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A subluminous Type IIP supernova 2008in having properties unknown so far

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Abstract. Supernova (SN) 2008in is a Type IIP event, which occurred in the outskirts of the nearby and nearly face-on spiral galaxy M 61. The spectroscopic observations of this event suggest that it resembles those of the archetypal low-luminosity Type IIP SNe 1997D and 1999br. However, the extensive photometry reveals that its light curve is quite different from that of low-luminosity events. The derived bolometric flux also indicates that the radioactive ^{56}Ni, produced during this process is significantly higher than that produced in case of low-luminosity events. Adopting an interstellar extinction of $A_V \sim 0.30$ mag along the SN line-of-sight and a distance of 13.19 Mpc, the estimated value of ejected ^{56}Ni mass is $\sim 0.015 M_\odot$. The prescription of Litvinova & Nadezhin indicates that the pre-SN radius of the SN 2008in was $\sim$ 126R$_\odot$ and the explosion energy is of $\sim 5.4 \times 10^{50}$ erg. This value is consistent with the explosion energy determined through the radiation-hydrodynamical simulations of core-collapse IIP SNe. These parameter values are comparatively smaller than those of normal type IIP events. The estimated amount of total ejected mass is $\sim$ 16.7M$_\odot$. Assuming the mass of compact remnant $\sim 1.5 - 2.0 M_\odot$, we can confine the zero age main sequence mass of the progenitor within 20M$_\odot$.

Keywords : supernovae: general – supernovae: individual (2008in)

1. Introduction

Core-collapse SNe (CCSNe) are in general a heterogeneous class of objects that produce a wide range of explosion energies and expansion velocities. Out of these events, low luminous type IIP CCSNe are still under debate due to the unknown nature of

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their progenitors. The first observed candidate was SN 1997D (Turatto et al. 1998; Benetti et al. 2001), which showed diverse properties in light curve and spectra. It was explained as a result of large fall-back of ejected material towards a newly formed stellar mass black hole, created by the collapse of the core of a massive progenitor ($M \geq 20M_{\odot}$, Zampieri, Shapiro & Colpi 1998) or as an explosion of a less massive progenitor ($8-10M_{\odot}$, Chugai & Utrobin 2000), close in mass to the lower limit for stars which can undergo core-collapse. A detailed study of optical light curves and spectra of only few nearby IIP SNe has been done so far and there exists a discrepancy in estimation of the mass of their progenitors. For the three well-studied events (namely, 1999em, 2005cs and 2004et), estimated value of the progenitor mass from hydrodynamical modeling of their light curves are found to be higher than that estimated from pre-SN imaging (Smartt et al. 2009; Utrobin, Chugai & Botticella 2010; Bersten, Benvenuto & Hamuy 2011).

SN 2008in was discovered by Koichi Itagaki on 2008 December 26.79 UT in the nearby galaxy M 61 (NGC 4303), with an unfiltered magnitude of 14.9. An independent observation of this event by K. Kadota revealed the transient at an unfiltered mag of 15.1. W. Wells also recorded the SN on 2008 December 28.46 UT at V and R band magnitudes of 14.3 and 13.2 mag, respectively (Nakano, Kadota & Wells 2008). Low and mid-resolution spectroscopic observations identify this event as Type IIP event with an early discovery.

The broad band light curve and the initial spectral evolution of SN 2008in were similar to those of normal type IIP SNe. However, from mid-plateau, the SN started to show a few spectral features (like Hα) which are similar to under-luminous events. Though SN 2008in was a proximate Type IIP event, it was never detected in radio (Stockdale et al. 2008, 2009).

2. Photometric and spectroscopic evolution

We report an extensive optical and IR photometric and spectroscopic follow-up observations of SN 2008in along with $Swift$ XRT (Burrows et al. 2005) and UVOT (Roming et al. 2005) observations, covering the total time interval of about 410 days from the date of discovery. The initial evolution of the transient was observed by ROTSE-IIIb automated telescope. Long-slit low resolution spectra (~ 6 to 14 Å) in the optical range ($0.33 - 1.0\ \mu$m) were collected at eleven epochs during +7d to +143d, including five epochs from the 2m IGO, three epochs from the 9.2m HET, two epochs from the 6m BTA and one epoch from the 3.6m NTT. The details of data reduction procedure and photometric results have been tabulated elsewhere (Roy et al. 2011b).

