Supernova

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Introduction

A supernova (SNa) is a stellar cataclysmic explosion which occurs at the end of a star's life. A SNa can be associated with low mass white dwarfs (WD's) deemed Type Ia, or with high mass stars (typically >10 solar masses) deemed Types Ib, Ic, and Type II variants.

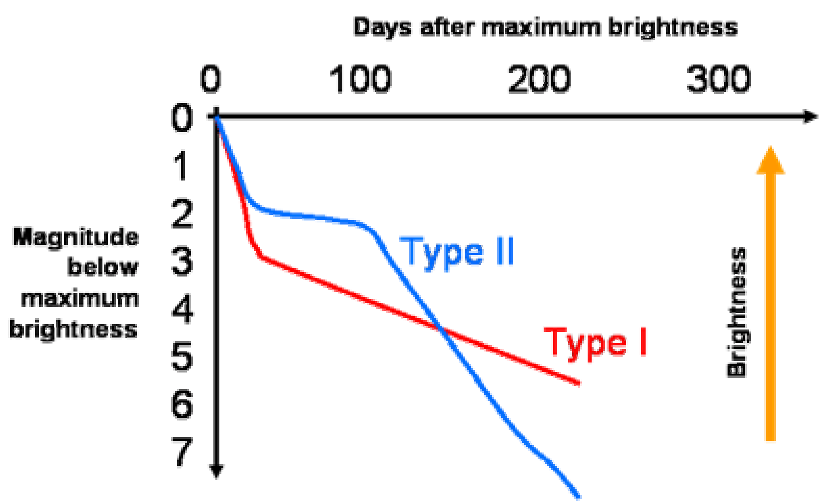
In this essay we will seek to explain the pre and post explosion physics that are intimately related to various supernovae (SNe) types in complement with spectral and photometric analysis and results. We will discuss results and will attempt to summarise and draw conclusions accordingly.

Supernova types and categories

Although SNe may be categorised by mass (as indicated above), spectroscopically and photometrically they are classified as Type I and Type II [18]. Spectroscopically, Type I SNe don't exhibit Hydrogen lines in their spectra as do Type II SNe, as the Hydrogen in their outer stellar layers may be stripped by strong stellar winds and/or stellar pulsations which typically occur in Type 1b & 1c SNe. The Hydrogen contained in the outer stellar layers may also be stripped via mass accretion in close binary system (typified by Type 1a) [4].

Type 1a SNe show strong spectral features of ionised Silicon as shown in Table 1. Photometric observations of Type I SNe (which include Type 1a SNe) show different light curve profiles as opposed to Type II SNe. The different rates of decline in brightness indicate differing rates of energy decay [1]. We will return to this point later.

Figure 1: Supernovae light curve characteristics



Physically Type Ia SNe are powered by nuclear energy released either by deflagration (core subsonic thermonuclear burning) or detonation (core supersonic thermonuclear burning[1]) in the WD's core. Type Ib, Ic and II SNe are powered by gravitational energy affecting stellar layers and the inner core. Gravity initially provides the means to drive the supersonic nucleosynthetic processes typically observed in these SNe types [1].

[1] Deflagration occurs when thermonuclear burning travels outwards from the stellar core at a speed less than the speed of sound. Detonation occurs when thermonuclear burning travels outwards from the stellar core at a speed greater than the speed of sound.

Various characteristics attributed to SNe can be summarised in Table 1:

