SN 1993J – The X-ray Story of a Supernova Slowly Transitioning To a Remnant

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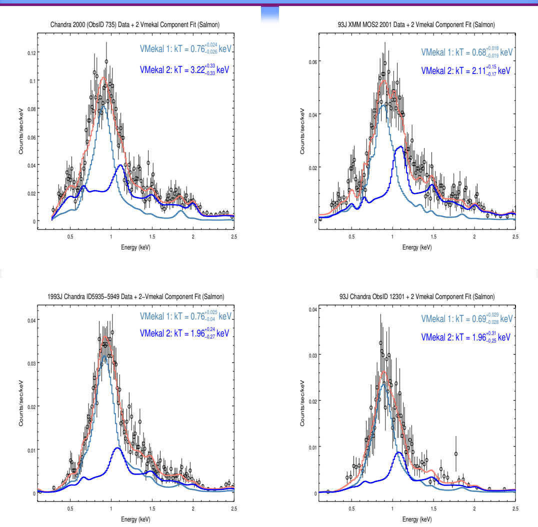
Abstract Supernova 1993J in the nearby galaxy M81 is one of the best observed supernovae (SNe) in X-rays, with better long-term X-ray time-sampling than any other SN. We re-analysed most of the available archival data on SN 1993J, combined with a 79ks *Chandra* observation obtained by our group in Aug 2010. Together, the data constitute a veritable history of a Type IIb SN from its explosion, through its outward journey into the surrounding medium, and on its way to becoming a remnant. The X-ray emission probes the characteristics of the surrounding medium, and the kinematics of the SN shock wave(s). In this poster we explore the evolution of these quantities in SN 1993J, together with the evolution of its X-ray spectrum.

Evolution of the SN 1993J X-ray Spectrum over the last decade:

Chandra 2000 XMM 2001

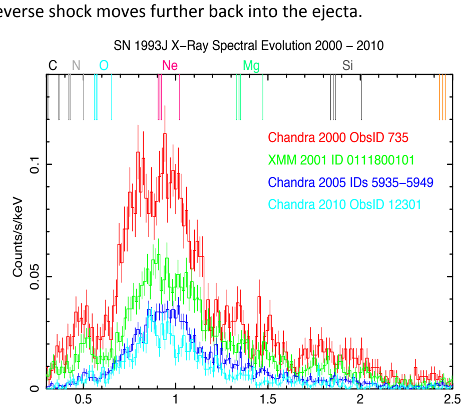


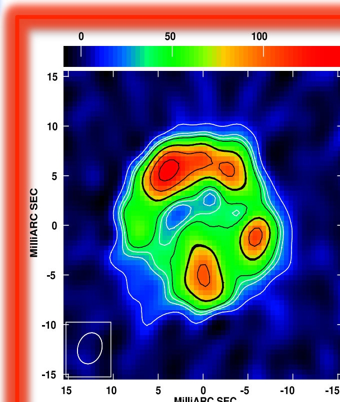
Chandra 2005 Chandra 2010

Above Fig: Data (black), fit (salmon), model components: dark & light blue

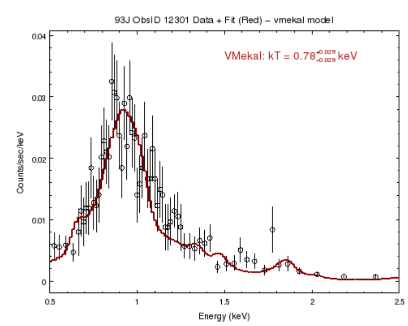
Over the last decade, the X-ray emission is clearly thermal. The shape of the X-ray spectrum has not changed significantly over the last decade, only the intensity has gradually decreased, as expected. The spectra are well fit by a combination of two Vmekal models, one at a temperature around 0.72 ± 0.04 keV and the other at a higher temperature, around 3.2 keV in 2000, dropping to just below 2 keV in 2010. The column density towards the source is set equal to the Galactic column. This is found to be an excellent approximation for data taken after the year 2000, whereas early ROSAT data indicate a much higher absorption column. If the column density is left as a free parameter, the best fit gives a value close to Galactic.

Below we show the well-sampled *Chandra* and *XMM* spectra from 2000 to 2010 on an absolute scale. The position of prominent X-ray lines is also marked. Some lines such as N are prevalent in the early spectra but have mostly vanished by 2010, presumably as the reverse shock moves further back into the ejecta.

