Narrow Lines in Type II Supernovae – Probing the Circumstellar Nebulae of the Progenitors

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ABSTRACT

We have carried out a high-dispersion (R∼30,000) echelle spectroscopic survey of 16 Type II supernovae (SNe) to search for narrow emission lines from circumstellar nebulae ejected by their massive progenitors. Circumstellar nebulae, if detected, provide invaluable opportunities to probe SN progenitors. Of the 16 SNe observed, SN ejecta are clearly detected in 4 SNe and possibly in another 2 SNe; interstellar gas is detected in 12 SNe, and circumstellar material is detected only in SN 1978K. The significance of the detections and nondetections is discussed. In the case of SN 1978K we are able to place an upper limit of ∼2.2 pc for the size of the circumstellar ejecta nebula and note that this is more consistent with the typical sizes observed for ejecta nebulae around luminous blue variables rather than Wolf-Rayet stars.

Subject headings: supernovae – circumstellar matter — ISM: bubbles

1. Introduction

Supernovae (SNe) of Types Ib, Ic, and II are believed to have massive progenitors, because they have been found frequently in or near spiral arms and H II regions but not in elliptical galaxies (Van Dyk, Hamuy, & Filippenko 1996). Few SNe (e.g. SN 1987A) have recognized massive progenitors; consequently, little is known about the stellar evolution immediately before the SN explosion.

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Evolved massive stars are known to undergo copious mass loss, forming circumstellar nebulae. The rings around SN 1987A are an example of such a nebula (Burrows et al. 1995). The chemical composition and kinematics of the rings have provided essential constraints that lead to the hypothesis that the B3I progenitor Sk$^{-69^\circ}202$ was a binary (Podsiadlowski 1992). These circumstellar nebulae can also be detected from the presence of narrow Hα emission lines (FWHM $\leq$ 200 km s$^{-1}$) in spectra of Type IIn SNe (Schlegel 1990; Filippenko 1991, 1997). The circumstellar nebulae of distant SNe cannot be resolved spatially, but their expansion, physical conditions, and chemical enrichment can be investigated by high-dispersion (R $\geq$ 30,000) spectra, as recently demonstrated for SNe 1997ab (Salamanca et al. 1998) and 1978K (Chu et al. 1999).

Most available spectroscopic observations of SNe have been made with low or intermediate spectral dispersion to study the broad spectral lines of SN ejecta. These spectra are useful for revealing the presence of narrow nebular lines, but are not adequate for analysis of nebular kinematics and physical conditions. Therefore, we have undertaken a high-dispersion spectroscopic survey of 16 Type II SNe. The results are reported in this paper.

2. Observations

High-dispersion spectra were acquired with the echelle spectrograph using the Kitt Peak National Observatory (KPNO) 4m telescope in March 1999. The 79 line mm$^{-1}$ echelle grating was used in combination with a 226 line mm$^{-1}$ cross-disperser and the long-focus red camera to achieve a reciprocal dispersion of 3.5 Å mm$^{-1}$ at Hα. The spectra were imaged with the T2KB CCD detector, where the pixel size of 24 µm corresponds to 0$\prime$.24 pixel$^{-1}$ along the slit and $\sim$3.7 km s$^{-1}$ pixel$^{-1}$ at the Hα line along the dispersion axis. The spectral coverage was roughly 4000–7000 Å. The instrumental resolution for the 1$\prime$ wide slit, as measured from the widths of sky lines, was $\sim$10 km s$^{-1}$(FWHM) at Hα.

The sky conditions were moderate to poor due to variable high cirrus and nearly full lunar phase, making the target acquisition difficult at times. The spectra were reduced using the echelle and longslit packages in IRAF with careful attention paid to the orders that contained Hα emission. Observations of the spectrophotometric standard GD 140 were used to correct for the blaze, illumination, and spectral response, but the resulting spectra were not calibrated to an absolute flux scale as the observing conditions were not photometric.

