

The Birth of a Supernova Seen in Real Time

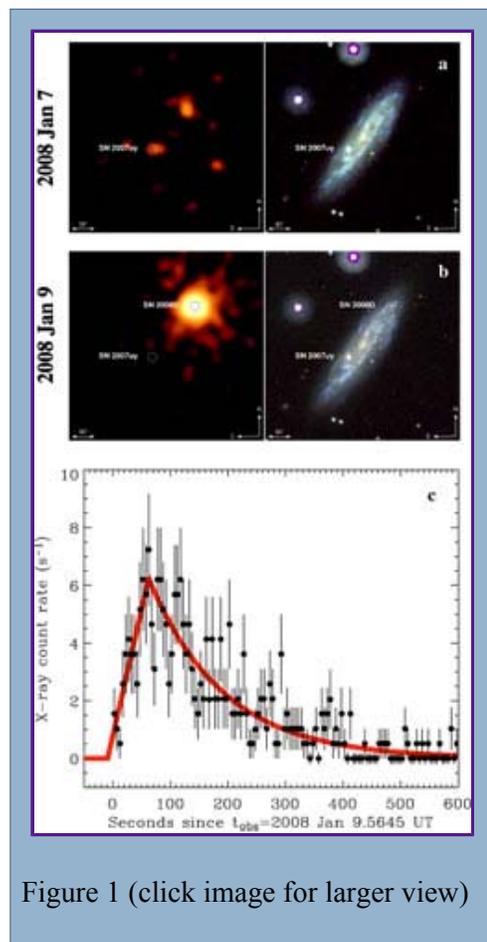


Figure 1 (click image for larger view)

Supernovae represent the explosive death of the most massive stars in the Universe, that live fast and die young, often within just a few million years. These explosions give birth to neutron stars and black holes, and fuel galaxy evolution through the injection of heavy elements and mechanical energy. Indeed, much of the material from which the Solar system and life on Earth were forged, processed and dispersed by supernovae and their progenitor stars.

The basic picture of a supernova explosion involves the collapse of the iron core at the end of the star's life. The collapsing core reaches nuclear densities within tens of milliseconds, and then rebounds, thereby generating a shock wave that eventually blows up the star. The details of the mechanism, however, remain highly uncertain, and even the most sophisticated numerical simulations fail to generate a clear explosion.

The explosion also leads to the synthesis of new elements. Of particular importance is Nickel-56 whose radioactive decay gives rise to bright optical emission — the hallmark of supernova explosions. The optical light becomes progressively brighter, reaching a peak level about two weeks after the explosion. Since supernovae are invariably discovered through their optical emission, they are generally found days to weeks after the actual explosion when most of the fireworks are already over.

However, it has long been predicted that the most extraordinary and luminous component of a supernova explosion is actually an intense and short-lived X-ray outburst at the moment that the shock wave rips the star apart, the so-called "break out" emission. Unfortunately, since such a transient signal is incredibly hard to detect, this X-ray signature has never been observed. As a result, no supernova has ever been seen at the time of explosion. We therefore lack an understanding of the first minutes, hours, and days in the evolution of supernovae.

All of this changed dramatically on January 9 of this year when we essentially won the astronomers' lottery. During our brief observation with Swift's X-ray Telescope (XRT) of a supernova in the nearby galaxy, NGC 2770 (d=27 Mpc), another star in the same galaxy exploded. The explosion was marked by an extremely luminous X-ray outburst,

$L_x \approx 10^{44}$ erg s⁻¹, lasting just a few minutes. Thanks to a stroke of good luck, we serendipitously recorded the whole event from start-to-finish with the XRT.

Swift's co-aligned Ultra-Violet Optical Telescope (UVOT) did not detect an optical counterpart contemporaneous with the X-ray outburst, but just two hours later it spotted a new optical source rising quickly in brightness. Through optical spectroscopy we quickly established that the nature of the transient was a very young supernova. In particular, the lack of hydrogen and silicon lines in the spectrum marked the event as a Type Ibc supernova (SN Ibc) which was thereafter designated SN 2008D. The phenomenal X-ray outburst can therefore be interpreted as the long-awaited confirmation and first ever detection of shock break out emission from a new-born supernova explosion.

However, it is also interesting to note that about 1 in every 1000 SNe Ibc gives rise to a gamma-ray burst (GRB) or an X-ray Flash (XRF). The hallmark of GRBs and XRFs are their ultra-relativistic outflows (bulk Lorentz factor, $\gamma \sim 100$), collimated into extremely narrow jets, and to which about 10^{51} erg is coupled. Given the extraordinary X-ray outburst we saw from Type Ibc 2008D, it is natural to question whether the high energy emission could be attributed to a relativistic GRB or XRF outflow.