Table 1: Key Supernovae characteristics

SNa Type	*Visual Magnitude*	*Spectrum Features***	*Photometric Profile*	*Progenitor Mass*	*Explosion Luminosity*	*Catalyst Power Source*	*Location*	*Elements Produced*
Ia	Highest	Ionised Silicon (S II)	linear decay	~ 1.4 M	roughly constant	nuclear	generally everywh ere	mostly around Iron
Ib	High	unionised Helium (H I)	linear decay	> 10 M	dependent on mass	gravity (core collapse)	galactic spiral arms	iron & heavier elements
Ic	High	No Hα or Helium	linear decay	> 10 M	dependent on mass	gravity (core collapse)	galactic spiral arms	iron & heavier elements
II-L	High	Hα	mostly linear decay	> 10 M	dependent on mass	gravity (core collapse)	galactic spiral arms	iron & heavier elements
II-P	High	Hα	plateau feature	> 10 M	dependent on mass	gravity (core collapse)	galactic spiral arms	iron & heavier elements
II-b	High	some Hα mostly He	mosty liner decay	> 10 M	dependent on mass	gravity (core collapse)	galactic spiral arms	iron & heavier elements
II-n	High	Narrow spectral features	mostly linear decay	> 10 M	dependent on mass	gravity (core collapse)	galactic spiral arms	iron & heavier elements

** Broad spectral features unless otherwise indicated

Physical Processes

Type Ia SNa

Type 1a SNe can originate either via a thermonuclear subsonic deflagration or supersonic detonation of a WD's carbon/oxygen (C/O) core, leading to a C/O core-flash resulting from runaway carbon burning. There are separate physical processes which can lead to C/O core-flash:

1) A WD may accrete sufficient matter from it's binary companion which over time will increase the WD's mass over the Chandrasekhar limit [2], or
2) Via merger of two WD's resulting in the combined mass exceeding the Chandrasekhar limit.

Although the deflagration model for Type 1a SNe has been successful at explaining spectral and photometric observations [3] it is still unclear which physical model (detonation or deflagration) or whether a combination of both acting on the C/O core leads to Type 1a SNe creation in mass accreting WD's [4].

Spectroscopic observations indicate ionised Silicon lines in spectra of Type 1a SNe as well as carbon burning which produces Iron (refer to Table 1). This may be explained by probing into the physics of events before and after the C/O core-flash:

- When the mass of a WD reaches 1.3 solar masses [3] which is at a point under the Chandrasekhar limit of 1.4 solar masses, carbon burning begins at the centre of the C/O core.
- Electron degeneracy [5] ensures that the pressure doesn't increase with increasing core C/O temperature as a result of gravitational core collapse. This leads to ignition of the centre of the C/O core.

- As the inside-out core deflagration or detonation occurs, elements of the Periodic Table including Silicon up to Iron are formed via nucleosynthesis [6].
- When the WD explodes, elements such as the remaining carbon, oxygen and the newly nucleosynthesised elements up to Iron, which include Silicon and Nickel are ejected into space.
- The ejected elements (detected via spectrometry) show that Type 1a SNe produce relatively large amounts of Iron and Silicon when compared to other SNe types [3].

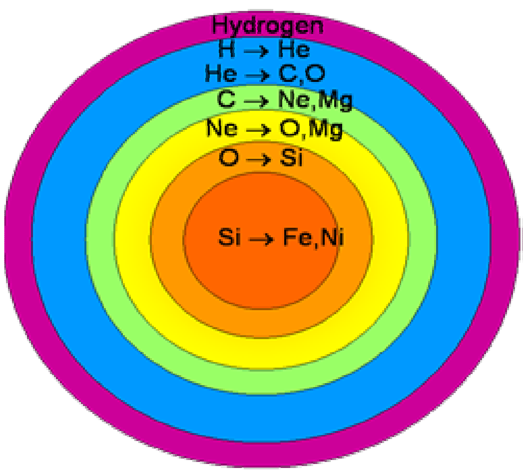
Table 1 indicates that the peak luminosity liberated in a Type 1a SNe explosion is roughly a constant maximum value (about 4 billion times the Sun's Luminosity) as it's governed by the mass of a WD, typically around 1.4 solar masses also known as the Chandrasekhar mass [12]. Type 1a SNe are also characterised by a distinct light curve shape (the physics of which we'll cover later in the discussion), and a lack of appreciable amounts of circumstellar material resulting from an almost non-existent stellar atmosphere prior to its thermonuclear explosion [4].

