A SILVER ANNIVERSARY OBSERVATION OF THE X-RAY-LUMINOUS SN 1978K IN NGC 1313

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ABSTRACT

We describe the results of a 2003 Chandra ACIS-I observation of SN 1978K. The spectrum shows little flux below 0.6 keV, in contrast to the 2002 Chandra ACIS-S observation, which showed flux to 0.4 keV. Fitting the ACIS-I spectrum alone leads to two solutions depending on the value of the column density. A joint fit using a dual thermal plasma model applied to the ACIS-I and a contemporaneous XMM-Newton spectrum, which if fit alone also leads to a two-column solution, yields a single column density fit. The fitted temperature of the joint fit for the soft component remains constant within the errors from a previous Chandra, XMM-Newton, and ASCA data. The hard temperature recovers from its 2000–2002 decline and corresponds to an increase in the column density during that time. The hard (2–10 keV) light curve is confirmed to be declining. The derived number density represents a lower limit of $\sim 10^5$ depending on the adopted filling factor of the emitting volume, leading to an estimated mass cooling rate of $\sim 0.1–0.15 M_{\odot} \; yr^{-1}$.

Key words: supernovae: individual (SN 1978K) — X-rays: stars

Online material: color figures

1. INTRODUCTION

The late X-ray emission of supernovae remains relatively unexplored (Schlegel 1995; Immler & Lewin 2003). SN 1987A’s initial emission turned on near day 115 and merged into the background near day 400 postexplosion (Inoue et al. 1991). Recent observations show a reappearance of the emission as the shock propagates into circumstellar matter (Zhekov et al. 2006). Other than SN 1987A, the only supernovae studied beyond $\sim 500$ days have been SN 1978K (Schlegel et al. 2004 and references therein, hereafter S04), SN 1995N (Chandra et al. 2005), SN 1993J (Zimmermann & Aschenbach 2003), and SN 1986J (Temple et al. 2005), plus a few objects recovered at late times (e.g., SN 1979C and SN 1970G; Immler & Kuntz 2005; Immler et al. 2005) that presumably will continue to be studied. Of these, SN 1978K has been the most luminous and hence the most frequently observed.

Although SN 1978K was first detected as a powerful radio source in 1982 (Ryder et al. 1993), it was not realized that it emitted X-rays until an observation was obtained with the ROSAT PSPC in 1992. The subsequent investigation examined archival optical plates, uncovered a light curve, and assigned an explosion date near 1978 May 22 (Ryder et al. 1993). Follow-up observations of SN 1978K in the X-ray, ultraviolet, optical, and radio bands were obtained during the mid and late 1990s with ASCA, the Hubble Space Telescope, the ROSAT High Resolution Imager, the Australia Telescope Compact Array, and the Anglo-Australian Observatory (Schlegel et al. 1999).

S04 described a 2002 Chandra and a 2000 XMM-Newton observation of SN 1978K. The spectra were best fit by a two-temperature, variable-abundance, optically thin gas model with temperatures of 0.6 and $\sim 3$ keV. The authors reported Si emission in the soft component at 90% significance. The flux in the 2–10 keV band showed the first hint of a decline in the X-ray flux from the 1990s plateau.

Since the 2004 paper, additional data have become available. Here we briefly describe a Chandra ACIS-I observation of SN 1978K obtained in 2003 October and an XMM-Newton observation obtained in 2003 November. We first describe the data and the spectral fit, then discuss the results in the context of the previous observations. Throughout we adopt a distance to NGC 1313 of 4.13 $\pm$ 0.11 Mpc (Méndez et al. 2002).

2. DATA AND ANALYSIS

Chandra observed SN 1978K and the other X-ray-emitting sources in NGC 1313 on 2003 October 2 for 14,827 s with the ACIS detector (ObsID 3551, PI: G. Garmire; Garmire et al. 2003). The aim point of the detector fell on the front-illuminated I3 CCD. The aim point on the I3 CCD differs from previous observations that were obtained with the back-illuminated S3 CCD; the effective area behaviors of the two types of CCDs differ. We discuss our approach to this difference below.