The left panel of Fig. 1 represents the light curve of SN 2008in . The light curve evolution of SN 2008in is similar to the well studied low-luminosity event SN 2005cs, starting from near UV to near IR bands. The plateau durations of SN 2008in is ~ 100

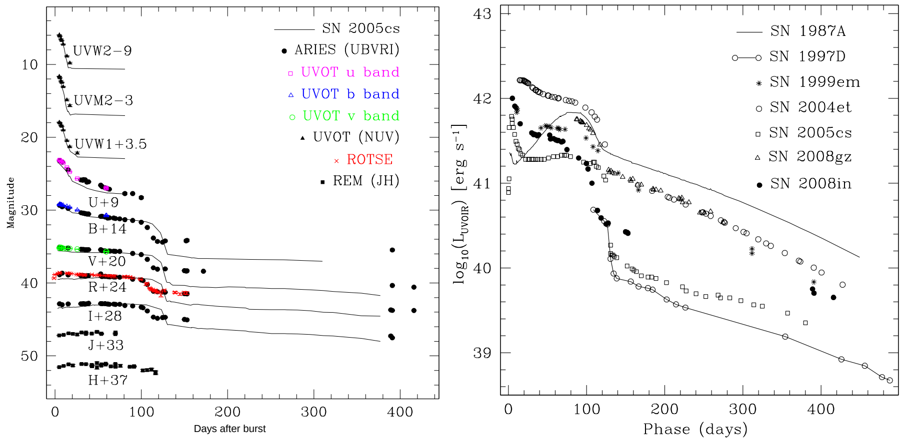

Figure 1. Light curves of SN 2008in in different observing bands is shown in left panel. The SN 2005cs light curves from Brown et al. (2009) and Pastorello et al. (2009) have been used as templates. In the right panel, comparison of the quasi-bolometric light curve of SN 2008in is plotted along with other low-luminosity SNe 1997D, 2005cs; the normal SNe 1999em, 2004et, 2008gz; and the peculiar Type II SN 1987A.

days, less than that seen in the case of SN 2005cs. Plateau to nebular drop of SN 2005cs is also more than that for SN 2008in . This deviation is about 2 mag in V band.

The quasi-bolometric light curves presented in the right panel of Fig. 1, has been estimated from the UV, Optical and IR broadband (*UVOIR*) magnitudes of SN 2008in after calculating the distance of the SN 2008in (13.19 ± 1.09 Mpc)[1] and extinction (A_V = 0.305 ± 0.322 mag, Roy et al. 2011b) along that direction. Since at late stage Type IIP SN luminosity is powered by synthesized radioactive ^{56}Ni and ^{56}Co, mid plateau and tail luminosity of these SNe are good estimators of ^{56}Ni generation. From bolometric light curve it has been derived that roughly 0.015 ± 0.003$M_\odot$ ^{56}Ni was produced during this event.

The spectroscopic observations illustrate the rapid evolution in the spectral features of SN 2008in during the plateau phase. The spectra of SN 2008in, after correcting for the recessional velocity of the host (~ 1567 ± 3 km s^{-1})[2] are shown in the left panel of Fig. 2. The first two spectra observed at +7d and +14d after the shock breakout show broad Hα , Hβ and He I lines indicating very high velocities of SN ejecta. The third spectrum which was observed nearly +54d after the burst, shows a

[1]The measured distance is the average of three different estimations, namely (i) Hubble flow distance estimation, (ii) Tully-Fisher method and (iii) Standard Candle method (Roy et al. 2011b). The cosmological model with H_0 = 70 km s^{-1} Mpc^{-1},Ω_m = 0.3 and Ω_Λ = 0.7 is assumed throughout the work.

