X-rays from Supernovae

A Unique Window on the Late Stages of Massive Star Evolution

A White Paper Submitted to the Astro2010 Decadal Survey Committee

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Science Frontier Panel: Stars and Stellar Evolution (SSE)
Facilities: *International X-ray Observatory (IXO), Generation-X*

1. Synopsis

X-ray emission from young (days to years old) supernovae (SNe) results from the collision of the explosion ejecta and the surrounding circumstellar material (CSM) and, as such, is a function of the density distribution and velocity of both. Sensitive, high resolution X-ray observations can measure these properties. Because the CSM is a result of the progenitor star's pre-supernova wind, measuring properties of the CSM provides vital information on the mass-loss history of the progenitor system. As the fast moving ejecta ($v_e \sim 10^4$ km/s) plough through the slow moving wind ($v_w \sim 10$ km/s), they encounter mass which was shed earlier and earlier in the life of the progenitor; thus, ***the X-ray observations are a time machine measuring the mass loss of the progenitor as a function of time before the explosion and are a unique probe of the latest stages of massive star evolution***. We currently have few constraints on the pre-SN mass-loss of massive stars. Furthermore, it seems that some very massive stars have strongly enhanced episodic mass loss in the decades or centuries before collapse (e.g., SN 2006gy shed a few $M_\odot$/yr – see Smith et al. 2007 – and other, less massive stars shed a few tenths $M_\odot$/yr). These mass-loss rates are far beyond what a normal steady stellar wind can achieve and are surprising to see in H-rich SN progenitors. This currently has no clear theoretical interpretation. Slightly less massive stars may also have complex CSM environments and display an active mass-loss history. X-rays are the best way to constrain this.

In addition, because the nucleosynthetic yields of the SN are a function of the progenitor's mass (e.g., Nomoto et al. 1995), measuring the ejecta elemental abundances from X-ray spectra can provide a determination of the progenitor mass. This requires high-quality, high-resolution spectral data to accurately determine the plasma properties.

2. The current state of affairs

About 50 young (days to years old) SNe have been seen in X-rays to date, but we are still in the infancy of understanding the detailed origins of this early X-ray emission. In general, the X-ray luminosities of these SNe dominate their total radiative output starting at an age of about one year. On the theoretical side, the interaction of a spherically symmetric SN shock and a smooth CSM has been calculated in detail (Chevalier & Fransson 1994). As the SN "outgoing" shock emerges from the star, its characteristic velocity is $\sim 10^4$ km/s, and the density distribution in the outer parts of the ejecta can be approximated by a power-law in radius, $\rho \propto r^{-n}$, with $7 \lesssim n \lesssim 20$. The outgoing shock propagates into a dense CSM formed by the pre-SN stellar wind. For red giant progenitors, this wind is slow ($v_w \sim 10$ km/s) and results from a high mass loss rate ($\dot{M} \sim 10^{-4} - 10^{-6}\ M_\odot$/yr). The density for such a wind follows $\rho = \dot{M}/4\pi r^2 v_w$. The collision between SNe ejecta and CSM also produces a "reverse" shock, which travels outward at