In addition to the objects observed at KPNO, we have also observed SN 1978K with the echelle spectrograph on the 4m telescope at the Cerro Tololo Inter-American Observatory (CTIO) in December 2000. The instrument was configured with similar optical elements as were used for the KPNO observations, and the spatial and spectral parameters are therefore similar. All observations are summarized in Table 1.
3. Results

Our high-dispersion echelle observations are useful in distinguishing among three sources of line emission in distant SNe:

- SN ejecta, which can be identified by a broad (width > 1000 km s$^{-1}$), spatially-unresolved H$\alpha$ line;
- Unshocked circumstellar material (CSM) ejected by the SN progenitor, which shows narrow (width $\leq$ 200 km s$^{-1}$), spatially-unresolved H$\alpha$ and [N II] $\lambda\lambda$ 6548, 6583 lines; and
- Interstellar medium (ISM) of the host galaxy, which is characterized by narrow, spatially-extended H$\alpha$ emission and forbidden lines such as [O III] $\lambda$ 5007 and [S II] $\lambda\lambda$ 6716,6731.

To search for emission from the SN, CSM, and ISM in each of our spectra, we used the spatio-kinematic descriptions of line emission given above along with the criterion that the statistical significance of the peak of an emission component be $>$3$\sigma$ per resolution element (e.g. $\sim$10 km s$^{-1}$ $\times$ 1$''$ at H$\alpha$) with respect to the background RMS noise. The results are summarized in Table 2.

Of the 16 SNe observed, we clearly detect broad line emission from the SN ejecta from four sources: SN 1978K, SN 1995N, SN 1997eg, and SN 1998S. In two further cases, SN 1999E and SN 1999Z, we detect emission that is so broad and faint that it is not possible to separate line emission from the SN ejecta from continuum emission from the SN ejecta.

Our low detection rate is likely caused by the faintness of the SNe and the poor sky condition. The majority of the SNe observed were not visible in the images taken by the acquisition camera. Blind offsets from nearby stars had to be employed for target acquisition. If the coordinates of a SN from the literature were off by more than 1$''$ perpendicular to the slit, our blind-offset observations would have missed the target entirely.

The H$\alpha$ echellograms and line profiles of SN 1995N, SN 1997eg, SN 1998S, SN 1999E, and SN 1999Z are presented in Figure 1a&b, along with finding charts. Spectral scales are given in both observed wavelengths and velocities relative to the host galaxy’s systemic velocity. The broad H$\alpha$ emission from the SN ejecta, detected over several thousand km s$^{-1}$, is evident in each image.

SN 1978K was detected with the highest signal-to-noise (S/N) ratio; several lines were detected. Its H$\alpha$ line image and the profiles of 10 spectral lines are presented in Figure 2. While H$\alpha$, H$\beta$, and He I $\lambda$ 5876 lines of the SN ejecta are broad, they are not as broad as the H$\alpha$ line of the other three SNe we detected. More interestingly, a narrow nebular component is detected in H$\alpha$, [N II] $\lambda\lambda$ 6548, 6583 and [O III] $\lambda$ 5007 lines. The high [N II]/H$\alpha$ ratio indicates that this narrow component originates from a circumstellar nebula (Chu et al. 1999). SN 1978K is the only SN among our sample whose circumstellar nebula is detected in our echelle observations.

Extended interstellar emission is detected in our observations of 12 SNe. This high detection rate (12 out of 16) is fully consistent with their being Type II SNe with massive progenitors. Three
examples of interstellar Hα emission are presented in Figure 3. The interstellar Hα line, compared to the telluric OH and Hα lines, is broader and shows velocity variations along the slit.

In the remainder of this section we summarize the observed properties of individual objects that are interesting.

3.1. SN 1954J and SN 1961V

SN 1954J and SN 1961V, in NGC 2403 and NGC 1058 respectively, had spectral properties similar to a Type II SN, but were peculiar in four respects: 1) the linewidths of SN 1961V correspond to an expansion velocity of only 2000 km s\(^{-1}\), 2) the progenitors were known, 3) they were underluminous, and 4) their SN light curves were followed in the optical for up to eight years. It has been suggested that SN 1954J and SN 1961V are luminous blue variables (LBVs) similar to η Car (Humphreys & Davidson 1994; Goodrich et al. 1989).

