X-ray Emission From Young Supernovae as a Probe of their Progenitor Stars

Abstract: After several decades of study, the progenitor stars of supernovae (SNe) have still proven difficult to identify. The identification of progenitors has generally been the purview of optical astronomy, aided by stellar evolution models. But observations at other wavelengths can provide important clues about the progenitors. We have aggregated together data available in the literature, or analysed by us, to compute the X-ray lightcurves of most young SNe. We use these, coupled with analytical calculations and numerical simulations, to explore the various SN types, investigate SN expansion, explore the characteristics of the medium into which SNe are expanding, and examine the implications for their progenitors. The low X-ray luminosity of IIPs sets a limit on the mass-loss rate, and constrains the maximum initial mass of a red supergiant star which can become a Type IIP SN to < 19 $M_\odot$. We discuss the relationship between stellar evolution models and the X-ray emission from various SN types.

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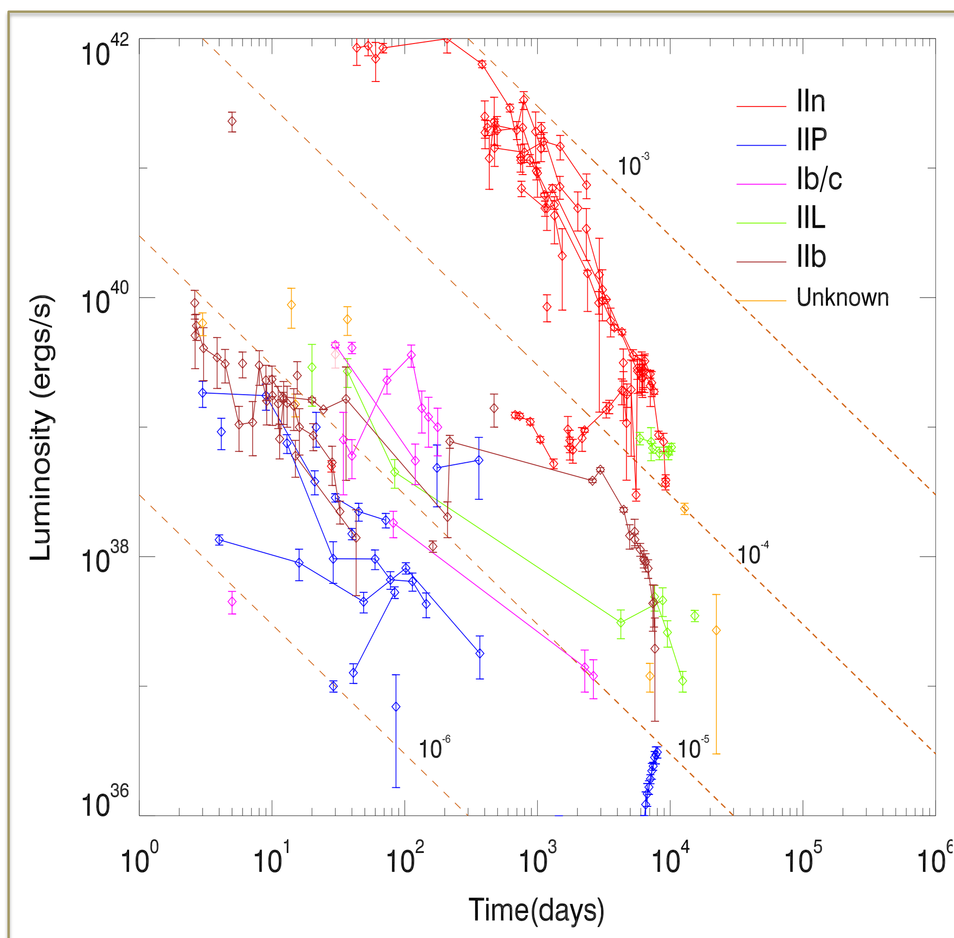

Fig 1: X-ray light curves of most SNe, grouped by SN type. Updated from Fig 3 in Dwarkadas & Gruszko (2012, MNRAS, 419, 1515). IIns make up the brightest group of X-ray SNe, and IIPs the faintest. GRB SNe not included. The dotted lines indicate the approximate mass-loss rate to produce the observed luminosity, assuming bremmstrahlung emission.