We extracted a background light curve and spectrum from a region proximal to the source. This much larger, source-free region was 1.5’ in radius and was positioned immediately west of SN 1978K. We examined the light curve for bright transients or flaring events and did not detect any evidence for either; consequently, the good exposure time was not reduced from 14.8 ks. The net source count rate was $\sim 0.083 \pm 0.002$ counts s$^{-1}$.

We fit the extracted spectra using XSPEC version 12.2.1 (Arnaud 1996); for the background spectrum we adopted a simple power-law continuum with a Gaussian at $\sim 1.8$ keV to model the possible Si fluorescent feature present in the ACIS background (S04).

The source events were extracted and binned to a spectrum using a region at the location of SN 1978K with an aperture of radius $\sim 18.5''$. Although the sharp point-spread function of the Chandra mirrors may cause concern about possible event pileup, the large off-axis angle of 2.6’ and low net count rate ensure that pileup in this case is negligible.

A single spectral bin exists below 0.6 keV, which is consistent with the background; this is in marked contrast to the 2002 spectrum for which source events were detected to $\sim 0.4$ keV. We refer the reader to S04 for a description of a variety of models that did not provide good fits to those data. Our adopted best-fit model is described below and is based on the best-fit model from the 2004 paper.

In S04 we used variable-abundance thermal plasma models (VMEKAL in xspec; Arnaud 1996). In the interim, updated atomic parameters have become available through the APED project (Smith et al. 2003). Along with the database, the project has
developed a new thermal plasma model for xspec (VAPEC) that we have used in fitting the data discussed here.

To fit the 2003 October Chandra spectrum, we may either fit the data without regard to previous fits or constrain the fit assuming little change over the intervening 12 months. This consideration is critical because of the differing spectral responses of the S and I chips. Given the effective area behavior of the ACIS-I3 CCD, the critical parameter to constrain is the column density. Fixing its value at 0.15, the best fit from the 2004 paper, we obtain a fit that differs largely in flux; the soft and hard temperatures are essentially identical (Fig. 1, Table 1; referred to as VAPEC-L, for “low $N_H$”).

If we do not place any constraints on the 2003 spectrum, the fit with the lowest $\chi^2/\nu$ yields a high column, $N_H \sim 0.62_{-0.19}^{+0.18} \times 10^{22}$ cm$^{-2}$, and a low soft temperature of $\sim 0.28$ keV (Table 1; referred to as VAPEC-H, for “high $N_H$”). The hard temperature drops slightly to 2.22 keV, but the error bars cover the value from the dual fit. The anticorrelation between $N_H$ and the soft temperature is expected given that there are few data points below $\sim 0.8$ keV to constrain the parameters separately. We note that the 99% contour includes the values obtained from the 2000 and 2002 data sets. We include both possibilities in our discussion.

The seemingly abrupt change in the $N_H$ parameter could stem solely from the differing behaviors of the effective areas of the I versus S CCDs that differ, particularly at energies below $\sim 0.7$ and above $\sim 4$ keV (Chandra X-Ray Center 2005). Consequently, a spectral fit to the I spectrum could lead to systematic differences from the previous spectrum.

To investigate any possible systematic differences, we extracted a spectrum from an XMM-Newton observation of SN 1978K. The XMM-Newton observation was obtained on 2003 November 25 (ObsID 0150280101, PI: I. Smith) for $\sim 12$ ks. The spectrum was extracted after filtering the data to eliminate times of high background that generally afflict XMM-Newton observations. The extracted net spectrum contains $\sim 600$ counts. The background spectrum was obtained from 1.6$^{+0.5}_{-0.4}$ south of SN 1978K’s location. It was featureless in the area of interest ($\sim 0.5–3$ keV) and represents $< 15\%$ of the source signal.

In fitting the VAPEC model to the XMM-Newton spectrum, we again obtain a dual solution to the soft temperature because of differing values of column density (Fig. 2). Otherwise, the Chandra-only and XMM-Newton-only fits are similar.