[2]http://leda.univ-lyon1.fr/

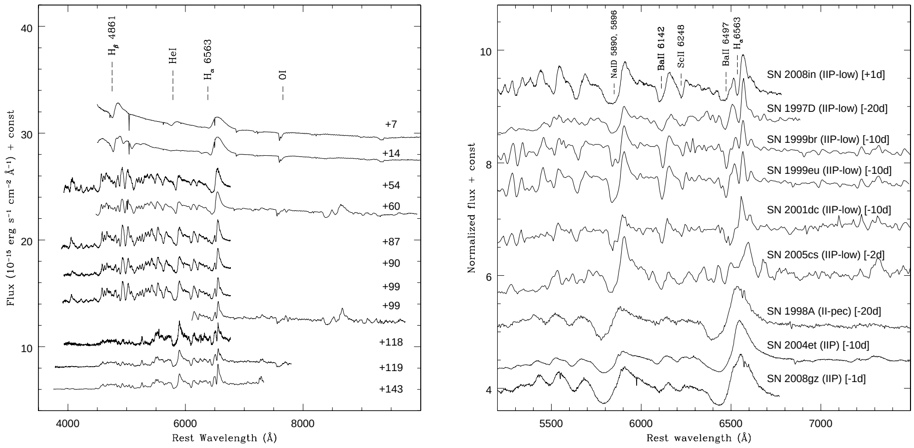

Figure 2. Left panel : Doppler corrected flux spectra of SN 2008in from +7 d to +143 d. Prominent Hydrogen and He lines are marked. Right panel : The end plateau spectrum (+99d) of SN 2008in, is compared with five low-luminosity SNe 1997D, 1999br, 1999eu, 2001dc, 2005cs (Pastorello et al. 2009 and references therein); two normal SNe 2004et (Misra et al. 2007), 2008gz (Roy et al. 2011a) and a peculiar Type II SN 1998A (Pastorello et al. 2005), observed at comparable epochs. The phases (quoted inside the square brackets) for each event are with reference to the moment of inflection, which is marked by the highest rate of decline in the V-band light curve during the end of the plateau and the beginning of nebular phase (Elmhamdi, Chugai & Danziger 2003). All the spectra have low spectral resolution (~ 10 Å). The P-Cygni features of Na I D, Ba II λ 6142, Sc II λ6248, Ba II λ6497 and Hα are also marked.

typical line profiles, common during the plateau phase of a type II event. Assuming a total plateau length is about 100 days, we can safely say that the spectrum of +54d represents the mid-plateau nature of this SN.

The right panel of Fig. 2, represents the comparative study of spectra of different Type IIP events observed at similar epoch with respect to the transition time, commonly known as epoch of inflection. Similar to other type IIP events (see Roy et al. 2011b and references therein), the spectrum of SN 2008in is dominated by the Hα P-Cygni feature throughout the whole plateau phase. Between +54d and +143d, a significant variation in spectral features can also be noticed.

In late plateau spectra strong P-Cygni features of Hα , O I 7774 Å , Na I D 5890, 5896 Å and also features from singly ionized Sc, Ba, Ti, Fe atoms are prominent. These features are almost similar to the features of low-luminosity events.

To estimate the explosion parameters like Explosion energy (E_0), Ejected mass ($M_{\rm ej}$) and Pre-SN radius (R_0) of SN 2008in we use the analytical relations derived by Litvinova & Nadezhin (1985) correlating the observed parameters (M_{Vmp} - the mid-plateau absolute magnitude at V, v_{mp} - the mid-plateau photospheric velocity and Δt_p -the plateau duration) with the physical parameters (E_0, $M_{\rm ej}$ and R_0) of the Type IIP events. The estimated values of explosion parameters are respectively $E_0 \sim 0.54 \times 10^{51}$ ergs, $M_{\rm ej} \sim 16.7$ M$_\odot$ and $R_0 \sim 127 R_\odot$. The estimated value of E_0 obtained in this formalism is consistent with the value 0.3×10^{51} ergs, measured from non-rotating pre-SN model of Dessart, Livne & Waldman (2010).

The explosion energy of SN 2008in indicate that the event was less energetic than the standard IIP SNe 1999em, 2004et and more energetic than low-luminosity event like SN 2005cs. Assuming a net mass loss ~ 0.5M$_\odot$ due to stellar wind and accounting for a compact remnant with mass $\sim 1.5 - 2$M$_\odot$, we find that the initial mass of the progenitor to be ≤ 20M$_\odot$.

