PHYSICAL PROPERTIES OF THE X-RAY–LUMINOUS SN 1978K IN NGC 1313 FROM
MULTIWAVELENGTH OBSERVATIONS

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ABSTRACT

We update the light curves from the X-ray, optical, and radio bandpasses which we have assembled over the past decade and present two observations in the ultraviolet using the Hubble Space Telescope Faint Object Spectrograph. The HRI X-ray light curve is constant within the errors over the entire observation period. This behavior is confirmed in the ASCA GIS data obtained in 1993 and 1995. In the ultraviolet, we detected Lyα, the [Ne iv] 2422/2424 Å doublet, the Mg ii doublet at 2800 Å, and a line at approximately 3190 Å that we attribute to He i 3187. Only the Mg ii and He i lines are detected at SN 1978K’s position. The optical light curve is formally constant within the errors, although a slight upward trend may be present. The radio light curve continues its steep decline. The longer time span of our radio observations compared to previous studies shows that SN 1978K is in the same class of highly X-ray and radio-luminous supernovae as SN 1986J and SN 1988Z. The [Ne iv] emission is spatially distant from the location of SN 1978K and originates in the preshocked matter. The Mg ii doublet flux ratio implies the quantity of line optical depth times density of approximately 10^{14} cm^{-3} for its emission region. The emission site must lie in the shocked gas.

Key words: supernovae: individual (SN 1978K)

1. INTRODUCTION

SN 1978K was the second supernova detected and recognized as a supernova from its radio emission and the first from its X-ray flux (Ryder et al. 1993, hereafter Paper I). It was discovered in a ROSAT PSPC observation of NGC 1313 but had not been detected by an Einstein observation of the same field 11 yr earlier.

SN 1978K is one of a handful of extremely luminous, X-ray emitting supernovae (Schlegel 1995). X-ray observations are difficult to obtain, so to date few observations exist. Currently nine supernovae are known to emit or have emitted X-rays sometime in the months and years following their outbursts (SN 1978K, SN 1979C, SN 1980K, SN 1986J, SN 1987A, SN 1988Z, SN 1993J, SN 1994I, SN 1995N (references are listed below). Of these, the X-rays from SN 1987A largely resulted from Compton scattered γ-rays from the radioactive decay of 56Co. SN 1987A is very likely starting to undergo a circumstellar interaction (Hasinger, Aschenbach, & Trümper 1996); it is expected to become a very bright X-ray source (Chevalier & Dwek 1995; Masai & Nomoto 1994; Suzuki, Shigeyama, & Nomoto 1993).

The remaining eight supernovae are all believed to emit X-rays solely because of a circumstellar interaction. SN 1980K (Canizares, Kriss, & Feigelson 1982) and SN 1993J (Zimmermann et al. 1994) were detected in the days immediately following their explosions. SN 1979C (Immler, Pietsch, & Aschenbach 1998a), SN 1988Z (Fabian & Terlevich 1996), SN 1994I (Immler et al. 1998b), and SN 1995N (Lewin, Zimmermann, & Aschenbach 1996) have all been recently detected so that we do not as yet have any X-ray light curves. Just three supernovae remain: SN 1978K, SN 1986J, and SN 1993J. SN 1986J and SN 1993J have been reported to be fading (Houck et al. 1998; Zimmermann et al. 1994); the X-ray light curve of SN 1978K appeared to be constant (Schlegel, Petrè, & Colbert 1996, hereafter SPC96) as of 1995.

Modeling of the radio spectrum by Montes, Weiler, & Panagia (1997; hereafter MWP) led them to infer the existence of absorption by an H II region along the line of sight to SN 1978K. Based on an optical spectrum of SN 1978K taken in 1992 October, Chuai, Danziger, & Della Valle (1995) hypothesized that the optical and X-ray emission is driven by shock waves propagating through a dusty circumnuclear wind, rather than through the extremely massive circumstellar envelope invoked in Paper I. In a recent paper, Chu et al. (1999) present a spectrum of the Hα + [N II] region at high resolution, which shows broad emission from the supernova ejecta, with superposed (narrow) nebular lines. They attribute the latter to a circumstellar ejecta nebula from the progenitor of SN 1978K, which the supernova ejecta could plough into quite soon. This would cause significant brightening of SN 1978K at all wavelengths, making continued monitoring all the more important.
In this paper, we update the X-ray light curve with additional ROSAT HRI observations that have been obtained since SPC96, briefly discuss the two epochs of ASCA data, update the optical and radio light curves, and present HST FOS spectra. Throughout this paper, we assume the distance to NGC 1313 is 4.5 Mpc (de Vaucouleurs 1963); the corresponding image scale is 1" = 22 pc.

2. OBSERVATIONS

For a multiwavelength paper such as this one, we present the details of the observations and the analyses (next section) of the data for each bandpass in separate subsections in case the reader chooses to skip some of the details. Each section is explicitly labeled for easier navigation. Figure 1 shows the distribution of all of the observations to be described.

2.1. X-Ray

2.1.1. ROSAT Observations

An early portion of the X-ray light curve of SN 1978K was presented in SPC96. Since that paper, we have accumulated another six observations of the supernova, which doubles the number of data points and increases the coverage to 7 yr, representing about one-third of the life of SN 1978K. Table 1 summarizes the observations where we also include the PSPC observations (SPC96). The light curve therefore shows all of the data of SN 1978K obtained by ROSAT. The 1998 April observation is among the last observations to be obtained with ROSAT.

Recently, Snowden (1998) analyzed the particle background of the ROSAT HRI. The issues raised in that paper could affect the X-ray light curve of SN 1978K if the particle background has not been properly subtracted. In the light of that paper, the entire HRI data set of SN 1978K has been reprocessed, using the tools described in Snowden (1998).

We extracted the counts for each epoch using an aperture of radius 40", which contains about 92% of the encircled energy (David et al. 1997). The counts from all of the observations were converted to a flux by adopting the best-fit model that describes the ROSAT PSPC and ASCA SIS data (Petre et al. 1994a). The model combines a soft ($kT \sim 0.84$ keV) thermal component and either a hard ($kT \sim 4.7$ keV) thermal component or a power law ($\Gamma \sim 1.08$). None of the HRI points show evidence of a spectral change as measured by a hardness ratio; the HRI's ability to discern spectral changes, however, is quite limited, so the lack of a spectral change is not restrictive (Prestwich et al. 1996). The final light curve (Fig. 2) does not differ from the light curve presented in SPC96 in any significant or systematic manner.

2.1.2. ASCA Spectra

Two observations of SN 1978K have been obtained with the gas proportional counter (GIS) and the CCD detectors.

![Fig. 1.—Distribution of all observations described in this paper. The vertical axis is an arbitrary index used to spread out the observations, but the observations are organized by energy from high (bottom) to low (top). The first of the two optical spectra was obtained by and described in Chugai et al. (1995). See Tables 1, 2, 3, 6, and 8 for the details of each observation.](image)