To extract the best spectral fit parameters with the least number of constraints, we fit the ACIS-I3 and XMM-Newton data simultaneously. Figure 3 shows the resulting spectral fit; Figure 4 shows the temperature contours. The simultaneous fit yields a lower value for the column density than described in S04 (0.12$^{+0.07}_{-0.05}$ vs. 0.23$^{+0.04}_{-0.03}$ in units of $10^{22}$ cm$^{-2}$), an identical soft temperature (0.64$^{+0.08}_{-0.05}$ vs. 0.61$^{+0.08}_{-0.06}$ keV), and a higher hard temperature (3.36$^{+0.38}_{-0.38}$ vs. 3.16$^{+0.40}_{-0.47}$ keV), although the 90% confidence ranges of the hard temperatures overlap.

Variable models such as VMEKAL and VAPEC permit altering the abundances of elements known to produce emission lines. We investigated elemental abundances because S04 reported Si to be present in the soft spectral component. We started with all elements in the ground that generally afflict ACIS-I3 and ACIS-S only fits are similar.

3. DISCUSSION

We base our discussion on the dual Chandra/XMM-Newton spectral fit because the evidence shows that fitting only one spectrum leads to systematic differences with the prior Chandra ACIS-S.
spectra (S04). The normalization values in the hard and soft components for the 2003 data (Table 1) are nonzero at the 90% level, so it is evident that the two components remain significantly detected, as was true in the 2002 Chandra observation.

To maintain consistency between the 2003 Chandra data and the earlier XMM-Newton, ASCA, and 2002 Chandra data, we also refit the previously published spectra using the dual-component VAPEC model. The fits yielded values very similar to those of the published VMEKAL values. The updated numbers are shown in Table 2 and are included for completeness. Differences between column densities and temperatures were generally within 5% of the values published in S04. The ASCA-1 and ASCA-2 values appeared to differ the most (~10%–20%), likely due to the poor low-energy response.3

We include in Table 3 the fluxes for the Chandra- and XMM-Newton-only model fits, the joint Chandra/XMM-Newton fit, and the refitted spectra from S04. Of particular interest is the soft Chandra component that shows a high column density. The corresponding unabsorbed flux is very high, demonstrating the necessity for care in handling the ACIS-I spectrum.

With a consistent set of model fits, the light curves of the soft and hard components may be constructed. Figure 5 displays the soft (top) and hard (bottom) unabsorbed light curves. Both light curves show a continuing decrease in flux, confirming the decline reported in S04.

Although the 2002 and 2003 data share the dual-component structure, significant differences exist between the two epochs. The results are shown schematically in Figure 6. Note that the

![Fig. 2.—Contour plots of the fitted temperatures for the XMM-Newton 2003 November spectrum illustrating the possible double-valued soft temperature. [See the electronic edition of the Journal for a color version of this figure.]

![Fig. 3.—Best-fit VAPEC model to the Chandra ACIS I3 and XMM-Newton MOS-1 2003 spectra. The background spectra have been suppressed for clarity. The top curve is Chandra; the bottom curve is XMM-Newton. [See the electronic edition of the Journal for a color version of this figure.]](image1)

![Fig. 4.—Contour plots of the fitted temperatures and column densities for the XMM-Newton November and Chandra 2003 spectra. Top, soft component temperature and column density; bottom, hard component temperature and column density. [See the electronic edition of the Journal for a color version of this figure.]

![TABLE 2

APEC FITS TO PREVIOUS CCD-RESOLUTION SPECTRA

| Observation   | Age | N_H | T_soft | T_hard |
|---------------|-----|-----|--------|--------|
| Chandra       | 8910| 0.25±0.02 | 0.63±0.02 | 2.43±0.16 |
| XMM-Newton    | 8184| 0.15±0.01 | 0.71±0.02 | 3.17±0.21 |
| ASCA-2        | 6401| 0.41±0.22 | 0.64±0.09 | 3.19±1.18 |
| ASCA-1        | 5531| 0.11±0.02 | 0.77±0.12 | 3.83±1.80 |

Notes.—Details of the previous observations are listed in S04. Units for the columns are as follows: Age = days; N_H = 10^{22} cm^{-2}; T_soft and T_hard = keV. * Age based on date of optical maximum = 1978 May 22, MJD 43,650.](image2)
values of two of the parameters have been divided by a constant to place the points in the plot.

