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Unveiling the structure of the progenitors of type-IIP Supernovae through multi-waveband observations

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Abstract. Observational evidence from archival, pre-explosion images, suggests that progenitors of type-IIP SNe (SNe-IIP) have $8 \leqslant M_P \leqslant 17\ M_\odot$. However, the post-explosion temporal evolution of the event suggests that even in this mass range, the stellar evolutionary paths, the ensuing mass loss, and the eventual interaction of the supernova shock with the resulting CSM can show considerable diversity. Here we present the results from our program on multi-waveband (mainly optical) observations of SNe-IIP. Mass loss in their progenitors, with a massive and extended H-envelopes, is seen to occur via both strong stellar winds, or episodic mass ejections. Moreover, some type-IIP SNe also show unusually steep decline, characteristic of type-IIL (e.g. SN-IIP 2013ej). Our early and late-time spectrophotometry of these events shows CSM- shock interaction to varying degree among progenitors of comparable mass. Combined with X-ray data, our findings suggest that SNe-IIP progenitors can lose mass via strong stellar winds (e.g. SN2013ej, and SN2014cx), have episodic mass loss (SN2011ja), or have negligible mass loss (SN2012aw, SN2013ab).

Keywords. (stars:) supernovae: individual (SN2013ej, SN2013ab, SN2012aw)

1. Introduction

The advent of small and medium scale synoptic surveys over the last decade or so had greatly increased the number of supernovae events detected across all types and subtypes, while the ready accessibility of archival data had made it possible to serendipitously identify the progenitors for some of nearby events. The total number of events discovered to date stand at > 12000, and while most of them have been faint ($V > 18$) at discovery, $\sim 5\%$ of these have been bright enough to permit an optical and multi waveband study of the temporal evolution of their spectral and photometric properties, some over durations ranging from as early as $\sim$ few hr post explosion to few years. With this proliferation of observational data, the distinction between the various sub-types of type-II supernovae appears to be blurring. The spectral and temporal characteristics of supernovae being dependent on the progenitor properties, its evolutionary history, and on the interaction of the supernova shock with the environment (mainly, the circumstellar material ejected by the progenitor on it path towards the explosive finale), this has brought about renewed interest in post main-sequence evolutionary models of massive stars, and especially in the mechanisms and epochs of mass loss as a function of progenitor mass (M_{Prog}), ZAMS metallicity (Z_{Prog}) and spectral characteristics.

Core collapse supernovae (hereafter CC-SNe) in progenitors with a residual H-envelope have been traditionally classified (according to their light curves, and their early time spectra) in to types -IIP (-Plateau), -IIL (Linear), -IIn (Narrow emission lines) and -IIb (analogues of type-Ib, but with some H in the early spectra), with SNe-IIP being the most common type. The identification of the progenitors of 11 SNe-IIP, 2 SNe-IIL and 3 SNe-IIb from archival (mainly HST), imply ZAMS masses for SNe-IIP / -IIL of $8 \leqslant M_{Prog}/M_{\odot} \leqslant 15$ (see Smartt, 2015 and references therein), although early x-ray emission from some SNe-IIP suggests a possible upper limit of $M_{Prog} \leqslant 19\ M_{\odot}$. The direct observations set an overall upper limit of $\log L_{Prog}/L_{\odot} \leqslant 5.1$ dex is set for progenitors of all SNe-II. This is in contradiction with stellar evolutionary models, which can generate SNe-IIP in red super giants (RSG) with $16 < M_{RSG} < 30$ $\mathrm{M}_{\odot}$. Moreover, the observed cosmic supernovae rate is significantly smaller than star formation rate. While there is some theoretical indication that this contradiction can be resolved if RSGs with compactness factor of $\zeta > 0.2$ collapse directly in to black holes (Horiuchi *et al.*, 2014), this solution than raises the question of the number of galactic, stellar mass, black holes – a problem which can only be resolved in the post-LIGO era. In the electromagnetic waveband, it becomes necessary to (a) increase the number of events with known or tightly constrained progenitors, and (b) to investigate both theoretically and observationally, all the possible scenarios of mass loss, including both continuous, as well as episodic (up to $\sim 1M_{\odot}$) even in low mass ($8 < M_{RSG} < 16$ $\mathrm{M}_{\odot}$) RSGs, occurring within a few months to a few decades immediately prior to the core-collapse.

