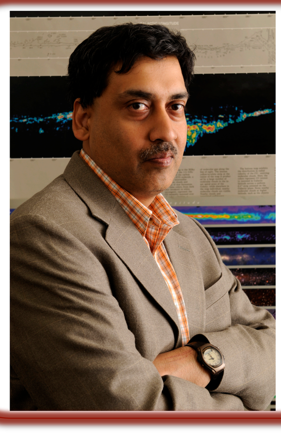
The X-Ray and Radio Emission from Supernova 2005kd



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Abstract

- ✧ SN 2005kd is one of the more luminous supernovae (SNe) at both X-ray and optical wavelengths.
- ✧ We have re-analysed all good resolution (> 20'' FWHM PSF) available archival X-ray data on SN 2005kd, combined with a 29ks *Chandra* observation obtained by our group in 2013.
- ✧ The data reveal an X-ray light curve that decreases gradually with time as $t^{-1.62}$. In this poster we explore the evolution of the X-ray spectrum of 2005kd, the characteristics of the ambient medium, and the kinematics of the SN shock wave(s).
- ✧ Reference: Dwarkadas et al. 2016, *MNRAS*, **462**, *1101*

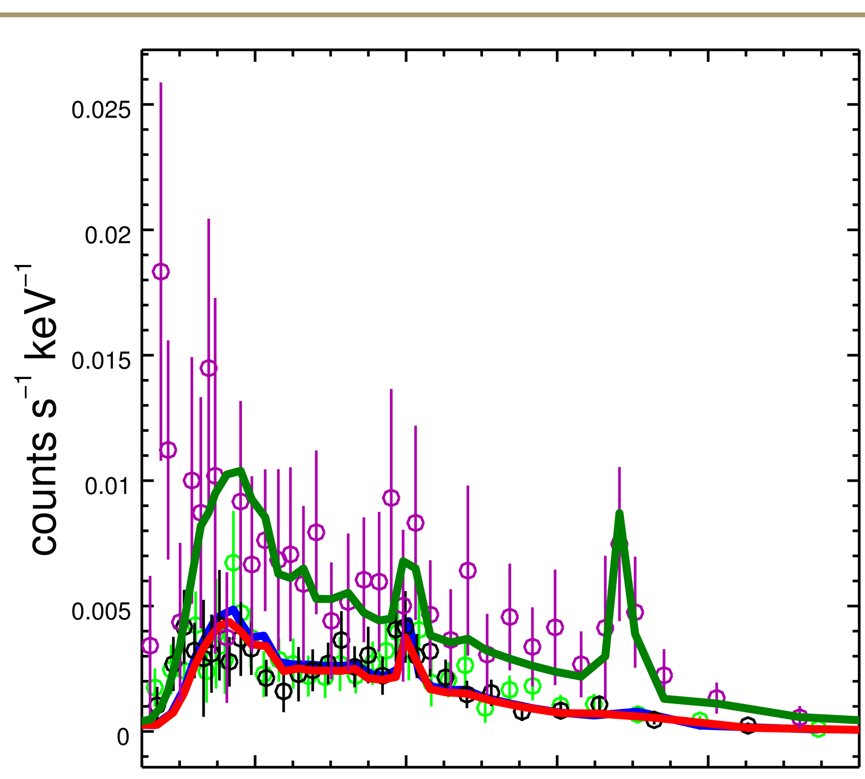
Introduction

- ❑ Supernova 2005kd was discovered in an automated search by Puckett and Pelloni on 2005 Nov 12.22 UT.
- ❑ Confirmed as a Type IIn SN, one that shows narrow lines in its optical spectrum.
- ❑ Galaxy LEDA 14370, Redshift 0.015, Distance 64.2 Mpc (H_0=71).
- ❑ X-ray emission observed at the position of the SN with *Swift* in 2007, and subsequently with *Chandra*.
- ❑ The optical lightcurve of SN 2005kd (Tsevtkov, 2008, *Variable Stars*, **28**) shows an unusually long plateau stage, unique for a Type IIn SN, which lasted for at least 192 days.
- ❑ The UV lightcurves (Pritchard et al., 2014, *ApJ*, **787**, 157) show an even larger plateau or increasing flux over almost 2000 days, before the light curve begins to drop off.