Type 1b, 1c and Type II SNe

Type 1b,c and Type II SNe originate via different physical processes as opposed to Type 1a SNe, as gravitational energy is responsible for driving their energy liberation process:

- As a massive star moves towards it's end-of-life it undergoes numerous dynamical stages of contraction and expansion as heavier and heavier elements are nucleosynthesised towards the stellar centre to a series of shells surrounding an Iron (Fe) core as depicted in Figure 2 below.

Figure 2: Nucleosynthesis in large stellar interiors



- Nuclear reaction sequence times become shorter and shorter as the star runs out of nuclear fuel and less binding energy [7] is liberated per nuclear reaction sequence as heavier elements up to Iron-56 are created.
- As the stellar temperature increases, by Wein's [8] and Plank's law [9] so does the energy of the photons produced, which in turn produce a first wave of neutrinos, most of which escape from the stellar core, thus lowering the core's energy.
- To compensate for the neutrino energy loss, the core contracts under gravity. This leads to the creation of more energetic photons via nucleosynthesis to a point where highly energetic photons begin to break down the Iron core of the

star in a process called photodisintegration [10], where the Iron core is destroyed via photons to produces Helium nuclei and free neutrons.

- The Helium produced is in turn photodisintegrated into free protons and free neutrons [3]. The protons in turn recombine with free electrons to create more neutrons and neutrinos.
- The recombination of free electrons and free protons remove pressure support in the core which via gravity, leads to outer stellar layers collapsing on the stellar core at high speed.
- The second wave of neutrinos created via photodisintegration begins to escape, thus causing the core to cool and collapse to nuclear density [11].
- At nuclear density the core becomes rigid causing a core rebound which creates a pressure wave that emanates outwards from the stellar core.
- As the pressure wave propelled in part by the second wave of neutrino pressure meets the gravitationally infalling outer layers, a shock front is created which liberates energy with solar luminosity in the order of billions which is observed as a SNa.

The ensuing shock front created from the outward pressure wave and the infalling material is a key component in fission nuclesynthesis reactions that occur in the ejecta. The end results are detected via spectrometry and photometry via spectrographic light curve and colour index analysis. As indicated in Table 1 the SNe luminosity of Type 1b,c and Type II variants varies according to the stellar mass which can be anywhere from 10 solar masses up to approximately as much as 150 solar masses [13].

Supernova spectral & photometric analysis

Spectral analysis reveals P Cygni [14] profile characteristics which are indicative of fast ejecta expansion (SNe blueshifted absorption lines) accompanied by emission peaks of elements found in the SNe ejecta. The speed of the ejecta can be inferred by spectral analysis, which assists in determining characteristics of the SNe explosion.

Spectral analysis is also able to distinguish between broad and narrow spectral features of SNe e.g. Type II-b and Type II-n SNe (refer to Table 1). It is thought that the narrow spectral features (introduced by Schegel in 1990) are caused by energy emission created when the SNe ejecta shocks the circumstellar medium (CSM) which exists around a SNe from mass loss as a consequence of advanced stellar evolution phases that occurred via stellar winds and thermal pulsations [19].

Photometric analysis of Type II SNe reveal, as indicated in Table 1, that light curve gradients vary such that some Type II SNe ‘plateau’ for a period whilst others show a ‘linear’ photometric decay (this is also shown in Figure 1). Spectral analysis indicates that the deposition of certain radioactive isotopes via beta decay [15] occurs, where gamma rays and positrons are produced with isotopes of Ni-56, Co-57, Na-22 and Ti-44 respectively. These isotopes are produced by the SNe shock front in varying amounts and have respective increasing radioactive ½ lives. They directly influence the shape and decay of the photometric light curve. This is demonstrated in the plateau behaviour of a Type II SNe light curve in Figure 1 where it’s ‘held up’ for a period of time after the explosion as a consequence of energy deposition of these decaying radioactive isotopes. As a consequence the photometric light curve gradient produced in light curve analysis greatly assists in determining the exact amount of each type of the isotope produced [3].