As the supernova shock propagates through the star, and its overlying medium, its interaction illuminates the progenitor's history. As the shocked ejecta rams in to the circumstellar (or interstellar) medium (CSM or ISM), the event itself brightens and dims in the various electromagnetic bands. The optical photosphere lies within the ejecta, and moves inwards, along with the recombination front. Thus, the very early ($\leqslant 1$ d) UV/optical emission can be used to estimate the photospheric temperature of the progenitor (Rabinak *et al.*, 2011). M_{Prog} can be inferred indirectly, by modelling the light curves (see SN2013ej-opt and references therein) to estimate the mass of radioactive ^{56}Ni in the post-collapse core. Propagation of the recombination front in to the deeper layers of the ejecta, combined with the optical thinning of the ejecta itself, then reveals the inner structure of the stellar envelope, with metal lines [Fe, Ca, Sc] revealing themselves as the event reaches nebular stage. By contrast, thermal x-ray and synchrotron radio emission occur from SNe when the fast moving ($\sim 10^4$ km s^{-1}) ejecta slams into the slow moving ($\sim 10^2$ km s^{-1}) winds ejected by the progenitor (Chevalier *et al.*, 2006). While both forward and reverse shocks can emits x-rays, since the latter is embedded and propagating deep in to the dense ejecta profile, x-ray emission from this region is attenuated. Therefore, the effective x-ray photosphere lies within the CSM and moves outwards with the forward shock. The unfolding x-ray light curve therefore probes the mass-loss from progressively earlier pre-explosion epochs.

2. Observations

All of the events in the case studies presented here occurred in isolated progenitors with extended H-envelopes. All were detected early, within 0.6 (SN2013ej) to ~ 2.5 d (SN2012aw) post explosion. All were bright, with peak M_V in the range -17.3 – -18.5. While both SN2012aw and SN2013ej were x-ray bright, no early x-ray emission was

Table 1. UV/Optical/NIR characteristics of the various SNe-II discussed herein. Unless otherwise mentioned, data for SN2013ej is from SN2013ej-opt, for SN2013ab from SN2013ab-opt, and that for SN2012aw from SN2012aw-opt.

Object	Explosion date MJD	distance Mpc	$(M_V)_{peak}$	E(B-V)	$\log_{10} L_{bol} \vert peak$ (UBVRI) erg s^{-1}	Plateau	
						duration d	decline δM_V (100 d)$^{-1}$
SN2013ej	56497.3 ± 0.3	9.57 ± 0.57	-17.5	0.06 ± 0.001	42.37	$\sim$ 85	1.74
SN2013ab	56340.0 ± 1.0	24.0 ± 0.9	-17.3	0.044 ± 0.066	42.25	$\sim$ 78	0.92
SN2012aw	56002.6 ± 0.8	9.9 ± 0.1	-18.5	0.074 ± 0.008	42.12	$\sim$ 100	0.55

detected from SN2013ab. Since early radio emission is often correlated with x-ray, no search is reported in the literature for the radio counterpart of SN2013ab. Their notable optical characteristics are tabulated in 2, while the x-ray and radio properties are in 2.

The densely sampled light curves of SN2012aw (see figure 4, Bose *et al.*, 2013) reveal the presence of a local minima (followed by a sudden brightening) in the I at 31 d (42 d in V, 39 d in R), followed by a slow rise to a plateau at $\sim$ 73 d (51 d in V; 59 d in R). A comparision with the bolometric light curves shows that the VRI bands contribute $>$ 80% to the total flux at these epochs, while the optical photospheric temperature (as inferred from the UBVRI curves) is $\sim$ 5000 K, i.e., well below that required for the onset of hydrogen - recombination. Thus, the local minima most likely signals a transition from a phase dominated by adiabatic cooling of the shocked ejecta, to one dominated by H-recombination, causing the characteristic plateaus of SNe-IIP. Since then, a similar dip has been seen observed in a few other events – notably, in SN2013ab (see figure 3, Bose *et al.*, 2015 I), and in SN2014cx around (53 d in V; Huang *et al.*, 2016). Such a minima is not seen in SN2013ej (figure 3, Bose etal.,2015 -II), which, while intrinsically brighter than 2012aw and 2013ab at discovery, declined steeply ($\delta M_V = 1.74$ (100 d)$^{-1}$) similar to a "typical" SNe-IIL rather than SNe-IIP, implying a more compact progenitor with a smaller, pre-explosion, H-envelope.