### TABLE 1

| Sequence | Detector | Observation Date | MJD | Approx. Age (days) | Expos. Time (s) | Flux \* | Pointing Center |
|----------|----------|------------------|-----|-------------------|----------------|--------|----------------|
| 150010\* | PSPC     | 1990 Jul 23      | 48,095 | 4445              | 3399           | 1.75 ± 0.15 | HD 20888 |
| 200044\* | PSPC     | 1991 Mar 18      | 48,333 | 4683              | 3031           | 1.51 ± 0.19 | HD 20888 |
| 60045n00\* | PSPC | 1991 Apr 24      | 48,370 | 4720              | 11118          | 1.99 ± 0.10 | NGC 1313 |
| 400065n00\* | HRI | 1992 Apr 18–May 24 | 48,730 | 5080              | 5365           | 1.24 ± 0.22 | NGC 1313 |
| 60050n400\* | PSPC | 1993 Nov 3       | 49,299 | 5649              | 15178          | 1.96 ± 0.09 | NGC 1313 |
| 60050s5a1\* | HRI    | 1994 Jun 23–Jul 24 | 49,538 | 5888              | 22199          | 1.53 ± 0.10 | NGC 1313 |
| 500400n000 | HRI  | 1995 Jan 31–Feb 10 | 49,753 | 6103              | 13314          | 2.04 ± 0.14 | SN 1978K |
| 500404n000 | HRI  | 1995 Feb 2–11    | 49,754 | 6104              | 26988          | 1.64 ± 0.09 | SN 1978K |
| 600505n000 | HRI  | 1995 Apr 12–20   | 49,823 | 6173              | 20143          | 1.85 ± 0.11 | NGC 1313 |
| 500403o000 | HRI  | 1995 May 9–Jul 21 | 49,883 | 6233              | 30736          | 1.81 ± 0.09 | SN 1978K |
| 500404a001 | HRI  | 1995 May 10–Jul 22 | 49,884 | 6234              | 18628          | 1.90 ± 0.12 | SN 1978K |
| 500492a001 | HRI  | 1997 Sep 30–Aug 10 | 50,726 | 7076              | 22537          | 1.74 ± 0.11 | SN 1978K |
| 500499n000 | HRI  | 1998 Mar 21–Apr 19 | 50,908 | 7258              | 23754          | 1.69 ± 0.10 | SN 1978K |

\* MJD at center of observation when spanning multiple days.
\* Based on adopted date of maximum of 1978 May 22 = MJD 43650.
\* Integrated, unabsorbed flux in 0.2–2.4 keV in units of 10^{-12} ergs s^{-1} cm^{-2} for thermal model with kT = 0.4 keV and N_H = 4.4 \times 10^{21} cm^{-2}.
\* In light curve presented in SPC96.
\* Data described in Colbert et al. 1995.
\* Data described in Stocke et al. 1995.
\* Data described in Miller et al. 1998.
We extracted spectra from each data set taking care to avoid the other sources in NGC 1313. The background was obtained from the same SIS chip or GIS field. Spectra were also summed. The spectrum for 1995 November is shown in Figure 3; the model fits will be described in § 3.2.

2.2. HST FOS Observations

An observation using the Faint Object Spectrograph on board the *Hubble Space Telescope* was obtained in 1994 September 26 using the best available radio and optical coordinates. Target lock failed, largely because the source is an emission-line object. This accounts for the large number of off-source pointings. The observation was rescheduled for 1996 September 22 after improved offset coordinates were obtained from short WFPC2 exposures (next section). Some of the pointing problems stem from the difficulties in tying together the optical and radio coordinate systems in the southern hemisphere (Ryder et al. 1993).

The SN 1978K observation was designed to obtain on-source “blue” (∼1200–2500 Å, using grating G160L) and “red” (∼2200–3200 Å, using grating G270H) spectra plus an off-source spectrum for each band. The approximate boundary between the two bands lies at about 2350 Å with an overlap of roughly 100 Å.

The pointing history, constructed from the “RA APER” and “DECAPER” keywords in the file headers, is shown in Figure 4, where the weight of a data point represents the exposure time at that location. The total observation set is described in Table 3. From the pointing history, we distinguish seven separate observations: a 1996 red-band observation centered on SN 1978K, 1996 blue- and red-band spectra northwest of SN 1978K, 1994 blue and red spectra northwest of the SN, and 1994 blue and red spectra to the southwest. We distinguish between the 1994 and 1996 observations at a given location because the source may vary.

The “on-source” exposure time is therefore a function of one’s definition of “on-source.” The “true” on-source observation is the red spectrum; no observation in the blue was obtained at that location. The observations obtained northwest of SN 1978K lie about 1′3 from the supernova; the observations obtained to the southwest lie about 2′3 away. These distances are approximately 4.3 and 7.6 times the size of the FOS aperture or approximately 6.5 and 11.5 times the 70% encircled energy radii of the COSTAR-corrected *HST* optics.

The data were calibrated using the standard FOS pipeline. We checked the wavelength calibration at the end points of the spectra and verified the flux calibration using FOS tasks in STSDAS. We carefully examined each spectrum for evidence of noisy or dead pixels. The red spectrum centered on the SN had a noisy pixel in the middle of the band; we clipped out the affected pixels. None of the candidate lines correspond to noisy pixels as listed in the 1994 August noisy pixel list (Leitherer 1996, *HST* manual). All of the candidate lines were visible in the raw and calibrated data. We then co-added the data for a given pointing and epoch. The spectra are shown in Figures 5 and 6.

All line fluxes were corrected for reddening using two different values. The first value of $E_{B-V} = 0.01$, comes from Burstein & Heiles (1984) while the second value (∼0.31) comes from Paper I. These values were converted to $A_\lambda$ using the reddening curve in Mathis (1990). The first value increases line fluxes by a factor of approximately 1.06 at $\lambda \sim 2800$ Å while the second increases the fluxes by a factor of approximately 1.06 at $\lambda \sim 2800$ Å.
of about 5.5. The second value would seem more likely, given the environment immediately after a supernova explosion. However, the optical spectrum (to be presented shortly) implies that the extinction has decreased to approximately zero.

2.3. Optical Light Curve

The optical light curve originates from two sources: ground-based optical photometry and WFPC2 snapshots using HST.

To obtain accurate coordinates and offset stars for SN 1978K in the HST reference frame, B- and V-band WFPC2 snapshots of the SN 1978K region were obtained. The observations occurred on 1996 January 3 with exposure times of 60 s for both the F555W (~V) filter and the F439W (~B) filter. We extracted the counts for SN 1978K, as well as the counts for stars “b” (~66° east of SN 1978K), “c” (~42° west), and “d” (~44° northwest) (qv, Paper I for a finding chart) using apertures 3° in diameter. We adjusted the resulting magnitudes for the gain, charge transfer efficiency, contamination corrections, and added the zero offset to place the magnitudes relative to Vega. These corrections are all described in the HST Data Handbook (version 2.0). For the V band, the magnitudes of stars b, c, and d differed from their published values (Paper I) by a mean value of ~0.759; for the B band, the mean value was ~1.396. Correcting the SN 1978K magnitudes by these offsets gave the B and V magnitudes for SN 1978K: 20.67 ± 0.11 and 19.81 ± 0.05, respectively.

The supernova has also been monitored intermittently on our behalf by various observers. The resulting magnitudes, determined from differential photometry relative to the sequence established in Paper I, are collated in Table 4 and shown in Figure 7. The data are not conclusive; an increase in brightness of 0.2–0.3 mag in all filters is suggested, but the possibility that there has been no change in brightness of SN 1978K between 1990 and 1996 cannot be ruled out.

2.4. Optical Spectrum

Spectrophotometry of SN 1978K in the wavelength range 3566–6715 Å was obtained on 1996 October 8 UT with the 3.9 m Anglo-Australian Telescope. The RGO Spectrograph was used with the 25 cm camera, a 300 line mm⁻¹ grating, a slit length of 77”, and a Tektronix 1K CCD. Three consecutive exposures of 1000 s each were obtained on the supernova, followed by a short exposure on the flux standard EG21 (Hamuy et al. 1994). The three exposures were reduced individually within IRAF, and then the line fluxes were measured separately for each spectrum to permit the flux errors to be calculated. The final resolution obtained after light smoothing is 12 Å. The result of coadding all three spectra is shown in Figure 8, and the line

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11 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.
Radio Observations

SN 1978K has been monitored at irregular intervals since its discovery using the six antennas of the Australia Telescope Compact Array (ATCA). Using the multifrequency agility of the ATCA, observations with a 128 MHz bandwidth are taken over an 4–12 hr period, with rapid switching between simultaneous measurements at 1380 and 2370 MHz or at 4790 and 8640 MHz. Beginning in 1998 August, the central frequency of the S-band observations was changed to 2496 MHz in an effort to avoid encroaching the central frequency of the S-band observations was.