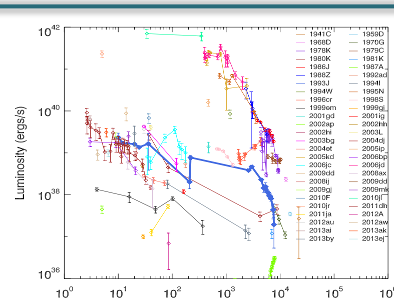




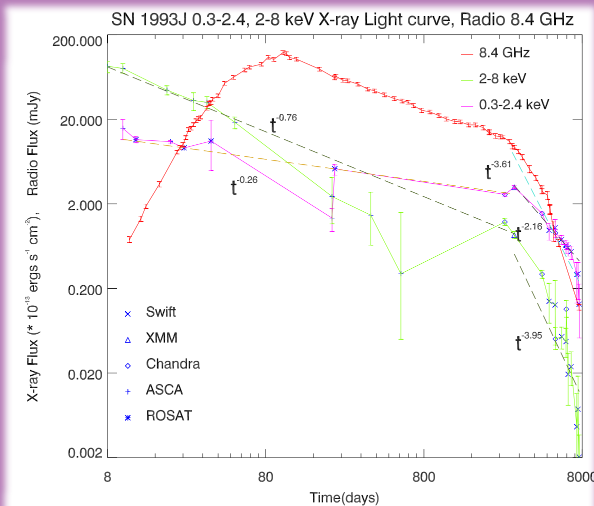
VLBI 1.7 GHz radio image of SN1993J, taken Mar 5-6 2010, (16.9 yr post explosion). FWHM of convolving beam at lower left. Contours and colour scale both indicate brightness. North is up, east to the left. Bietenholz et al, 2010 EVN Symp.



Single component fit to 2010 *Chandra* spectrum. Although the spectra are well fit by a two-component model, a single component spectrum also gives a satisfactory fit to the spectrum in 2005 and 2010, with a slightly higher χ^2 . An f-test suggests the 2-component fit is an improvement at about a 2σ level, which is inconclusive.



SN 1993J soft X-ray Light Curve (thick blue line) compared to those of other X-ray SNe. The steep slope of the 93J light curve after 3000 days is unusual, and only matched by a few other SNe, most of which are of Type IIn. The hard X-ray light curve has an even steeper slope, an effect that is seen in other SNe also, and is to be expected as the shock expands outwards, and its temperature consequently decreases with time.



The complete hard (2-8 keV) and soft (0.3-2.4 keV) X-ray light-curves of SN 1993J, using *ROSAT, ASCA, Swift, Chandra* and *XMM* data up to May 2014. The early hard X-ray light-curve (up to ~3000 days) decreases as $t^{-0.76}$, whereas the soft X-rays fall more slowly as $t^{-0.26}$, and dominate the emission after ~300 days. After day ~3000, the light curves begin to decrease much more steeply. The hard X-rays fall as $t^{-3.95}$, the soft X-rays somewhat slower, as $t^{-2.16}$. The slopes do not indicate self-similar behavior. This effect is also seen in the 8.4 GHz radio light curve, which also falls off as $t^{-3.61}$ after about 3000 days (although a power-law fit is not an ideal description). Other radio frequencies show similar behavior, suggesting that whatever the reason for the steep slope, it affects both thermal bremsstrahlung as well as synchrotron emission.

Discussion: The change in slope of the radio and X-rays light curves may indicate a change in the slope of the ambient density profile, with a sharper fall-off in density (Weiler et al. 2007, ApJ, 671, 1959). This would also imply that the forward shock would expand faster, whereas the reverse shock (still in the higher density ejecta) would go slower. The gap between the forward and reverse shocks would be expected to increase with time, as the evolution is no longer self-similar (if it was before). Exactly this effect is seen in the VLBI data, where after 8 years the ratio of forward to reverse shock radius begins to increase (Bietenholz et al. 2010, EVN Symp.). Thus the data suggest a sharp change in the density profile. Assuming a progenitor wind velocity of 20 km/s, the change in slope implies that around 4000 years before explosion, the mass-loss rate increased significantly. The slope of the early X-ray light curves suggests that the rate may have continued to slowly increase after that time. It is tempting to associate the two X-ray components with the forward and reverse shocks. However the constancy of the low temperature component, the fact that the higher temperature component hardly changes over 9 years even though the forward shock would be expanding into a steep density gradient, and that the high-temperature component may not even be necessary in the later data, make it difficult to associate it with the forward shock. Nymark et al. (2009, A&A, 494, 179) suggest both components in the 2001 XMM spectrum arise from the reverse shock, due perhaps to an adiabatic and a radiative shock. Chandra et al. (2009, ApJ, 699, 388), as well as hydrodynamic simulations carried out by us, find that the X-ray emission in the first ~15 years is dominated by the reverse shock. The fact that the spectral shape, and dominant low temperature component, do not vary at later times suggests that the reverse shock continues to dominate the emission.

Conclusions: We have analysed most available X-ray data on SN 1993J through May 2014. The emission is thermal, with several indications that it is arising from the reverse shock. Both the X-ray and radio light-curves start to decrease much more quickly about 3000 days after explosion. This suggests a steep decrease in the circumstellar density profile, or that the progenitor wind mass-loss increased significantly about 4000 years before explosion. A similar increase a few 1000 years or less before explosion is postulated in many other SNe, such as SN 1996cr, SN 1994w, SN 1987A, SN 2006gy, SN 2008iy, etc.

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