X-Ray and Radio Emission from the Luminous Supernova 2005kd

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ABSTRACT
SN 2005kd is among the most luminous supernovae (SNe) to be discovered at X-ray wavelengths. We have re-analysed all good angular resolution (better than 20″ FWHM PSF) archival X-ray data for SN 2005kd. The data reveal an X-ray light curve that decreases as t$^{-1.62±0.06}$. Our modelling of the data suggests that the early evolution is dominated by emission from the forward shock in a high-density medium. Emission from the radiative reverse shock is absorbed by the cold dense shell formed behind the reverse shock. Our results suggest a progenitor with a mass-loss rate towards the end of its evolution of $\geq 4.3 \times 10^{-4}$M⊙yr$^{-1}$, for a wind velocity of 10 km s$^{-1}$, at $4.0 \times 10^{16}$ cm. This mass-loss rate is too high for most known stars, except perhaps hypergiant stars. A higher wind velocity would lead to a correspondingly higher mass-loss rate. A Luminous Blue Variable star undergoing a giant eruption could potentially fulfill this requirement, but would need a high mass-loss rate lasting for several hundred years, and need to explain the plateau observed in the optical light curve. The latter could perhaps be due to the ejecta expanding in the dense circumstellar material at relatively small radii. These observations are consistent with the fact that Type IIn SNe appear to expand into high density and high mass-loss rate environments, and also suggest rapid variability in the wind mass-loss parameters within at least the last 5000 years of stellar evolution prior to core-collapse.

Key words: circumstellar matter; stars: mass-loss; supernovae: individual: SN 2005kd; stars: winds, outflows; X-rays: individual: SN 2005kd; X-rays: individual: SN 2006jd

1 INTRODUCTION
The core-collapse of a massive star greater than about 8 M⊙ results in a spectacular explosion, and the expansion of a very high velocity shock wave into the ambient medium, leading to the formation of a supernova (SN) of Type II or Type Ib/c. Type II SNe are further divided into different subclasses, depending mainly on their optical spectra or light curve. Type IIn SNe form one of the more recent subclasses of Type II SNe, having been first identified in 1990 (Schlegel 1990). They are characterized by narrow lines on a broad base in the optical spectrum (Schlegel 1994; Kankare et al. 2012; Mauerhan et al. 2013). Surveys have revealed that they comprise between 1 and 4% of the total core collapse SN population in a volume limited sample (Eldridge et al. 2013). Observations at optical (Filippenko 1997; Taddia et al. 2013), infra-red (Fox et al. 2011), X-ray (Dwarkadas et al. 2010; Chandra et al. 2012), and radio (Chandra et al. 2009, 2012) suggest that this class of SNe arises from circumstellar interaction with a high-density medium. Spectropolarimetric observations of luminous IIn stars (Bauer et al. 2012) are consistent with circumstellar interaction, but point to a complex origin for the various emission components.

There exists a wide diversity in SNe that exhibit II objects, which has greatly complicated the task of identifying their progenitors. The prototypical IIn SN 1986J, SN 1988Z, and SN 1978K were only observed years after explosion. More recently transient surveys have found SNe that show II-like features very early in their evolution. Despite over two decades of study, no consensus has been reached on the identity of their progenitor stars, and it seems quite likely that the class of IIn does not have one class of progenitors. Luminous Blue Variable (LBV) stars have been

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suggested as the progenitors of IIns \cite{Gal-Yam2002,Smith2010}, although this has been disputed by some authors \cite{Dwarkadas2011}. Analysis of some IIns led \cite{Dwarkadas2011} to suggest that RSG stars that undergo high mass-loss at the end of their lifetimes could be IIn progenitors, while \cite{Smith2009} have suggested extreme RSGs such as VY CMa as Type IIn progenitors. Thus, although many theories exist, identifying the progenitors will require observations and analysis of a large sample of Type IIns over the entire wavelength spectrum.

Supernova 2005kd was discovered in an automated search by \cite{Puckett2005} on 2005 Nov 12.22 UT. It was confirmed by \cite{Eastman2005} to be a Type IIn SN. It lies in the galaxy LEDA 14370, at a redshift of $z=0.01540$, which translates to a luminosity distance of about $63.2$ Mpc ($H_0=71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\text{matter}} = 0.27$, $\Omega_{\text{vacuum}} = 0.73$). X-ray and UV emission was observed at the position of the SN with Swift in January of 2007 \cite{Immler2007}. Following this, X-ray emission was detected with \textit{Chandra} \cite{Pooley2007}. The SN was also detected in the radio band at 8.4 GHz \cite{Chandra2007}. This is one of the furthest SNe to be detected in X-rays, suggesting an unusually high X-ray luminosity. SN 2005kd was observed in the infra-red by the WISE satellite, however the detection is questionable due to the proximity of the host nucleus \cite{Fox2013a,Fox2013b}.

The optical lightcurve of SN 2005kd \cite{Tsvetkov2008} shows an unusually long plateau stage, unique for a Type IIn SN, which lasted for at least 192 days. The UV lightcurves \cite{Pritchard2011} show an even larger timespan where the flux appears to be either constant or even increasing. Clearly, even for the strange class of Type IIn’s this represents a unique evolution.

In this paper we re-analyse and present all available X-ray data on SN 2005kd, combined with a 29 ks \textit{Chandra} spectrum that we obtained in Nov 2013. We use this data to study the evolution of the X-ray light curve, the nature of the X-ray emission, the density structure of the surrounding medium, and thereby the mass-loss properties of the progenitor star. In §2 we summarize the available data, and describe the X-ray data reduction and fitting methods. §3 presents the X-ray lightcurve of SN 2005kd. In §4 we interpret the lightcurve using semi-analytic calculations, use it to extract information regarding the medium which the SN is expanding in, and attempt to delineate the SN progenitor. Motivated by the results from this section, in §5 we present available radio archival data that we have reduced and analysed in order to improve our understanding of the SN evolution. Finally, §6 summarizes our work, and places this SN in the context of other IIn SNe as well as the complete group of core-collapse SNe.

