

Detection of Pre-Shock Dense Circumstellar Material of SN 1978K

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ABSTRACT

The supernova SN 1978K has been noted for its lack of emission lines broader than a few thousand km s^{-1} since its discovery in 1990. Modeling of the radio spectrum of the peculiar SN 1978K indicates the existence of H II absorption along the line of sight. To determine the nature of this absorbing region, we have obtained a high-dispersion spectrum of SN 1978K at the wavelength range 6530–6610 Å. The spectrum shows not only the moderately broad $\text{H}\alpha$ emission of the supernova ejecta but also narrow nebular $\text{H}\alpha$ and [N II] emission. The high [N II] λ 6583/ $\text{H}\alpha$ ratio, 0.8–1.3, suggests that this radio absorbing region is a stellar ejecta nebula. The expansion velocity and emission measure of the nebula are consistent with those seen in ejecta nebulae of luminous blue variables. Previous low-dispersion spectra have detected a strong [N II] λ 5755 line, indicating an electron density of $3\text{--}12 \times 10^5 \text{ cm}^{-3}$. We argue that this stellar ejecta nebula is probably part of the pre-shock dense circumstellar envelope of SN 1978K. We further suggest that SN 1997ab may represent a young version of SN 1978K.

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1. Introduction

Massive stars lose mass via stellar winds throughout their lifetime. Stellar winds expand away from the stars and form circumstellar envelopes. As a massive star ends its life in a supernova (SN) explosion, the SN ejecta plows through the circumstellar material, driving a forward shock into the circumstellar material and a reverse shock into the SN ejecta. Optical emission is generated in the ionized SN ejecta, cooled SN ejecta behind the reverse shock, shocked circumstellar material, and the ambient ionized circumstellar material (Chevalier & Fransson 1994). These four regions have different physical conditions and velocity structures. Consequently, optical luminosities and spectral characteristics of Type II SNe not only vary rapidly for individual SNe, but also differ widely among SNe with different progenitors.

Optical spectra of Type II SNe older than a few years are characterized by broad hydrogen Balmer lines and oxygen forbidden lines, with FWHM greater than a few thousand km s^{-1} , reflecting the rapid expansion of the SN ejecta (e.g., SN 1979C and SN 1980K - Fesen et al. 1998; SN 1986E - Cappellaro, Danziger, & Turatto 1995; SN 1987F - Filippenko 1989; SN 1994aj - Benetti et al. 1998). Some Type II SNe, however, do not seem to show such broad emission lines. The most notable case is SN 1978K.

SN 1978K in NGC 1313 was discovered in 1990 during a spectrophotometric survey of extragalactic H II regions (Ryder & Dopita 1993). Ryder et al. (1993) examined archival optical images of NGC 1313 and established that the optical maximum of the supernova occurred in 1978, possibly two months before July 31. However, the optical spectra of SN 1978K obtained in 1990–1992 do not show any emission line broader than 600 km s^{-1} (Ryder et al. 1993; Chugai, Danziger, & Della Valle 1995). This is in sharp contrast to SN 1980K, which shows broad, 6000 km s^{-1} emission lines in spectra obtained in 1988 and 1997 (Fesen et al. 1998).

SN 1978K is intriguing at radio wavelengths as well. While its radio flux shows temporal variations consistent with the expectation of a typical Type II SN, its radio spectrum shows a low-frequency turnover that is most plausibly caused by free-free absorption from an H II region along the line of sight (Ryder et al. 1993). Montes, Weiler, & Panagia (1997) re-analyzed the radio observations of SN 1978K, and find that the intervening H II region has an emission measure $\text{EM} = 8.5 \times 10^5 (T_e/10^4 \text{ K})^{1.35} \text{ cm}^{-6} \text{ pc}$, where T_e is the electron temperature.

To determine the nature of this “H II region” toward SN 1978K, we have obtained a high-dispersion echelle spectrum at the wavelength range of 6530–6610 Å. This spectrum clearly resolves the narrow [N II] $\lambda\lambda 6548, 6583$ lines and a narrow H α component from a

moderately broad $H\alpha$ component. The narrow $H\alpha$ and $[N\text{ II}]$ lines must arise from the “H II region”, and the broad $H\alpha$ component from the SN ejecta. In this paper, we report the echelle observation (§2), compare our spectrum with previous low-dispersion spectra (§3), argue that the “H II region” toward SN 1978K is circumstellar, and suggest a feasible explanation for SN 1978K’s apparent lack of very broad emission lines (§4).