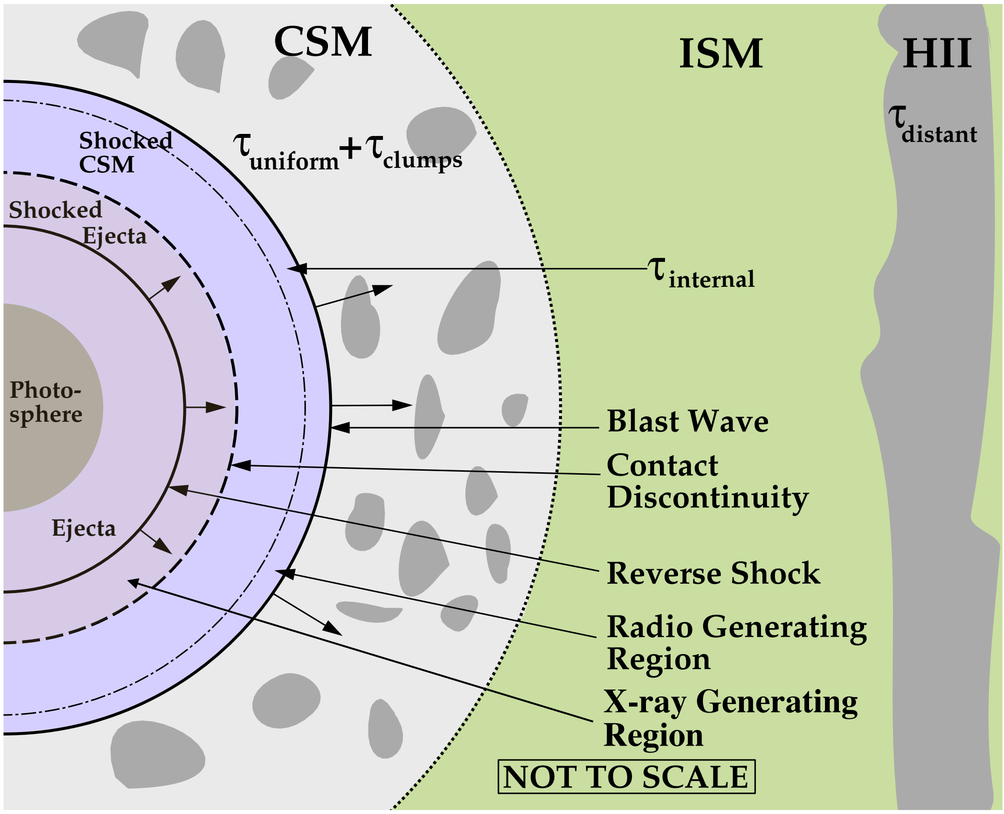

Figure 1: Schematic of a SN shock interacting with the CSM (adapted from Weiler et al. 2001)

$\sim 10^3$ km/s slower than the fastest ejecta. Interaction between the outgoing shock and the CSM produces a hot shell ($\sim 10^9$ K), while the reverse shock produces a denser, cooler shell ($\sim 10^7$ K) with much higher emission measure from which most of the observable X-ray emission arises.

In the unusual cases of type IIn SNe (and only those cases), the visual-wavelength emission spectrum and continuum radiation can also be used to diagnose the shock and CSM properties, but this in only possible in the most extremely dense, massive CSM environments (which can decelerate the blast wave and make a dense radiative shock that allows gas to cool). For these SNe, the X-rays provide a direct measure of the shock properties and can be used together with observed velocities from optical spectra. In most cases (>90% of core collapse SNe), however, the CSM is not dense enough to give rise to a strongly radiative shock that can be seen at visual wavelengths. Thus, for the more traditional stellar winds that are representative of **most** SN progenitors, *X-rays are our best and sometimes only way to trace the CSM properties*. Sensitive X-ray observations are therefore a vital tool if we wish to study the full range of pre-SN mass-loss rates in order to constrain pre-SN stellar evolution.

Within the framework of CSM interaction, Chevalier, Fransson, & Nymark (2006) have shown how X-ray and radio measurements of type IIP SNe are excellent probes of the mass loss of the progenitor star. The origin of Ib/c X-rays is less clear; Chevalier & Fransson (2006) have suggested an inverse-Compton+synchotron mechanism. The type IIn SNe are perhaps the least understood but can be the most X-ray luminous subtype. The narrow optical lines that characterize the IIn subclass are clear evidence of dense circumstellar gas; they probably arise from reprocessing of X-ray emission. The X-ray emission could result from the shocked ejecta, as in the case of the normal type II SNe, or it could originate from shocked clumps of gas in the CSM (e.g., Chugai 1996). These two scenarios predict vastly different widths for X-ray emission lines,