SNe-II light curves decline most rapidly in the UV bands. All 3 events in tab. 1 were detected in the *Swift*-UVOT bands for up to $>$ 100 d post-explosion. While the early light curves of SN2012aw and 2013ab decline steeply ($\sim$ 0.2 mag d^{-1} for 2013ab), by $\sim 30d$, they settle in to a plateau, as expected. By contrast, while the *Swift/UVOT* `uvw2` and `uvm2` light curves of SN-IIL 2013ej continued to decline until end of the observations at $\simeq$ 80 d, the NUV band `uvw1` light curve "plateaus" at 40 d, nearly concurrent with the `uvv` band light curve, and then sharply declines to the nebular tail powered by radioactive decay of $^{56}Ni \rightarrow^{56} Co \rightarrow^{56} Fe$ at 100 d

Temporal evolution of the spectra of all three events reveal interesting possibilities about the presence of anisotropic, inhomogeneities in the ejecta's density and abundance profiles. Weak absorption features at 4300 Åand 4850 Å, and stronger absorption features at 5500 Åand 4500 Å, associated with high velocity (hereafter HV) components of [He I] and H-β, were detected in the early spectra of SN2012aw (see Fig. 10, Bose *et al.*, 2013). The [He I] features at 17665 km/s on 7 d slowed down to 16643 km/s on 8 d, and does not appear in the spectrum taken 12 d post-explosion. A similar HV feature in the H-β is also seen to slow down from 21785 km s^{-1} to 21477 km s^{-1}, and then disappear over the same period. Finally, we note the reappearance of the HV feature in H-β near the start of the nebular phase at 104 d post-explosion, blended with [Ba II] and [Sc II] lines. While similar features have been detected in some other, well studied, luminous SNe-IIP, e.g. SN1999em, 1999gi and 2007od but they are by no means typical of SNe-IIP, and are not detected in the spectra of SN2013ab. Interestingly, these features are never seen in H-α, and their origins are yet disputed, although they may possibly be from dense

Table 2. Early radio and x-ray characteristics of our target type-IIP SNe. Unless otherwise mentioned, $3-\sigma$ upper limits are provided.

Event	x-ray		radio		
	days post-explosion	unabsorbed f_X (0.2-10 keV) erg cm^{-2} s^{-1}	days post-explosion	frequency GHz	flux f_r mJy
SN2013ej[1]	5.7	5.463×10^{-13}	7	6.7	< 35
SN2013ab[2]	4.11	$\leqslant 5.97 \times 10^{-13}$	–	–	–
SN202aw	4.35 [3]	$(7.8 \pm 2.1) \times 10^{-14}$	7.65[3] 13.5[4]	20.8 21.2	0.160 ± 0.025 0.315 ± 0.01

Notes:
[1] From Swift detection (Margutti *et al.* 2013-II). Radio detection from 32m INAF-IRA in Medicina and Noto (Sokolovsky *et al.* 2013).
[2] Based on Swift observations (Margutti *et al.* 2013) with 10 keV thermal plasma model, and total column density of $N_H = 4.7 \times 10^{20}$ cm^{-2}.
[3] Swift detection (Immler & Brown, 2012.) and EVLA detection (Stockdale *et al.* 2012).
[4] EVLA detection (Yadav *et al.* 2012).

clumps within the ejecta itself. In this respect, the spectra of SN2013ej (see Figure 9, Bose etal.,2015 -II) are somewhat anomalous, in that we see the formation of an absorption feature in emission component of the H-α P-Cygni profile 97 d post-explosion onwards. Since 2013ej is also x-ray bright and showed x-ray emission at similar epochs, we interpret this as due to interaction of the ejecta with the CSM. Moreover, weak absorption features in the blue wing of H-α and H-β P-Cygni profiles in the early (12 d to 42 d) spectra of SN2013ej may also be early signs of CSM interaction, although they can also be modelled as HV features from [H I], or blended lines of [Si II] at 6347 and 6371 Å.

In addition to the early x-ray and radio characteristics of these events (see table 3), SN2013ej was also observed with Chandra over 5 epochs, from 28.9 d to 145.1 d post-explosion (see Table 2, Chakraborti *et al.*, 2016). The early x-ray emission is dominated by hard x-rays, generated via inverse Compton scattering of optical and UV photons in to x-ray energies. However, this component fades 28.9 d post explosion, and is replaced with a soft x-ray (thermal) component with median (0.5-8.0 keV) flux of 7.0×10^{-15} erg cm^{-2} s^{-1}. Treating the inverse Compton component as a power law, and the thermal component as a combination of bremsstrahlung and line emission from a hot plasma, x-ray spectral fitting was used to determine the column density of the cool shell embedded between the forward and the reverse shocks, as well as the temperature of the reverse shock itself. The mass of the surrounding shell, and hence the mass-loss rate as a function of look back time was then inferred as ranging from $(4.38 \pm 1.53) \times 10^{-6}$ to $(2.61 \pm 0.50) \times 10^{-6}$ $\dot{M}_\odot$ yr^{-1}, over look back times ranging from 48 ± 17 to 338 ± 19 yr. While no follow-up observations in x-ray or radio were carried out for the x-ray and radio-dim SN2013ab, Yadav *et al.* 2014 carried out extensive radio observations of SN2012aw at frequencies ranging from 1.3 to 32.0 GHz with the GMRT. Their radio light curves cover 8 d – 183 d post explosion, i.e. from the initial peak to early nebular stage of the optical light curve. Modelling the radio emission as synchrotron emission from relativistic electrons with a high energy cut-off, they determine a mass loss rate of 1.9×10^{-6} $\dot{M}_\odot$ yr^{-1} (see table 2) for the progenitor of this event.