2. High-Dispersion Spectrum of SN 1978K

We obtained a high-dispersion spectrum of SN 1978K using the echelle spectrograph on the 4-m telescope at Cerro Tololo Inter-American Observatory (CTIO) on 1997 February 27. The spectrograph was used in a long-slit, single-order mode; the cross disperser was replaced by a flat mirror and a broad $H\alpha$ filter (FWHM = 75 Å) was inserted behind the slit. The slit width was 250 μm , or $1''.64$. The data were recorded with the red long-focus camera and a Tektronix 2048 \times 2048 CCD. The pixel size was 0.08 Å pixel⁻¹ along the dispersion and 0''.26 pixel⁻¹ in the spatial axis. The instrumental FWHM was 14 ± 1 km s⁻¹. The data were wavelength-calibrated but not flux-calibrated.

The echelle observation of SN 1978K was made with a 10-min exposure. SN 1978K and two unrelated H II regions are detected. No spatially extended H II features exist at the position of SN 1978K. A spectrum extracted from a 5'' slit length² centered on SN 1978K is presented in Figure 1. The high-dispersion spectrum shows three sets of lines with distinct velocity widths. The narrowest (unresolved) are the telluric $H\alpha$ and OH $\lambda 6553.617$ and $\lambda 6577.285$ lines (Osterbrock et al. 1996). The broadest is the $H\alpha$ emission from the supernova ejecta. It is centered at 6572.76 ± 0.22 Å, corresponding to a heliocentric velocity (V_{hel}) of 455 ± 10 km s⁻¹; its FWHM is ~ 450 km s⁻¹ and FWZI $\sim 1,100$ km s⁻¹.

The third set of lines consists of the narrow $[N\text{ II}]\lambda\lambda 6548, 6583$ lines and a narrow $H\alpha$ component. The narrow $H\alpha$ component is superimposed near the peak of the broad $H\alpha$ emission of the supernova, hence its central velocity, $V_{hel} \sim 419$ km s⁻¹, and FWHM, 75–100 km s⁻¹, are somewhat uncertain. The $[N\text{ II}]\lambda 6583$ line, at $V_{hel} = 419\pm 5$ km s⁻¹, shows a line split of ~ 70 km s⁻¹; its FWHM is ~ 125 km s⁻¹. The $[N\text{ II}]\lambda 6548$ line, being weaker, does not show an obvious line split; however, its asymmetric line profile indicates the presence of a brighter red component and a weaker blue component, consistent with those seen in the $[N\text{ II}]\lambda 6583$ line.

The narrow $H\alpha$ component and the narrow $[N\text{ II}]$ lines most likely originate from the same emitting region, and will be referred to as “nebular” emission. We have measured the nebular $[N\text{ II}]\lambda 6583/H\alpha$ ratio to be 0.8–1.3. The large uncertainty in this ratio is caused by

²This large slit length is necessary to include all the light from SN 1978K, as the telescope was slightly out of focus for this observation. When the focus problem was resolved (2 hours later), SN 1978K had already set.

the uncertainty in the nebular $H\alpha$ flux, as it is difficult to separate the nebular and supernova contributions to the observed $H\alpha$ emission. The possible range of nebular $[N\text{ II}]/H\alpha$ ratio is derived from the lower and upper limits of the nebular $H\alpha$ flux, estimated by assuming high and low peaks of supernova emission, respectively.

3. Comparison with Previous Low-Dispersion Spectra

A relatively low-dispersion spectrum of SN 1978K was obtained on 1990 Jan 23 by Ryder et al. (1993). That spectrum showed an $H\alpha$ line centered at $6570.2 \pm 0.6 \text{ \AA}$ with a FWHM of 563 km s^{-1} . It also detected the $[N\text{ II}]\lambda 6583$ line at $6589.6 \pm 1.0 \text{ \AA}$. As this spectrum has a resolution of $\sim 5 \text{ \AA}$ and a pixel size of $1.5 \text{ \AA pixel}^{-1}$, the $[N\text{ II}]$ lines are not well resolved from the $H\alpha$ line and consequently the velocity and flux measurements might not be very accurate. The $[N\text{ II}]\lambda 6583/H\alpha$ flux ratio, 0.049, derived from this low-dispersion spectrum is really the ratio of nebular $[N\text{ II}]\lambda 6583$ flux to the combined supernova and nebular $H\alpha$ flux. The $[N\text{ II}]\lambda 5755$ line is also detected and the $[N\text{ II}]\lambda 5755/H\alpha$ flux ratio is 0.025.

