X-ray Spectra of Young Supernovae

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Summary. X-ray spectra of young supernovae (SNe) can provide information on the progenitor star and the interaction of the supernova ejecta and the circumstellar material. I will discuss some examples, with particular emphasis on SN 1998S, whose X-ray spectrum revealed for the first time in a young supernova a wealth of heavy element emission features (Ne, Al, Si, S, Ar, and Fe). By comparison with detailed calculations of supernova explosion elemental yields, these data can be used to constrain the progenitor mass. With increasingly sophisticated models and additional high quality data, application of this technique could result in many more reliable progenitor mass determinations. In addition, high resolution X-ray spectra allow us to measure the temperature evolution of a supernova and can give us a detailed picture of the progenitor's pre-supernova evolution. As we build up additional examples from the great diversity of core collapse supernovae, we hope to come to a better understanding of the last stages of massive star evolution.

1 The Utility of X-ray Spectra

In this talk, I will focus on two particular uses of X-ray spectra, both of which rely on emission lines. The first use is simply to measure the velocity-broadened width of an emission line. This would unambiguously determine whether the X-ray emission originated from the reverse shock region (with a characteristic speed of ~10,000 km s^{-1}, see [1]) or from a shocked, clumpy wind (with a characteristic speed of ~9,000 km s^{-1}, see [2]). The second use requires multiple emission lines in the spectrum. The observed elemental abundance ratios are compared with those calculated from numerical simulations of supernova explosions with a range of progenitor masses. This comparison will constrain the progenitor mass.

2 Observed Spectra with Emission Lines

To date, 20 core-collapse supernovae have been observed in X-rays, and nine of these have been observed just in the last four years since the launch of the *Chandra X-ray Observatory* and *XMM-Newton*. An online list of all the observations is maintained by Stefan Immler and available at *http://lheawww.gsfc.nasa.gov/users/immler/supernovae_list.html*. Of these 20

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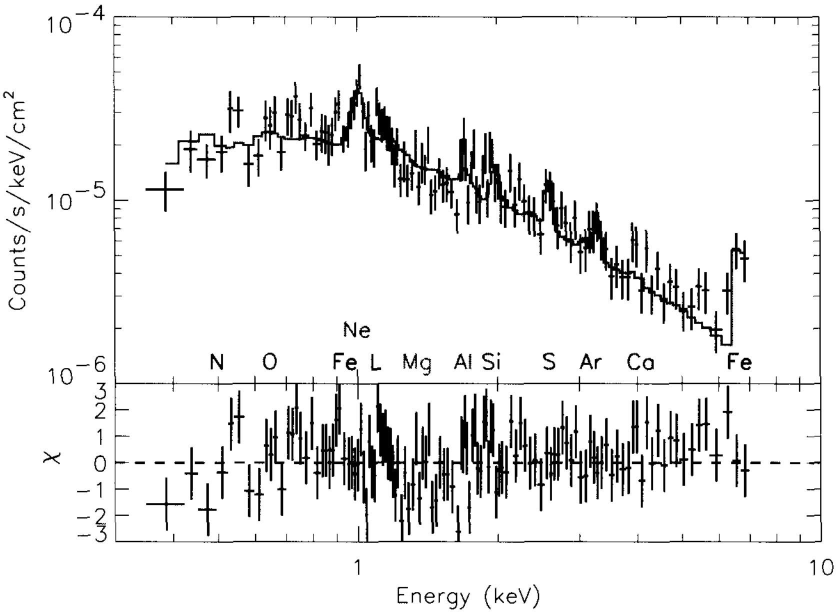

Fig. 1. MEKAL fit (solid line) to the summed spectrum (crosses) of SN 1998S. Labels indicate approximately where emissions lines for each element would be observed.

supernovae, only a handful have shown emission features in their X-ray spectra. I will now briefly review these.

2.1 SN 1986J – *ASCA* Reveals an Fe Line

The type IIn SN 1986J was observed twice with the *ASCA* satellite, once in 1994 and again in 1996. Houck et al. [4] reported the detection of an Fe K line at 6.7 keV. SN 1986J was relatively near (d = 9.6 Mpc) and luminous ($L_x = 2 \times 10^{40}$ erg s^{-1}), but the low collecting area of *ASCA* resulted in only about 6200 counts in the 1994 observation and about 6000 counts in the 1996 observation. The authors were only able to constrain the width of the Fe line on the upper end, with a 90% confidence limit that the width is less than 20,000 km s^{-1}.

2.2 SN 1993J – *ASCA* Reveals an Fe Line

This nearby (d = 3.6 Mpc) type IIb supernova was observed many times with *ASCA* in the year following the explosion. These early observations are described by [6]. The first observation was eight days after explosion, when the X-ray luminosity was $L_x = 1.5 \times 10^{40}$ erg s^{-1}. An Fe K line at 6.7 keV

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Table 1. Observed and Calculated Elemental Abundance Ratios

Ratio	SN 1998S	13 $M_\odot$	15 $M_\odot$	18 $M_\odot$	20 $M_\odot$	25 $M_\odot$	40 $M_\odot$
Ne/Si	0.6–14	0.14	0.17	*0.86*	*1.1*	*2.2*	0.56
Mg/Si	0–0.7	*0.18*	*0.49*	*0.58*	1.1	2.1	1.1
O/Si	0–1.2	*0.20*	*0.43*	*0.80*	1.4	2.4	1.6

was detected, but again the width could not be constrained on the lower end. The 90% upper limit on the width is 27,000 km s^{-1}.

