularly DIB $\lambda 5780$), consistent with small cations or charged fullerenes.

3.3. *Implications of a DIB–SN Subtype Correlation*

Two other core-collapse SN in the literature exhibit conspicuous DIBs in low-resolution spectra, and we examined their archival data: the Type Ib SN 2008D with spectra published by Modjaz et al. (2009), and the broad-lined Type Ib/c SN 2009bb published by Pignata et al. (2011). Figure 3 shows early-time spectra of these objects, with conspicuous DIB features highlighted. Although the relatively low spectral resolutions and limited temporal sampling prevent detailed analyses of these additional objects, the archival spectra suggest that some DIB features seen in these other SN have both narrow and broad components and that they may vary as they do SN 2012ap.

All three SN exhibited broad spectral features associated with ejecta moving at high velocities ($\gtrsim 2 \times 10^4\,\mathrm{km\,s^{-1}}$) within weeks of explosion and all were observed to have a color excess $E(B-V) \gtrsim 0.5$ mag that implies substantial extinction (Soderberg et al. 2008; Modjaz et al. 2009; Pignata et al. 2011; Milisavljevic et al., in prep.). SN 2012ap and SN 2009bb share similar explosion parameters of estimated ejecta mass ($\sim$ 2–

$4\,M_\odot$), ^{56}Ni mass ($\sim 0.2\,M_\odot$), and explosion kinetic energy ($\sim 1.5 \times 10^{52}$ erg). On the other hand, SN 2008D is different in that its broad lines disappeared within weeks as it transitioned to a SN Ib and its explosion energy (~ 1.5–6×10^{51} erg; Soderberg et al. 2008; Tanaka et al. 2009) is lower than those of SN 2012ap and SN 2009bb.

Chance alignments between DIB carrier-rich molecular clouds and these SN are possible. However, given that the three SN with conspicuous DIB absorptions examined in the literature are spectroscopically similar, it may be that the SN progenitor systems are related to the sources of the DIBs. If true, the carrier material responsible for the observed DIB absorptions in these SN should lie fairly close to the explosion site and could be associated with mass loss from the progenitor star.

Mass loss in massive stars is influenced by a number of factors including the strength of their winds, rotation, the presence of a binary companion, possible eruptive mass-loss episodes, and environmental metallicity (Chiosi & Maeder 1986; Humphreys & Davidson 1994; Nugis & Lamers 2000). To investigate what role metallicity might play in linking the three SN, the relative strengths of narrow lines from coincident host-galaxy emission at the site of SN 2012ap were measured using the method described by Sanders et al. (2012). From the N2 diagnostic of Pettini & Pagel (2004), we measure an oxygen abundance $\log(O/H) + 12 = 8.79$ with uncertainty 0.06 dex. Adopting a solar metallicity of $\log(O/H)_\odot + 12 = 8.69$ (Asplund et al. 2005), our measurement indicates that SN 2012ap exploded in an environment of around solar metallicity that lies in between the metallicity estimates of SN 2009bb (1.7–3.5 $Z_\odot$; Levesque et al. 2010) and SN 2008D (0.5–1 $Z_\odot$; Soderberg et al. 2008). Considering broad-lined SN Ic are typically found in environments of subsolar metallicity (Kelly & Kirshner 2012; Sanders et al. 2012), the metallicity of these three SN is somewhat anomalous. However, these objects were discovered by surveys targeting high-mass metal-rich galaxies, so this weak trend may be influenced by an observational bias.

A handful of reports connect strong DIB features observed in a narrow subset of mass-losing stars with circumstellar shells (e.g., Tug & Schmidt-Kaler 1981; Cohen & Jones 1987). The circumstellar material is often nitrogen-rich and the strength of the associated DIB features may vary (Heydari-Malayeri et al. 1993). Le Bertre & Lequeux (1993) identified Wolf-Rayet (WR) stars of the WN subtype and luminous blue variable (LBV) stars enriched in nitrogen as candidate objects with circumstellar shells containing DIB carriers, and proposed that nitrogen could act either as a constituent of the DIB carriers or as a catalyst for their production.

It is intriguing that families of WR and LBV stars may be associated with DIB features. WR stars are suspected progenitors of SN Ib/c (Gaskell et al. 1986), and have been implicated for SN 2008D and SN 2009bb (Soderberg et al. 2008; Modjaz et al. 2009; Soderberg et al. 2010; Pignata et al. 2011). Although LBVs are not widely believed to be the direct progenitors of SN Ib/c, WR stars can evolve from a prior LBV phase (Conti 1976). These stars exhibit varying degrees of asymmetric mass loss (see, e.g., Nota et al. 1995), thus an observer's line of sight with respect to a circumstel-

lar disk could be an important factor in explaining why strong DIB detections like those reported here are rare.

Finally, we note that varying strength in narrow absorption lines attributable to interaction between a SN and a local environment has recently been recognized in a growing number of cases, with significant implications for the nature of the progenitor systems (e.g., Patat et al. 2007; Blondin et al. 2009; Dilday et al. 2012). However, those reports have been for Na I D, Ca II, Hα, He I, and Fe II lines with line-of-sight blueshifted velocities of $\lesssim 100\,\mathrm{km\,s^{-1}}$ originating from circumstellar material around Type Ia SN. This is not the same as what is being observed in the core-collapse SN 2012ap, where the DIB features are near zero velocity and are associated with a carrier material having radically different physical properties.

4. CONCLUSIONS

The broad-lined Type Ic SN 2012ap exhibits DIB absorptions that are among the strongest ever detected in an extragalactic object. The DIB features centered around 4428 Å, 5780 Å, and 6283 Å undergo changes in EW over relatively short timescales ($t < 30$ days) indicative of interaction between the SN and DIB carriers. Similar absorptions observed in archival spectra of two additional SN suggests that SN 2012ap may belong to a subset of energetic SN Ib/c that exhibit changes in conspicuous DIB absorption features. If true, this correlation is consistent with the DIB carrier-rich material being located close to the explosion, fairly resistent to the strong UV field, and potentially associated with mass loss of the progenitor star.

Our data with 4–7 Å resolution that monitored the spectral evolution of SN 2012ap during its rise and fall in flux was on the cusp of detection for this uniquely strong source of DIB absorptions. Only the broadest DIB features known to have FWHM widths of approximately $2 - 12$ Å were observed in our data set. Thus, multi-epoch observations of SN with spectral resolutions of $\leq$ 1 Å beginning within days of explosion could uncover the presence of a larger family of DIB features. Such observations would be much more sensitive to possible variations in Na I absorption strength, as well as detect possible subtle changes in the velocities of the NaI/DIB features. Observed in this way, SN with DIB absorptions have the potential to reveal unique information about mass-loss environment of their progenitor systems and probe DIB carriers in new ways that can bring us closer to understanding the their nature.

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