Another low-dispersion spectrum of SN 1978K was obtained on 1992 October 22 by Chugai et al. (1995). The resolution of this spectrum is 10 \AA . Thus the redshifts and widths of spectral lines cannot be reliably determined. The $[N\text{ II}]\lambda 6583/H\alpha$ flux ratio is 0.072, and the $[N\text{ II}]\lambda 5755/H\alpha$ flux ratio is 0.016.

Using our echelle spectrum, we have measured the ratio of nebular $[N\text{ II}]\lambda 6583$ flux to the combined supernova and nebular $H\alpha$ flux to be 0.06. This is different from the previous measurements, 0.049 and 0.072. While our measurement should be more accurate because of our higher spectral resolution, the supernova $H\alpha$ flux might have varied from 1990 to 1997 (Chugai et al. 1995). It is not clear whether the $[N\text{ II}]$ flux itself has changed.

Nebular lines toward SN 1978K are also detected in the UV spectra of SN 1978K obtained with the Faint Object Spectrograph on board the Hubble Space Telescope on 1994 September 26 and 1996 September 22–23 (Schlegel et al. 1998). The $Ly\alpha$ line and the blended $[Ne\text{ IV}]\lambda\lambda 2421, 2424$ doublet are detected. Both lines have FWHMs comparable to the instrumental resolution, 7 \AA , corresponding to 1727 km s^{-1} at $Ly\alpha$ and 866 km s^{-1} at $[Ne\text{ IV}]$. These $[Ne\text{ IV}]$ lines have critical densities of 8×10^4 and $2.5 \times 10^5 \text{ cm}^{-3}$, respectively (Zheng 1988); therefore, these $[Ne\text{ IV}]$ lines must originate from the nebula. The $Ly\alpha$ line emission, like the $H\alpha$ emission, contains both the supernova ejecta and nebular components.

4. Discussion

4.1. Origin of the Narrow H α and [N II] Lines

The most intriguing features detected in our high-dispersion spectrum of SN 1978K are the narrow nebular H α and [N II] lines, which are presumably emitted by the “H II region along the line of sight” implied by the radio spectrum of SN 1978K (Ryder et al. 1993). However, as we argue below, the [N II] line strengths suggest that this “H II region” is circumstellar, rather than interstellar.

The nebular [N II] λ 6583/H α line ratio, 0.8–1.3, is unusually high for normal interstellar H II regions in a spiral galaxy. For example, H II regions in M101 have [N II] λ 6583/H α ratios ≤ 0.3 (Kennicutt & Garnett 1996). SN 1978K is at the outskirts of NGC 1313, where abundances are expected to be low and the H II excitation is expected to be high. If the nebular H α and [N II] lines toward SN 1978K originate in an interstellar H II region, we would expect the [N II] λ 6583/H α ratio to be ~ 0.1 or lower. A low interstellar [N II]/H α ratio is confirmed by the bright H II region detected along the slit at $\sim 90''$ east of SN 1978K. This H II region is brighter than the nebula toward SN 1978K in the H α line, but its [N II] λ 6583 line is not detected. We may rule out an interstellar H II region explanation for the narrow nebular lines seen in SN 1978K.

The high [N II] λ 6583/H α ratio may be caused by a high electron temperature or a high nitrogen abundance. These conditions can be easily provided by SN 1978K and its progenitor. If the nebula was ionized by the UV flash of SN 1978K, the electron temperature may be higher than that of a normal H II region, as in the case of SN 1987A’s outer rings (Panagia et al. 1996). However, the [N II] λ 6583 line intensity increases by only a factor of 2 for an electron temperature increase from 10,000 K to 15,000 K. This increase cannot explain fully the observed high [N II]/H α ratio. A higher nitrogen abundance is needed. An elevated nitrogen abundance is characteristic of ejecta nebulae around evolved massive stars, such as luminous blue variables (LBVs) and Wolf-Rayet (WR) stars; the [N II] λ 6583/H α ratios of these ejecta nebulae are frequently observed to be ~ 1 (Esteban et al. 1992; Smith et al. 1998). Therefore, the most reasonable origin of the nebular emission lines toward SN 1978K would be a circumstellar ejecta nebula. The observed high [N II]/H α ratio may be caused by the combination a high nitrogen abundance and a high electron temperature.