2 DATA ANALYSIS

SN 2005kd was first detected in the X-ray band around 15 months after explosion, and thus no data exist for the first year of evolution. We have reduced all good angular resolution ($< 20''$ FWHM PSF) data, including data from \textit{Swift}, \textit{Chandra} and \textit{XMM-Newton}. The exposure times in general were short, such that much of the data has low signal-to-noise. Table 1 summarizes the available data and lists the derived fluxes.

The data from each satellite was reduced according to the standard reduction procedures. X-ray spectral fitting was done using SHERPA with thermal XSPEC models. We have presented results using the \textit{vmekal} models, but note that using either \textit{raymond} or \textit{apec} models does not alter the derived conclusions. Given the low number of data counts in all cases except for the \textit{XMM-Newton} pointing, all fits and flux estimations were done by fitting the background first using a polynomial function, and then simultaneously fitting the data plus the background, using the \textit{cstat} statistic on unbinned data. The high statistics of the \textit{XMM-Newton} observation allowed use of the \textit{chi2gehrels} statistic on binned data combined with background subtraction. The flux estimates are shown in Table 1. Below we discuss the data reduction and analysis in detail.

2.1 XMM-Newton

The SN was observed at an age of 500 days using \textit{XMM-Newton}. This is the longest exposure, with by far the best spectral resolution and effective area, and was used as a template for the subsequent data reduction. The $> 600$ source counts allow for a reliable fitting of the spectrum, providing the model template that we adopted to fit all the other spectra. A 25'' region was used for the source, with the background region being of the same size several arcseconds away. The data were appropriately filtered and spectra obtained using version 14 of the \textit{XMM-SAS} software, following standard data reduction procedures. The \textit{Chandra} SHERPA software \cite{Freeman2001} was used for analysis and fitting of all spectra. All the three datasets were fitted simultaneously to ensure the tightest constraints. Figure 1 shows the spectra from the MOS1, MOS2 and PN instruments on board \textit{XMM}, together with a thermal \textit{vmekal} model that was used to jointly fit the three spectra. A Ca line at 4 keV can be seen. The presence of lines indicated that a thermal model was appropriate. In the fits we find that allowing Ca, Ar, and Fe to deviate from solar values allows for the best fit. These elements were allowed to float freely but linked to have the same values in the MOS spectra, with only the normalization varying freely in each case. As can be seen from Figure 1, the best-fit normalization is quite similar for MOS1 and MOS2. In general with all the fits, it is clear that allowing the α-element values to float freely tends to improve the fit. The best-fit abundances in both the MOS and PN fits were found to be higher than solar, with Fe and Ar having enhanced values $> 10$ (in terms of \textit{Anders} \& \textit{Grevesse} 1989) solar values, and Ca showing even larger abundances but with an equally large 1-$\sigma$ variation: $280 \pm 279$. The MOS fits did not change appreciably with S thawed, but the PN fit demanded values of $S > 10$. The best-fit temperature is high, beyond the measurable range of \textit{XMM-Newton}. In each case we have used a single temperature model, which seems to match the spectra well. The best fit column density is found to be $9.4 \pm 0.29 \times 10^{21}$ cm$^{-2}$, consistent with the trend seen earlier. Unabsorbed fluxes are listed in Table 1. The error on the flux was computed using the \textit{Sherpa} \texttt{sample flux} routine, which computes the flux (typically) 1000 times, taking the variations in the parameters into account, and then de-
termines the average flux and 1-σ error from the computed fluxes.

We also attempted to fit a two temperature model to the XMM-Newton data, tying the abundance values of the two components together. The two temperature model results in a very low second temperature component as it tries to mainly fit the low temperature region, giving temperatures around 0.2 keV. It does not change the fit appreciably, but increases the unabsorbed flux considerably, because the high column density results in an unabsorbed flux at low temperatures that significantly exceeds the absorbed flux. We do not consider these models viable, and they do not improve the fit in the high-temperature region. It is possible that allowing the abundance values of each component to vary completely independently of the other may provide a better fit. This also significantly increases the parameter space and fitting time however. Our main purpose in this paper is to get a reasonable fit in order to estimate the flux and luminosity from the SN, and calculate the light curves. We have found that the 1-component fits are adequate for this purpose. The fluxes so obtained are consistent within the error bars with those listed in the XMM-Newton Serendipitous Source Catalogue, 3XMM-DR4, further validating our choice of model and fits. Finally, some of the assumptions inherent to our model, such as ionization equilibrium, are validated in §4.

### 2.2 Swift

SN 2005kd was observed several times between 2007 and 2012 with the Swift X-ray Telescope (XRT), which has a 23′×23′ field-of-view, 18″ FWHM PSF (although the 90% encircled energy diameter is ≳43″ with mild energy dependence), and provides spectra over the 0.3-8.0 keV band with

