Astro2010 White Paper

Formation of the Elements

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Overview

The theoretical understanding of cosmic nucleosynthesis obtained by astrophysicists over the last century surely ranks as one of the great accomplishments of science. In general, however, this theory has been tested largely against ensemble-averaged measurements, such as the relative abundance distribution of the elements in various environments (e.g., solar), the atmospheres of stars, and so on. Nucleosynthesis is a rich, complex field that involves many disparate processes operating in different environments and at different phases of stellar evolution. Observational tests of specific model components, especially of the most energetic processes, are woefully lacking. In particular, the processes that produce Fe and Fe-group elements and eject them into the interstellar medium during the explosions of both core collapse and thermonuclear supernovae (SNe) are among the most poorly tested parts of the entire nucleosynthesis picture. X-ray studies of young supernova remnants (SNRs) can provide critical tests of the nucleosynthesis picture especially as regards the production of Fe and Fe-group elements in specific individual examples of core-collapse and thermonuclear SNe. In addition since the production of Fe and Fe-group elements is at the heart of these explosions, they offer critical insights into the explosion processes in SNe. The key astrophysical question that this white paper addresses is

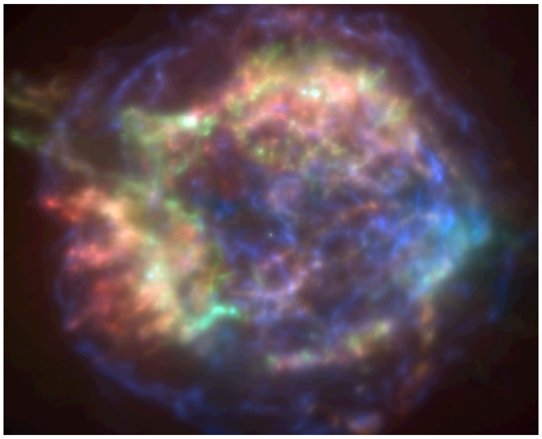
How do supernovae explode and create the iron group elements?

In the following we first describe the state-of-the-art in this research area based on *Chandra*, *XMM-Newton*, and other existing X-ray facilities, before moving on to demonstrate the enormous potential of the *International X-ray Observatory* (IXO) to enable compelling science across a broad range of core questions in nucleosynthesis and SN physics.

Background

Core collapse (CC) SNe make up roughly three-quarters of all observed SNe. They come from stars more massive than $8M_{\odot}$ and from a nucleosynthetic point of view are the dominant producers of O, Ne, and Mg, although they do produce a broad spectrum of elemental species including the Fe-group. They leave compact remnants in the form of neutron stars or black holes, while their gaseous remnants tend to be highly structured with dense optically-emitting knots and typically more diffuse X-ray features. It is known that the precipitating event for a CC SNe is the collapse of a stellar core, but the process whereby the core rebounds and ejects the rest of the star is still poorly understood with at least two competing ideas currently in vogue: neutrino-driven convection (e.g., Herant et al. 1994; Burrows, Hayes, & Fryxell 1995; Kifonidis et al. 2000), including in its latest development the instability of the stalled shock (e.g., Blondin & Mezzacappa 2006; Foglizzo, Scheck & Janka 2006; Burrows et al. 2007; Scheck et al. 2008); and jet-induction (e.g., Khokhlov et al. 1999). It is also the case that at present nucleosynthesis predictions still rely on spherically symmetric models with an assumed neutron star/black hole "mass cut" (e.g., Woosley & Heger 2007).

The other main class of SNe are the thermonuclear or Type Ia SN (SN Ia). These make up roughly one-quarter of all SNe and are widely believed to result from the total incineration of a carbon-oxygen white dwarf that grows close to the Chandrasekhar mass.