In optical and near-infrared imaging observations more recent than our echelle observations, Smith, Humphreys, & Gehrz (2001) have identified a faint red star with a position consistent with V12, the progenitor of SN 1954J. Similarly, using *Hubble Space Telescope* (HST) WFPC1 images of SN 1961V, Filippenko et al. (1995) have tentatively identified a faint red star with a position consistent with SN 1961V. In either case, these red sources could be a post-eruption LBV, but neither observation can rule out that these sources are an unrelated red supergiant. Spectroscopic observations similar to those reported in this paper are needed. Our observations of SN 1954J and SN 1961V were based on the best coordinates for the SNe that were available. While no emission from a SN or a post eruption LBV are detected in these spectra, interstellar emission red-shifted by \(\sim 20 \text{ km s}^{-1}\) with respect to the systemic velocity of each host galaxy are present in the spectra. The coordinates of the candidate post-eruption LBV tentatively associated with SN 1954J (Smith et al. 2001) place it more than 2′′ from our 1′′ echelle slit center and therefore our observations do not include significant emission from this source.

Optical Hα+[N II], [O III], and [S II] images of the vicinity of SN 1961V show two H II regions separated by \(\sim 3′′\) (Fesen 1985) that are coincident with two non-thermal radio sources (Branch & Cowan 1985; Cowan, Henry, & Branch 1988). The eastern source is roughly coincident with SN 1961V. Recent VLA observations at 6 cm and 18 cm by Stockdale et al. (2001) confirm that both radio sources are non-thermal and show that SN 1961V’s radio emission has decayed. These observed properties are consistent with many known SNe that have been recovered at radio wavelengths.

Our observations show two narrow-line (\(\sim 30 \text{ km s}^{-1}\)) sources in Hα and [O III] that are coincident with the two H II regions, but no broad Hα emission line is detected in 2 hrs of integration time. Furthermore, we do not detect [N II] emission that might be expected if nitrogen enriched material in an LBV ejecta nebula is present. It is possible that our slit just missed SN 1961V. As shown in Figure 4, the two radio sources are not exactly coincident with the two H II regions. The
eastern radio source, corresponding to SN 1961V and coincident with the LBV candidate identified by Filippenko et al. (1995), is \( \sim 2'' \) southwest of the core of the eastern H II region. Since our E-W echelle slit was centered on the two H II regions, whose central star clusters were the only objects visible in the telescope acquisition image, the 1'' slit width could have easily missed SN 1961V and the LBV candidate.

3.2. SN 1978K

A host of lines are detected from SN 1978K in NGC 1313 (see Figure 2). We clearly detect broad H\( \alpha \), H\( \beta \), and He I \( \lambda 5876 \) emission lines. Furthermore, we have a tentative weak detection of broad [O I] \( \lambda 6363 \) emission. Note that the stronger [O I] \( \lambda 6300 \) was not detected because it has been Doppler shifted into a gap between echelle orders. In addition to broad emission lines, we detect narrow, spatially unresolved, emission from He II \( \lambda 4686 \), [O III] \( \lambda \lambda 4959,5007 \), [N II] \( \lambda 5755 \), and [N II] \( \lambda \lambda 6548,6583 \). Interestingly, the [S II] \( \lambda \lambda 6716,6731 \) lines are not detected. The implications of the line detections and non-detections from SN 1978K will be discussed further in § 4.

3.3. SN 1995N

We detect broad H\( \alpha \) emission from SN 1995N (see Figure 1a), with FWZI (full-width at zero intensity) of \( \sim 3,000 \) km s\(^{-1}\). In addition, a narrow interstellar component with FWHM \( \sim 30 \) km s\(^{-1}\) is present. While the interstellar emission is red-shifted by roughly 40 km s\(^{-1}\) from the the systemic velocity of the host galaxy Arp 261, the broad H\( \alpha \) emission appears to be blue-shifted by \( \sim 200 \) km s\(^{-1}\).