Radio observations are the only way to address this question since they uniquely measure the energetics and geometry of the fastest material ejected in supernova explosions. These fast ejecta race out ahead of the slower bulk stellar debris and shock-accelerate electrons in the supernova's immediate environment. Synchrotron emission is produced as the electrons gyrate in amplified magnetic fields. By monitoring the evolution of the synchrotron emission, the properties of the fastest ejecta and the density of the environment are directly revealed.

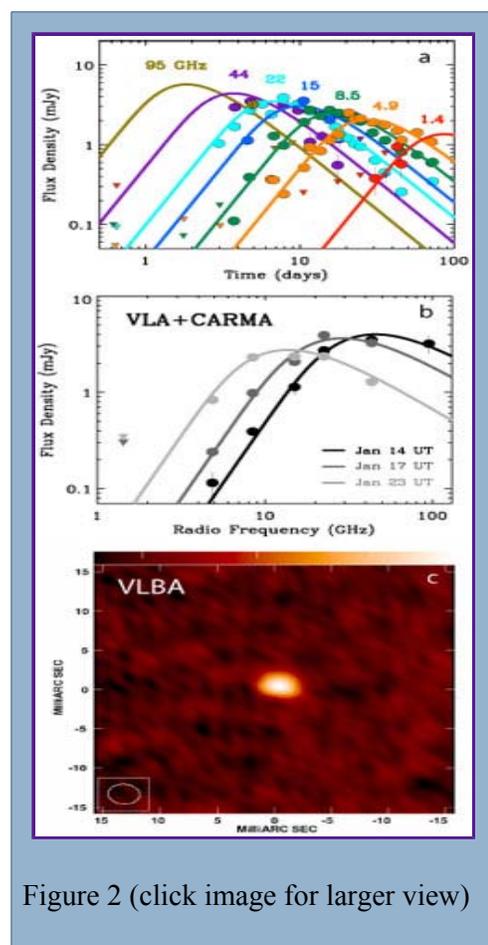


Figure 2 (click image for larger view)

To determine the nature of the X-ray outburst of SN 2008D — shock break out emission or relativistic outflow — we initiated a dedicated monitoring campaign with the VLA and CARMA beginning just hours after the X-ray outburst. Shortly thereafter, we detected a new radio source that grew in intensity over the next few weeks. Our densely sampled observations spanning 1.4 to 95 GHz are shown in Figure 2.

Twenty days after the outburst, the radio emission peaked at 8.46 GHz with radio spectral luminosity of $10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$, a factor of 10^4 lower than those of typical GRB afterglows, but comparable to the radio luminosities observed for nearby core-collapse SNe. Based on our modeling of the temporal and spectral evolution of the radio emission, we firmly constrain the velocity of the fastest ejecta to be just $v = 0.25c$ with a kinetic energy 10^{48} erg , or 0.1% of the total kinetic energy of the explosion. As a result, this explosion bears no resemblance to the extraordinary energetics and velocities inferred for GRBs and XRFs. The radio emission thus points to an ordinary core-collapse supernova in which only a tiny fraction of the explosion energy is coupled to fast ejecta.

Of course, the ultimate clincher in constraining the expansion speed of the ejecta is through direct measurements with VLBI since it may enable us to actually resolve the ejecta. Along this line, we obtained VLBA observations of SN 2008D at 1 month after the explosion (Figure 2). While the relativistic ejecta from a GRB or XRF would be easily resolved in this observation, the non-relativistic material from an ordinary supernova would be far too small. We show that the ejecta are not resolved in the VLBA map, imposing a conservative upper limit on the speed of the fastest ejecta to be $\gamma \approx 3$. We further note that these observations rule out the possibility of a relativistic jet pointed away from our line-of-sight.

In conclusion, our radio observations have enabled us to distinguish the nature of the SN 2008D X-ray outburst. As we report in a recent paper to Nature, every aspect of the supernova was fully in line with expectations for an ordinary core-collapse explosion. The X-ray outburst is well described by the long-predicted, but never yet seen, shock break out emission, and we clearly rule out any contribution from an associated GRB or XRF.

The most exciting conclusion of this study is that SN 2008D was perfectly ordinary explosion, caught in the act of exploding for the very first time. We can therefore expect that all ordinary supernova produce similarly spectacular X-ray outburst marking the time of explosion which may be used as an early warning beacon to enable follow-up from ground based facilities enabling searches for neutrino and gravitation wave signatures, which may ultimately unravel the mystery of supernova explosions. Looking forward, the field of supernova discovery and study is on the brink of a paradigm shift -- with more powerful X-ray satellites being designed now (e.g. EXIST), we predict that hundreds of supernovae will be discovered each year in the act of exploding, thanks to their powerful X-ray outbursts.

Alicia Soderberg (Hubble / Carnegie-Princeton Fellow, Princeton Astrophysics and Carnegie Observatories)

References:

Soderberg et al., 2008, Nature, 453, 469 (arxiv:0802.1712)