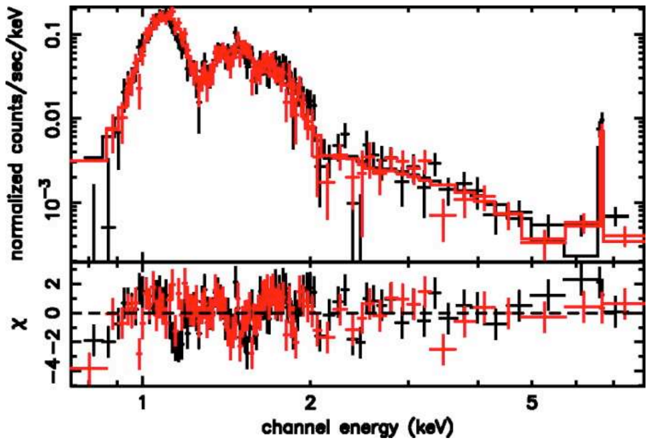
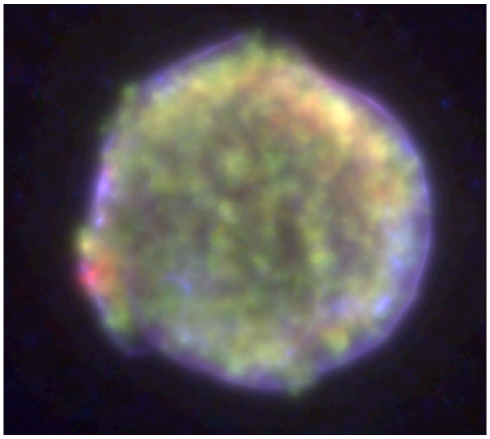


Figure 1–(Left) Color-coded X-ray image of Cas A: red corresponds to Fe L emission, green to Si K emission, and blue to 4-6 keV continuum emission. This is derived from the *Chandra* observations after smoothing with the IXO point-spread-function.
Figure 2–(Right) *Chandra* spectrum of a nearly pure Fe knot from the eastern limb of Cas A. The broad bumps at energies between 1 and 2 keV are the unresolved complex of Fe L-shell lines; the Fe K-shell emission appears at 6.5 keV. No lines from lower-Z species are present.

How the star increases its mass is unknown; single degenerate scenarios where the white dwarf accretes matter from a normal-star companion in a binary and double degenerate scenarios where two white dwarfs coalesce are the two favored possibilities. During the explosion about half of the star's mass is converted to ^{56}Ni which decays to stable ^{56}Fe. Even with hundreds of well-observed type Ia SNe and the intense focus of the theoretical community over the past 15 years, the SN Ia explosion process, i.e., how nuclear ignition occurs and the subsequent burning proceeds, remains an unsolved problem (e.g., Röpke & Bruckschen 2008; Jordan et al. 2008). Models that most successfully reproduce optical spectra of SNe Ia essentially parameterize the speed of the burning front through the star (e.g., Iwamoto et al. 1999).

We submit that understanding the synthesis of the Fe-group elements in SNe is the key to understanding these explosions. In CC SNe, Fe comes from the innermost parts of the exploding star; it is the ejected matter that has been subjected to the highest temperatures and the most extreme conditions in the rebounding core. In SN Ia, nucleosynthesis *is* the explosion (i.e., it provides the energy to unbind the star). Indeed since the optical light from these SNe has its origin in the radioactive species produced by the explosive nuclear burning, the cosmologically relevant observations of optical light curves of SN Ia rest directly on the amount and composition of the Fe-group ejecta.

X-ray studies of SNRs are an essential part of this scientific investigation. X-ray emission is optically thin (except, possibly, for a few of the strongest resonance lines) so the gaseous remnants of SNe offer a comprehensive three-dimensional view of the ejecta; this is impossible to obtain on any individual SN event, for which we sample a single line-of-sight. Light echoes (now detected from Cas A, Tycho, and SNR 0509−69.0 in the LMC) provide definitive SN typing and in some cases sub-typing, so that individual SNRs become as useful as any individual SN to probe nucleosynthesis and explosion mechanisms. Of course a nearby SN, like SN 1987A, will offer a wealth of new opportunities for scientific



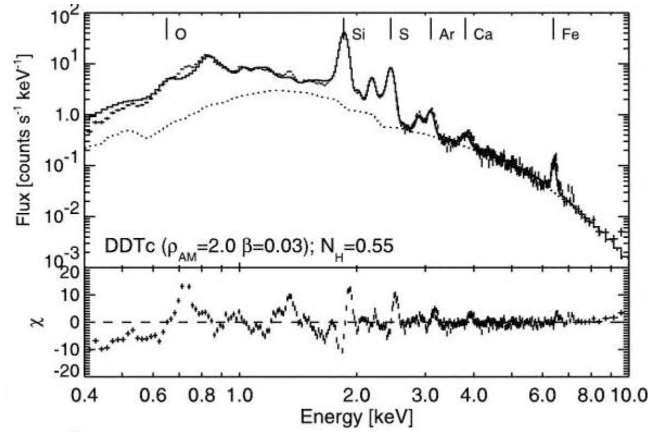


Figure 3–(Left) Color-coded X-ray image of the Tycho SNR: red corresponds to Fe L emission, green to Si K emission, and blue to 4-6 keV continuum emission. This is derived from the *Chandra* observations after smoothing with the IXO point-spread-function.
Figure 4–(Right) Spatially integrated *XMM-Newton* spectrum of the Tycho SNR with best fit ejecta model.