3.4. SN 1997eg

Our observations of SN 1997eg detect broad H\( \alpha \) emission with FWZI of \( \sim 3,500 \) km s\(^{-1}\) which is blue-shifted by \( \sim 400 \) km s\(^{-1}\) with respect to the host galaxy NGC 5012. Furthermore, these observations show narrow H\( \alpha \) and [N II] \( \lambda 6583 \) emission components and possibly narrow [S II] \( \lambda \lambda 6716,6731 \) emission blue-shifted by \( \sim 160 \) km s\(^{-1}\) with respect to the systemic velocity of the host galaxy. The H\( \alpha \) and [N II] emission are both narrow and are clearly visible throughout the echelle slit and therefore are interstellar in origin. Salamanca, Terlevich, & Tenorio-Tagle (2002) observed SN 1997eg \( \sim 1 \) yr earlier and detected a strong, narrow, P-Cygni profile caused by circumstellar material, which has completely vanished at the time of our observations.
3.5. SN 1998S

SN 1998S shows three broad spectral components with total width greater than 10,000 km s\(^{-1}\). The narrow H\(\alpha\) feature at \(\sim 6581 \text{ Å}\) is spatially extended throughout the slit and is clearly interstellar in origin. Narrow, interstellar [N II] \(\lambda 6583\) and [O III] \(\lambda 5007\) emission lines are also detected blue-shifted by \(\sim 65\) km s\(^{-1}\) with respect to the systemic velocity of the host galaxy.

3.6. SN 1998bm

The galactic environment of SN 1998bm is complex and it remains unclear whether it is in NGC 2820 or NGC 2820A. SN 1998bm itself is not detected, but the interstellar emission in the echellogram appears consistent with that of an expanding shell of size \(\sim 600\) pc. While this interstellar emission might be from a supergiant shell, the expansion velocity, \(\sim 75\) km s\(^{-1}\), is relatively high compared to similar resolved structures in the Large Magellanic Cloud (Points et al. 1999) and other galaxies (Hunter & Gallagher 1997). We therefore conclude that the emission lines detected are likely a superposition of the interstellar medium of both NGC 2820 and NGC 2820A. Each of these interstellar emission components is blue-shifted with respect to the systemic velocity of the two galaxies. The brighter component (toward the western end of the slit) is probably associated with NGC 2820A and is blue-shifted by \(\sim 80\) km s\(^{-1}\). It is less certain from which galaxy the fainter component might arise but it is blue-shifted by either \(\sim 120\) km s\(^{-1}\) or \(\sim 160\) km s\(^{-1}\) from the systemic velocity of NGC 2820 and NGC 2820A, respectively.

3.7. SN 1999E

Our observation of SN 1999E detects faint, spatially-unresolved, broad emission features throughout the entire echellogram. The high dispersion of the spectrum and the gaps between echelle orders make it difficult to identify these emission features. It is nevertheless clear that these emission features are unlike that of any stars; therefore, we believe that the broad emission features are from the young SN 1999E. In addition to the broad features, narrow interstellar H\(\alpha\), H\(\beta\), and [O III] \(\lambda 5007\) emission are detected. The H\(\alpha\) emission detected has an average heliocentric velocity of \(7,925 \pm 10\) km s\(^{-1}\) and FWHM of \(\sim 100\) km s\(^{-1}\). Both the H\(\beta\) and [O III] lines have similar redshifts and all lines have a velocity \(185\) km s\(^{-1}\) greater than the previously reported systemic velocity of the host galaxy IRAS 13145−1817 (Nicolaci da Costa et al. 1998).

3.8. SN 1999Z

Our observation of SN 1999Z also detects faint, spatially-unresolved, broad emission features throughout the entire echellogram. Similarly, we believe that these emission features originate
from SN 1999Z. The Hα line is red-shifted into a gap between echelle orders but narrow interstellar components of Hβ, [O III] λ5007, and [S II] λλ6716,6731 are detected. Based on the two strongest lines, Hβ and [S II] λ6716, we find a heliocentric velocity of 15,450±10 km s\(^{-1}\) for the emission lines which is \(\sim\)350 km s\(^{-1}\) greater than that previously reported for UGC 05608 by Jha et al. (1999) which were based on the apparent velocity centroid of the then newly detected SN line emission.