SN 1978K’s circumstellar ejecta nebula has a very high density, as strong [N II] λ 5755 line is observed in SN 1978K’s spectrum. The [N II] (λ 6548+ λ 6583)/ λ 5755 ratio is measured to be 2.55 by Ryder et al. (1993), and 6.0 by Chugai et al. (1995), indicating that collisional de-excitation is significant for the 1D_2 level of N $^+$. If we assume an electron temperature of $1\text{--}1.5 \times 10^4$ K, the observed [N II] line ratios imply electron densities of $3\text{--}12 \times 10^5$ cm $^{-3}$.

The circumstellar ejecta nebula of SN 1978K can be compared to those observed around LBVs and WR stars. The density of SN 1978K’s nebula is higher than those of WR nebulae, but within the range for LBV nebulae (Stahl 1989; Esteban et al. 1992). We adopt the emission measure $EM = 8.5 \times 10^5 (T_e/10^4 K)^{1.35}$ cm $^{-6}$ pc determined from the radio observations

(Montes et al. 1997) for SN 1978K’s nebula. This emission measure is much higher than those observed in ejecta nebulae around WR stars, typically a few $\times 10^2$ to 10^3 cm^{-6} pc (Esteban et al. 1992; Esteban & Vílchez 1992), but lies toward the high end of the range typically seen in LBV nebulae, a few $\times 10^3$ to 10^5 cm^{-6} pc (Hutsemékers 1994; Smith et al. 1998). Finally, the $\text{H}\alpha$ and $[\text{N II}]$ velocity profiles seen in our SN 1978K spectrum suggest an expansion velocity³ of 40–55 km s^{-1} , which is lower than those of most ejecta nebulae around WR stars but is within the range for LBV nebulae (Nota et al. 1995; Chu, Weis, & Garnett 1999). It is thus likely that the observed nebula toward SN 1978K was ejected by the progenitor during a LBV phase before the SN explosion.

This ejecta nebula could be either part of the circumstellar envelope that the SN ejecta expands into, or a shell that is detached from the circumstellar envelope. We will demonstrate below that the latter is unlikely. If the ejecta nebula is a detached shell, the observed emission measure and density imply that the shell thickness is only 4×10^{-5} to 4×10^{-6} pc. The thickness of a detached, dense shell will be broadened by diffusion, and may be crudely approximated by $(c/V_{exp})R$, where c is the isothermal sound velocity, V_{exp} is the expansion velocity, and R is the radius. We find that the radius of SN 1978K’s free-expanding ejecta shell would have to be no greater than $\sim 2 \times 10^{-4}$ pc, which is smaller than the expected radius of the SN ejecta. This is impossible. Therefore, we conclude that the narrow $\text{H}\alpha$ and $[\text{N II}]$ lines must originate in the pre-shock, ionized circumstellar envelope of SN 1978K.

The narrow nebular lines from the pre-shock, ionized circumstellar envelope of SN 1978K are not unique among SNe. The high-dispersion spectrum of SN 1997ab shows narrow P-Cygni $\text{H}\alpha$ and narrow $[\text{N II}]\lambda 6583$ lines, and the FWZI of the P-Cygni $\text{H}\alpha$ line, 180 km s^{-1} , is comparable to that of SN 1978K’s $\text{H}\alpha$ line (Salamanca et al. 1998). The P-Cygni profile of SN 1997ab’s narrow $\text{H}\alpha$ line indicates a high density, $\geq 10^7$ cm^{-3} . This density exceeds the critical density of the 1D_2 level of N^+ , and causes a weak $[\text{N II}]\lambda 6584$ line (see Figure 1 of Salamanca et al. 1998). If SN 1997ab’s circumstellar material is nitrogen-rich like that of SN 1978K, we predict that its $[\text{N II}]\lambda 5755$ line is strong and should be detectable as well. SN 1997ab is very likely a younger version of SN 1978K, and SN 1978K’s nebular $\text{H}\alpha$ line may have exhibited a P-Cygni profile in 1979-1980.