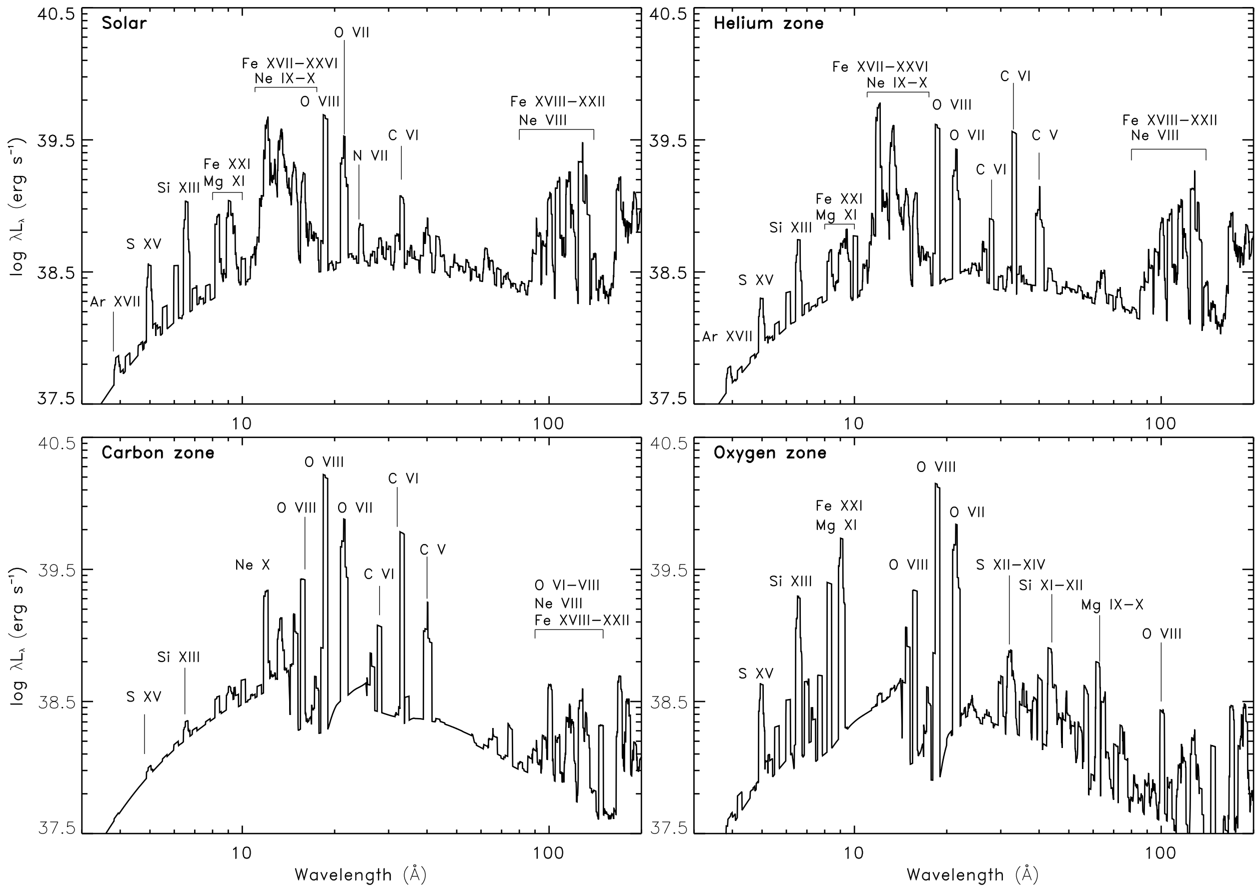

Figure 2: From Nymark et al. 2006 (their Fig. 11): "X-ray spectra produced by four models with different composition. All models have $V_4 = 1$ and $T_0 = 1.0$ keV." Details of the models can be found in the their paper. These are the most accurate models to date of the spectra produced by Type IIn SNe, but we currently lack high quality data to which we can compare them (see, e.g., Figs. 3 and 4).

but we have not yet obtained an X-ray spectrum of sufficient quality to make the distinction. For the case where the emission comes from the shocked ejecta, Nymark, Fransson, & Kozma (2006) have shown the complexity of the resulting X-ray spectrum (e.g., see their Fig. 11 reproduced in Fig. 2) and the dangers of using single-temperature spectral models. Their calculations reveal the rich emission-line spectrum and temperature profile of the radiative shocks. The X-ray spectrum and the ejecta velocities are thus sensitive functions of the density distribution and together constitute unique probes of the explosion dynamics, as well as nucleosynthesis. As for the type Ia SNe, there has not yet been a convincing X-ray detection.

Observationally, despite the five-fold increase in the number of X-ray detections of young SNe since the launch of *Chandra*, *XMM*, and *Swift*, we have made little progress in the interpretation of the X-ray data. Generally, because so few counts are detected, a number of simplifying assumptions need to be made to model the spectra — the absorbing column density, the plasma temperature and composition, the wind velocity, and the ejecta velocity are fixed, and the ejecta is usually assumed to be smooth and go as $1/r^2$. These simplifications allow for a basic luminosity determination, and in turn an estimate of the mass-loss rate, albeit with large uncertainties given the inherent assumptions.