| Satellite | Obs Date | Days After Outburst | Days After Outburst (Rest Frame) | Exposure (ks) | Count Rate (10⁻³ counts s⁻¹) | N_H (10²² cm⁻²) | kT (keV) | Flux (10⁻¹⁴ erg s⁻¹ cm⁻²) |
|-----------|----------|---------------------|----------------------------------|--------------|-------------------------------|-----------------|--------|--------------------------|
| Swift     | 2007-01-24 | 440                 | 433.5                            | 8.9          | 3.9 ± 0.7                     | 0.4 ± 0.27      | 17 ± 7 | 26⁺⁻ 13                   |
| Chandra   | 2007-03-04 | 479                 | 472.0                            | 3.0          | 22 ± 2.7                      | 0.77 ± 0.17     | > 20   | 49.6⁺⁻ 14                 |
| XMM       | 2007-03-29 | 504                 | 496.5                            | 54.2         | 15 ± 0.7                      | 0.94 ± 0.29     | > 30   | 41.4⁺⁻ 9.4                |
| Chandra   | 2008-01-03 | 784                 | 772.4                            | 5.0          | 17 ± 1.8                      | 0.95 ± 0.49     | 6 ± 0.1 | 44.6⁺⁻ 25.3               |
| Swift     | 2008-08-21 | 1015                | 1000.0                           | 9.3          | 2.2 ± 0.5                     | 0.75⁺⁻ d        | 4.9⁺⁻ 3.3 | 19.86⁺⁻ 1.87               |
| Swift     | 2011-10-22 to 2012-01-05 | 2200 | 2167.4                           | 9.9          | 0.96                          | 0.4⁺⁻ d         | 3.5⁺⁻ 6.7 | 19.86⁺⁻ 1.87               |
| Swift     | 2012-06-01 to 2012-07-16 | 2419 | 2383.0                           | 16.5         | 0.7 ± 0.3                     | 0.15⁺⁻ 0.15     | 4.4⁺⁻ f [75.5] | 3.35⁺⁻ 1.65               |
| Chandra   | 2013-11-29 | 2940                | 2896.5                           | 29.0         | 2.4 ± 0.4                     | 0.43⁺⁻ 0.12     | 3.1⁺⁻ 0.30 | 1.98⁺⁻ 0.36               |

a average value in case of combined exposures
b using cstat statistic (except XMM-Newton)
c average MOS1, MOS2
d assumed
e converges to minimum set value (Galactic value)
f upper bound unconstrained

c 2003 RAS, MNRAS 000.
to get the unabsorbed flux, we used the Chandra PIMMS calculator, assuming an $N_H=4.0\times10^{21}$ cm$^{-2}$ (again based on a decreasing $N_H$ within the 2008 and 2012 values) and a temperature of 3.5 keV (intermediate between neighbouring values). A much lower temperature could increase the flux by about 30-40%, but we think this is a better estimate given the parameters for the other observations closest in time. This gives an unabsorbed flux limit of about $6.7\times10^{-14}$ erg s$^{-1}$ cm$^{-2}$.

By 2012 the column density seems to have dropped to a value approaching the Galactic value, the temperature has decreased, and the flux is lower, as seen in Figure 3.

### 2.3 Chandra

SN 2005kd was observed three times with the ACIS-S instrument on Chandra. Observations of 3 and 5 ks were made in 2007 (ObsID 8518) and 2008 (ObsID 9095), respectively. Even in these short observations, the SN was easily detected with $\sigma > 3\sigma$ significance. After the SN was re-detected by Swift in 2012, we proposed for, and were awarded a 30 ks observation, which was carried out in Nov 2013 (ObsID 15999). The SN is detected with $\sigma > 7\sigma$ significance, thus confirming the Swift re-detection.

The Chandra data were reduced and analyzed using the analysis pipeline in the CIAO software version 4.7, and CALDB 4.6.8. A 4-arcsec source region centered on the point source was used. Our spectra were fitted with a thermal plasma {	exttt{vmekal}} model with a variable temperature and column density. Given the results from the XMM-Newton fitting, we thawed elements Ca and Fe, as well as Si. The C-statistic decreases, and the fit improves, when these elements are thawed. We find abundance values of Fe and Ca similar to those obtained with XMM-Newton, with Ca once again resulting in highly elevated abundance values with large error bars. For ObsID 8518, this gives a flux that is larger than the 2007 Swift value by almost 80%. We note that Pooley et al. (2007) fitted a power-law model to the data, found a column density comparable to the Galactic one and a luminosity about 85% higher than their Swift value, so these results are quite consistent. Our best fit gives a column density 7.7$\pm$1.7$\times10^{21}$ cm$^{-2}$, which is higher than the Galactic column density. The best fit also suggests that the abundance of metals such as Fe and Ca exceeds the solar value.

SN 2005kd was observed again by Chandra 10 months later. The same thermal model was used as for the prior Chandra dataset. We find the column density is 9.5$\pm$4.9$\times10^{21}$ cm$^{-2}$, an elevated Ca abundance exceeding solar, and temperature of $\sim$ 6 keV.

Finally, SN 2005kd was observed using ACIS-S on Chandra in Nov 2013. As mentioned before, the SN was detected with a high significance, confirming its reappearance since 2011. The best fit thermal model gives a $kT=1.47\pm0.39$ keV, and $N_H=4.3\pm1.11\times10^{21}$ cm$^{-2}$, with a preference for an elevated Si abundance. The column density is somewhat higher than the Swift 2012 value. The temperature is slowly decreasing as expected, since the higher temperatures in the first 500 days.
X-ray wavelengths, unless the kinetic energy substantially
spectral modelling. This means that the SN radiated more
be much larger given the high temperatures inferred from
indicated a decreasing luminosity with time. If we assume,
10
4 decade, or the total kinetic energy exceeds the canonical
lightcurve that decreases as
as is generally the case, that the light curve decays as a
indicates a decreasing luminosity with time. If we assume,
4 ANALYSIS AND INTERPRETATION

Figure 3 (top panel) shows the complete X-ray lightcurve

Figure 2. Images from the Swift observations of SN 2005kd, in the 0.3-8 keV energy range. From left to right: 2007, 2008, 2011 and
2012. The region is 11.5′ on each side. The pink circle (35′′ in radius) denotes the region used to extract the data for SN 2005kd. The
annulus used for the background region is shown in blue in the 2011 panel. Clearly, the SN is not detected in 2011, but it is detected in
all the other frames.