Deconvolved images of SN 1978K show the source still to be unresolved at all frequencies. Since SN 1978K is the only significant source of continuum emission in the field (Fig. 5 of Paper I), it was decided to measure the fluxes directly from plots of the calibrated visibility amplitudes, binned into 10–20 time periods, to give a truer reflection of the errors, which are dominated more by atmospheric conditions than by the model fitting to the deconvolved images. The results from eight epochs are compiled in Table 6, together with three observations at 0.843 GHz using the Molonglo Observatory Synthesis Telescope (MOST). The post-1990 radio light curve, including data from Paper I and MWP, is presented in Figure 9.

3. ANALYSES BY BAND

3.1. X-Ray Light Curve Modeling

SPC96 presented the first X-ray light curve for SN 1978K and showed that the light curve was consistent with zero slope. The updated X-ray light curve (Fig. 2) should decay as $t^{-0.9}$ (e.g., Chevalier & Fransson 1994, hereafter ChevFran). The formal fitted value of the exponent to all of the data.

| UT Date  | MJD  | Approx. Age$^a$ | Telescope | B   | V   | R   | I   |
|----------|------|----------------|-----------|-----|-----|-----|-----|
| 1990 Nov 17 | 48,212 | 4562 | AAT 3.9 m | ... | 20.23 ± 0.28 | ... | 20.52 ± 0.39 |
| 1992 May 1  | 48,743 | 5093 | MSSSO 1.0 m | ... | ... | ... | 19.90 ± 0.24 |
| 1992 Nov 3  | 48,929 | 5279 | MSSSO 1.0 m | ... | 19.97 ± 0.13 | ... | ... |
| 1994 Jan 9  | 49,361 | 5711 | MSSSO 1.0 m | 20.89 ± 0.28 | 19.94 ± 0.19 | 18.73 ± 0.20 | 19.60 ± 0.22 |
| 1995 Feb 24 | 49,722 | 6122 | CTIO 1.5 m | 20.80 ± 0.26 | ... | ... | 20.14 ± 0.50 |
| 1996 Jan 3  | 50,085 | 6435 | HST$^b$ | 20.67 ± 0.11 | 19.81 ± 0.05 | ... | ... |
| 1996 Jun 12 | 50,246 | 6596 | MSSSO 1.0 m | 20.66 ± 0.26 | ... | ... | 19.80 ± 0.55 |
| 1996 Sep 15 | 50,341 | 6691 | AAT 3.9 m | ... | 18.49 ± 0.29 | ... | ... |

$^a$ Age based on adopted date of maximum of 1978 May 22 = MJD 43,650.
$^b$ Pseudo-$B$ and $V$ magnitudes; $B$ from F439W filter, $V$ from F555W filter.
(flux vs. days past maximum) is $\alpha = (-3.71 \pm 6.52) \times 10^{-5}$ (90% confidence range) if all of the data points are included in the fit. This fit is illustrated in the figure as the solid line. The dashed lines show the ±90% range of the slope. Note that the range is consistent with zero. As a check, we fit only the HRI data points, obtaining a value for $\alpha = (+5.60 \pm 11.72) \times 10^{-5}$. This slope also includes zero and covers approximately the same range. Additional observations must be obtained to ascertain whether SN 1978K has started its slide into obscurity or if the last data point is a fluctuation. Given the scatter of the other data points, a fluctuation provides the most likely explanation. Fluctuations in the X-ray light curve with amplitudes of about 20% are expected if the ejecta are inhomogeneous (e.g., Cid-Fernandes et al. 1996).

Fransson, Lundqvist, & Chevalier (1996, hereafter FLC96) discussed several regimes for the decay of X-rays from SN 1993J. Those regimes were (1) the optically thick shock case, (2) the adiabatic case, and (3) the radiative case. The time behavior from each differed. For the optically thick case $L \propto T^{0.16} t^{(3-2s)(n-3)/(n-s)}$, where $T$ = temperature, $t$ = time, $n$ = power-law index for the density profile of the ejecta, and $s$ = power-law index for the density profile of the circumstellar matter. The power law is an approximation to the supernova density profile; typical values from models lie between 7 and 12. The ChevFran model requires $n \approx 9$ for an adiabatic shock; for $n \approx 8$ radiative cooling becomes important. A steady stellar wind will create a circumstellar medium with $s = 2$, so that value is usually adopted. But FLC96 showed that $1.5 \leq s \leq 1.7$ described the SN 1993J X-ray behavior more accurately.

For the adiabatic case $L \propto t^{-[(2s-3)n-5s+6]/(n-s)}$, while for the radiative case $L \propto t^{-(15-6s+3n-2n)/(n-s)}$. If we assume the slope is precisely zero, then we can explore the possible values for $n$ and $s$. A value of $s = 2$ is usually adopted because it describes the circumstellar density distribution

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**Fig. 5.—HST FOS spectra at SN 1978K.** The top plot shows the 1996 red spectrum at the position of SN 1978K; the middle plot shows the spectrum obtained 1.5 away to the northwest. The spectra have been corrected neither for reddening nor for the redshift of SN 1978K (439 km s$^{-1}$). Note that both the top and middle spectra show a small flat excision, just blueward of the Mg II line, where a noisy pixel was located. The bottom spectra expand the regions around the Mg II line at 2800 Å (left) and the line at 3190 Å (right).
from a steady wind. A value of approximately 1.5 for $s$ is supported by the SN 1993J data (FLC96); however, subsequent analysis shows that $s = 2$ is correct (Fransson & Bjornsson 1998). While $s = 2$ has physical significance, we will also explore the effect of $s = 1.5$. For the optically thick case, either low $n$ ($\sim 4$) or $s = 1.5$ plus any $n$ yields a solution. For the adiabatic case, if $s = 2$, $n$ must again be low ($\sim 4$), while $s = 1.5$ leads to no solution. For the radiative case, if $s = 2$ leads to no solution, while if $s = 1.5$, then $n = 12$.

Using just the light curve, we are unable to obtain sufficient information to establish the emission behavior uniquely, because either the optically thick shock or the radiative cases fit the data equally well. We only establish a range for $n$ ($\sim 4$-$12$). Further, these two models use $s = 2$ and $s = 1.5$. By comparison, hydrodynamic models establish a power-law distribution with $n \sim 8$-$20$ within a day or two of the explosion (Chevalier 1990). Only additional observations across a wider time span will yield sufficient information to break the degeneracy and allow the model to be directly tested.

3.2. Analysis of the ASCA X-Ray Spectrum

Each epoch’s spectrum was fitted using simple, absorbed models (bremsstrahlung, power law, and emission from a hot, diffuse gas; Table 7). Within the errors, the model fits were identical for the two epochs regardless of the model. Figure 3a shows the 1995 November spectrum and Figure 3b shows the fitted contours both for the hot gas model. We present the spectral fit using the model with a thawed abundance to show the range of the parameters and the degeneracy of the model. The fitted 1993 spectrum in Petre et al. (1994b) fixed the abundance at 1.0; when we use the same fixed abundance for the 1995 spectrum, we obtain the same fitted temperature as did Petre et al. The corresponding figure for the first epoch appears nearly identical (Petre et al. 1994b). No one model provided a significantly better fit than the others. We integrated the model spectra across
several bands (0.5–2.0, 2.0–3.0, 3.0–4.0, 4.0–5.0, and 5.0–9.0 keV) to obtain fluxes in each band for each epoch. The fluxes are also consistent with each other within the errors. No lines were detected in either epoch. The unabsorbed 0.5–2.0 keV flux is $\sim 1.3 \times 10^{-12} \text{ ergs s}^{-1} \text{ cm}^{-2}$, which corresponds to a luminosity of $\sim 3 \times 10^{39} \text{ ergs s}^{-1}$. This flux lies within 10%–20% of the mean flux obtained with ROSAT, depending upon the adopted model for the X-ray spectra.