Massive Stars: Core-Collapse SN Progenitors

- Cool Massive Stars (Red Supergiants [RSGs]): Single stars ~(8)11-30(?) $M_\odot$ initial mass end their life as Red Supergiants.
- RSGs have dense, low velocity winds (~ 10-50 km s^{-1}, 10^{-7}-10^{-4} $M_\odot$ yr^{-1}).
- Single Massive stars (solar metallicity) > above 30-35 $M_\odot$ may explode as Wolf-Rayet (W-R) stars.
- W-R stars have fast, dense winds (1000-3000 km s^{-1}, 10^{-7} - 5×10^{-5} $M_\odot$ yr^{-1}).
- One SN whose progenitor is known reasonably well, SN 1987A, had a blue supergiant progenitor, with a wind velocity in the range of 500 km s^{-1}, and a mass-loss rate < 10^{-8} $M_\odot$ yr^{-1}.

Environments of Massive Stars

- Chevalier (1982, ApJ, 259, 302): X-rays ➡ thermal bremsstrahlung.
- X-ray emission probes ambient medium.
- Thermal bremsstrahlung $\propto$ $(\rho_{wind})^2$.
- The crucial ingredient is the ambient medium density, which depends on wind velocity and wind mass-loss rate as $\rho_{wind} \propto \frac{\dot{M}}{v_w}$
- For RSGs, v_w ~20 km/s, for W-R stars v_w ~ 2000 km/s.

➡ Density is much higher around RSG stars.

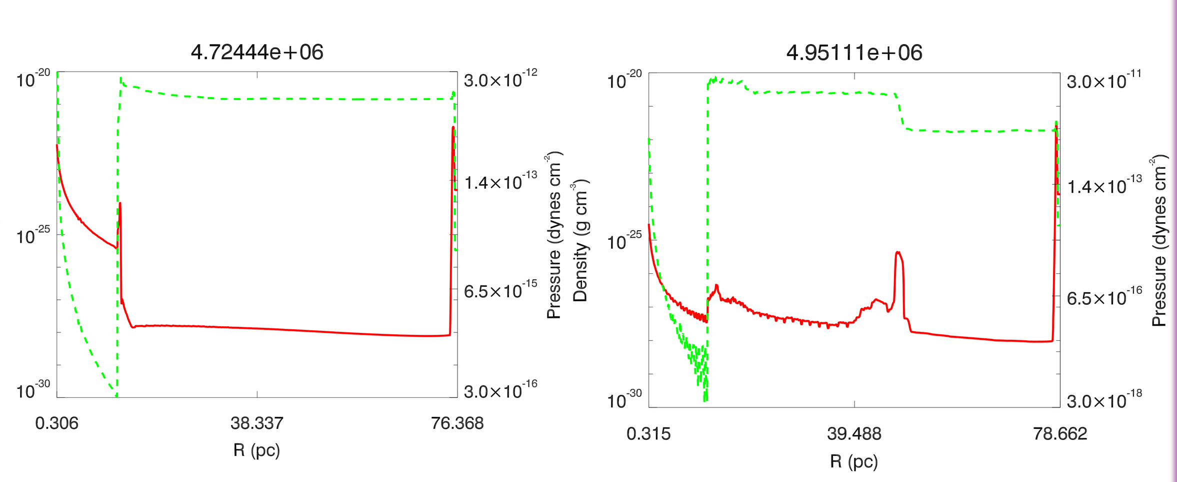

Fig (2a) [Left]: The expected structure of the circumstellar medium around a RSG star, the presumed progenitors of Type IIP SNe. Fig (2b) [Right]: Structure around a Wolf-Rayet star, the progenitors of Ib/c SNe. From Dwarkadas (2007, ApJ, 667, 226). Red – density; green – pressure; title - Time in years. SN first expands into freely expanding wind. Since RSG wind velocity is lower, expected wind density is higher.

Why do Type IIPs have the lowest luminosities?

1. The emission is not due to thermal bremsstrahlung.
2. IIPs do not arise from RSG stars. Our understanding of stellar evolution is incomplete.
3. We don't have a large enough statistical sample to judge.
4. The higher density, that results in the higher emission, also results in higher absorption (if the surrounding medium is not fully ionized). Maybe the high emission ones are totally absorbed?