studies, but why wait when we have the potential to study the twenty to thirty nearest Galactic SNRs?

Results from Current Observatories

Chandra and *XMM-Newton* imaging with low-resolution spectroscopy has already shown the power of X-ray studies to illuminate the processes that occur in the hottest parts of the interiors of exploding stars. In the case of the core collapse SN Cas A (Fig. 1) the spatial distribution of the main nucleosynthetic products (Fe, Si, O) are seen to vary widely in the reverse-shock-heated ejecta. Large bulk velocities (of order ± 2000 km s^{-1}) are inferred from Doppler shifts of Si and Fe lines (Hwang et al. 2001; Willingale et al. 2002). One of the earliest *Chandra* results was the discovery that Fe-rich ejecta lie at the outermost edge of the remnant (Hughes et al. 2000), establishing that violent processes must have operated on the core of the SN during the explosion. These Fe-rich knots vary in precise composition including some that are nearly pure Fe (see Fig. 2, Hwang & Laming 2003), possibly from α-rich freeze out, while other knots appear to come from explosive complete Si-burning under varying conditions. **Because of the limited spectral resolution and modest effective area of current instruments, it is not possible to detect any of the lower abundance Fe-group species in these small spatial-scale features.**

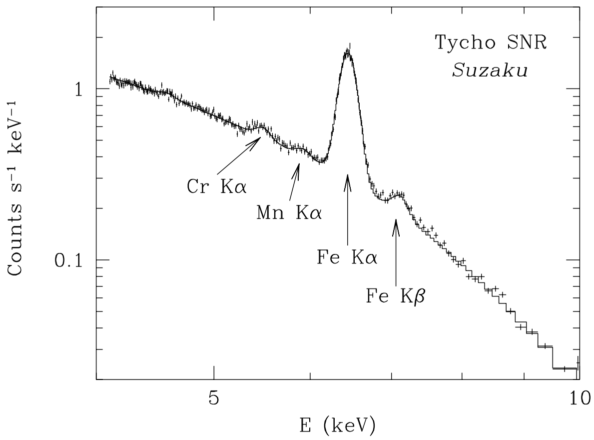
Significant advances in studies of remnants of thermonuclear SNe Ia have been made using current X-ray instruments. In two cases we have now established consistency between the X-ray properties of a remnant and the optical light of its originating SN, observed through spectroscopy of light echos. The first case where this was done was the LMC SNR 0509−69.0: both the optical light (Rest et al. 2008a) and the X-ray spectrum and dynamics (Badenes et al. 2008) require a bright, highly energetic Type Ia explosion, similar to SN 1991T. More recently the spectral subtype of the Tycho SNR (Fig. 3) was determined, again based on light echo spectra (Rest et al. 2008b, Krause et al. 2008), to be consistent with the majority class of normal type Ia supernovae. Previously it had been shown that the X-ray properties of the remnant were consistent with the hypothesis that SN1572 was a normal SN Ia (Badenes et al. 2006). Fig. 4 (taken from this paper) shows the excellent agreement between the observed *XMM-Newton* spectrum spatially integrated over the remnant and the best fit ejecta model appropriate to a normal SN Ia.

One of the great promises of future high spectral resolution studies of SNRs is the possibility to detect and measure spectral lines from trace elements, that is species other than the most abundant ones (e.g., O, Ne, C, Si, S, Fe) that are now commonly studied at CCD spectral resolution. As an example of the scientific value of this work, we point to the recent paper by Badenes, Bravo, & Hughes (2008) on using the Mn to Cr ratio in SN Ia remnants to constrain the initial metallicity of the progenitor. The basic idea is that the mass ratio of Mn to Cr produced though nuclear burning during the explosion depends sensitively on the electron-to-nucleon fraction (Y_e) in the white dwarf. Timmes et al. (2003) have already shown that Y_e is linearly proportional to the metallicity of the white dwarf progenitor. Thus from the observed Mn/Cr ratio in the remnant we learn about the metallicity and therefore the age of the original progenitor system. Applying this technique to the recent *Suzaku* spectrum of the Tycho SNR where Mn and Cr were both detected (Tamagawa et al. 2009), Badenes, Bravo, & Hughes (2008) were able to show that the metallicity of Tycho's progenitor star was supersolar. Although the errors were large, values of metallicities much below solar can be rejected.