3. Comparison with other events

The host of SN 2008in is a spiral galaxy of SBbc type and the SN is located $\sim 1.8'$ away from its center. This corresponds to a deprojected distance ~ 7 kpc. Adopting the formulation of Pilyugin, Vîlchez & Contini (2004), the derived oxygen abundance [O/H]($\equiv 12 + \log(N_O/N_H)$) at the SN location is about 8.44 dex which is marginally sub-solar and comparable with that of low-luminosity SNe 1994N, 1999br, 2001dc, 2003gd and 2004dj (~ 8.4 dex) whereas slightly larger than that of the faint SN 1997D and normal type IIP SN 2004et (both are at 8.3 dex).

The average tail magnitude of SN 2008in at V band is ~ -12.16 mag, which is nearly 2.3 mag brighter than those of the low luminosity SNe 1997D and 2005cs (~ -9.6 mag), and about 1.3 mag fainter than the average tail V-band magnitude (~ -13.5 mag) of normal type IIP events such as SNe 1992H, 2004et and 2008gz. This is consistent with the radioactive ^{56}Ni mass derived in Sec 2. The luminosity and shape of the tail depend on the ^{56}Ni mass and the energy emission per unit ejected mass (E/M) (Turatto et al. 1998 and references therein). ^{56}Ni produced by the Type IIP events like SNe 2003gd, 2004dj and 2008in are more than twice that produced by the low-luminosity SNe 1997D and 2005cs, although it is at least 3 times less than the ^{56}Ni produced by normal type IIP SNe such as 1992H, 2004et and 2008gz. On the other hand, the measured E/M ratio for SN 2008in is 3.5×10^{49}ergs.M$_\odot{}^{-1}$, which is twice the E/M ratio measured for low luminosity SNe 1997D, but it is half of those of SN 2008gz, SN 2004dj and SN 2004et. Finally, it is almost one-third of the E/M ratios of SNe 1987A and 2003gd (Hendry et al. 2005) and about 8 times smaller than the luminous 1987A-like SN 1998A.

The yields of SNe depend on the masses of progenitors, metallicity of the environments and on the explosion energies. By comparing the observed and calculated spectra and light curves of supernovae, we can estimate the main sequence mass of the progenitor, explosion energy and the amount of radioactive ^{56}Ni ejected in the environment. Events like SNe 1998bw, 2003dh, 2003lw are all hyper-energetic explosions where (30−50)$\times 10^{51}$ ergs energy were liberated along with a production of

