# Explosive nucleosynthesis and beyond: Energy generation in supernovae from massive progenitors

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**Abstract.** Massive stars (initial mass $\gtrsim 10\mathrm{M}_\odot$, where $\mathrm{M}_\odot$ is the mass of the Sun) end their life through violent explosions known as core-collapse supernovae, which are supposed to be among the brightest events of the universe. Nucleosynthesis inside the ejecta of such exploding stars was proposed to be the main source of its years-long radiated power. With the advent of time-domain astronomy, brilliant supernovae with longer evolutionary time scales and larger peak luminosities (10-100 times) than canonical supernovae, have been revealed. These are Superluminous Supernovae (SLSNe). The powering mechanisms of SLSNe are yet not resolved. The proposed theories are the interaction of SN-shock with circumstellar medium (CSM), the presence of a spin-down magnetar, or pair-instability (PISNe) in very massive stars. Most likely, In the case of SLSNe, these physical processes generate extra radiated power in addition to the radioactive power due to explosive nucleosynthesis inside the ejecta. Here, I review different mechanisms behind the radiated luminosity of supernovae created from massive progenitors.

## 1 Introduction

*Supernovae* (SNe) are the *extreme cosmic catastrophe* that liberate a total energy of $\sim 10^{50}$ ergs in the form of radiation. Such explosions also feedback all major metals to their host galaxies that were produced at the core of the stars during their evolution and/or inside the exploded SN-ejecta through Nucleosynthesis processes (c.f. [1]). Out of these events which are produced at the end state of massive stars ($\mathrm{M} \gtrsim 10\mathrm{M}_\odot$), are known as *core-collapse supernovae* (CCSNe). The total energy of a CCSN (considering neutrino and kinetic energy of the explosion) is $\sim 10^{51} - 10^{52}$ ergs (depending on the nature of the SN).

This huge radiated energy is actually liberated within a time duration of several months to years, producing a bolometric lightcurve with a peak radiated power of $\sim 10^{41} - 10^{44}$ $\mathrm{ergs\,s^{-1}}$. The shape of the lightcurve is highly dependent on the synthesized radioactive elements, particularly $^{56}$Ni, mixed homogeneously in the exploded material (c.f., [2–4]). The timescale of production of $^{56}$Ni, is $\sim$ 1 day. Therefore, in the first few hours (to day) SN is mainly powered by the Shock ([5]), witnessed in a few serendipitous discoveries (c.f., [6]). In less massive progenitors ($10\mathrm{M}_\odot \lesssim \mathrm{M} \lesssim 20\mathrm{M}_\odot$), a substantial fraction of Hydrogen (H) is retained at the outer surface of the star as a puffy layer, causing an extra source of power due to the recombination process within the outer layer of H – creating a plateau in the

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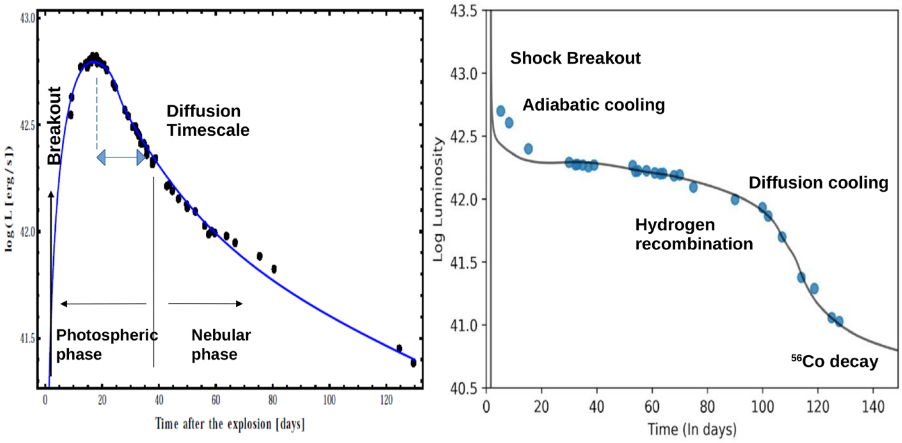

**Figure 1.** A comparison between the lightcurves of stripped-envelope SNe (**left panel**) and Hydrogen-rich SNe (**right panel**). The left panel has been reproduced from [4]. Right panel shows Bolometric lightcurve of SN2008in (also see [15, 16]). In both cases the timescale of the shock breakout is a few hours to days. In case of stripped-envelop SNe effect of radioactive heating in the photospheric phase is prominent. In both types of SNe, nebular lightcurve gives a direct estimation of the mass of $^{56}$Ni.

lightcurve. The third category of explosions are powered by the interaction of the SN-shock with the circumstellar material (CSM) of the star, causing an extra source of power on top of the radioactive heating and making the SN quite luminous. These happen in very massive stars known as Luminous Blue Variables (LBVs).