The luminosities of the ASCA (1–10 keV) and ROSAT (0.1–2.4 keV) bands provide an estimate of the shock temperature (FLC96) via $L_{\text{ASCA}}/L_{\text{ROSAT}} \sim 2.4 e^{-7.9 \times 10^{7}/T}$. Our luminosities yield $T_e \sim 6 \times 10^9$ K. This is the temperature of the reverse shock, where soft X-rays are expected to be produced (ChevFran).

### 3.3. HST FOS Spectrum

As expected for a nebular object, we do not see a continuum in the HST spectra. The pointing history makes the UV spectra (Figs. 5 and 6) difficult to interpret. At the distance of NGC 1313, 1" is about 22 pc, so we are sampling relatively widely spaced regions with the FOS spectra.

The Mg II 2800 Å line is a good starting point because the line is the easiest to interpret. It is visible in the on-source spectrum and not to the northwest. This is a clear detection of SN 1978K. The Mg II $\sim 2800$ Å is a doublet with components at 2795 and 2803 Å. We fitted the lines with double Gaussians and constrained the FWHM to be identical for the two components. The results of the fits are shown in Table 8. The fitted FWHM corresponds to the instrumental resolution, so the lines are unresolved. We derive velocities for the gas of 632 and 640 km s$^{-1}$, respectively. With errors on the line centers from the Gaussian fits of order 10–15 km s$^{-1}$, the two line velocities are identical. The redshift for SN
1978K, taking into account the rotation velocity of NGC 1313 at the position of the supernova, is 439 km s\(^{-1}\) (Paper I); the lines have intrinsic velocities of about 200 km s\(^{-1}\).

The Ly\(\alpha\) and [Ne iv] lines are detected in the northwest and southwest pointings. We need not discuss Ly\(\alpha\) because it is emitted by nearly every source in the sky. The [Ne iv] line is not observed in the on-source pointing. It must arise from a location farther from SN 1978K than the projected aperture size. The FOS aperture is about 0.15 in radius, which corresponds to about 3.3 pc at NGC 1313. The northwest and southwest pointings lie at projected spatial distances of approximately 28 pc and approximately 50 pc from SN 1978K. While the gas velocities of the [Ne iv] lines are larger (by a factor of two) than the velocities measured from the optical and Mg ii (UV) emission lines, the projected distances are far larger than the distance any ejecta of SN

### TABLE 5

**Optical Line Fluxes and Upper Limits**

| \(\lambda\) (Å) | \(\lambda_o\) (Å) | ID | Flux \((H\beta = 100)\) | Velocity \((\text{km s}^{-1})\) |
|----------------|------------------|----|----------------------|-----------------------------|
| 3636.1 ± 0.5……  | 3628.6           | [Fe ii] | 27 ± 3               | 620 ± 40 |
| 3871.1 ± 1.1……  | 3868.7           | [Ne iii] | 12 ± 2               | 263 ± 80 |
| 3892.7 ± 0.3……  | 3889.0           | He i, H\(\gamma\) | 41 ± 1               | 285 ± 25 |
| 3973.3 ± 0.2……  | 3970.1           | He i, [Ne iii] | 28 ± 3               | 241 ± 20 |
| 4033.0 ± 4.0……  | 4026.2           | He i | 7 ± 1               | 500 ± 300 |
| 4074.2 ± 1.0……  | 4068.6           | [S iii] | 21 ± 2               | 410 ± 70 |
| 4106.2 ± 0.2……  | 4101.7           | H\(\beta\) | 35 ± 5               | 330 ± 15 |
| 4248.4 ± 2.0……  | 4244.0           | [Fe ii] | 13 ± 2               | 310 ± 140 |
| 4290.5 ± 2.0……  | 4287.4           | [Fe ii] | 19 ± 1               | 220 ± 140 |
| 4325.1 ± 1.0……  | 4319.6           | [Fe ii] | 5 ± 2               | 380 ± 70 |
| 4345.5 ± 0.3……  | 4340.5           | H\(\gamma\) | 53 ± 2               | 345 ± 20 |
| 4363.4 ± 0.6……  | …                | [O iii], [Fe ii] | 16 ± 1               | … |
| 4421.1 ± 2.0……  | 4415.0           | [Fe ii] | 12 ± 1               | 415 ± 135 |
| 4579.2 ± 0.4……  | 4571.2           | Mg i | 9 ± 6               | 460 ± 30 |
| 4691.6 ± 0.4……  | 4685.7           | He ii | 7 ± 3               | 380 ± 30 |
| 4867.2 ± 0.2……  | 4861.3           | H\(\beta\) | 100\(^b\)          | 365 ± 15 |
| 4965.5 ± 0.3……  | 4958.9           | [O iii] | 14 ± 6               | 400 ± 20 |
| 5013.0 ± 0.3……  | 5006.9           | [O iii] | 23 ± 3               | 380 ± 20 |
| 5165.1 ± 1.0……  | 5158.8           | [Fe ii] | 19 ± 5               | 390 ± 60 |
| 5758.1 ± 1.5……  | 5754.6           | [N iii] | 9 ± 1               | 290 ± 80 |
| 5882.0 ± 0.6……  | 5875.7           | He i | 20 ± 4               | 320 ± 30 |
| 6036.6 ± 1.5……  | 6300.3           | [O i] | 23 ± 5               | 300 ± 70 |
| 6369.2 ± 3.5……  | 6363.8           | [O i] | 8 ± 2               | 260 ± 165 |
| 6569.0 ± 0.2……  | 6562.8           | H\(\alpha\) | 276 ± 10             | 285 ± 10 |
| 6589.3 ± 0.4……  | 6583.4           | [N ii] | 26 ± 2               | 270 ± 20 |

\(^a\) From October 1996 (age ~ 6714 days) AAT spectrophotometry.

\(^b\) The flux of H\(\beta\) is ~ 2.0 \(\times\) 10\(^{-14}\) ergs s\(^{-1}\) cm\(^{-2}\) to within 10%.

### TABLE 6

**New Radio Fluxes (MJy) for SN 1978K from ATCA and MOST Monitoring**

| UT Date | MJD | Approx. Age\(^a\) | L  | S  | C  | X  | MOST |
|---------|-----|------------------|----|----|----|----|------|
| 1992 Jul 2 ……. | 48,805 | 5155 | 139.7 ± 1.2 | 111.4 ± 1.6 | 67.1 ± 0.3 | 43.2 ± 0.4 | … |
| 1993 Feb 8 ……. | 49,026 | 5376 | 140.7 ± 4.5 | 104.2 ± 3.2 | 61.6 ± 0.6 | 38.7 ± 0.4 | … |
| 1993 Oct 24 ….. | 49,284 | 5634 | 129.0 ± 2.1 | 97.4 ± 1.0 | 58.4 ± 0.5 | 37.8 ± 0.7 | … |
| 1994 Oct 2 …….. | 49,627 | 5977 | 118.0 ± 4.3 | 86.6 ± 1.8 | 52.7 ± 0.5 | 33.2 ± 0.5 | … |
| 1995 Sep 9 ……. | 49,969 | 6319 | 105.5 ± 1.9 | 82.5 ± 1.2 | 48.7 ± 0.4 | 31.7 ± 0.3 | … |
| 1995 Nov 8 …….. | 50,029 | 6379 | … | … | … | … | 113 ± 8 |
| 1996 Feb 8 ……. | 50,121 | 6471 | 120.5 ± 6.5 | 81.5 ± 3.7 | 46.4 ± 1.5 | 30.5 ± 0.4 | … |
| 1996 Apr 10 …… | 50,183 | 6533 | 109.2 ± 1.3 | 80.3 ± 1.2 | 49.3 ± 0.6 | 37.1 ± 0.4 | … |
| 1996 Oct 30 ……. | 50,386 | 6736 | … | … | … | … | 108 ± 5 |
| 1997 Aug 31 ……. | 50,691 | 7041 | … | … | … | … | 86 ± 3 |
| 1998 Aug 25 ……. | 51,050 | 7400 | 88.1 ± 4.9 | 63.5 ± 1.6 | 37.4 ± 0.6 | 24.5 ± 0.3 | … |

\(^a\) Age based on adopted date of maximum of 1978 May 22 = MJD 43,650.