Future Advances

Improvement in numerical calculations will be an important component in advancing this research field. Full 3D hydro calculations of the collapse, rebound, and explosion of core collapse SNe are only now at the beginning stages and detailed predictions of the nucleosynthetic yields of the resulting ejecta are not yet available. However, it seems likely that differences in the temperature, density and Y_e in the zones undergoing explosive nucleosynthesis will be imprinted on the relative composition of the Fe-group elements in the ejected matter. As shown above, this is also the case for thermonuclear SNe. By measuring the composition of Fe-rich ejecta in young SNRs, including the trace species, we will provide critical constraints on the temperatures and conditions under which the nuclear burning occurred. This will put strong constraints on the allowed models for the explosions.

Observational results obtained to date, as important and relevant as they are, suffer, fundamentally, from a lack of precision. CCD-type spectral resolution is unable to provide accurate measurements of even the most basic thermodynamic quantities that characterize the plasma, i.e., electron temperature and the charge states of the relevant ions. This introduces large errors in relative abundance measurements. Studies of dynamics are limited to only the most extreme speeds (1000's of km s^{-1}). Significant advances require improved spectral resolution and considerably more effective area than provided by current X-ray satellites or missions under development, such as *Astro-H*. The *International X-ray Observatory* offers vastly improved spectral resolution over current CCD devices (ΔE of 2.5 eV vs. 150 eV at the Fe K-shell line near 6.5 keV), coupled with a large increase in effective area (6500 cm^2 vs. 800 cm^2 for *XMM-Newton* or 300 cm^2 for *Astro-H*, at 6 keV). These



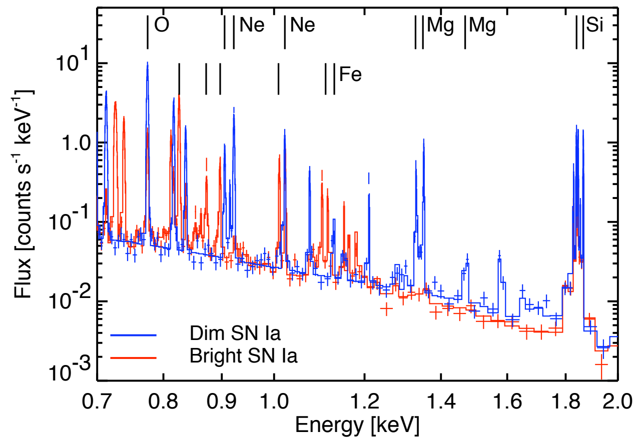


Figure 5–(Left) Spatially integrated *Suzaku* spectrum of the Tycho SNR showing the detections of faint lines from the trace Fe-group elements Cr and Mn.
Figure 6–(Right) Simulated IXO spectrum of the spatially integrated X-ray emission from 400-year-old remnants of dim (blue curve) and bright (red curve) SN Ia in the Local Group galaxy M33 observed for 100 ks each.

are the essential next steps in the observational domain. We note that the planned angular resolution of IXO ($5''$) is sufficient to address many of the important science goals in this subject area. Figures 1 and 3 (where the *Chandra* images have been convolved with the expected IXO beam) show that IXO can resolve many individual spectrally-distinct features in young SNRs.

