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INTRODUCTION TO SUPERNOVAE PHENOMENA

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The term Super-Novae was coined in 1931. The hyphen disappeared in 1938 with the realization that Supernova is a completely distinct phenomena and is not a scaled-up version of Novae. The earliest work on Supernovae brought out the main characteristic features which have retained their validity over the years. These time-tested conclusions are:

(i) Total amount of energy released during a supernova event varies from $3x10^{51}$ ergs to 10^{55}ergs.,

(ii) Supernova represents the transition of an ordinary star into a neutron star,

(iii) The transition is explosive in nature,

(iv) Ionized gas shells are expelled at great speeds during the explosion,
and

(v) that supernovae produce cosmic rays.

The bit about the cosmic rays has undergone revisions and modifications in terms of number of supernovae events per year per galaxy etc.

Classification

Supernovae are known by their light curves and spectra. An unambiguous classification requires spectral information at a time when the light curve is near its maximum. For lack of such observations the attempts to classify historical supernovae have turned out to be rather frustrating. Supernova SN1054 has changed its alliance from type I to type II in the last two decades. This can happen even for modern supernovae because of the overlap in luminosity and spectra which is a pointer to the basic underlying feature of all supernovae that the large amounts of energy released has to propagate through large amount of circumstellar and interstellar material. Nevertheless, five distinct types of supernovae have been recognized. Type I supernovae are identified with absence of hydrogen and type II with the presence of hydrogen. Type III has hydrogen and a light curve with a broad maximum and a slow decline. The gas is ejected with large speeds. An example is SN1961i. Type IV has faint Hr emission, the spectrum that of type I and a light curve showing stepped decline. An example is SN 1961f. Type V has hydrogen and helium with He abundance about four times that of sun. Stars with masses as large as 100 $M_\odot$, gravitationally collapsing through electron-positron pair production are believed to produce type V supernovae. An example is SN1961V. Type III and type IV are believed to be variants of type I and type II, whereas type V forms a rather distinct class of its own. Only type I and type II supernovae will be discussed in the rest of the paper.

Type I Supernovae

Light curves of type I supernovae are shown in Figure (1). One notices: a smooth and rapid rise; a broad peak; homogeneity near maximum; a sharp decline, change of slope about 30 days after the maximum, and a long exponential tail with half life of about 56 days. Type I supernovae are generally weak in non optical bands. The peak optical luminosity is more or less constant for all type I and the absolute magnitude varies from $M_B = -19.7$ to $M_B = -20.1$. An example of the spectra of type I supernova is shown in Figure (4). Words fail to convey the complexity of the spectra. The main inferences