3 X-RAY LIGHTCURVE

Figure 3 (top panel) shows the complete X-ray lightcurve of SN 2005kd calculated using background fitting. The data
are converted to the rest frame epoch, and k-corrected unabsorbed flux is plotted. The fluxes are calculated as indicated
above, with 1-σ error bars. Subsequent to the 2008 Swift observation, for over a 1000 days, there were no X-ray observations of SN 2005kd. We have combined exposures from Oct 2011 to Jan 2012 to get a combined almost 10 ks exposure with Swift. The SN is not detected at all within this exposure. However it is in the next two exposures, with Swift and Chandra.

SN 2005kd represents one of the most X-ray luminous Type IIns. Figure 3 shows the lightcurve of other observed Type IIn SNe. The X-ray lightcurve of SN 2005kd is shown as a thick black line. The upper limit from the Swift 2011 observation is not shown. It is clear that SN 2005kd is one of the most luminous, even among Type IIn SNe, with a luminosity exceeding 10^{49} ergs s^{-1} over a period of about 550 days starting from day 440. The total energy deposition, in the 0.3-8 keV X-ray band alone, from days 400 to about 3000 is > 10^{51} ergs. The total energy in X-rays is likely to be much larger given the high temperatures inferred from spectral modelling. This means that the SN radiated more than 1% of its kinetic energy within the first 3000 days at X-ray wavelengths, unless the kinetic energy substantially exceeds 10^{51} ergs. Tsvetkov (2008) had calculated a lower limit to the energy radiated at optical wavelengths, finding it to be 3.2 × 10^{50} ergs in the first 500 days. Either the SN is radiating away a large fraction of its energy in its first decade, or the total kinetic energy exceeds the canonical 10^{51} ergs by a substantial margin.

4 ANALYSIS AND INTERPRETATION

The overall lightcurve of SN 2005kd from 440 to 3000 days indicates a decreasing luminosity with time. If we assume, as is generally the case, that the light curve decays as a power-law in time, the best fit to the data points gives a lightcurve that decreases as t^{-1.62±0.06} (Figure 3). The temperature suggested by the first 4 epochs is higher than the range of values that can be measured by Chandra, XMM-Newton and Swift, and is thus relatively unconstrained. The column density is higher than the Galactic N_H towards that direction (1.5 ×10^{21} cm^{-2}) by a factor of 3-10, and appears to slowly decrease over time within the (large) error bars. At ~ 1000 days, the best fit spectral model suggests a lower temperature and higher column density, but plotting the 2D confidence contours of temperature vs. column density indicates that it is also compatible with the previous observations of a high temperature and N_H around 5 times the Galactic value.

The time evolution of the luminosity can be related to the density structure of the surrounding medium, as shown in Fransson et al. (1996) and Dwarkadas & Gruszko (2012). To summarize, if we use the Chevalier (1982) description for a SN shock wave evolving in a self-similar manner, assuming spherical symmetry, the SN ejecta has a density that goes as ρ_{SN} ∝ v^{-n} t^{-3}, and the uniform circumstellar medium into which the SN evolves has a density profile that decreases as ρ_{CSM} ∝ r^{-s}, then the X-ray luminosity of the SN will decrease as

$$L_x ∝ t^{-(12 - 7s + 2ns - 3n)/(n - s)}$$ (1)

or

$$L_x ∝ t^{-(6 - 5s + 2ns - 3n)/(n - s)} E << kT_{sh}.$$ (2)

Equation 1 is valid when one is considering the total X-ray emission, equation 2 when one is considering the emission in an energy band E where E << kT_{sh}, and T_{sh} is the shock temperature. Neither is an exact fit to this situation; the latter is probably a better approximation over the first several hundred days, the former over the later period, but the resulting values are not significantly different using either equation. If we consider a luminosity decreasing as t^{-1.62±0.06}, we find that s varies between 2.3-2.46 for n = 9 − 12. Given the variation in parameters, we assume s = 2.4 ± 0.1 in our analysis. This range of s indicates that the density decreases marginally faster than r^{-2}, which would be the case for a wind with constant mass-loss rate and wind velocity. We note from figure 3 that this steeper decrease is not uncharacteristic of Type II SNe at this age; in fact many IIns appear to show a similar steep decrease in the lightcurves.
In order to calculate the mass-loss rate, we follow the procedure outlined in Fransson et al. (1996). Given the high temperature of the emission over most of the first 1000 days, we assume that it arises from the forward shocked circumstellar medium, and we do not see any emission from the reverse shocked ejecta (this is addressed later). We will calculate the quantity \( \dot{M}_{\text{f}} \) at a specific temperature, it is not modified by line emission, spectral luminosity at 1 keV. Since it is a spectral luminosity, we use the XMM-Newton observation given it has the best statistics. Following Fransson et al. (1996), we use the spectral luminosity at 1 keV. Since it is a spectral luminosity at a specific temperature, it is not modified by line emission, unless the line emission is present exactly at this frequency, which is not the case. We write the luminosity of the forward (circumstellar) shock as \( L_{\text{cs}} \sim j_{\text{ff}}(T_{\text{cs}})M_{\text{cs}}\rho_{\text{cs}}/m_{\text{H}}^2 \), where \( j_{\text{ff}} \rho_{\text{cs}}/m_{\text{H}}^2 \) is the emissivity per unit mass, \( \rho_{\text{cs}} \) is the density behind the forward shock, \( M_{\text{cs}} \) is the mass swept-up by the forward shock, and \( T_{\text{cs}} \) is the temperature behind the forward shock. The Gaunt factor \( g_{\text{ff}} \) at 1 keV can be written as \( g_{\text{ff}} = 1.87 T_{\text{cs}}^{1.264} \), where \( T_{\text{cs}} \) is the temperature of the forward shock in terms of 10^8 K. This approximation does not deviate by more than 30% from more accurately tabulated values at each temperature, as long as the energy \( E < 15 \text{ keV} \), but may not be as appropriate for higher energies Margon (1973). Using this value of \( g_{\text{ff}} \), we can write the luminosity of the forward shock at 1 keV as:

\[
L_{\text{cs, 1 keV}} = 1.4 \times 10^{38} \xi T_{\text{cs}}^{-0.236} e^{-0.116/T_{\text{cs}}} \left( \frac{M_{\text{f}}}{v_{\text{w}}^{-1}} \right)^2 \frac{\dot{M}_{\text{f}}}{v_{\text{w}}^{-1}} \left( \frac{t_d}{11.57} \right)^{3-2s} \text{ergs s}^{-1} \text{ keV}^{-1} .
\]  

where \( \dot{M}_{\text{f}} \) is the mass-loss rate scaled to \( 10^{-5} M_{\odot} \text{ yr}^{-1} \), \( v_{\text{w}} \) is the wind velocity in terms of 10 km s^{-1}, \( V_{4} \) is the maximum ejecta velocity scaled to \( 10^4 \text{ km s}^{-1} \), \( \xi = [1 + 2n(\text{He})/n(H)]/[1 + 4n(\text{He})/n(H)] \approx 0.85 \), and \( t_d \) is the time in days. We note that this expression has different approximations from the previous ones, and is independent of \( n \). For \( s = 2.4 \) it gives a flux decreasing as \( t^{-1.8} \). It is close enough given the other uncertainties.

At 500 days, the average XMM flux at 1 keV is 6.53 ± 2.12 × 10^{-14} ergs cm^{-2} keV^{-1}. Using a distance of 63.2 Mpc, and inserting in equation 3 with values of \( 0.6 < V_{4} < 0.9, 6 \leq T_{\text{cs}} < 9, \text{ and } 2.3 < s < 2.5 \) in equation 3 gives

\[
192 \leq \left( \frac{\dot{M}_{\text{f}}}{v_{\text{w}}^{-1}} \right) \leq 656 .
\]

Therefore we deduce that, for a wind velocity of 10 km s^{-1}, the mass-loss rate must be around \( (1.9-6.6) \times 10^{-3} M_{\odot} \text{ yr}^{-1} \) at \( 10^{15} \text{ cm} \). If the wind velocity is higher, the mass-loss rate is correspondingly higher. It is difficult to find a progenitor that satisfies the velocity, mass-loss rate and light-curve characteristics (discussed in further detail in §). We emphasize that the mass-loss rate is a time-varying quantity. However, it is clear that the ambient medium around the SN has a high density.

As described in §, we have assumed thermal models to describe the SN, which are in ionization equilibrium. We can now go back and confirm if that approximation is reasonable. We note that we have calculated the mass-loss rate and wind velocity at \( 10^{15} \text{ cm} \); thus the electron density at \( 10^{15} \text{ cm} \) is:

\[
\text{Figure 4.} \text{ The lightcurves of observed Type IIn X-ray SNe that have multiple exposures. For information on the data for each SN, the X-ray fluxes, and the bands referenced for each SN, refer to Dwarkadas & Gruszko (2012), from which this figure has been adapted, with several additions. SN 2005kl is shown with a thick black line. It’s X-ray luminosity is high even among IIn SNe, which in general have the highest luminosities of all X-ray detected SNe.}
\]
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\[ s = 2.5 \]

The density is somewhat lower, but still gives values > \(10^{12}\) cm\(^{-3}\) s, whereas for \(s = 2.3\) the density is higher. In all cases we may conclude that the plasma is in ionization equilibrium at all times during which the observations were taken. A lower velocity will give a smaller radius and higher density so it will further reinforce this argument. Thus we can justify our use of models for plasma in ionization equilibrium.

Why do we not see (low-temperature) emission from the reverse shock, given that the temperature behind this shock is lower, and more likely to fall in the range of Swift, XMM-Newton and Chandra? Presumably it is because most of the emission from the reverse shock is absorbed. This is possible if the reverse shock is radiative and a cool dense shell has formed behind it, which absorbs the emission from the shock. The cooling time from the reverse shock can be written as:

\[
t_{\text{cool},r} = 3.5 \times 10^9 \frac{(4-s)(3-s)^{4.34}}{(n-3)(n-4)(n-s)^{3.34}} \left( \frac{V_s}{10^4} \right)^{1-s} \left( \frac{t_d}{11.57} \right)^{s} \text{s}.
\]  

For \(2.3 < s < 2.5\), \(9 < n < 12\), and \(V_s < 1\) we find that the reverse shock is radiative throughout the evolution, for the derived values of \(\frac{M_{\text{ion}}}{\dot{M}}\). Thus our initial assumption of the emission arising from the forward shock is validated. For large values of \(n\), the cooling time goes as \(n^{-3.4}\) and thus is strongly dependent on the value of \(n\). The shock will be radiative for any larger value of \(n\).

Within the error bars, we find that the column density is \(3\times10^{21}\) cm\(^{-2}\), and decreases slowly over the first 1000 days. This suggests that there is some extra absorbing column density ahead of the forward shock too. Assuming the ambient density extends outwards continually with the same slope, the column density ahead of the circumstellar shock can be written as

\[
N(H)_{\text{cs}} = 2.1 \times 10^{22} \left( \frac{\dot{M}}{\dot{M}_{\text{ion}}} \right) \left( \frac{M_{\text{ion}}}{\dot{M}} \right)^{1-s} \left( \frac{V_s}{8.9} \right)^{s} \text{cm}^{-2}.
\]  

We note that this is the additional column that must be added to the value of the Galactic column density. For parameters between \(\frac{M_{\text{ion}}}{\dot{M}}\) = 192 - 656, 0.6 < \(V_s\) < 0.9, \(s = 2.3 - 2.5\) and \(t_d < 1000\), this value starts off as a few to several times larger than the measured column of \(\sim 3 \times 10^{21}\), and then slowly decreases, with the decrease being larger for higher values of \(s\) as expected from equation \(\text{(7)}\). For values of \(s = 2.4-2.5\) and the lower end of the mass-loss rate, the column density is generally less than the Galactic column by about 3000 days, and does not contribute much. For \(s = 2.3\), the value is still larger than Galactic even at day 3000. For the top end of the mass-loss rate range, the values are quite high, especially for \(s = 2.3\) and low \(V_s\). The highest mass-loss rates are less likely, since we do not see such a large observed column, unless the medium is almost fully ionized (which is not the case as we show below). This implies that higher values of \(s\), combined with mass-loss rates at the lower end of their appropriate range for high \(s\), are more probable.