With the advent of the all-sky survey programs (e.g., [7–10]) several brilliant explosions like 'Superluminous Supernovae' (SLSNe, [11, 12]) have been discovered in the distant universe that are ∼10−100 times more luminous than canonical SNe. The proposed mechanisms of SLSNe are (i) energy liberated by the spin-down of proto-magnetar (instead of a proto-neutron star) produced just after the collapse of the progenitor (cf. [13]), or (ii) due to the interaction of SN-shock with very dense CSM (e.g., [14] and references therein). Some of them may also have radioactively powered peak (SLSN-R) due to pair-Instability in very massive stars (PISN; e.g., [12] and references therein).

Here, we describe the process of radioactive heating in canonical SNe (§2) and give an overview of the present understanding of the extra powering mechanism of SLSNe (§3). Since radioactive heating mainly affects the temporal evolution of light, our discussion is mostly based on the photometric evolution of the SNe (spectroscopic evolution will not be discussed in detail).

## 2 Radioactive power in Supernovae

Figure 1 shows the typical lightcurves of Type-Ibc (H-deficit) and Type-II (H-rich) CCSNe. Both lightcurves show the influence of radioactive elements on the temporal evolution of light in these types of events. In the case of Type-II another power source due to the recombination of ionized Hydrogen (H) fronts shapes the lightcurve during the initial 100 days as well. Here, we will summarize the effect of radioactive heating on the lightcurves of Type-Ibc CCSNe. The detailed derivation can be found elsewhere (c.f. [16] and references therein).

During the initial $1 \lesssim t \lesssim 30$ days (after the explosion), the luminosity evolution of the photospheric phase of Type-Ibc (progenitor is evolved massive stars with mass $\gtrsim 30 M_\odot$) is described by the following equation (also applicable to thermonuclear explosions).

$$L_{ph}(t) = M_{Ni} \times e^{-x^2} \times \left[ (\epsilon_{Ni} - \epsilon_{Co}) \int_0^x A(z)dz + \epsilon_{Co} \int_0^x B(z)dz \right] \tag{1}$$

Here $A(z)$ and $B(z)$ are functions of half-lives of $^{56}$Ni, $^{56}$Co mixed homogeneously within the ejecta; energies emitted per unit time per unit mass of these two isotopes; diffusion timescale of the radiation inside the exploded material; and the time elapsed after the explosion.

While the early evolution is governed by the radioactive decay of synthesized $^{56}$Ni to $^{56}$Co inside the optically-thick exploded material, the late-time evolution is entirely due to the radioactive decay of $^{56}$Co to $^{56}$Fe inside the evolved optically-thin SN-ejecta, producing a nebular luminosity

$$L_{neb}(t) = S^{Ni}(\gamma) + S^{Co}(\gamma) + S^{Co}_{e^+}(\gamma) + S^{Co}_{e^+}(KE), \tag{2}$$

Where $S^{Ni}(\gamma)$ is the energy due to $^{56}$Ni decay, $S^{Co}(\gamma)$ is the energy due to $^{56}$Co decay, $S^{Co}_{e^+}(\gamma)$ is the energy due to the positron annihilation, and $S^{Co}_{e^+}(KE)$ is the source term due to the kinetic energy of the positrons. Essentially, the above set of equations can be utilized to produce the bolometric lightcurve and to measure the parameters. Studies show that $\sim 0.05 - 0.9$ $M_\odot$ $^{56}$Ni is produced during Type Ibc SNe from stars with mass $\gtrsim 30$ $M_\odot$, while $\sim 0.002 - 0.3$ $M_\odot$ $^{56}$Ni is produced in SNe from stars with $10M_\odot \lesssim M \lesssim 20M_\odot$. In several cases asymmetry in the explosion, the effect of segregation/clumpiness inside the ejecta, and inhomogeneity in the distribution of radioactive material within the ejecta have been noticed (c.f., [17]). On the other hand, the very early phase ($t \lesssim 1$ day) of the lightcurves is entirely dictated by the shock physics. During this time $^{56}$Ni is actually produced inside the ejecta through the explosive nucleosynthesis process.

At the deep nebular phase (which is roughly 150 days after explosion) the radiated power ($L_{neb}$(t)) of the SN is solely determined by the production of radioactive power due to the transition of $^{56}$Co to $^{56}$Fe. Thus the amount of radioactive $^{56}$Ni produced in terms of solar mass can also be computed directly from the observation, using following expression ([18]):

$$\frac{\mathrm{M}_{Ni}}{\mathrm{M}_\odot} = (7.866 \times 10^{-44}).L_{neb}.exp \left[ \frac{(t - t_0)/(1 + z) - 6.1}{111.26} \right] \tag{3}$$

Where $t_0$ is the epoch of explosion and $z$ is the redshift of the object.