3. What is necessary for progress?

Typical X-ray observations of young SNe have contained only dozens to hundreds of counts

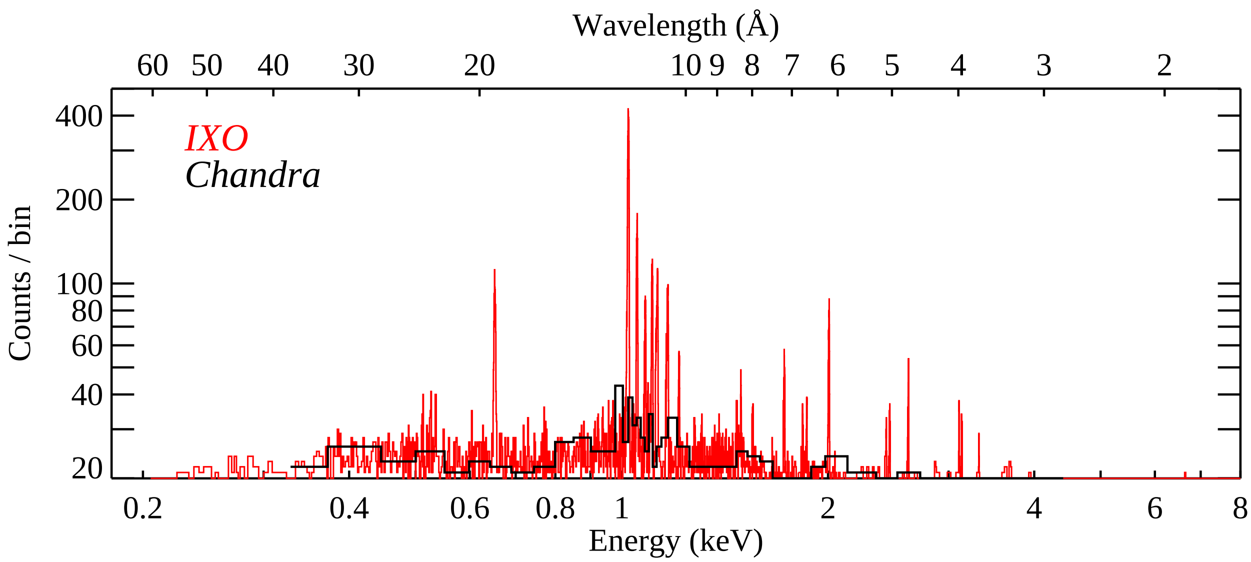

Figure 3: 50-ksec simulations of a $kT = 2$ keV plasma with $F_x = 10^{-13}$ erg cm^{-2} s^{-1} and elemental abundances expected for a SN, binned to have at least 20 counts per bin. The sharp, detailed emission features are washed out in the *Chandra* data but very strong in the *IXO* data.

in the telescopes' imaging modes; likewise, dispersed spectra with *Chandra* and *XMM* are of such low signal-to-noise as to be unusable. Thus far, many assumptions and simplifications have been made in order to interpret the *Chandra* and *XMM* data. ***Accurate determinations of the CSM and ejecta properties (and thus the progenitor's mass-loss and mass) require high quality, high resolution X-ray spectra***, which are currently infeasible with *Chandra* and *XMM*. To make substantial progress will require substantial improvements in the collecting area available to a high spectral resolution X-ray instrument, such as what would be provided by the *International X-ray Observatory* (*IXO*).

As an example of the improvement that can be made, Figs. 3 and 4 show 50-ksec simulations of a $kT = 2$ keV plasma with $F_x = 10^{-13}$ erg cm^{-2} s^{-1} (a representative flux level — see