The soft component $kT$ has held steady within the errors at $0.6 \text{ keV}$. In contrast, the hard component temperature has held steady at $3.2–3.4 \text{ keV}$ with the exception of the day 8910 spectrum, when it dropped to $2.4 \text{ keV}$ at the same time that the column density increased.

The column density varied from $0.15$ to $0.25$ (in units of $10^{22} \text{ cm}^{-2}$) and back. The known column toward NGC 1313 is $3 \times 10^{20} \text{ cm}^{-2}$ (S04). As pointed out in S04, the $E_{B-V}$ value from the optical spectrum is $0.31$, which corresponds to $N_{H} \approx 1.6 \times 10^{21} \text{ cm}^{-2}$, a value matched by the fitted $N_{H}$ for days 5531, 8184, and 9209/9263. The $E_{B-V}$-derived value also matches the

| Observation                  | Age (days) | Band (keV) | Complete | Soft | Hard |
|------------------------------|------------|------------|----------|------|------|
|                              |            |            | Abs.     | Unabs. | Abs. | Unabs. | Abs. | Unabs. |
| Joint Chandra                | 9209       | 0.5–2      | 3.33     | 4.65  | 1.06 | 1.59   | 2.27 | 3.07   |
| + XMM-Newton                 | 9263       | 0.5–2      | 2.35     | 3.34  | 1.13 | 1.70   | 1.61 | 1.92   |
| XMM-Newton only              | 9263       | 0.5–2      | 2.36     | 3.72  | 1.22 | 2.09   | 1.13 | 1.63   |
| Chandra only                 | 9209       | 0.5–2      | 3.29     | 4.86  | 1.56 | 2.28   | 2.24 | 3.00   |
| Low $N_{H}$                  |            |            | 3.58     | 3.64  | 1.10 | 1.11   | 3.51 | 3.56   |
| Chandra only                 | 9209       | 0.5–2      | 3.30     | 27.2  | 2.25 | 23.8   | 1.46 | 3.76   |
| High $N_{H}$                 | 8910       | 0.5–2      | 3.41     | 3.63  | 1.15 | 1.12   | 3.35 | 3.60   |
| 2002 Chandra$^{a}$           | 8910       | 0.5–2      | 4.25     | 6.57  | 2.06 | 3.37   | 2.21 | 3.20   |
| XMM-Newton$^{a}$             | 8184       | 0.5–2      | 4.50     | 7.45  | 2.15 | 3.79   | 2.35 | 3.65   |
| ASCA-2$^{a}$                 | 6401       | 0.5–2      | 6.29     | 16.9  | 4.08 | 11.8   | 3.40 | 6.23   |
| ASCA-1$^{a}$                 | 5531       | 0.5–2      | 4.25     | 5.30  | 1.02 | 1.31   | 3.21 | 3.96   |

Note.—All fluxes are in units of $10^{-13} \text{ ergs s}^{-1} \text{ cm}^{-2}$. The values generally differ by a few percent from those reported in S04. We include the values here to be complete, having redefined the best-fit adopted model from that paper. "Abs." and "Unabs." represent fluxes determined from the model with (Absorbed) and without (Unabsorbed) the column density component.

$^{a}$ Fluxes recalculated for VAPEC model; values should be considered to replace those presented in S04.

values of two of the parameters have been divided by a constant to place the points in the plot.

The soft component $kT$ has held steady within the errors at $\sim 0.6 \text{ keV}$. In contrast, the hard component temperature has held steady at $\sim 3.2–3.4 \text{ keV}$ with the exception of the day 8910 spectrum, when it dropped to $\sim 2.4 \text{ keV}$ at the same time that the column density increased.