The timescale for recombination is \(\sim 3 \times 10^{12}/n_e\) s. Using \(n_e\) from equation \(\text{(7)}\) we see that the circumstellar ma-
terial ionized by the progenitor star would have already re-
combined by the time the shock wave reaches it (see also
Dwarkadas 2014). Hence the main mechanism for ionization
of the medium is the X-ray emission itself, which depends
on the ionization parameter $\chi = L/nr^2$ (Kallman & McCray
1982). This can be written as:

$$\chi = 2 \times 10^{-38} L \xi^{-2} \left( \frac{M}{v_{w1}} \right)^{-1} v_4^{s-2} \left[ \frac{t_4}{8.9} \right]^{s-2}. \quad (8)$$

Note that for $s = 2$, this becomes independent of time
(if $L$ is not time dependent), as expected. For the luminosities
of 2005kd, and the high densities, the value of $\chi$ should be
less than 100 throughout most if not all of the evolu-
tion. For high temperatures outside the range probed by
Chandra and XMM-Newton, e.g. $T_0 \sim 10^5$, Chevalier & Irwin
(2012) find that elements such as C, N, and O are only ion-
ized when $\chi \sim 500$. This indicates that even the elements
like C, N, and O are not fully ionized in the high tempera-
ture plasma. Heavier elements such as Fe are only ionized at
$\chi \sim 5000$ (Chevalier & Irwin 2012). Overall the ionization
factor is very low, which suggests that the medium is mainly
neutral, and we are seeing almost the entire column that is
present. The combination of equations 4 and 8 indicates a
preference for higher values of $s$, which give higher ioniza-
tion parameter and lower column, that is more consistent
with the data.

5 RADIO EMISSION FROM 2005KD

In an attempt to further constrain the evolution, we have
investigated the radio emission from the SN. We have ana-
yzed SN 2005kd radio data at three different bands obtained
with the Very Large Array (VLA). Data reduction was done
following standard procedures using the NRAO Astronomi-
cal Image Processing System (AIPS) for data taken in 2009
and earlier. For data taken after the VLA upgrade completion,
we used the Common Astronomy Software Applications
package (CASA, McMullin et al. 2007).

We used natural weighting in the imaging process of all
the epochs to increase their sensitivity. Additionally there
were observations at 22 GHz made in November 2005 and
August 2007, but no detections were obtained. We do not
discuss the emission at this frequency further since the limits
provide no additional constraints.

The observations included here were made using 0410+769 as a phase calibrator. To test the reliability of the SN flux density variations, we made maps of the phase
calibrator and measured a peak intensity of $\sim 2.7\;\mathrm{Jy/beam}$ for all the 4.5 GHz observations, and $\sim 1.8\;\mathrm{Jy/beam}$ at 8.5 GHz. At 4.5 GHz there is also a visible source at about
1.2' West from SN 2005kd. This source has a flux density
$\sim 1\;\mathrm{mJy/beam}$ in all those epochs. Thus, we consider the
flux densities shown in Table 2 as highly robust measurements.
The upper limits are given at a 3$\sigma$ confidence level.

The SN was detected as a point source, hence, the peak intensities shown in Table 2 also represent flux den-
sities. The uncertainties include the contribution of the local
r.m.s. and a conservative uncertainty in the absolute flux
calibration of 5 per cent. We note that the 2007 August
14 epoch corresponds to the radio discovery reported by
Chandra & Soderberg (2007). Their value and the one we
report here are consistent within the uncertainties. Furthemore, the epochs previous to the VLA upgrade in 2009 are
limited by a poor dynamic range owing to the existence of
other sources in the field which are much stronger than the
SN itself. To account for this effect, we have carefully mea-
sured any background emission at the position of the SN in
each epoch.

SN 2005kd was detected in the L, C and X bands over
the first 9 years. The C and X band flux densities are decreas-
ing with time, whereas the L band light curve appears to
be still rising. Thus the radio emission appears to have
already peaked at the higher frequencies and transitioned
from the optically thick to the optically thin regime at
4.86 and 8.46 GHz, whereas it is perhaps still in the opti-

cally thick phase, or just transitioning to the optically
thin phase at 1.4 GHz. This is consistent with observations
of other radio SNe (Weiler et al. 2002). On 2012 August,
the two-point spectral index between 4.49 and 1.78 GHz is
$\alpha = -0.72 \pm 0.35$. Using this information, and assuming
that the flux varied little between August 16 and 22, and
that the spectral index extends from 1.78 to 4.86 GHz, we
have converted the flux density measured on 2012 August
16 at 4.49 GHz to a flux at 4.86 GHz. The corresponding
value is $125.37 \pm 31.35\mu\mathrm{Jy/beam}$.