Exploring The Above Suggestions

1. Chevalier et al. (2006, ApJ, 641, 1029) ➡ emission from IIPs not thermal; due to Inverse Compton scattering. But in a high density region (> 10^{-5} $M_\odot$ yr^{-1}), why is thermal bremsstrahlung not dominant? Perhaps density, and mass-loss rate, is not that high?
2. IIPs have the only observationally determined progenitors (aside from 87A and 93J) and all of them are RSG stars (Smartt 2009, ARAA). Strangely, all progenitor stars appear to have initial mass < 17 $M_\odot$.
3. This relates partly to the next question. From the X-ray lightcurves (Fig 1), it is clear that we detect other SNe with high mass-loss rates. Why would IIPs be preferentially not detected? Serendipitous surveys have not detected them either. Also absorption should decrease with time, so high mass-loss rate ones should be detectable at late times (> a few months).
4. Is all the emission from high mass-loss rate IIPs absorbed? Close to the SN, the ambient medium during the first 100 days is ionized by the SN flash. Due to the high densities close to the star ($\rho_w \propto r^{-2}$), this material recombines quickly. However X-ray emission itself can ionize the circumstellar medium.

Ionization of the Circumstellar Medium by Supernova X-rays

X-ray ionization depends on the value of the plasma parameter

$$\chi = \frac{L_x}{nr^2} = 120\,\dot{M}_{-5}\, v_{w,1}^{-1} t_{10d}^{-1}$$

Where the parameters refer to the mass-loss rate in 10^{-5} $M_\odot$ yr^{-1}, wind velocity in 10 km s^{-1}, and time in days.

- If $\chi > 100$, then C, N, O are ionized (Chevalier & Irwin 2012, ApJ, 747, L17). However to ionize all elements requires $\chi >$ 1000.
- For $\dot{M}$ ~ 10^{-5}, C, N, O are fully ionized for first few days, but are partially ionized after the first few weeks.
- For $\dot{M}$ ~ 10^{-4}, C, N, O are fully ionized first couple of weeks, but then lower stages of ionization dominate.
- For mass-loss rates > 10^{-5} $M_\odot$ yr^{-1}, it appears that the medium after a couple of weeks will be partially ionized. The optical depth of the medium can be written as (Fransson 1982, A&A, 111, 140):

$$\tau_{(E)} \sim 43\,\dot{M}_{-4}\, v_{w6}^{-1} r_{15}^{-1} E_{keV}^{-8/3}$$

This is approximately correct to a factor of two.

- First 10 days, for all $\dot{M} > 2\times10^{-6}$, the optical depth at 1 keV > 1, and no emission will escape. Therefore the SN is undetectable.
- After 1 month, for $\dot{M}$ ~ 10^{-5}, τ < 1, and we should begin to detect it.
- Higher mass-loss rates: Optical depth high, emission goes as $\dot{M}^2$.
- Thus even if the optical depth is high, we could get observable flux.
- At highest mass-loss rates, the X-ray flux for a SN within 10 Mpc will be ~ 10^{-14} ergs/s/cm^2, which should be detectable with Chandra.
- For high mass-loss rates, the reverse shock will be radiative. At later times > a few months, depending on the mass-loss rate, the shock will become adiabatic, and reverse shock emission will kick in. So it should enhance the emission.
- Another difficulty: If T_e << T_i, then initially the temperature and emission may be lower than in equilibrium by a factor of 5-10 (Fransson et al. 1996, ApJ, 461, 993). However, the flux will be high and still just about detectable. Over time T_e will approach T_i.
- Comptonization is not important.
- Conclusion: At least some IIPs with high mass-loss rates should be detectable, either at early or late times. But from the figure, none are detected.
- Perhaps IIPs with high luminosities, or mass loss rates greater than about 10^{-5} $M_\odot$ yr^{-1}, do not exist!

Maximum Mass of IIP progenitors

Geneva mass-loss rate luminosity relation for RSGs: $\dot{M} = 4.7\times10^{-6}(L/10^5)^{1.7}$

For $\dot{M}$ ~ 10^{-5}, this implies a maximum luminosity of about 1.6 × 10^5 $L_\odot$

Using M-L relation from Mauron & Josselin (2011, A&A, 526, 156): M ≈ 0.14 $L^{0.41}$ we get: $M_{max,IIP}$=19 $M_\odot$ (Dwarkadas 2014, MNRAS, 440, 1917)

Thus X-ray data suggest maximum mass of a IIP progenitor ≈ 19 $M_\odot$.

Smartt (2009, ARAA, 47, 63): optical limit ≤ 16.5 $M_\odot$ for IIP progenitors.