The column density varied from $\sim 0.15$ to $0.25$ (in units of $10^{22} \text{ cm}^{-2}$) and back. The known column toward NGC 1313 is $\sim 3.7 \times 10^{20} \text{ cm}^{-2}$ (S04). As pointed out in S04, the $E_{B-V}$ value from the optical spectrum is $0.31$, which corresponds to $N_{H} \sim 1.6 \times 10^{21} \text{ cm}^{-2}$, a value matched by the fitted $N_{H}$ for days 5531, 8184, and 9209/9263. The $E_{B-V}$-derived value also matches the

Fig. 5.—Light curves of soft (top) and hard (bottom) spectral components. The fluxes used in all cases are the unabsorbed values.

Fig. 6.—Schematic plot of the fitted parameter values vs. time, including $N_{H}$, $kT_{\text{soft}}$, $kT_{\text{hard}}$, and Si abundance. The $kT_{\text{hard}}$ and Si abundance values have been divided by a constant to fit them into the range. Several data points have been shifted in age for clarity.
where

\[ T_r \]

although the 2002 data showed an abundance well above solar and suggests the existence of a recent, local density enhancement. The difference between the shock temperature. Assuming that \( n \) and \( s \), of the ejecta and circumstellar matter distribution, respectively (Fransson et al. 1996). The usual adoption of \( s = 2 \) allows us to solve for \( n \) using one of the predictions of the thin shell model (Fransson et al. 1996): \( (T/T_r) = (3 - s^2)/(n - 3) \), where \( T_r \) is the reverse shock temperature and \( T_f \) is the forward shock temperature. Assuming that \( T_r \) is given by \( T_{\text{soft}} \) and \( T_f \) is given by \( T_{\text{hard}} \) \( n \) is calculated as \( 5.29 \pm 0.88 \) for the 2003 Chandra observation. The \( n \) values for the 2002 Chandra, XMM-Newton, ASCA-2, and ASCA-1 observations are 4.96 \pm 0.04, 5.29 \pm 0.10, 7.97 \pm 0.62, and 5.23 \pm 0.83, respectively. The weighted mean value is 5.02. This is a lower value for the power-law index than is generally assumed for mass distributions (typically 8–12; Fransson et al. 1996) but within the errors of other X-ray-emitting supernovae (e.g., SN 1993J; S04). Smaller values of the index lead to longer cooling times, as observed in SN 1978K.

We may infer X-ray properties following the arguments in Schlegel & Petre (2006) that were based on analyses first used by Immler and coworkers (summarized in Immler & Lewin 2003). Thermal plasma emission is given by \( L_X = \Lambda(T)n_e^2V_X \), where \( \Lambda(T) \) is the emissivity, \( n_e \) is the electron density, and \( V_X \) is the emitting volume. Here \( \Lambda \) is \( \sim 10^{-23} \text{ ergs s}^{-1}\text{cm}^{-3} \) for plasmas with temperatures of \( \sim 0.5–10 \text{ keV} \) in the 0.2–5 keV band (Raymond et al. 1976). The quantity \( n_eV_X \) is the volume emission measure. An estimate of the volume then delivers an estimate of the number density from which we may calculate the mass of the cooling gas, \( M_X \) (Table 4).

\[
\begin{align*}
\text{Soft Component} \\
5531 & & 690 & 0.010 & 2.84 & 4.82 & 4.8 \times 10^{-2} & 0.05 \\
6401 & & 620 & 0.011 & 26.11 & 12.66 & 1.3 \times 10^{-1} & 0.17 \\
8184 & & 520 & 0.011 & 8.06 & 7.03 & 7.0 \times 10^{-2} & 0.10 \\
8910 & & 490 & 0.012 & 7.08 & 5.79 & 5.8 \times 10^{-2} & 0.10 \\
9209 & & 480 & 0.012 & 3.33 & 3.97 & 3.9 \times 10^{-2} & 0.07 \\
9263 & & 475 & 0.012 & 3.55 & 4.10 & 4.1 \times 10^{-2} & 0.07 \\
\text{Hard Component} \\
5531 & & 690 & 0.010 & 20.91 & 13.09 & 1.3 \times 10^{-1} & 0.13 \\
6401 & & 620 & 0.011 & 30.25 & 12.66 & 1.4 \times 10^{-1} & 0.18 \\
8184 & & 520 & 0.011 & 14.21 & 9.34 & 9.3 \times 10^{-2} & 0.13 \\
8910 & & 490 & 0.012 & 12.02 & 7.55 & 7.5 \times 10^{-2} & 0.13 \\
9209 & & 480 & 0.012 & 13.52 & 8.00 & 8.0 \times 10^{-2} & 0.14 \\
9263 & & 475 & 0.012 & 7.71 & 6.04 & 6.0 \times 10^{-2} & 0.11 \\
\end{align*}
\]