\(^b\) Central frequencies are 1380, 2370, 4790, and 8640 MHz for L, S, C, and X bands, respectively, except for 1998 Aug 25, when the central S-band frequency was 2496 MHz. MOST central frequency is 843 MHz.
1978K could cover in the roughly 20 yr since its detonation. This is particularly critical given that the supernova is supposed to be evolving in a dense circumstellar medium, which means that the ejecta are rapidly decelerated (e.g., Terlevich et al. 1992, hereafter Ter92). If we assume that the X-ray flux has illuminated the surrounding volume for the entire lifetime of SN 1978K, the volume's radius is about 20 pc. The [Ne iv] is produced outside of this volume and either must be located in the preshock medium or is unrelated to SN 1978K. If the [Ne iv] matter moved at its measured velocity, it would cover the roughly 30–50 pc in about 42–70 Kyr, which is entirely consistent with durations of mass-loss phases in massive stars (e.g., Schröder, Winters, & Sedlmayr 1998).

The UV line fluxes to the northwest, the only position for which we have spectra at both observation epochs, are constant within the errors across the 2 yr gap. This is expected if these lines originate outside of the shocked material.

We also include in Table 9 upper limits on ultraviolet lines that are typically found in other SNR and H ii regions and have been predicted by models (e.g., Ter92; ChevFran). These upper limits were estimated by fitting a Gaussian to noise spikes at the location of the expected emission line and were dereddened using the adopted two values above.

### 3.4. Optical Light Curve and Optical Spectrum

The optical light curve (Fig. 7) shows the predicted behavior of the interaction model of ChevFran assuming an explosion date near 1978 June 1. If the slight rise in the optical magnitudes continues, it will increasingly be at odds with the prediction (i.e., decline) of this model. The increase can not be attributed to a simple increase in emitting area because the necessary expansion velocity, roughly 2000 km s⁻¹, is not supported by the observations. Figure 7 also shows the predicted −11.7 (leading shock) and −8.7 (material behind shock) decays from Ter92; their eqs. [5]

### TABLE 7

**Model Fits to ASCA Spectra**

| Label          | INDEX OR TEMP (keV)* | N_H⁺ (10¹⁹ cm⁻²) | UNABSORBED FLUXb 0.5–2.0 keV | 2.0–10.0 keV | χ²/dof |
|----------------|----------------------|------------------|-------------------------------|-------------|--------|
| 1993 July 12–13: |                      |                  |                               |             |        |
| Power .......... | 3.06 0.74           | 0.28 0.15        | 1.4(−12)                      | 3.7(−13)    | 45.1/41|
| Brems .......... | 1.27 0.41           | 0.14 0.07        | 8.0(−13)                      | 2.7(−13)    | 44.0/41|
| Mekal-frozen   | 0.68 0.03           | 0.76 0.12        | ...                           | ...         | 42.3/41|
| Mekal-thaw     | 0.83 0.00           | 0.25 0.13        | 1.1(−12)                      | 1.4(−13)    | 39.2/39|
| 1995 November 29–30: |              |                  |                               |             |        |
| Power .......... | 2.81 0.35           | 0.26 0.07        | 1.4(−12)                      | 4.3(−13)    | 75.1/68|
| Brems .......... | 1.27 0.50           | 0.16 0.03        | 9.2(−13)                      | 2.9(−13)    | 71.3/68|
| Mekal-frozen   | 0.63 0.03           | 0.79 0.07        | ...                           | ...         | 74.2/68|
| Mekal-thaw     | 0.71 0.00           | 0.37 0.20        | 1.6(−12)                      | 1.2(−13)    | 62.9/66|

* Error bars are 1 σ.

### TABLE 8

**Fits to Emission Lines: HST Observation**

| LOCATION* | LINE | λ (Å) | Flux* | DEREDDENED FLUXb | LUMINOSITIESb | REST λ (Å) | RADIAL VELOCITY (km s⁻¹) | FWHM (Å) |
|-----------|------|-------|-------|------------------|---------------|------------|--------------------------|----------|
| NW ……    | Lyα  | 1219.0| 2.2   | 2.4              | 52.0          | 7.4        | 160.0                    | 1215.7   | 830                   | 6.40  |
| NW ……    | [Ne iv] | 2431.6| 0.05  | 0.05             | 0.48          | 0.15       | 1.3                      | 2422.3   | 1150                  | 9.45  |
| SW ……    | Lyα  | 1219.3| 3.6   | 4.0              | 86.0          | 12.0       | 270.0                    | 1215.7   | 890                   | 6.68  |
| SW ……    | [Ne iv] | 2433.2| 0.03  | 0.04             | 0.16          | 0.10       | 0.32                     | 2422.3   | 1350                  | 5.86  |
| NW ……    | Lyα  | 1220.4| 2.4   | 2.7              | 57.0          | 8.4        | 180.0                    | 1215.7   | 1170                  | 4.09  |
| NW ……    | [Ne iv] | 2435.1| 0.03  | 0.04             | 0.29          | 0.10       | 0.96                     | 2422.3   | 1600                  | 11.3  |
| SN ……    | Mg ii | 2801.4| 0.03  | 0.03             | 0.16          | 0.09       | 0.47                     | 2795.5   | 630                   | 3.4*  |
| SN ……    | Mg ii | 2808.7| 0.02  | 0.02             | 0.11          | 0.05       | 0.26                     | 2802.7   | 640                   | 3.4*  |
| SN ……    | He i  | 3190.2| 0.01  | 0.01             | 0.05          | 0.03       | 0.29                     | 3187.7h  | 240                   | 6.2   |

* Location: SN = centered on SN; NW, SW = offset from SN.

b Two values used for because Ryder et al. (1993) found E_k - ν ≈ 0.31, while the 1996 AAT optical spectrum implies that E_k - ν is very low (perhaps as low as the Burstein & Heiles 1984 value of E_k - ν = 0.01).

* Units: 10⁻¹⁶ ergs s⁻¹ cm⁻¹.

* Units: 10⁻¹⁷ ergs s⁻¹.

* FWHM was fit, but constrained to be identical for both lines.

* Assuming the He i identification is correct.
and [6]). The two curves have been arbitrarily normalized to magnitude 16 at 230 days (1 e-folding time). The arbitrary normalization was chosen to show that the 8/7 curve decays too quickly. If the increase in brightness continues, both curves increasingly fail.

The optical spectrum is presented in Figure 8. The most significant change since the 1990 and 1992 spectra presented in Paper I is that the Balmer line ratios indicate that the line-of-sight extinction toward SN 1978K has dropped from $A_\text{B} \approx 2$ mag to virtually zero. Despite using a wide slit in moderate seeing (1.5), it is possible that differential refraction could cause us to lose more of the red light than the blue (the slit was oriented north-south and not at the parallactic angle). Indeed, with a drop in the extinction of 2 mag, we might have expected SN 1978K to have brightened optically in that time, but the optical photometry (Table 4) suggests little or no increase in brightness. We conclude that radiative transfer effects have altered the decrement. Table 10 lists the Balmer line strengths for the 1990, 1992, and 1996 observations, along with values for case A and case B recombination assuming $T = 5000$ K (case A) and $T = 10^4$ K and $N_e = 10^6$ cm$^{-3}$ (case B; Osterbrock 1989). For case A at $T = 10^4$ K, the values are nearly identical to case B.

Extended emission is visible in the spatial direction. About 8.5 north, emission is present in H$\alpha$, H$\beta$, and [O III] 3727 Å. This matches very well with a nearby compact H II region just visible in the plate in Ryder et al. (1993).