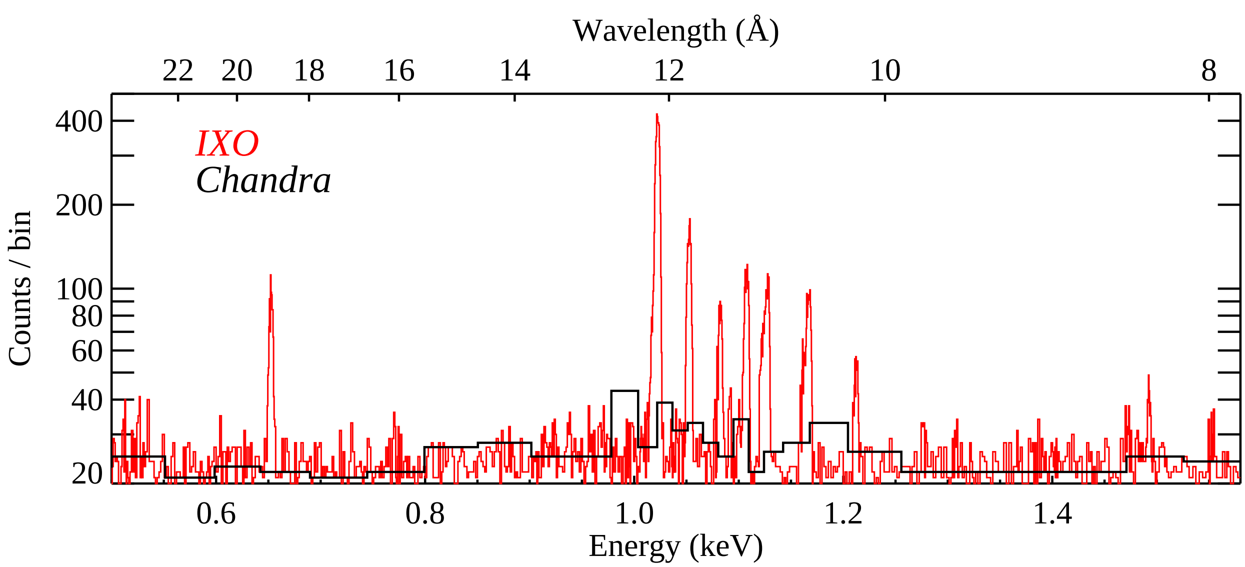

Figure 4: Same as Fig. 3 but showing a narrower energy range.

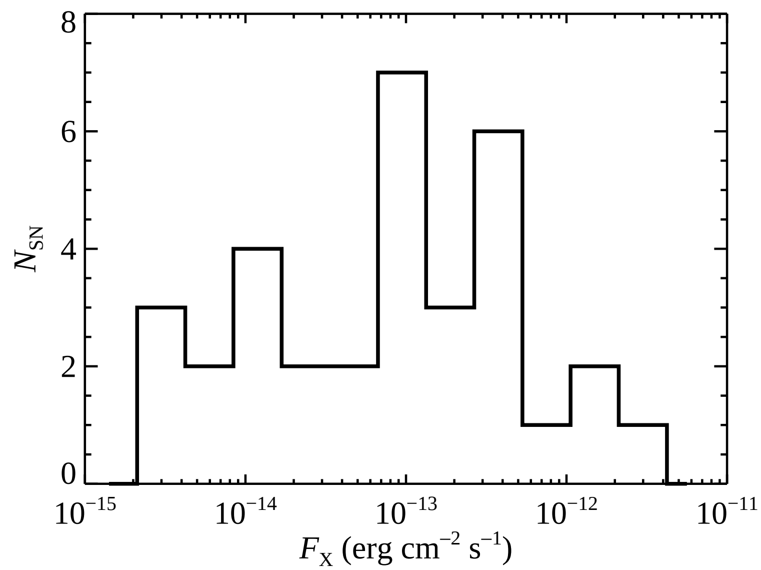

Figure 5: Histogram of the X-ray flux of SNe at the time of initial X-ray detection.

Fig. 5) and with elemental abundances similar to what was seen in the *Chandra* spectrum of SN 1998S (Pooley et al. 2002). The red line shows what the microcalorimeter on *IXO* would detect, and the black line shows what the ACIS-S3 CCD on *Chandra* would detect. Structure of the type expected from SNe (see Fig. 2) is lost in the *Chandra* observation, but *IXO* would allow for detailed spectral study.

4. X-rays and radio

Historically, all strong radio SNe are also X-ray sources, and the combination of X-ray and radio data is invaluable in understanding the emission mechanisms. A separate white paper is being written on the importance of radio emission.

5. Summary

High quality X-ray observations (along with optical/UV and radio data) will measure the temperature and radiative cooling rate and determine the (i) structure of the SN ejecta, (ii) structure of the CSM, and (iii) details of the star's pre-SN mass-loss evolution. Currently, only gross estimates of the mass-loss rates can be made because the X-ray data are not of sufficient quality to determine many of the CSM-interaction details. A high-throughput, high spectral resolution X-ray satellite would allow this field to make a huge leap forward and reliably determine the mass-loss rates of massive stars as a function of time in their very latest stages. Such vital information is difficult, if not impossible, to obtain by any other means.

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