Photometric and spectral analysis of Type 1a SNe also show similar nucleosynthetic fission processes occurring whereby the light curves are powered by the deposition of the gamma rays and positrons from radioactive decay of Ni-56 synthesised in the thermonuclear explosion. It has been found that the energy of a SNa explosion is dependant on the amount of Ni-56 synthesised. The nuclear process involved for Type I and II SNe explosions where this occurs is where 56Ni -> 56Co -> 56Fe.

The shape of the light curves near maximum (refer to y-axis in Figure 1) observed in SNe (both types) is highly dependant on the following:

- The amount of energy being deposited by gamma photons and positrons.
- The propagation time of the photons through the ejecta. Over time, the ejecta becomes optically thin and allow more photons to propagate past the SNe shock front.
- In the case of Type 1a SNe, in late photometric phases where the ejecta becomes optically thin, the gamma ray energy deposition becomes less efficient and the remaining light curve is powered by the deposition of positrons from beta decay processes.

Progenitor stars of Type 1a SNe that have low matellicities can affect light curves particularly at moderate redshifts (z>0.2), where for instance the colour index B-V can be altered by as much as by a factor of 0.3 magnitudes. A decrease in metallicity also has a similar effect on other photometric passbands such as V-I at higher redshifts (z>1) [17].

Progenitor stars of Type 1a SNe have C/O cores whose carbon amount also affect the shape of light curves at various photometric passbands. Lower C/O ratios i.e. less than one (where more oxygen that carbon is present in the core of the progenitor star) reduces the amount of Ni-56 produced, hence producing a larger cooling effect in SNe outer layers which is shown in light curve redness in the B-V passband [17].

Figure 3: SNe Light Curves in U,B,V,R,I,JH & K Passbands

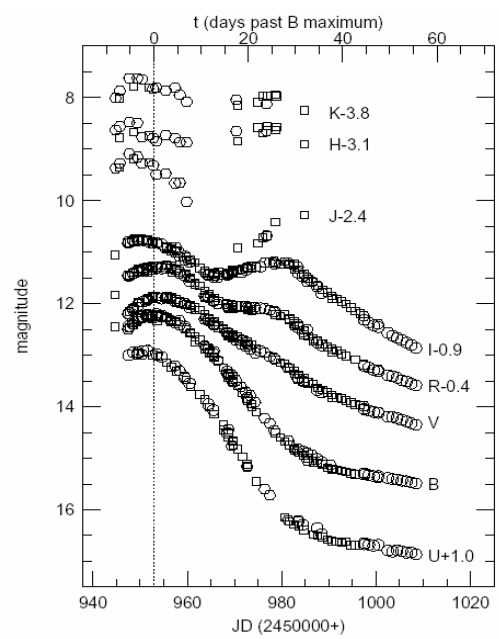


Figure 3 is an example of the difference in peak time (horizontal axis) and magnitude (vertical axis) of SNe in various photometric passbands. This is a common effect found in light curves as is explained in part by thermal effects such as the high opacity to shorter wavelengths difference of the supernova ejecta and also by the interaction between more energetic photons and iron-group elements existing in the ejecta [4]. We observe earlier and higher peak magnitudes for longer wavelength passbands when compared to shorter wavelength passbands.

It is also evident though that the complexities associated with SN radiative transport also affect when maximum peaks are observed in various passbands. For instance non-thermal effects in the ejecta contribute to the earlier and higher peak in longer wavelength passbands than shorter wavelength passbands [20].

Conclusion

SNe are generally categorised by their photometric and spectrum attributes. Their mass and evolutionary phases dictate the SNe explosion process observed.

The presence of circumstellar material (CSM), ejecta and related opacity, deposition of thermal energy via nucleosynthesis from isotopes, gamma rays and positrons, as well as their metallicity abundances, non-thermal effects and radiative transport effects, impact on spectroscopic and photometric results observed.

Observations of these complex processes provide a useful astronomical insight into stellar lifecycle and element creation in the Universe.

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