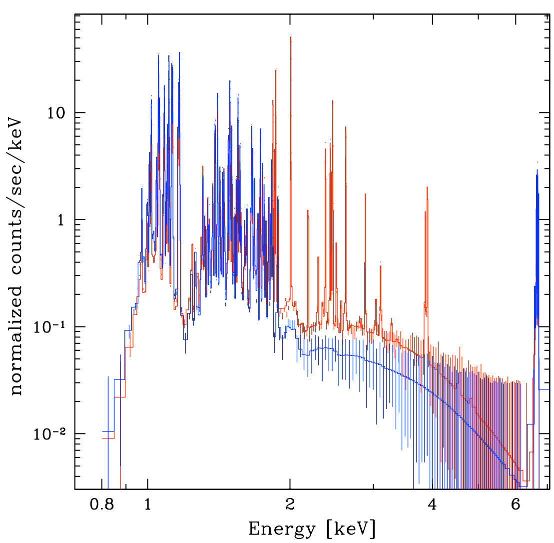
Many IXO investigations of SNRs are possible. For example, in the case of radioactive ^{44}Ti in Cas A, the measured fluxes from INTEGRAL/IBIS (Renaud et al. 2006) predict an IXO count rate of $\sim$0.25 cts s^{-1} for the innershell Kα lines of each of the daughter products ^{44}Sc and ^{44}Ca. This is sufficient to allow for a complete census, including mapping both the spatial extent and dynamics (i.e., radial velocities), of the ^{44}Ti in Cas A. This is critical information pertinent to the unsolved question of where the neutron star/black hole mass cut lies in core collapse SNe.

IXO will map the intensities and Doppler velocity shifts of the Fe-group lines (most importantly from Mn, Cr, and Ni) as well as the much brighter lines from lighter species across the Tycho SNR as well as the half-dozen or so other Galactic SN Ia remnants. As Fig. 3 indicates, the Tycho SNR shows a distinct asymmetry in the ejecta distribution, namely, Si- and Fe-rich ejecta knots along the southeast limb. The key to understanding type Ia SN (SN Ia) lies in understanding how they produce the large quantities of Fe-group elements they do. This is what IXO is ideally suited to do.

Chandra and *XMM-Newton* surveys of the Local Group galaxies M33 and M31 (which are at distances of roughly 800 kpc) have generated catalogs of hundreds of X-ray sources, a number of which are going to be young SNRs (although none have yet been found). Once young SNRs are identified in these galaxies, IXO will be able to carry out follow-up spectroscopy. One exciting project will be to discriminate between remnants of core collapse and Type Ia SNe and relate the properties of the remnants to their local environments. In particular for SNe Ia, there is growing evidence that bright and dim SNe Ia have different kinds of progenitors (Scannapieco & Bildsten 2005). This could introduce systematic errors that compromise the role of SN Ia in the forthcoming era of precision cosmology with the JDEM candidate missions (Aldering 2005). Type Ia SNe at high redshift are relatively common, but they are too far away to study their environments (stellar populations, metallicities, etc.) with enough detail to constrain the nature of the progenitors. IXO observations of young remnants of SN Ia in the Local Group could represent a breakthrough in this field. The X-ray spectra of young SNRs are sufficiently well understood to (a) identify the Type Ia objects (Hughes et al. 1995) and (b) discriminate the SNRs from bright and dim Type Ia SNe (Badenes et al. 2006, 2008). IXO would observe enough Type Ia SNRs (several dozens) to allow a statistical study of their progenitor properties in relation to the well-characterized stellar populations of M33 and M31.

In Fig. 6, we present the simulated spectra of two 400 yr old Type Ia SNRs at the distance of M33, with exposures of 100 ks. One spectrum was generated from a bright SN Ia model ($\sim$1 $M_\odot$ of ^{56}Ni), the other from a dim SN Ia model ($\sim$0.3 $M_\odot$ of ^{56}Ni). The X-ray spectra of the SNRs are instantly distinguishable: one is dominated by Fe L lines (red curve), and the other by lines from intermediate mass elements like Ne and Mg (blue curve). Similar studies are possible in M31 as well.

We close this white paper with two final IXO spectral simulations. Fig. 7 shows the IXO spectra of two Cas A Fe-rich knots, including the pure Fe one discussed above (c.f., Fig. 2) from alpha-rich freeze-out and another from explosive incomplete Si-burning. Fig. 8 shows the IXO spectra for the Si-rich and Fe-rich knots along the southeastern limb of Tycho. The richness of these spectra graphically demonstrate the power of the *International X-ray Observatory* to usher in a new era of precision studies of nucleosynthesis and SN explosion physics.