SN 2005kd – Summary table of X-ray observations

(Note: we have combined some of the smaller Swift exposures together to give a larger total exposure.)

Satellite	Start Date of Observation	Days After Outburst	Exposure (ks)
Swift	2007-01-24	440	8.95
Chandra	2007-03-04	479	3.
XMM	2007-03-29	504	54.2
Chandra	2008-01-03	784	5.
Swift	2008-08-21	1015	9.3
Swift	2011-10-22 to 2012-01-05	2200	9.9
Swift	2012-06-01 to 2012-07-16	2419	16.54
Chandra	2013-11-29	2940	29



XMM-Newton MOS1, MOS2 and PN data and fits. All datasets fitted simultaneously using the same thermal *vmekal* model. Required excess abundances of Ca, Ar and Fe. MOS1 data (light green), fit (blue). MOS2 data (black), fit (red). PN data (purple), fit (dark green). Similarity in the fits shows that the same model adequately fits all datasets simultaneously. The Fe-Kα line at 6.7 keV is visible only in the PN data, a result of the effective area differences between MOS and PN detectors at 6.7 keV.

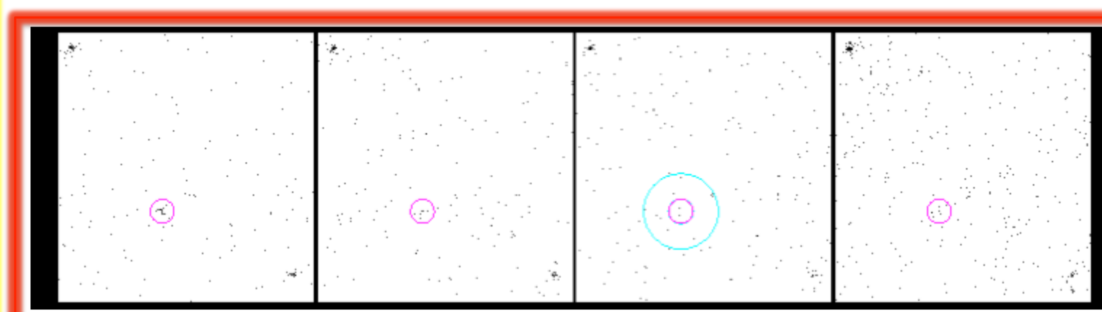
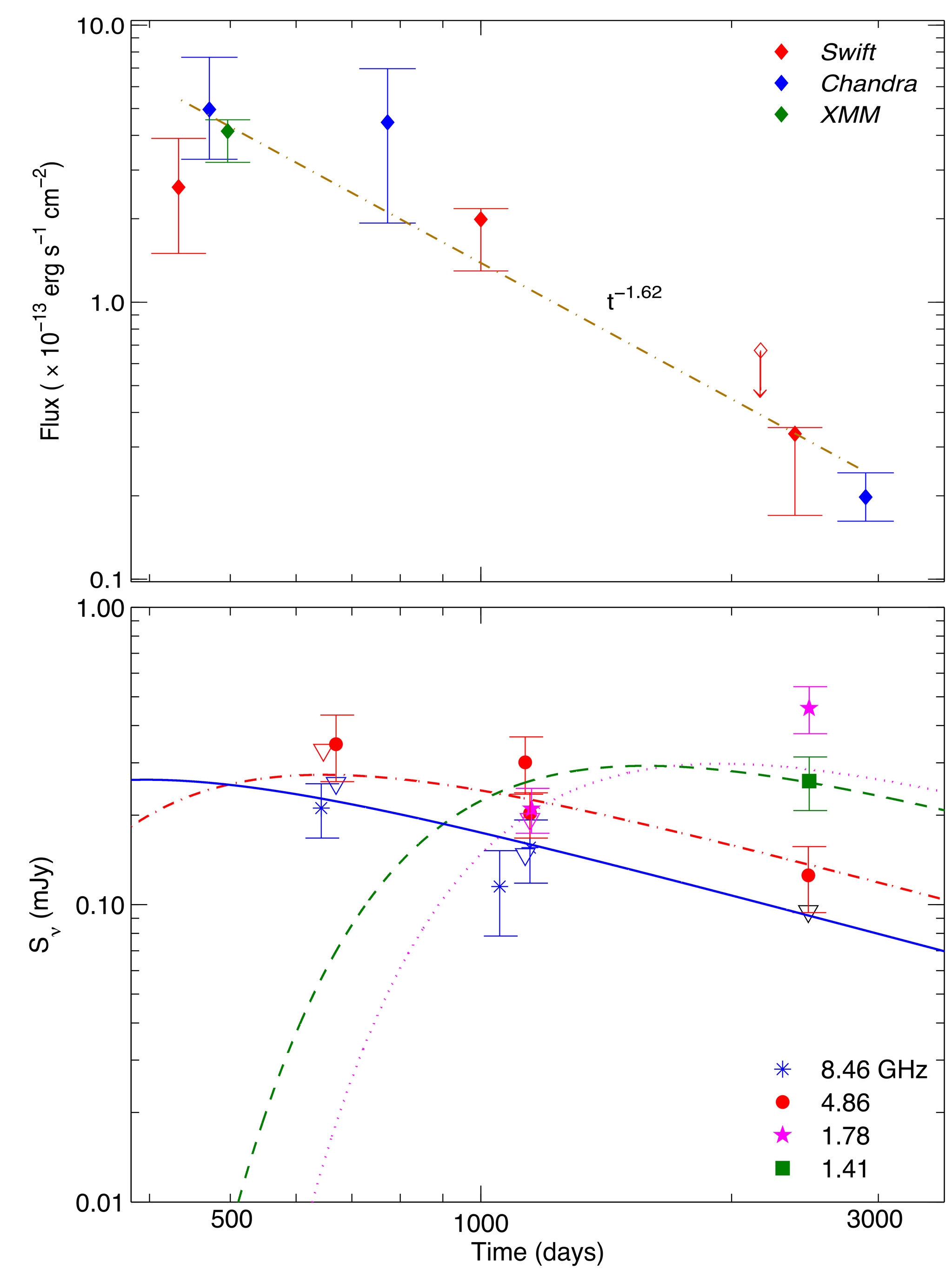


Fig 2: Swift observations of SN 2005kd. From left to right: 2007, 2008, 2011 and 2012. The region is 11.5' on each side. The pink circle (35'' in radius) denotes region used to extract the data. The annulus used for the background region is in blue in 2011 panel. The SN is detected at all epochs except in 2011.