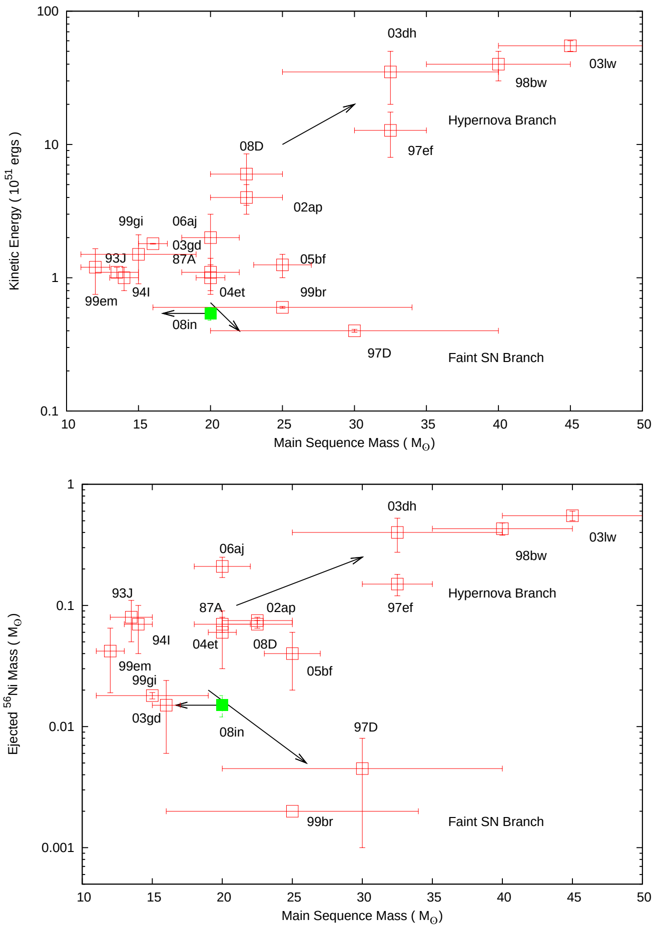

Figure 3. This figure is reconstruction of fig. 8 of Tanaka et al. (2009). Kinetic energy of the explosion (upper panel) and ejected ^{56}Ni mass (lower panel) vs. main-sequence mass of the progenitor for different CCSNe. Location of SN 2008in (this work) has been shown with an upper limit of main sequence mass. Data for SN 1999em, SN 1999gi and SN 2004et have been borrowed from Misra et al. (2007), for SN 2003gd data has been taken from Hendry et al. (2005) and for all other remaining CCSNe, data from Tanaka et al. (2009) have been plotted.

0.3–0.5$M_\odot$ radioactive ^{56}Ni. In contrast, Type II SNe 1997D, 1999br and 2005cs are very faint with very low kinetic energy and synthesized ^{56}Ni (less than 0.01$M_\odot$). Figure 3[3] represents a bimodal distribution of ejected ^{56}Ni and explosion energy for

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[3]Here we have reconstructed the figure 8 of Tanaka et al. (2009). Five well studied type IIP events – SNe 1999em, 1999gi, 2003gd, 2004et and 2008in have been included to make the plot more robust statistically.

different main sequence mass of the CCSNe progenitors. Starting from the location of all normal and peculiar type II events, two distinct branches, one for hypernovae and other for faint SNe can be noticed. SN 2008in stands somewhere between normal and faint SNe. Here we have shown the plausible upper limit of the progenitor's mass of SN 2008in . On the basis of ejected ^{56}Ni, is that it has close neighbors like SN 1999gi and SN 2003gd, but in the domain of explosion energy, they are quite off from SN 2008in position. So, possibly, SN 2008in represents a class of events that fall between normal type IIP and low luminosity type IIP events.

4. Conclusions

Type IIP SNe belong to a class of events, which are still under debate due to the nature of their progenitors and the explosion mechanisms. Pre-SN *HST* images revealed that upper limit of precursors' mass of normal events cannot exceed $20M_{\odot}$ (Smartt et al. 2009), though observations of these kind of events strongly disagree with this upper mass limit.

Spectroscopically as well as photometrically, low luminosity events show a great diversity among themselves as well as with normal and peculiar type IIP events. Number of such events discovered is also very less. After SN 2005cs, SN 2008in and SN 2009md are probably the only events, occurred in nearby galaxies and monitored extensively. The photometric and spectroscopic comparisons of SN 2008in with other core collapse events having a wide range of physical parameters puts observational constraints on the nature of the progenitor of this event, pointing towards a star which was more compact than a typical M-type red super-giant, and closer to a blue super giant. Unfortunately, due to lack of any pre-SN image, direct estimation of progenitor mass was not possible. The event was not detected in radio whereas we were able to constrain an upper limit of X-ray flux. The results of photometric and spectroscopic observations could be summarized as follows:

Spectroscopically SN 2008in appears to be like low-luminosity SNe IIP, but photometrically it appears close to a normal type IIP event. The observed properties such as plateau duration, mid-plateau luminosity as well as the photospheric velocity were determined accurately from the light curve and spectra of the object. Further estimates of explosion energy, ejected mass and pre-SN radius of the exploding star indicates that the progenitor of SN 2008in is much compact than that of normal type IIP events and produced energy is comparatively less than that produced in IIP events. Morphologically, host of SN 2008in is a spiral galaxy of type SBbc which is supposed to be a common birth place of Type II progenitors. We also found that the metallicity of the supernova environment is marginally sub-solar and comparable with the metallicity of low luminosity events. SN 2008in represents a subclass of Type II SNe, that shows the characteristics of both normal and low-luminosity events.

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