4. Discussion

The very last evolutionary stage of a massive star before SN explosion is not well known. It is impossible to study SN progenitors after they have exploded, but it is possible to study the circumstellar material shed by the progenitors and photoionized by UV flashes from the SNe. The physical properties of these circumstellar nebulae may provide invaluable information about the doomed massive stars.

In the last hundred years, SN 1987A has been the only SN observed in the Local Group. All the other SNe are in distant galaxies, where circumstellar nebulae can only be detected in high-dispersion spectra of SNe as narrow nebular lines with high [N II]/Hα ratios. The size of an unresolved circumstellar nebula can be determined if the SN is spectroscopically monitored until the SN ejecta impact the circumstellar nebula. For example, if SN 1987A were at a large distance, the size of its inner ring nebula could still be determined from the 10–11 years time lapse from the SN explosion to the emergence of a broader nebular component, and the 15,000 km s\(^{-1}\) expansion velocity of the SN ejecta inferred from its broad Lyα emission (Michael et al. 2000).

There are apparently two types of circumstellar nebulae produced by SN progenitors. The first type of circumstellar nebulae are swept-up by SN ejecta within a year or two, as demonstrated dramatically in time-sequenced spectra for SN 1988Z (Stathakis & Sadler 1991). In the case of SN 1997eg, previous observations have shown a narrow P-Cygni component to the SN spectrum (Salamanca et al. 2002) which has disappeared at the time of our observations, one year later. These nebulae are small (\(\sim\)0.01 pc), and, for the case of SN 1997eg, very dense (\(\geq\)10\(^7\) cm\(^{-3}\)). Such nebulae have not been observed around any known evolved massive stars. This circumstellar material must have been ejected immediately before the SN explosion.

The second type of circumstellar nebulae are longer lived, indicating a larger size. These nebulae might be the counterparts of circumstellar nebulae observed around Wolf-Rayet (WR) stars or LBVs (Chu, Weis, & Garnett 1999). For a nebular radius of 2 pc and a SN ejecta expansion velocity of 10,000 km s\(^{-1}\), the impact of SN ejecta on the circumstellar nebula is expected at \(\sim\)200 yr after the SN explosion, and the impact will produce X-ray-luminous SNRs such as the one observed in NGC 6946 (Dunne et al. 2000) and the SNR 0540−69.3 in the Large Magellanic Cloud (Caraveo, Mignani, & Bignami 1998).

Among the SNe we surveyed, SN 1978K was the only SN that showed clear evidence for a circumstellar nebula. The Hα and [N II] lines of this circumstellar nebula have been previously
reported by Chu et al. (1999). Our new observations confirm these results with a higher S/N ratio and detect additional nebular lines. The Hα, [N II], and [O III] lines from SN 1978K all show split line profiles, suggesting a nebular expansion velocity of \( \sim 35 \) km s\(^{-1}\). As this circumstellar nebula was not yet hit by the SN ejecta 21 years after the SN explosion, the nebula might be large enough to be resolved by the HST. Therefore, we obtained the HST archive WFPC2 images of SN 1978K taken with F656N and F606W filters on 1998 September 23 as part of program GO-6713 (PI: W. Sparks). In these observations the SN is centered in the PC and a point-like source is detected (see Figure 5). Also shown in Figure 5 are the expected point-spread-functions for position of the SN in the PC for observations with the F656N and F606W filters. These images clearly place an upper limit of 0.1 on the size of the circumstellar nebula of SN 1978K. At the distance of the host galaxy NGC 1313, 4.5 Mpc (de Vaucouleurs 1963), this upper limit on the size corresponds to 2.2 pc. This small size is more consistent with the sizes of LBV nebulae than WR nebulae, as also concluded by Chu et al. (1999).