The [O III] lines provide an estimate of the temperature $T$ of about $1 - 1.5 \times 10^4$ K (Czyzak, Keyes, & Aller 1986) for $n_e \sim 10^6$ cm$^{-3}$, if we assume all of the 4363 Å emission is [O III]. The estimated temperature changes very little if $n_e$ varies from $10^5$ to $10^7$ cm$^{-3}$.

None of the lines is resolved, which implies that the shock velocity is low; the instrumental resolution is of the order of 10–12 Å, which corresponds to about 500–600 km s$^{-1}$. These values are similar to the velocities in the HST spectrum.

### 3.5. Radio Light-Curve Modeling

With the exception of the 1996 observations, SN 1978K continues to show a fairly uniform decline in radio luminosity over the frequency range 1.4–8.6 GHz, given by

$$S \propto (t - t_0)^\beta,$$

with $\beta = -1.53 \pm 0.13$ and $(t - t_0)$ the number of days since the explosion ($t_0$ assumed to be 1978 May 22 UT, as suggested by MWP).

Several of the radio points deviate from the fitted curve. Although the MOST coverage at 0.843 GHz spans a longer time baseline, observations are less frequent, although there are indications that the rate of decline may be accelerating at the lower frequencies. Observations at the L band near day 5000 (log $t = 3.7$) fall below the fitted curve.

Near the beginning of 1996, the supernova remnant appears to have undergone a brief flare-up in brightness, which shows up first in the L band, then a couple of months later at the higher frequencies, but has since returned to

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### TABLE 9

**Upper Limits to Emission Lines: HST Observations**

| LINE | REST WAVELENGTH | FLUX$^a$ | DEREDDENED FLUX$^b$ |
|------|-----------------|---------|---------------------|
|      |                 | (Upper Limit) | Low | High |
| N V  | 1240            | 5(-16)   | 5.6(-16) | 1.2(-14) |
| O I  | 1304            | 6(-16)   | 6.5(-16) | 9.5(-15) |
| Si IV/O IV | 1400 | 5(-16) | 5.5(-16) | 6.5(-15) |
| C IV | 1550            | 4(-17)   | 4.3(-17) | 4.1(-16) |
| He II | 1640        | 3(-16)   | 3.2(-16) | 2.9(-15) |
| C III | 1909        | 3(-16)   | 3.2(-16) | 3.2(-15) |
| C III | 2324        | 2(-16)   | 2.2(-16) | 1.9(-15) |
| Si II | 2335        | 7(-17)   | 7.6(-17) | 6.6(-16) |
| [O II] | 2470       | 3(-17)   | 3.2(-17) | 2.9(-16) |
| He II | 2733        | 5(-17)   | 5.3(-17) | 3.1(-16) |
| C I  | 2967            | 3(-17)   | 3.2(-17) | 2.0(-16) |

$^a$ Units = Å.

$^b$ Units = ergs s$^{-1}$ cm$^{-2}$; notation defined as $N(\text{XX}) = N \times 10^{-\text{XX}}$.

### TABLE 10

**Comparison of Balmer Decrement in Optical Spectra**

| OBSERVATION DATE | 1990 JAN$^a$ | 1992 MAR$^a$ | 1996 OCT | CASE A$^b$ | CASE B$^c$ |
|-----------------|-------------|-------------|----------|-----------|-----------|
| H$\alpha$/H$\beta$ | 476 ± 54 | ... | 276 ± 10 | 3.10 | 2.81 |
| H$\beta$/H$\beta$ | 100 | 100 | 100 | ... | ... |
| H$\gamma$/H$\beta$ | 38 ± 6 | 46 ± 2 | 53 ± 2 | 0.46 | 0.47 |
| H$\delta$/H$\beta$ | 19 ± 2 | 16 ± 4 | 35 ± 5 | 0.25 | 0.26 |
| H$\epsilon$/H$\beta$ | 16 ± 1 | 12 ± 1 | 28 ± 3 | 0.15 | 0.16 |

$^a$ Ryder et al. 1993.

$^b$ Assumes $T = 5000$ K. For $T = 10,000$ K values are nearly identical to Case B.

$^c$ Assumes $T = 10,000$ K and $N_e = 10^6$ cm$^{-3}$.
close to its normal rate of decline. Unfortunately, only one observation at another bandpass was obtained near this flare: an optical $B$ magnitude, which shows no evidence of a change in the optical light.

The time and spectral evolution of Type II radio supernova has been successfully modeled by Weiler et al. (1986) and Weiler, Panagia, & Sramek (1990) using a variation on the minishell model of Chevalier (1982). MWP attempted to apply this model to the ATCA and MOST data up to 1992 July, but they were unable to fit the data at all five frequencies using just a single value for the radio spectral index $\alpha$. In addition to being attenuated by a uniform absorbing medium of varying optical depth $\tau$ and a clumpy external absorbing medium of varying optical depth $\tau'$, they needed to invoke an extra (time-invariant) absorption, such as might be produced by an H II region along the line of sight to SN 1978K, in order to account for the fact that SN 1978K appears subluminous at late epochs in the low-frequency regime probed by the MOST. Their new model has the form

$$S = K_1 \left( \frac{\nu}{5 \text{ GHz}} \right)^{1/0.76} e^{-(\tau + \tau') \left( \frac{1 - e^{-\tau'}}{\tau'} \right)} \text{mJy},$$

where

$$\tau = K_2 \left( \frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \left( \frac{t - t_0}{1 \text{ day}} \right)^{\delta},$$

$$\tau' = K_3 \left( \frac{\nu}{5 \text{ GHz}} \right)^{-2.1} \left( \frac{t - t_0}{1 \text{ day}} \right)^{\delta'},$$

and

$$\tau'' = K_4 \left( \frac{\nu}{5 \text{ GHz}} \right)^{-2.1}.$$

$K_1$ and $K_2$ are the unabsorbed flux density and the optical depth in the uniform absorbing medium at $\nu = 5$ GHz one day after the explosion, respectively; $K_3$ is the optical depth in a clumpy, nonuniform medium at the same epoch; $K_4$ is the (time-independent) optical depth toward SN 1978K at 5 GHz due to thermal ionized hydrogen; and $\delta$ and $\delta'$ are related to the combination of the frequency and time dependence by $\delta \equiv \alpha - \beta - 3$ and $\delta' \equiv \alpha + 3$ (MWP; Weiler et al. 1990).

We have attempted to apply the model described by eq. (2) to the full ATCA + MOST data set (now covering twice the time baseline available to MWP). We also include here, for the very first time, three prediscovery observations taken from Peters et al. (1994): a 1420 MHz observation with the Two-Element Synthesis Telescope (TEST) in 1981, a 1415 MHz observation with the Fleurs Synthesis Telescope in 1985, and a 8420 MHz observation with the Tidbinbilla 64 m Deep Space Network antenna in 1986. These data allow us to solve simultaneously for all the free parameters in eq. (2), including the $\tau'$ term, which influences the early evolution of the radio supernova but was neglected by MWP owing to insufficient data at early epochs.

Our best-fit model is shown in Figure 10, which has $K_1 = 3.1 \times 10^7$ mJy, $\alpha = -0.76$, $\beta = -1.53$, $K_3 = 6 \times 10^6$, $K_4 = 1.05 \times 10^{11}$, and $K_4 = 1 \times 10^{-2}$. Despite the large number of free parameters in the model, the difficulty in simultaneously fitting the data at all five frequencies in both the early and late phases of evolution is well illustrated in this figure. No combination of parameters can make the L-band model fit both of the early Peters et al. (1994) points and fit the data at late epochs. By balancing the values of mainly $\beta$, $K_1$, and $K_4$, it is possible to arrive at a solution that fits both the TEST and earliest MOST observations (Fig. 10) but which still predicts too much flux in these bands at or just past the maximum. We were able to identify a solution with $\beta = -1.90$, which fits all the MOST points except the last, but then the fit to the very latest points at all other frequencies is also poor. We have explored the range of parameter space that allows acceptable fits to the bulk of the data, and we tabulate the allowable ranges in Table 10.