2.3 SN 1995N – A Possible Si Line

This type IIn supernova at 24 Mpc was still quite luminous ($L_x = 15 \times 10^{40}$ erg s^{-1}) when an *ASCA* observation was made in 1998. Although there were no clear line detections in the 3200-count spectrum, Fox et al. [3] point out a "hint in the fit residuals" near the Si K line.

2.4 SN 1998S – *Chandra* Reveals a Wealth of Emission Lines

This type IIn supernova at 17 Mpc was observed with *Chandra* five times from early 2000 to late 2001. Pooley et al. [8] reported there was little evolution of the spectral shape, and the X-ray luminosity decreased steadily from 9.3×10^{39} erg s^{-1} in the first observation to 5.3×10^{39} erg s^{-1} in the last. The individual spectra were summed to produce a 2600-count spectrum in which emission lines were seen from Ne, Al, Si, S, Ar, and Fe (see Fig. 1). Unfortunately, none of the emission lines was strong enough to have a well-constrained width. However, given the plethora of emission lines, Pooley et al. compared the observed abundance ratios (derived from MEKAL fits in XSPEC) to those calculated from the numerical simulations of [7] in the hopes of constraining the progenitor mass. This was the first time such an analysis had been done with X-ray data. Although there were large uncertainties, Table 1 shows that the observed abundance ratios are compatible with a progenitor mass in the range 15–20 $M_\odot$.

This progenitor mass determination comes with some caveats, however. First, it assumes the ejecta are well mixed, but such mixing has been observed, for example in the Cas A supernova remnant [5]. Another caveat is that the observed abundance ratios are model-dependent, in this case the MEKAL model. In addition, there are uncertainties in not only the data but also the model calculations. However, as our understanding of the explosion grows and as we continue to obtain high-quality X-ray data and develop increasingly sophisticated models, this method could yield many progenitor mass determinations of future supernovae.

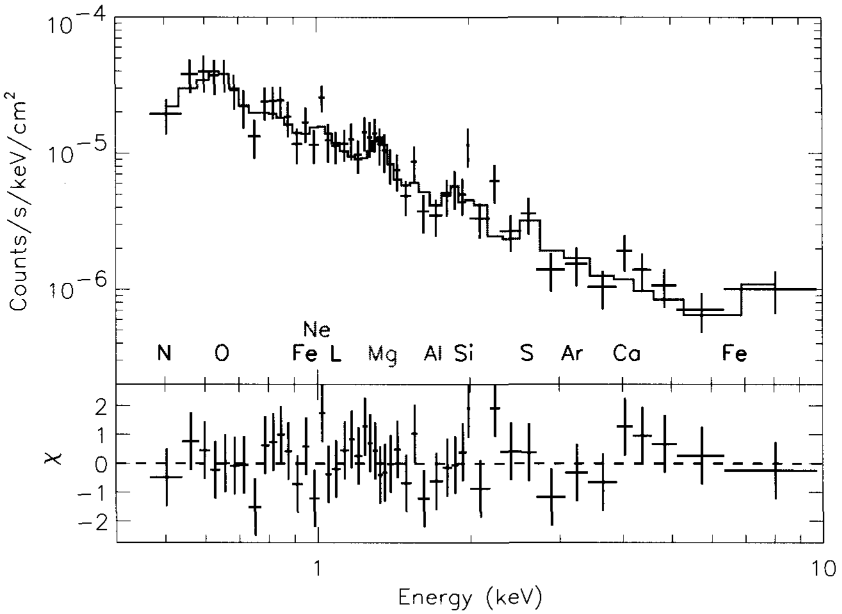

Fig. 2. MEKAL fit (solid line) to the spectrum (crosses) of SN 2003bg. Labels indicate approximately where emissions lines for each element would be observed.

2.5 SN 2003bg – *Chandra* Reveals a Wealth of Emission Lines Again

This type Ic/pec supernova at 19 Mpc was observed with *Chandra* about a month after discovery. A preliminary analysis of the data [9] indicates an X-ray luminosity of 4×10^{39} erg s^{-1}, and MEKAL fits in XSPEC indicate emission features from O, Mg, Si, S, Fe, and possibly Ne (see Fig. 2). In comparison to SN 1998S, there is much stronger O emission and much weaker Ne emission in SN 2003bg. An analysis of the abundance ratios is in preparation, as is the analysis of a follow-up *Chandra* observation taken a few months after the first one (Pooley et al., in prep.).

3 Summary and Future Prospects

The X-ray spectra of young supernovae can be a powerful tool to determine the X-ray emitting regions and to constrain the progenitor mass. The ability to accurately measure the width of an X-ray emission line is hampered by the relatively low X-ray flux of all but the closest supernovae; the situation should improve as the collecting area of satellites grows. The current generation of X-ray satellites (*Chandra* and *XMM-Newton*) is ushering in a new era in the study of young supernovae. Future satellites (such as *Astro-E* and *Constellation-X*) will feature larger collecting areas and will have exquisite energy resolution (by using calorimeter instruments). With future instruments, we will be able to resolve emission line complexes and perform detailed plasma diagnostics to determine elemental abundances with less dependence on specific models.

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