Our high-dispersion (R\( \sim 30,000 \)) spectroscopic observations of SNe have demonstrated the possibility of detecting circumstellar nebulae ejected by SN progenitors and deriving information on the progenitors from the nebular properties. Our observations have also demonstrated the difficulty of such work because of the faintness of the SNe and their associated circumstellar nebulae. In order to identify emission from such nebulae, high-dispersion spectroscopic observations of SNe with large telescopes such as Gemini and Keck are needed. Only after a large number of such circumstellar nebulae have been detected and studied can we hope to better understand SN progenitors and their circumstellar environment.

REFERENCES


\(^4\)The theoretical PSFs were generated using Tiny Tim V5.0 written by John Krist and Richard Hook which is available from http://www.stsci.edu/software/tinytim.


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Fig. 1a.— (Left column) Digitized Sky Survey image of the host galaxy/environment for each SN. The slit position for the echelle observations is overlaid as a line segment. (Right column) The echellogram and the Hα line profile for each SN. The velocity scale at the top of each panel is relative to the systemic velocity of the galaxy. In some spectra gaps appear; these are cases where multiple echelle orders contain Hα emission from the SN ejecta.
Fig. 1b.— Same as Figure 1a for SN 1999E and SN 1999Z.
Fig. 2.— (Top) Same as Figure 1a for SN 1978K. (Bottom) Profiles of ten spectral lines from SN 1978K that were detected by the echelle observations.
Fig. 3.— Same as Figure 1a for SN 1954J, SN 1961V, and SN 1998bm.
Fig. 4.— *HST* WFPC1 observations of SN 1961V with the F675W filter (greyscale image) overlaid with contours (0.07, 0.11, 0.15, 0.20, and 0.24 mJy) to show 6 cm radio continuum emission from the VLA observations by Stockdale et al. (2001). Coordinates given for the image are J2000. The radio continuum emission shows the rough location of the H II regions while the HST image shows the cluster. Our echelle observations were centered on the H II region and thus may have missed the proposed optical counterpart for SN 1961V.
Fig. 5.— (Top left panel) HST Hα (F656N) image of SN 1978K, which was situated on the PC chip and is clearly unresolved. (Top center panel) Synthetic PSF generated by TinyTim, assuming a monochromatic point source, for comparison. (Top right panel) Average radial profile where the SN 1978K F656N observations are plotted using triangles and the PSF generated by TinyTim is shown as a solid line. (Bottom left panel) Broad-band (F606W) image of SN 1978K, also situated on the PC chip. Note the source size is indistinguishable from the narrow-band image. (Bottom center panel) Synthetic PSF generated by TinyTim for the F606W filter, using our echelle spectrum as input (i.e. no continuum emission). (Bottom right panel) Plot of average radial profile for the observations and synthetic PSF for the F606W observations (triangles) and model (solid line).
Table 1. Journal of Observations

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$^a$Exposures are denoted as (number of exposures)× (exposure time in seconds for each exposure).

$^b$Observations obtained with the CTIO 4 m telescope (all other observations were obtained with the KPNO 4 m telescope).
Table 2. Summary of Observations

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<td>SN 1998S</td>
<td>II</td>
<td>NGC 3877</td>
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<td>SN 1998bm</td>
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<td>NGC 2820/20A</td>
<td>1534/74</td>
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<td>SN 1999E</td>
<td>IIb</td>
<td>IRAS 13145−1817</td>
<td>7925&lt;sup&gt;b&lt;/sup&gt; likely</td>
<td>yes</td>
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<tr>
<td>SN 1999Z</td>
<td>IIb</td>
<td>UGC 05608</td>
<td>15453&lt;sup&gt;b&lt;/sup&gt; likely</td>
<td>yes&lt;sup&gt;c&lt;/sup&gt;</td>
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<sup>a</sup> Systemic velocities of the host galaxies are given in the heliocentric frame and come from Tully (1988).

<sup>b</sup> The observed heliocentric velocity of the ISM component from this paper. These values are likely more accurate for the systemic velocity of the galaxy than previous values in the literature.

<sup>c</sup> The detection of emission from the ISM of UGC 05608 is based on Hβ, [S II], and [O III] emission but not Hα.