We show in this same table the parameters arrived at by MWP, as well as comparable models for other Type II SNe from the literature. We find best agreement with MWP on the spectral index $\alpha$ and on the absorption due to the foreground H II region $K_4$. The most significant difference arises from our post-1992 data, which clearly requires a much steeper rate of decline than that suggested by MWP. Consequently, we also require an initial flux density $K_1$ that is as much as 3 orders of magnitude larger, coupled with a similar reduction in initial optical depth $K_2$ from uniform obscuration, if the model is to come close to accounting for the observed evolution over a full decade in frequency and
more than 15 yr in time. Our fit to the new predisscovery data points yields a value for the external, nonuniform absorption $K_\alpha$ that is within the upper bounds established by MWP.

We further conclude, on the basis of the range of allowable model fits, that SN 1978K reached its peak 5 GHz luminosity some 240–300 days later than claimed by MWP (i.e., 940–1000 days after the explosion), and that it was at least 50% more luminous (350–830 mJy). This then brings SN 1978K up into the same peak luminosity range as the highly luminous Type IIn supernovae SN 1986J and SN 1988Z (Table 11). Furthermore, SN 1978K is now showing the same type of very steep decline. With the benefit of the new radio observations at late epochs, together with the inclusion of extra predisscovery data, we must refute the statement of MWP that "SN 1978K was almost certainly a fairly normal Type II supernova" and instead restore it to the class of radio and X-ray luminous Type II supernovae exemplified by SN 1986J and SN 1988Z.

4. DISCUSSION

A detailed picture is emerging for the X-ray luminous supernovae, particularly the SN IIn variety. The supernova explodes into a very dense ($\sim 10^{6–8}$ cm$^{-3}$) circumstellar medium. In such a medium, the evolution of the supernova is accelerated, so the evolving remnant goes directly from the explosive phase to the radiative phase. The pioneering theoretical studies for supernovae exploding in dense media were carried out over the past 25 yr (Chevalier 1974; Wheeler, Mazurek, & Sivaranakrishnan 1980; Shull 1980; Ter92). Ter92 coined the term "compact SNR" because the bulk of the original kinetic energy ($\sim 10^{51}$ ergs) is radiated while the supernova is about $10^{6–7}$ cm in size. The object then radiates large quantities of energy in the X-ray, ultraviolet, and radio bands. The velocities of the emission lines are low ($\lesssim 50$ km s$^{-1}$), representing the extreme deceleration that has occurred.

SN 1978K clearly belongs to this category of behavior. The Mg II lines originate in the ejecta (detected in the on-source pointing), which has been decelerated; the narrow lines widths ($\sim 500–900$ km s$^{-1}$) support this picture. The Ly$\alpha$ and [Ne IV] lines show a larger velocity offset than the Mg II lines, but have similar line velocity widths. These lines may originate in the preshock medium but the inferred separations from the explosion site are very large.

The [O III] lines indicate a high density (Paper I; Chugai et al. 1995), as do the preshock circumstellar lines of [N II] (Chu et al. 1999). The critical densities of the observed lines also provide clues to the number density of the emitting gas. Critical densities range from [Ne IV] $\sim 4 \times 10^4$ to [Ne III] $3869$ A at about $8 \times 10^6$ cm$^{-3}$. Note that no evidence for any emission near 3727 A is present; the critical density for the [O III] line is approximately $5 \times 10^3$ cm$^{-3}$. The lack of detectable emission implies that the number density is not less than about $10^4$ cm$^{-3}$.

The flux ratio of the Mg II lines is approximately 1.8:1. These lines originate in transitions from the levels $3p^2 P_{1/2}$ and $3p^2 P_{3/2}$ to the ground level ($3s^2 S_{1/2}$). The collisional deexcitation rates $q$ are $3.6 \times 10^{-7}$ and $7.3 \times 10^{-7}$ s$^{-1}$, respectively (Pradhan & Peng 1995). The radiative rate $A = 2.6 \times 10^8$ s$^{-1}$ (Morton 1991). Since collisional deexcitation dominates for $\tau_{\text{line}} \gg A/q$, where $\tau$ is the line center optical depth, then $\tau_{\text{line}} \sim 10^{14–15}$ cm$^{-3}$. This density is very high even for a line center optical depth greater than $10^2$. The density in the intercloud wind in the model of Chugai et al. (1995) is approximately $10^6–7$ cm$^{-3}$. The site of the Mg II emission must be in the shocked region. The observed emission lines definitely associated with SN 1978K provide density estimates in the range of $10^4–14$ cm$^{-3}$, indicating that we are sampling a large spatial extent of the region around SN 1978K.

The X-ray and radio luminosities are high (Paper I). MWP argue, based on the classification of radio light curves, that the fitted value of $\beta$ ($-0.9 < \beta < -0.5$) for SN 1978K better matches normal SN II radio behavior than the behavior and $\beta$ values of SN IIn and SN Ib/c ($\beta < -1.1$). Our fit to all of the available radio data now yields a $\beta \lesssim -1.55 \pm 0.35$, placing SN 1978K well into the SN IIn camp. The high inferred radio flux supports this result.

We could only establish a range for the index $n$ from the X-ray light curve ($\sim 4–12$). If we use the radio light curve

| Parameter* | SN 1978K$^b$ | SN 1978K$^c$ | SN 1986J$^d$ | SN 1988Z$^e$ | SN 1993F | SN 1979C$^* | SN 1980K$^b$ |
|------------|-------------|-------------|-------------|-------------|----------|-------------|-------------|
| $K_1$ (mJy) | (0.2–76) $\times 10^7$ | (2.1–38) $\times 10^5$ | (3.8–92) $\times 10^4$ | (6.6–11.5) $\times 10^4$ | (6.18–6.25) $\times 10^4$ | (1.1–1.8) $\times 10^4$ | 81–168 |
| $\beta$ | $-0.77 \pm 0.01$ | $-0.81 \pm 0.73$ | $-0.59 \pm 0.71$ | $-0.69 \pm 0.78$ | $-1.60 \pm 0.67$ | $-0.66 \pm 0.79$ | 0.56–0.67 |
| $\delta$ | $-1.55 \pm 0.35$ | $-1.0 \pm 0.69$ | $-1.16 \pm 1.22$ | $-1.43 \pm 1.47$ | $-0.89 \pm 0.53$ | $-0.76 \pm 0.81$ | 0.78–0.68 |
| $\delta$ | $0.3 \pm 0.3$ | $1.8 \pm 1.6$ | $0.63 \pm 3.0$ | $0.2 \pm 0.75$ | $0.22 \pm 0.35$ | $0.16 \pm 0.35$ | 0.88–0.75 |
| $K_2$ | $-2.2 \pm 0.36$ | $2.92 \pm 1.92$ | $2.69 \pm 2.69$ | $2.2 \pm 2.35$ | $2.15 \pm 1.61$ | $2.85 \pm 3.03$ | 2.12–3.21 |
| $K_3$ | $(0.3–30) \times 10^1$ | $4 \times 10^2$ | $2.1 \times 10^2$ | $4 \times 10^3$ | $4 \times 10^1$ | $1.46 \times 10^3$ | ... |
| $K_4$ | $(9 \pm 1) \times 10^3$ | $(7.6 \pm 1) \times 10^3$ | ... | ... | ... | ... | ... |
| $L_{\nu,51}$ | $(0.9–2.0) \times 10^{28}$ | $6.1 \times 10^{27}$ | $1.7 \times 10^{28}$ | $2.1 \times 10^{28}$ | $1.1 \times 10^{28}$ | $8.8 \times 10^{29}$ | $7.6 \times 10^{28}$ |

* $P_{\text{5GHz}}$ = model peak 5 GHz luminosities: Units are ergs s$^{-1}$ Hz$^{-1}$. Luminosity values for SN 1986J and SN 1988Z are taken from the revised values in MWP.

a This paper.

b MWP.

c Weller et al. 1990.

d Van Dyk et al. 1993.

e Van Dyk et al. 1994.

f Weller et al. 1991.

h Montes et al. 1998.
\[ n = (2m - 3)/(m - 1), \] with \( m = -\delta/3 \), we obtain a similar range: \( 3.4 \leq n \leq 12.6 \). This range is similar to values of \( n \) for SN IIn and SN Ib/c and dissimilar to the \( n > 20 \) values typical of the SN III (Weiler et al. 1996). We also estimate a mass-loss rate of approximately \( 10^{-4} M_{\odot} \text{yr}^{-1} \), using, for example, equation (11) of Montes et al. (1998). This value is only slightly less than the estimate in MWP.