4.2. SN Evolution in a Very Dense Circumstellar Envelope

The most notable SN characteristic of SN 1978K is its apparent lack of very broad (a few thousand km s^{-1}) emission lines. Adopting canonical expansion velocities and sizes for SN 1978K, Ryder et al. (1993) has derived a mass of $>80 M_{\odot}$ for the circumstellar envelope.

³The expansion velocity implied by the line split in the $[\text{N II}]$ line is >35 km s^{-1} . The expansion velocity can also be approximated by the HWHM of the $\text{H}\alpha$ and $[\text{N II}]$ lines, 40–55 km s^{-1} .

This mass is too large to reconcile with the current understanding of massive stellar evolution. To lower the circumstellar mass, Chugai et al. (1995) propose that the circumstellar envelope is clumpy.

We consider that the large size ~ 0.1 pc adopted by Ryder et al. (1993) is over-estimated and inconsistent with the expansion velocity implied by our observed $H\alpha$ FWHM of 450 km s^{-1} . There is no need to assume an unseen, larger expansion velocity. We suggest that the small expansion velocity of SN 1978K is caused by the dense circumstellar envelope, which has quickly decelerated the expansion of SN ejecta. If optical spectra had been obtained immediately after the SN explosion in 1978, very broad emission lines would have been detected.

Rapid deceleration of SN ejecta has been observed in two other SNe, SN 1986J and SN 1997ab. SN 1986J has been noted to have very similar spectral properties as SN 1978K⁴. SN 1986J probably exploded four years before its initial discovery in 1986 (Rupen et al. 1987; Chevalier 1987). Its optical spectra obtained soon after the discovery show narrow hydrogen Balmer lines and nitrogen forbidden lines, indicating an expansion velocity $< 600 \text{ km s}^{-1}$ (Leibundgut et al. 1991). SN 1997ab is the only other SN for which narrow nebular emission lines from the dense circumstellar envelope have been unambiguously resolved and detected. SN 1997ab’s light curve peaked in 1996; the FWHM of its $H\alpha$ line decreased rapidly from 2500 km s^{-1} on 1997 March 2 to 1800 km s^{-1} on 1997 May 30 (Hagen et al. 1997; Salamanca et al. 1998).

Clearly, SN 1978K, SN 1986J, and SN 1997ab all possess very dense circumstellar envelopes, and we may expect them to evolve similarly. The expansion of SN 1978K might have slowed down to below 1000 km s^{-1} within the first ~ 2 years after the explosion, and the SN ejecta could not have reached a radius greater than ~ 0.02 pc in 1990. A factor of 5 reduction in the radius would lower Ryder et al.’s (1993) estimate of mass to a reasonable value, and the hypothesis of a clumpy circumstellar envelope will no longer be necessary.

4.3. Future Work

Previous spectrophotometric observations of SNe were rarely made with spectral resolutions better than 2 \AA . Our echelle observation of SN 1978K has demonstrated that high-dispersion spectroscopy is powerful in resolving pre-shock, ionized circumstellar material. A high-dispersion spectroscopic survey of young SNe in nearby galaxies may detect more circumstellar envelopes and even detached ejecta ring nebulae, such as the rings around

⁴We have examined a large number of SN spectra reported in the literature. SN 1986J appears to be the only SN besides SN 1978K that shows strong $[N \text{ II}]\lambda 5755$ line, indicating a very high density and possibly an enhanced nitrogen abundance.

SN 1987A (Burrows et al. 1995). The density and velocity structures of these circumstellar envelopes would shed light on the mass loss history as well as physical properties of the massive progenitors.

Our spectrum of SN 1978K unfortunately covers only the [N II] and H α lines. In order to measure the density, temperature, and abundances of the circumstellar material, it is necessary to obtain high-dispersion spectra covering a large wavelength range. It is also important to monitor the spectral changes indicative of density changes in the circumstellar envelope. A large change at all wavelengths is expected when the SN ejecta expands past the outer edge of the circumstellar envelope.

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Figure Captions

Fig. 1.— High-dispersion spectrum of SN 1978K taken with the echelle spectrograph on the CTIO 4 m telescope. The spectrum has been smoothed with a boxcar of 5 pixels, or 0.4 Å. The telluric lines are indicated by the \oplus symbol.