In short, for H-deficit CCSNe (also known a stripped envelop SNe) the peak luminosity of the lightcurve measures the mass of $^{56}$Ni produced in the explosive nucleosynthesis process. Whereas, the width of the lightcurve (which is comparable to the diffusion timescale) measures the total mass of the ejecta. Needless to say, the mass of $^{56}$Ni must be less than the total ejected mass. For all kinds of CCSNe mass of the $^{56}$Ni can also be computed directly from their nebular lightcurves.

## 3 Superluminous Supernovae and peculiar events

SLSNe are 10−100 times more luminous than CCSNe. Some show sharp rises (fast-rising events), while others are relatively slow-rising events. This has been demonstrated in the figure 2. Spectroscopically, the most interesting and noticeable spectral signature of H-deficit SLSNe is the presence of OII doublet at around 4500 Å(commonly known as 'W' feature) in their early spectra (c.f. [19] and references therein), which are not visible in canonical CCSNe. Assuming the peak luminosity and width of lightcurve are proportional to the mass of synthesized $^{56}$Ni and ejected mass respectively, it has been found that the required amount

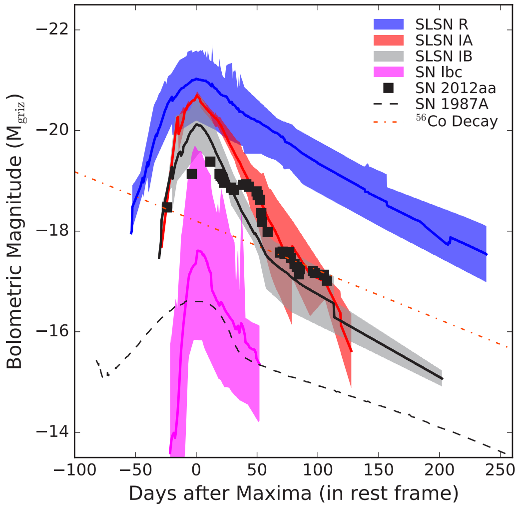

**Figure 2.** The plot has been borrowed from [22]. The average peak luminosity of canonical Type Ibc events (pink solid line) is much lower than the average peak luminosities of SLSNe (black, red and blue solid lines). It is also evident from the figure that among SLSNe, the objects marked by the blue lightcurves have broader and brighter peaks, while objects marked with black and red lightcurves have narrow width. Further, the lightcurves with black shed show a tail similar to $^{56}$Co→$^{56}$Fe radioactive transition nearly 100 days after the peak, while the lightcurves marked with red shed do not show any behaviour in their lightcurves.

of radioactive Ni to produce peak luminosity of an SLSN is several times larger than the Solar mass, and sometimes even larger than the ejected mass. Such results immediately nullify the possibility of only radioactive heating in producing large radiated power in SLSNe.

The two most compelling as well as competing theories that have been used to explain the broader and brighter SLSNe lightcurves are (i) heating of SN-ejecta due to energy liberated by the spin-down proto-magnetar produced just after the collapse of the progenitor, (ii) interaction of SN-shock with very dense CSM. In the first scenario, we expect to observe a sharp rise and sometimes pre-maximum bump in the lightcurve (c.f. [20]). Whereas in the second scenario, we expect a bright lightcurve, undulation (bumps) in the post-maximum phase due to clumpy CSM, as well as in a few cases sharp spikes in the emission lines as a consequence of interaction in the electron-scattering environment of the SN (c.f. [21]). In several cases, a post-maximum bump in lightcurve has been observed (e.g., see the lightcurve of SN2012aa in figure 2, and [22]). In CSM-interaction dominated SNe like Type-IIn events and SLSNe-II, the interaction features in spectra are also prominent (c.f. [23] and references therein). The third possibility is pair-instability supernovae (PISN), where extremely massive stars (mass$\sim 100 M_{\odot}$) collapse due to the production of $e^-$, $e^+$ plasma from outward radiation through a pair production process. Evidence of such events is less (c.f. [24] and references therein).

Neither the powering mechanism nor the role of radioactivity in SLSNe explosions is well understood. Very recently several other types of SNe have been found which also showed peculiarity in their lightcurves and spectra, that can not be explained under existing theories (c.f. [25] and references therein).

## 4 Conclusion and future outlook

Supernovae are sites where elements with atomic numbers larger than H and He are being formed and feedback to the galaxies (e.g., [26], and references therein). Essentially, these astrophysical events are responsible for enriching the metallicity of their host galaxies. The source of the radiated power of these objects is not well understood. Here, we have discussed the importance of radioactivity and other physical processes that are responsible for powering these events and the open issues in SN-physics.

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