The X-ray flux has remained constant (SPC96; this paper), while the radio flux has declined. SN 1978K’s behavior may be typical of the “IIn” subclass of Type II supernovae (Schlegel 1990; Filippenko 1989), although the timescale for the decline remains to be established. SN 1986J shows a declining X-ray flux (Houck et al. 1998) but has an age approximately equal to that of SN 1978K. SN 1988Z is considerably younger, yet the X-ray and radio fluxes are also declining (Aretxaga et al. 1999). Undoubtedly, the density and extent of the circumstellar medium dictate the subsequent decline timescale. The recent supernova SN 1997ab provides another example (Salamanca et al. 1998) based upon its optical spectra, although radio and X-ray observations have not yet been published.

Two models exist with which to interpret the observations: the shell model (e.g., ChevFran; Ter92) and the cloud model (Chugai et al. 1995). Both models explain the overall observational situation; the differences are in the details. The shell model postulates a uniform presupernova wind with a power-law density distribution \( \rho_{\text{circ}} \sim r^{-s} \), with \( s = 1.5 - 2 \). The supernova ejecta is modeled as a power-law distribution with \( \rho \sim r^{-n} \), with \( n \) in the range of 8–12. The cloud model attempts to reduce the potentially large mass of circumstellar matter the shell model can imply. The cloud model naturally allows radiation to leak out while the shell model may require a flattened geometry plus a scattering atmosphere to permit radiation to escape.

The shell model has been used to make specific predictions for emission lines (ChevFran; Ter92). Figure 11 and Table 12 compare the observed emission lines with those predicted for the shell model by ChevFran and Ter92, which uses the clump model to predict a spectrum for a narrow-line region of an AGN. Figure 11 shows the major lines; Table 12 includes lines for which upper limits have been assigned from the observed spectra. We have also included the “B52” model of Binnette, Dopita, & Tuohy

![Figure 11](image)

**Figure 11.** Comparison of the UV-optical line strengths of SN 1978K with published models. **Top:** Ter92, the compact SNR model for the Narrow Line Region of AGN by Ter92. **Middle:** Radiative shock model B52 (Binnette et al. 1985). **Bottom:** ChevFran, the 17.5 yr model for interacting supernovae from ChevFran. The lines are identified below the bottom plot. The open squares are the observed line strengths; the solid lines connect the model predictions. Any model that did not predict a line strength was assigned an arbitrary value of \( \log \text{strength} = -2.0 \).

| Line          | NLR\(^a\) | CF94\(^b\) | BDT85\(^d\) | 1992\(^e\) | 1996\(^f\) |
|---------------|-----------|------------|-------------|-----------|-----------|
| L\(\alpha \)  | 24.9      | 74.6       | ...         | ...       | 9.90      |
| 2325 C II     | 0.25      | 3.08       | ...         | ...       | <0.03     |
| 2422 [Ne iii]| 0.001     | 0.52       | ...         | ...       | 0.05      |
| 2800 Mg II    | 1.14      | 17.05      | ...         | ...       | 0.05      |
| 3869 [Ne iii]| 1.40      | 1.62       | 0.06        | ...       | 0.15      |
| 4069 [S ii]  | 0.04      | 1.04       | 0.22        | ...       | 0.26      |
| 4363 [O iii]| 0.26      | 0.0        | 0.07        | ...       | 0.18      |
| 4861 H\(\beta\)| 1.0       | 1.0        | 1.0         | 0.41      | 1.0       |
| 4959 + 5007 [O iii]| 22.3 | 13.75 | 1.37 | 0.15 | 0.35 |
| 5876 He i     | 0.10      | 0.0        | 0.09        | 0.06      | 0.16      |
| 6300/6363 [O i]| 0.60     | 2.13       | 0.57        | 0.16      | 0.23      |
| H\(\alpha\)   | 2.75      | 2.98       | 3.0         | 2.90      | 1.98      |
| 6584 [N ii]  | 0.93      | 2.22       | 1.92        | 0.21      | 0.19      |

\(^a\) All values are scaled to dereddened \( H\beta = 1.0 = (5.7 \times 10^{-14} \text{ergs s}^{-1} \text{cm}^{-2}) \).

\(^b\) NLR = narrow-line region prediction of Ter92.

\(^c\) CF94 = ChevFran.

\(^d\) BDT85 = Binnette et al. 1985; model B52.

\(^e\) 1992 observation of Chugai et al. 1995.

\(^f\) HST and AAT data using “high” reddening correction to obtain the most conservative comparison.
(1985). This model uses a shock velocity of 86 km s\(^{-1}\). The approximate match of the model to the dereddened line emission implies that the shock velocity is about 100 km s\(^{-1}\), rather than a high velocity (e.g., 1000 km s\(^{-1}\)) as is typical of young supernovae (e.g., Fesen et al. 1999), so rapid deceleration must have occurred in SN 1978K.

Neither the clump model nor the shell model provide a good description of the observed line emission. Some of the mismatches can be attributed to the large range of densities that must be present in the expanding debris of SN 1978K: from about \(10^4\) (from [Ne \(\text{iv}\)] 2422 Å and [N \(\text{ii}\)] 6583 Å lines) to about \(10^6\) (from the [Ne \(\text{iii}\)] line) to about \(10^{14}\) cm\(^{-3}\) (from the Mg \(\text{ii}\) lines). We also note that the Ter92 model was generated to describe the spectrum shortly after the explosion and not to match a spectrum obtained 20 yr later. The large X-ray flux must also produce emission lines via photoionization.

We can also compare the results from these observations of SN 1978K with recent observations of the Type IIL supernovae SN 1979C and SN 1980K (Fesen et al. 1999). The X-ray and radio luminosities of the IIL supernovae are lower by a factor of 10 or more with respect to SN 1978K. The optical lines are all broad (~1000–6000 km s\(^{-1}\)) in the IIL supernovae. In addition, no emission lines are detected that have critical densities below a few times \(10^5\) cm\(^{-3}\). On the basis of these results, the IIL supernovae are clearly undergoing a different evolution. Fesen et al. conclude that the shell model is in general agreement with the observations of the SN IIL remnants. SN 1978K shows generally poor agreement with the shell model. We may infer that the shell model is most descriptive of the SN IIL objects but not the SN IIn’s.

A recent paper by Aretxaga et al. (1999) presents a spectral energy distribution of the similar SN 1988Z. Figure 12 shows the corresponding distribution for SN 1978K near day 6600. The distribution looks very similar to that of SN 1988Z near day 1600. The bulk of the emission is carried by the X-ray and ultraviolet bands as with SN 1988Z. This suggests that the circumstellar medium surrounding SN 1978K is more dense. If the evolution timescales directly with the density, then the medium surrounding SN 1978K is at least a factor of 4 higher in density. The other conclusions of the SN 1988Z study apply equally well to SN 1978K.

5. CONCLUSIONS

We have followed the evolution of SN 1978K from its discovery in 1992 to the present across the electromagnetic spectrum. SN 1978K’s evolution can be summarized briefly: the X-ray flux is constant, the optical flux is constant or rising slightly, and the radio flux is declining. The constancy of the X-ray flux cannot continue, particularly if the models of dense or compact supernova are at all correct in predicting rapid evolution. We intend to continue our observing program.

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