Georgy et al. (2012, A&A, 538, 8): Rotating Stars > 16.8 $M_\odot$ will not explode as RSGs but become W-R stars. Non-rotating star limit 19 $M_\odot$.

Theory and observations indicate that stars up to 19 $M_\odot$ explode to form IIPs.

Stars with initial mass greater than 19 $M_\odot$

What about stars with initial mass > 19 $M_\odot$? Georgy et al (2012) suggest that they all explode as W-R stars of one or another type.

1b/c SNe are presumed to arise from W-R stars. But W-R stars have lower densities than IIPs (Fig 2b), because of the high wind velocities. To account for the higher X-ray luminosities, presumably the luminosity must not come from the density. This indicates that their X-ray emission may be non-thermal, as suggested by Chevalier & Fransson (2006, ApJ, 651, 381). The emission is presumably inverse Compton, as found for several 1b/c SNe.

What about Type IIL and Type IIb?

We know that SN 1993J, a IIb, arises from a binary, which may be the reason for its high mass-loss rate. Its X-ray emission is definitely thermal. It is possible that all extended (Type eIIb) SNe come from binaries, have high mass-loss rates and show thermal emission. While the compact (Type cIIb) are the more traditional ones that arise from a single W-R progenitor with fast shocks, and presumably show non-thermal emission.

Not clear where IILs fit in. They presumably arise from a more massive RSG or YSG progenitor that ended its life in a WR phase but has a dense envelope surrounding it.

Type IIn SNe

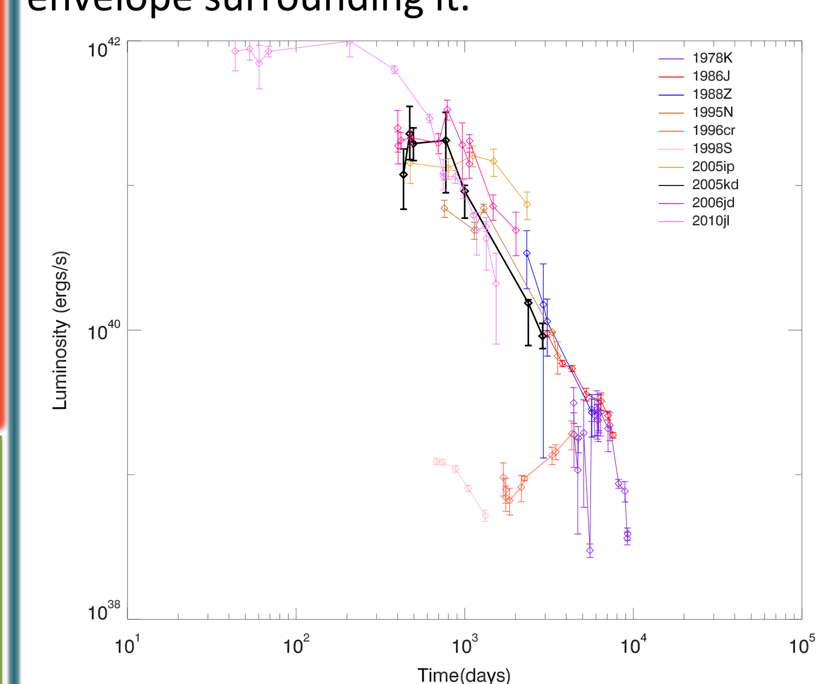

Fig 3: Observed X-ray lightcurves of Type IIn SNe. They have the highest X-ray luminosities, up to 10^{42} ergs s^{-1}. They also show the largest variety of lightcurves, with some having steep slopes, others showing initial steady luminosity for a couple of years, and one where the X-ray flux increased for almost a decade.

As a class, they presumably have multiple progenitors (Dwarkadas 2011, MNRAS, 412, 1639). Many show clear thermal emission, but it may be that in a few cases the emission is non-thermal.

For some Type IIns such as SN 1988Z and SN 1986, steep X-ray decreases cannot be fitted with any known analytic model. These may perhaps be better fitted by a two-component medium, consisting of dense clumps in a less dense wind medium (Chugai & Danziger 1994, MNRAS, 268, 173). Others such as SN 2006jd and SN 2005kd require high densities that are not consistent with W-R stars, for one or two component media, and require a different progenitor.