3. Conclusions

The inferred properties of SN2012aw, 2013ab and 2013ej are given in table 2. Unless otherwise mentioned, M_P and R_P are extracted from the optical observations, using methods discussed in section I. The mass-loss rates for SN2013ej are inferred from

Table 3. Inferred properties of the supernova explosion and its progenitor from UV/optical/NIR , x-ray and radio observations

Event	Mass of ^{56}Ni $M_\odot$	Explosion energy 10^{51} erg.	M_P $M_\odot$	R_P $R_\odot$	$\dot{M}$ $\times 10^{-6}$ $M_\odot \mathrm{yr}^{-1}$	Comments Mass loss via stellar winds
SN2013ej	0.02	~ 2.3	13.7 ± 0.3 [1]	~ 450	4.38 ± 1.53 to 2.61 ± 0.50	Continuous mass-loss over look-back times ranging from 48 ± 17 to 338 ± 19 yr
SN2013ab	0.064	0.35	~ 9	~ 600	–	No evidence of a CSM seen.
SN2012aw	0.06 ± 0.01	0.9 ± 0.3	14 ± 5	337 ± 67	1.9	Assumes continuous mass-loss.

Notes:

[1] Note Based on MESA simulations of progenitors with a median mass loss rate of $(2.6 \pm 0.2) \times 10^{-6}$ $\dot{M}_\odot$ yr^{-1}, as inferred from Chandra observations (Chakraborti *et al.*, 2016). This is consistent with the optical value (from mass of ^{56}Ni) of ~ 14 $M_\odot$.

x-ray, and for SN 2012aw, from radio observations. As demonstrated, these observations provide far more stringent limits on the M_P than those set from models to the optical data alone. Archival HST exist only for fields of SN2012aw and SN2013ej, and set limits of $M_{prog}/M_\odot \leqslant 15.5$ and $8 < M_{prog}/M_\odot < 15.5$ respectively, consistent with the values derived from models to post-explosion observations.

We note that even within this very limited set of events, with $9 \leqslant M_P \leqslant 13.7$ $M_\odot$, there is a considerable diversity, both in the event characteristics, as well as in the progenitor-environment properties and their interaction. SN2012aw appears to be an unusually luminous SN-IIP, and with a progenitor mass-loss rate similar to that of SN2013ej. Moreover, the two events have similar M_P. Nevertheless, SN2013ej is closer to a "classic" type-IIL, while SN2012aw was similar in most optical aspects to the archetypal type-IIP SN1999em. It is to be noted that SN2013ej was initially identified as an SN-IIP based on its early time spectra. It is possible that it represents a transitionary event between the two classes – a feature which has been noted for several other SNe-II, as has been reported by other groups in the literature. The HV features near nebular stage may also suggest a possible bipolar distribution of ^{56}Ni, but detailed hydrodynamic models are not yet available to us, to confirm this. Events like SN2013ej demonstrate the need for spectral follow-up of SNe at several epochs, especially when classifying events for the determination of the cosmological SNe rate, as a function of the supernova type.

Next, comparing the inferred mass-loss rates of the progenitor of SN2013ej with that of SN2011ja (Chakraborti *et al.*, 2013), we note that while the former appears to have had strong stellar winds for the last ~ 400 yr of its lifetime, the latter appears to have either CSM bubbles caused by the hot progenitor wind, or was a progenitor with episodic mass loss. Finally, we note the occasional, brief, emergence of narrow line features, similar to those seen in the spectra of type-IIn events, in the H$-\alpha$ feature in the optical spectra of SNe-II, e.g., most prominently in the case of SN1999gi at 35 d and 82 d post-explosion, but also in SN2014cx (at 20.6 d and again at 27.8 d) and, to a lesser extent, in SN2016gkg. In the case of type-IIn, these features have been attributed to a dense, slow moving, clumpy CSM. Since typical $M_P/M_\odot \simeq 40$ for type-IIn, they are not expected in type-II with $M_P/M_\odot \leqslant 17$. While it is possible that in some cases this may be due to line blending from other atomic species (most notably, He), it may also imply the existence of a clumpy CSM due to episodic mass ejections from the progenitors. All of this suggests the need to explore multiple mechanisms for mass-loss from massive stars, as it could drastically change both their evolutionary track in the post main-sequence HR diagram, and the fate of the final, explosive, event.

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Discussion