ANALYSIS

- First 3 spectra suggest a temperature higher than the range measureable by either Swift, Chandra or XMM. The temperature is difficult to constrain.
- Large X-ray temperature and early time period suggest that the emission arises from the forward shocked circumstellar medium. Temperature behind the reverse shock is expected to be lower.
- The SN light curve fits a decline rate of $t^{-1.62 \pm 0.06}$.
- Using Fransson et al. (1996, *ApJ*, **461**, 993, hereafter FLC96) and Dwarkadas & Gruszko (2012, *MNRAS*, **419**, 1515), with the Chevalier (1982, ApJ, 258, 790) self-similar model for the evolution of SN shocks in the circumstellar medium, the decreasing flux indicates a density decreasing as $r^{-2.4+/-0.1}$. Results are only weakly dependent on the slope of the ejecta density profile n for 9 < n < 12.
- The density for a constant wind with fixed mass-loss parameters falls as r^{-2}, showing that the wind parameters were not constant in the final stages of the progenitor star evolution. The mass-loss rate is a function of time and position.
- The high flux indicates a high circumstellar wind density and therefore a high mass-loss rate. Using equation 3.11 in FLC96, a reference radius of 10^{15} cm, and the *XMM-Newton* flux at 1 keV as reference point (best statistics), we can calculate the value of the quantity $\dot{M}_{-5}/v_{w1}$, where $\dot{M}_{-5}$ is the wind mass-loss rate in units of 10^{-5} solar masses yr^{-1}, and v_{w1} is the wind velocity in units of 10 km s^{-1}.
- Given the uncertainties in the flux and its exact temperature, the latter being more crucial, we find that $192 < \dot{M}_{-5}/v_{w1} < 656$. Thus at the reference radius, mass-loss rate > 10^{-3} $M_\odot$ yr^{-1}, and could be as large as 6.6×10^{-3} $M_\odot$ yr^{-1} for wind velocity 10 km s^{-1}.
- If the wind velocity increases, mass-loss rate increases. A high mass-loss rate is consistent with the high X-ray luminosity of SN 2005kd, and is still lower than that derived for the IIn SN 2010jl.
- At early times, low temperature emission from the reverse shock is not observed. This suggests that perhaps the reverse shock is radiative.
- If maximum ejecta velocity < 10^4 km s^{-1}, reverse shock is found to be radiative throughout the evolution for n > 9. A cold dense shell forms behind the shock which absorbs all emission.

Following the XMM-Newton fit, all spectra were fit with a single thermal vmekal model (a two vmekal model fit does not provide a better fit to the XMM data). Best fits to the spectra show that the first three epochs, up to day 504, are fit by a high temperature component, with a column density NH that varies between 1. to 0.4 (x 10^{22} cm^{-2}). The temperature decreases gradually in subsequent spectra, as does the column density, which approaches the Galactic value by about 3000 days.



Top The 0.3-8 keV X-ray lightcurve of SN 2005kd, showing unabsorbed flux with 1σ error bars. Time is given in the rest frame of the SN, along with the k-corrected flux. The data comprise 4 *Swift*, 3 *Chandra* and 1 *XMM-Newton* data-points. The best fit to the data (dashed line) suggests the flux is decreasing as $t^{-1.62 \pm 0.06}$.
Bottom Radio lightcurve of SN 2005kd at 8.46 GHz (blue, solid line), 4.86 GHz (red, dashed-dotted line), 1.78 GHz (green, dashed line) and 1.41 GHz (magenta, dotted line). Downward triangles - 3σ upper limits. Black triangle - upper limit at 7.91 GHz. Error bars at ± 1σ. Where necessary, the flux has been converted using the calculated radio spectral index. The few available data points do not allow for a robust fit, but the extracted parameter values are not inconsistent with those obtained from the X-ray data.

Analysis (continued)

- Plasma is found to always be in ionization equilibrium due to the high densities, justifying our use of equilibrium models to fit the emission.
- We have also reanalyzed archival radio data on SN 2005kd. The long-lasting radio emission also suggests evolution in a high density medium. The sparse data prevent an accurate mass-loss determination, but they are consistent with those derived from X-rays.
- Derived X-ray mass-loss rates are higher than expected from stars usually considered as SN progenitors - red supergiants, Wolf-Rayet stars, even yellow hypergiants (mass-loss rates ≤ 10^{-3} $M_\odot$ yr^{-1}).
- This suggests a high mass-loss rate at the end of the star's evolution, perhaps due to ejected mass shells or eruptions, as in Luminous Blue Variables (LBVs).

Conclusions

- ➢ The X-ray emission is thermal, and arises from the forward shock in a high density medium – the reverse shock is radiative throughout the evolution.
- ➢ The derived mass-loss rate for the progenitor is extremely high, ≥ 2 x 10^{-3} $M_\odot$ yr^{-1} (for wind velocity 10 km s^{-1}), suggestive of mass ejections or eruptions seen in LBVs.
- ➢ The growing number of LBV-like progenitors of IIn SNe poses problems for standard stellar evolution models.

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