We have fitted (see Figure 3) a multi-frequency light
curve to the data shown in Table 2 following the parametri-
ization described in Weiler et al. (2002), using a Monte-
Carlo simulation to obtain a robust fit (see details in
Romero-Cañizales et al. 2014). We have adopted $\alpha = -0.72$
and $t_0 = 2005$-Nov-10 as explosion date (Tsvetkov 2008).
The optically thick region is generally attributed to ab-
sorption by the external medium or the medium inter-

to the SN (free-free absorption, FFA) or due to syn-

crotron self-absorption (SSA). SN 2005kd displayed radio

emission at late stages in its evolution, and a high but
non-relativistic ejecta velocity (based on the X-ray temper-
atures in the first 1000 days). Hence, we exclude the con-
tribution of a clumpy CSM (see e.g. van Dyk et al. 1994),

as well as synchrotron self-absorption (Chevalier et al. 2012
Romero-Cañizales et al. 2014) and consider FFA in the uni-
form local CSM. Thus, to represent the flux density evolu-
tion at a given frequency, we have used:

$$\left( \frac{S}{1\;\mathrm{mJy}} \right) = K_1 \left( \frac{\nu}{5\;\mathrm{GHz}} \right)^{\alpha} \left( \frac{t - t_0}{1\;\mathrm{day}} \right)^{\beta} e^{-\tau_{\mathrm{CSM}}} \quad (9)$$

where

$$\tau_{\mathrm{CSM}} = K_2 \left( \frac{\nu}{5\;\mathrm{GHz}} \right)^{-2.1} \left( \frac{t - t_0}{1\;\mathrm{day}} \right)^{\delta}$$

The fitted parameters ($K_1 = 13.5-148.0$, $K_2 = 2.4 \times 10^4$
$-7.4 \times 10^7$, $\beta = -0.74^{+0.17}_{-0.16}$ and $\delta = -2.30^{+0.46}_{-0.66}$) allow us to infer a peak luminosity at 4.86 GHz of $1.29 \times 10^{37}$ ergs

on day 631 after explosion (rest frame). We thus estimate a mass loss rate of $\sim 0.5 \times 10^{-4} M_\odot \;\mathrm{yr}^{-1}$ (assuming a wind ve-

locity of $10\;\mathrm{km\;s^{-1}}$ and using equation 17 from Weiler et al.

2002) at a radius of $\sim 4.6 \times 10^{15}$ cm. The fit gives a value
$s = 1.82 \pm 0.37$. This slope is a bit lower than our X-ray de-

rived values. It is clear that there are problems with both the
fit and its interpretation. The former is due to the sparsity

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Table 2. VLA observations of SN 2005kd

| Observation Date | Days after outburst (rest frame) | $\nu$ (GHz) | Conv. beam (arcsec$^2$) | r.m.s. (\(\mu\)Jy/beam) | Peak intensity (\(\mu\)Jy/beam) |
|------------------|----------------------------------|-------------|-------------------------|--------------------------|----------------------------------|
| 2007-Aug-14      | 632.5                            | 8.46        | 0.38×0.29, 42.7$^\circ$  | 42.42                    | 211.06±43.71                      |
| 2007-Sep-10      | 659.1                            | 8.46        | 0.37×0.29, 40.3$^\circ$  | 80.19                    | <255.85                          |
| 2008-Dec-13      | 1112.3                           | 8.46        | 0.39×0.24, 36.5$^\circ$  | 47.88                    | <147.47                          |
| 2008-Dec-28      | 1127.1                           | 8.46        | 0.36×0.24, 20.4$^\circ$  | 36.37                    | 155.36±37.19                      |
| 2012-Aug-16      | 2434.4                           | 7.91        | 1.47×0.89, 2.2$^\circ$   | 31.10                    | <94.92                           |
| 2007-Aug-18      | 636.4                            | 4.86        | 0.62×0.44, 37.6$^\circ$  | 82.41                    | <331.13                          |
| 2007-Sep-10      | 659.1                            | 4.86        | 0.58×0.44, 38.2$^\circ$  | 85.56                    | 346.57±87.30                      |
| 2008-Dec-13      | 1112.3                           | 4.86        | 0.93×0.38, 42.3$^\circ$  | 64.04                    | 300.91±65.78                      |
| 2008-Dec-28      | 1127.1                           | 4.86        | 0.74×0.36, 33.0$^\circ$  | 33.56                    | 202.54±35.05                      |
| 2012-Aug-16      | 2434.4                           | 4.49        | 2.57×1.57, 2.0$^\circ$   | 32.53                    | 132.80±33.20                      |
| 2008-Dec-28      | 1127.1                           | 1.42        | 2.66×1.41, 45.3$^\circ$  | 47.71                    | <193.57                          |
| 2009-Jan-02      | 1132.0                           | 1.42        | 2.52×1.37, 6.7$^\circ$   | 34.54                    | 209.94±36.10                      |
| 2012-Aug-22      | 2440.3                           | 1.41        | 6.71×5.18, 178.2$^\circ$ | 79.14                    | 458.04±82.39                      |
| 2012-Aug-22      | 2440.3                           | 1.78        | 5.32×4.08, 1.1$^\circ$   | 51.70                    | 269.40±53.31                      |

of data, which makes fitting unreliable; the latter is mainly due to the complexity of the system.

The smooth decline of the radio emission at both 4.86 and 8.46 GHz suggests a fairly smooth transition from 1000 to 3600 days. However, the long-lasting radio emission does favour the presence of an overall high density CSM, which is also inferred from the X-rays.

6 DISCUSSION AND CONCLUSIONS

In the previous section we form an overall picture of Type IIn SN SN 2005kd. In our model the SN expands in a medium with a density slope $s \sim 2.3-2.5$, with a value of $(\frac{M_{\text{r}}}{M_{\text{e}}}) \sim 192-656$ at a radius of $10^{15}$ cm, and decreasing with time. The X-ray emission is likely dominated by the forward shock, with a high temperature and a column density that reflects the high mass-loss rate. The reverse shock remains radiative, with all emission from the reverse shock being absorbed by a presumed cool dense shell behind it. The data suggest a slight, although not conclusive, preference for higher values of $s = 2.4-2.5$, and lower mass-loss rates. Further observations are needed to confirm or refute this.