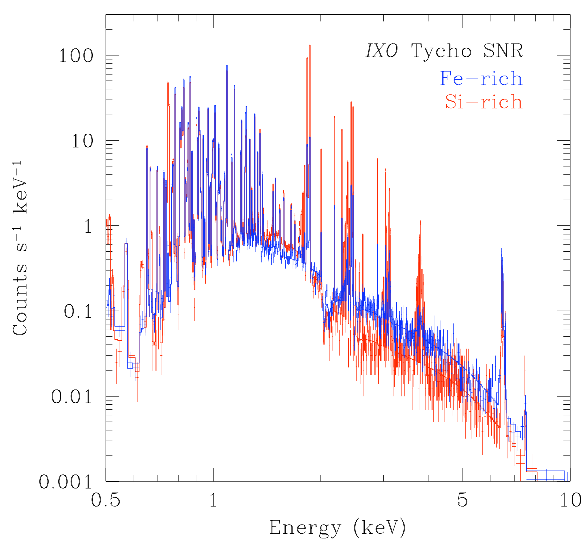


Figure 7–(Left) Simulated IXO spectrum of Fe-rich knots in Cas A for exposures of 50 ks. The blue spectrum is pure Fe, while the red spectrum contains an admixture of Si, S, Ar, and Ca in addition to Fe. *Figure 8*–(Right) Simulated IXO spectra (50 ks) of the Si-rich (red) and Fe-rich (blue) knots along the southeastern limb of the Tycho SNR.

References

Aldering, G. 2005, New Astronomy Review, 49, 346

Badenes, C., Bravo, E., & Hughes, J. P. 2008, ApJ, 680, L33

Badenes, C., Borkowski, K. J., Hughes, J. P., Hwang, U., & Bravo, E. 2006, ApJ, 645, 1373

Badenes, C., Hughes, J. P., Cassam-Chenaï, G., & Bravo, E. 2008, ApJ, 680, 1149

Blondin, J. M., & Mezzacappa, A. 2006, ApJ, 642, 401

Burrows, A., Dessart, L., Ott, C. D., & Livne, E. 2007, Phys. Rep, 442, 23

Burrows, A., Hayes, J., & Fryxell, B. A. 1995, ApJ, 450, 830

Foglizzo, T., Scheck, L., & Janka, H.-Th. 2006, ApJ, 652, 1436

Herant, M., Benz, W., Hix, W. R., Fryer, C. L., & Colgate, S. A. 1994, ApJ, 435, 339

Hughes, J. P., et al. 1995, ApJ, 444, L81

Hughes, J. P., Rakowski, C. E., Burrows, D. N., & Slane, P. O. 2000, ApJ (Letters), 528, L109

Hwang, U., & Laming, J. M. 2003, ApJ, 597, 362

Hwang, U., Szymkowiak, A. E., Petre, R., & Holt, S. S. 2001, ApJ (Letters), 560, L175

Iwamoto, K., Brachwitz, F., Nomoto, K., Kishimoto, N., Umeda, H., Hix, W. R., & Thielemann, F.-K. 1999, ApJS, 125, 439

Jordan, G. C., IV, Fisher, R. T., Townsley, D. M., Calder, A. C., Graziani, C., Asida, S., Lamb, D. Q., & Truran, J. W. 2008, ApJ, 681, 1448

Khokhlov, A. M., Höflich, P. A., Oran, E. S., Wheeler, J. C., Wang, L., & Chtchelkanova, A. Y. 1999, ApJ, 524, L107

Kifonidis, K., Plewa, T., Janka, H.-T., Müller, E. 2000, ApJ, 531, L123

Krause, O., Tanaka, M., Usuda, T., Hattori, T., Goto, M., Birkmann, S., & Nomoto, K. 2008, Nature, 456, 617

Renaud, M., et al. 2006, ApJ, 647, L41

Rest, A., et al. 2008a, ApJ, 680, 1137

Rest, A., et al. 2008b, ApJ, 681, L81

Röpke, F. K., & Bruckschen, R. 2008, New Journal of Physics, 10, 125009

Scannapieco, E., & Bildsten, L. 2005, ApJ, 629, L85

Scheck, L., Janka, H.-Th, Foglizzo, T., & Kifonidis, K. 2008, A&A, 477, 931

Tamagawa, T., et al. 2009, PASJ, 61, S155

Timmes, F. X., Brown, E. F., & Truran, J. W. 2003, ApJ, 590, L83

Willingale, R., Bleeker, J. A. M., van der Heyden, K. J., Kaastra, J. S., & Vink, J. 2002, A&A, 381, 1039

Woosley, S. E., & Heger, A. 2007, Phys. Rep., 442, 269