Table 4 lists the inferred quantities where we also include a volume filling factor, \( \phi \), that describes the emitting matter within the volume enclosed by the shock. The shock volume is estimated from the maximum observed line width of the 1996 optical spectrum (\(~600 \text{ km s}^{-1}\); Schlegel et al. 1999). To estimate velocities for the other epochs, we adopt the velocity profile from SN 1988Z, \( t^{-5/7} \), as described by Aretxaga et al. (1999). We justify the adoption of this velocity profile on the basis of the similar X-ray luminosities and optical spectral line widths. SN 1988Z is the only other supernova with sufficient data at late times, hence our adoption of the velocity profile.

If the plasma uniformly fills the shock volume, the density must be \( >10^9 \text{ cm}^{-3} \). An order of magnitude higher density requires a filling factor smaller by the factor \( 10^{1/2} \). These estimates require the assumption of collisional ionization equilibrium, which occurs if the product \( n_e \tau > 10^{13} \text{ s cm}^{-3} \). Our estimates at the age of SN 1978K exceed that criterion by at least a factor of 20.

If we take at face value the results of the spectral fits, then the column density increased between 2000 and 2003 from \( \sim 1.5 \times 10^{21} \) to \( \sim 2.5 \times 10^{21} \text{ cm}^{-2} \) and back. Is the increase real? The larger effective area of the ACIS-S CCD in the 2002 observation, as well as the longer exposure time, serves to establish that the increase in column density is not an instrumental effect or an artifact of effective area.

Is the increase physically reasonable? The path length during that interval increased by \( \sim 3 \times 10^{15} \text{ cm} \) based on the adopted shock velocity from Table 4. This translates to an increase in the number density from \( \sim (2-4) \times 10^7 \) to \( \sim (7-8) \times 10^7 \text{ cm}^{-3} \), or an increase of a factor of \( 1.7–2 \). This range has been observed in SN 2001ig, where an increase in the radio flux by a factor of \( \sim 3 \) was attributed to an increase in the number density by a factor of \( \sim 2 \) over a time span of \( \sim 150 \text{ days} \) (Ryder et al. 2004). For SN 1978K, the time span could be as long as 400–500 days, assuming the enhancement started immediately after the XMM-Newton observation in 2000 and halted immediately before the Chandra observation of 2003. Hence, we conclude that the increase in column density is physically possible.
That the Si abundance also appears to have increased implies enhanced emission as a shock overran a density enhancement and specifically a Si enhancement. A Si enhancement requires production of Si, which occurs in stars of mass 11–35 $M_\odot$ based on a study of the integrated yield assuming a Salpeter initial mass function (Limongi & Chieffi 2006).

In summary, with the 2003 observation, we now see a higher column density occurring approximately in 2002. The increase in column density can be explained as a local increase in prior mass loss as observed in several X-ray-emitting supernovae (e.g., SN 1979C and SN 2001ig). This behavior argues for increased time sampling of the late phases of X-ray-emitting supernovae. The benefit of such observations is the possibility of insight into the mass loss of massive stars. Will, for example, the flux from SN 1978K increase if the outgoing shock runs over another density enhancement? We also confirm the decrease in the X-ray flux from SN 1978K that started in ~2000–2002 and was first reported in S04, a forlorn epitaph for a silver anniversary.

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