This analysis of the X-ray emission from a Type IIn SN confirms that the SN expands into a very high density medium with density decreasing somewhat faster than $r^{-2}$. The density is higher than those encountered among the majority of stars. This is consistent with other Type IIn SNs, although as we see from Figure 8 SN 2005kd’s X-ray luminosity appears to exceed that of most Type IIn SN. The instantaneous density at any given radius, $M_{\text{r}}$, can be written as: $M_{\text{r}} \propto (r/r_0)^{-\theta}$. Thus the mass-loss rate is about $10^{-3} M_{\odot}$ yr$^{-1}$ at $4.0 \times 10^{16}$ cm.

The density profile, indicating a variation in the wind parameters in the years leading up to the SN explosion. If we assume that the wind velocity was of order 10 km s$^{-1}$, then this variation occurred over at least the last 5000-7000 years of stellar evolution, suggesting that the progenitor star increased its mass-loss rate (and/or decreased the wind velocity) a few thousand years before explosion.

It is hard to determine which progenitor best fits this analysis. The high mass-loss rate of $0.43-1.5 \times 10^{-3} M_{\odot}$ yr$^{-1}$, at $4.0 \times 10^{16}$ cm, for a 10 km s$^{-1}$ wind, is too high even for a red supergiant (RSG) star at the extreme high-mass end of mass-loss rates [Mauer & Josselin 2011]. Humphreys et al. [1997] have shown that the yellow hypergiant IRC+10420 may have undergone high mass-loss episodes where it lost mass at a rate of $10^{-3} M_{\odot}$ yr$^{-1}$ for about a 1000 years. This is lower than the time period of high mass-loss inferred by us for a wind velocity of $\sim 10$ km s$^{-1}$, but not significantly so. It is possible that a hypergiant star with a somewhat higher mass-loss rate may just about meet the required characteristics at the lower end of the deduced mass-loss rate. The star must lose several solar masses of material in this period. The derived high Ca abundances are consistent with the finding that supergiant atmospheres are rich in Ca-Al silicates [Speck et al. 2004]. A RSG or hypergiant progenitor is also compatible with the fact that the optical lightcurve from 2005kd showed a plateau for about 192 days [Tsvelkov 2008], indicating that it may arise from a progenitor with a large stellar radius. In this context it is interesting to note that, from an analysis of their R-band light, it has been found that the SNe IIn population statistically bears more similarity to the SN IIP population than the SN Ic population [Habergham et al. 2014]. The latter would be expected for really massive progenitors. The overall behaviour of SN 2005kd is reminiscent of other IIns that show photometric evolution similar to IIPs, as outlined in [1] [Mauerhan et al. 2014] have defined a subclass of SNe called Type IIn-P to describe these SNe that showed both IIn and IIP characteristics. The energy radiated by all of these in the plateau phase must arise from circumstellar medium interaction, as demonstrated for SN 2005kd. As compared to the IIn-Ps however, SN 2005kd shows a much longer plateau duration, and does not appear to decline as rapidly as the others at the end of the plateau phase. Unfortunately, the
lack of optical spectroscopy on SN 2005kd precludes more detailed comparison.

If the surrounding wind velocity were assumed to be much higher than 10 km s\(^{-1}\), the mass-loss rate would need to be correspondingly higher, thus making it difficult to ascribe a known progenitor to the SN. LBVs have been suggested as IIn progenitors. Their wind velocities are about an order of magnitude higher than those of RSGs, and consequently the required mass-loss rates would jump up by an order of magnitude. LBVs undergoing a giant eruption (Smith 2014) would be needed to satisfy the required mass-loss rates, which would exceed \(1 \times 10^{-3} M_\odot \text{yr}^{-1}\) for LBV wind velocities at 4.0 \(\times 10^{16}\) cm. The high mass-loss rates would also have to be sustained for several hundred years, which has generally not been observed in LBVs. Importantly, any progenitor without a large stellar radius as in RSGs would furthermore require a different explanation for the plateau region in the optical light curve. This could perhaps be a consequence of the SN being surrounded by a massive dense shell into which the shock expanded after breakout (Dessart et al. 2016). The shell would have to exist from a radius of around \(10^{16}\) cm, given the current observations.

We have interpreted the obvious high density suggested by the observations as a high mass-loss rate (in equation 4). This however is not the only interpretation. A high density shell can also be due to sweeping up of external material by a lower density wind (Dwarkadas 2011). A similar model was found adequate to explain the X-ray emission from SN 1996cx (Dwarkadas et al. 2010). The decreasing light curve makes this appear less likely in the present case, however the lack of X-ray observations in the first 400 days makes it difficult to entirely rule out the possibility.

Figure 4 shows the similarity between the X-ray evolution of SN 2006jd and that of SN 2005kd. The X-ray luminosities are comparable. In their interpretation of the X-ray lightcurve from SN 2006jd, they have approximated it as a simple power-law decline, similar to our assumption here. Their derived densities were in excess of \(10^6\) cm\(^{-3}\) at 1000 days, comparable to the values found herein. The slope that they found was less steep than that found here, but overall the similarities between these two Type IIn SNe are obvious.

In summary, SN2005kd provides further confirmation that II In SNe evolve in high mass-loss rate winds (Smith et al. 2007; Ofek et al. 2007; Chatzopoulos et al. 2011; Chandra et al. 2012; Fransson et al. 2014). They often appear to show rapid changes in wind parameters near the end of the star’s lifetime. Such changes have also been postulated for many other Type II In SNe (Dwarkadas et al. 2011, and references within). The high mass-loss rates could just about accommodate a hypergiant star as a progenitor. An alternative possibility is that the surrounding wind velocity, and consequently mass-loss rate, are higher, and the progenitor is not a RSG that turned hypergiant but an LBV star undergoing a giant eruption, as has been often suggested for IIn S. The latter though would require extremely high mass-loss rates to be sustained for at least several hundred years. Any progenitor model must also be able to account for the change in wind parameters in the years prior to the explosion, as well as the optically observed plateau region. Further continual and consistent monitoring of Type II In SNe at all wavelengths, but particularly in the X-ray and radio bands, is suggested if we are to unambiguously determine their progenitors.

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