One SN with a possible W-R star progenitor is SN 1996cr. Using the increasing X-ray and radio emission, coupled with a 485 ks HETG spectrum, Dwarkadas et al. (2010, MNRAS, 407, 812) showed that the SN evolved in a low density windblown medium before impacting a dense shell 0.03pc away from the star. Further studies showed that the wind properties of the star were consistent with a W-R progenitor, although they could not rule out a SN 1987A-type progenitor (Fig 4).

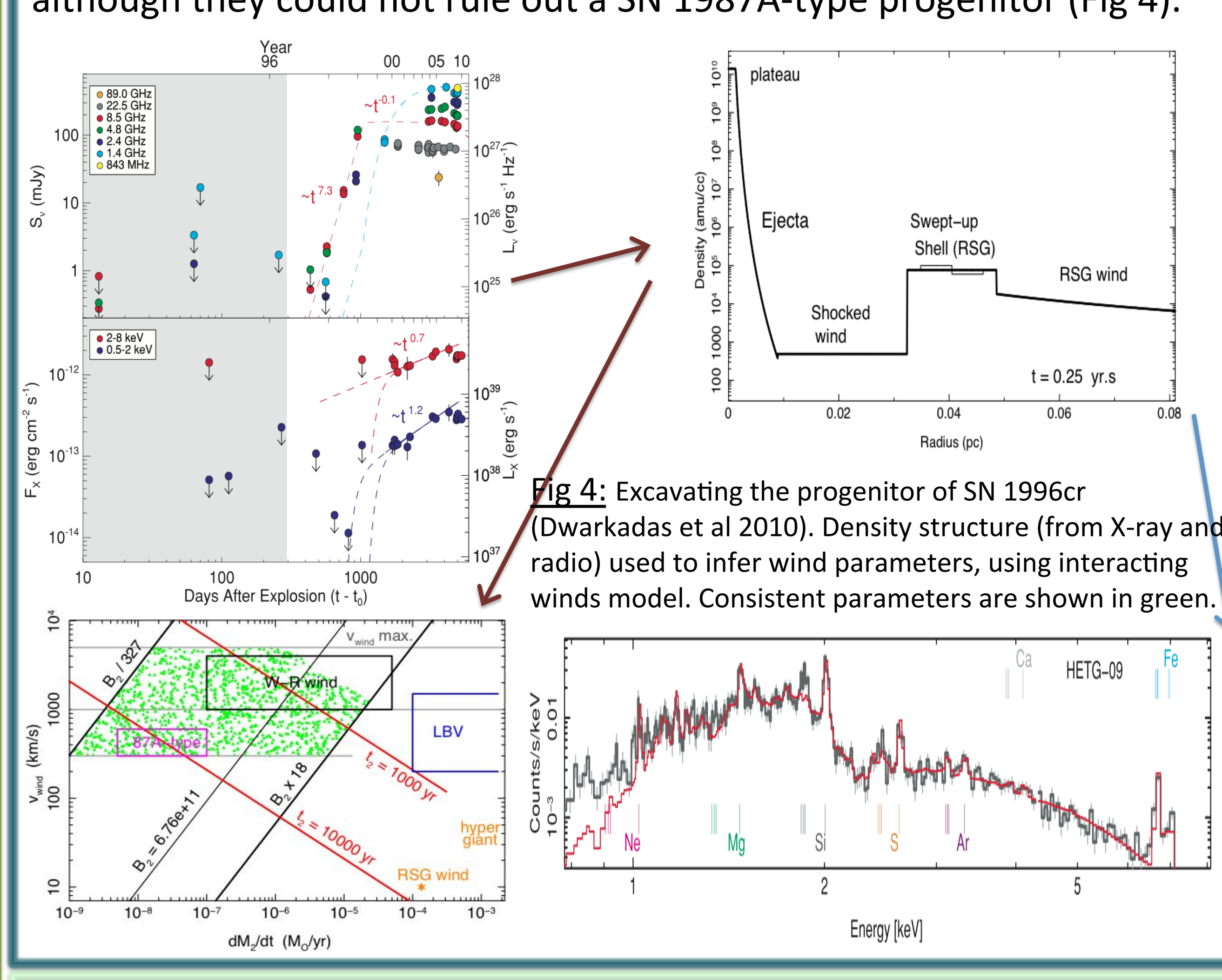

Fig 4: Excavating the progenitor of SN 1996cr (Dwarkadas et al 2010). Density structure (from X-ray and radio) used to infer wind parameters, using interacting winds model. Consistent parameters are shown in green.

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