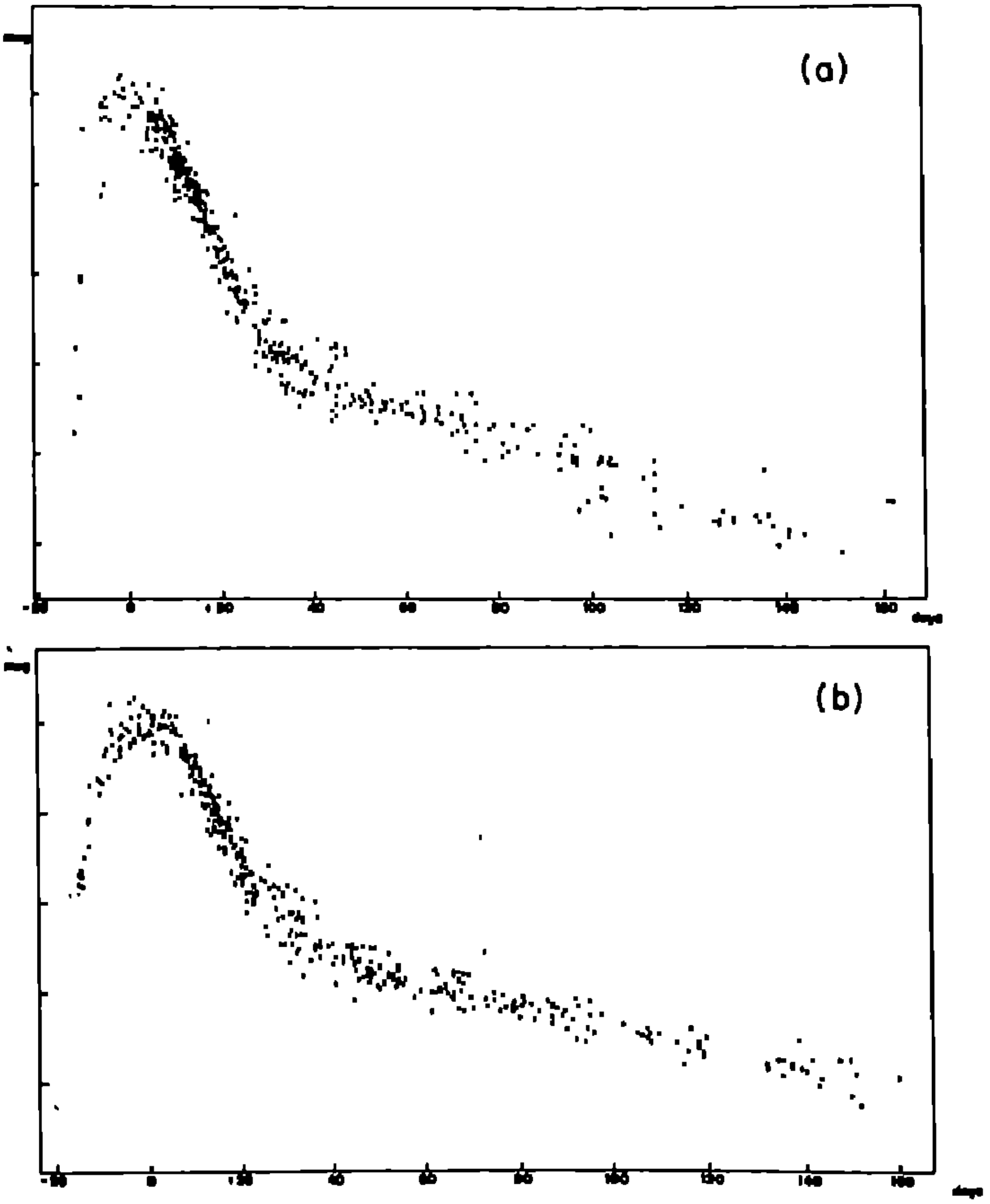

Fig.1. Composite blue light curves of Type I supernovae: (a) 11 events of the "fast" decline subtype, and (b) 15 events of the 'slow' decline subtype. Time is in days from maximum light; brightness in blue magnitudes, adjusted to make peaks of all events coincide. From V.Trimble (1982).

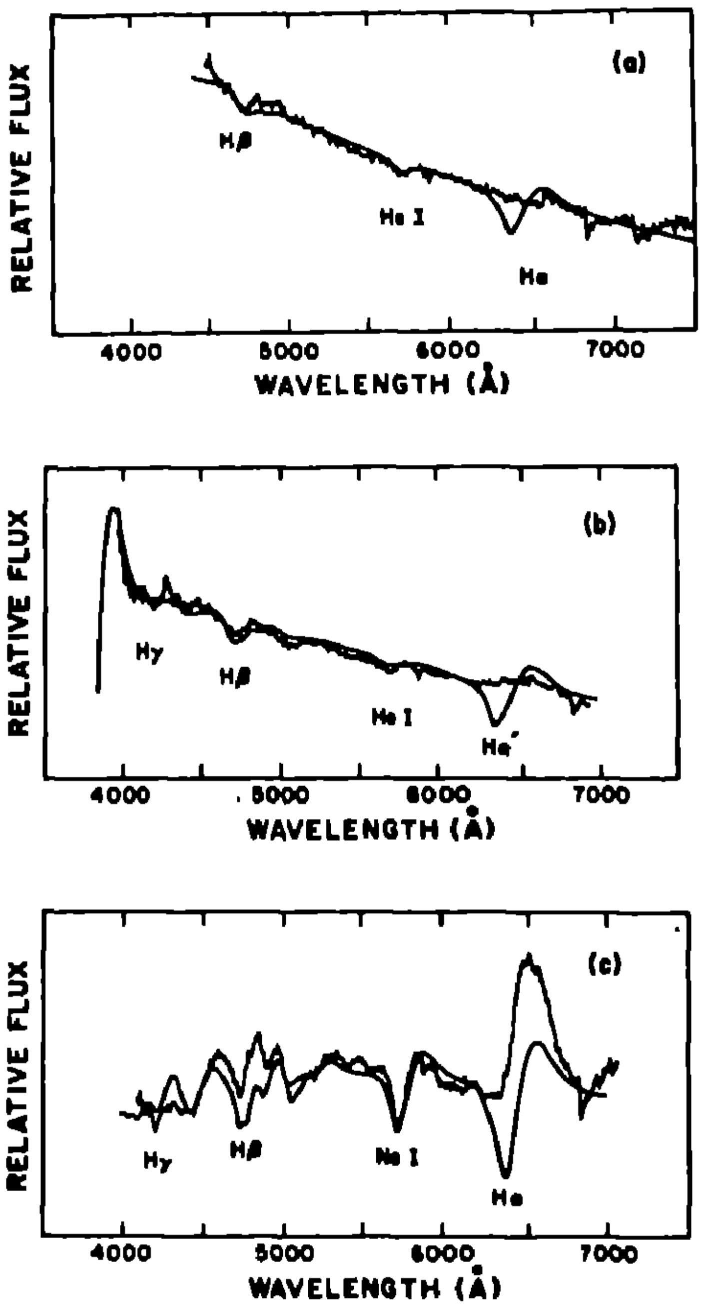

Fig.2. Observed spectra (the wigglier lines) and synthesized fits (the smoother lines) for the type II SN 1979C in M100 : (a) at maximum light, (b) six days thereafter, and (c) 36 days after maximum. The flux scale is linear in units of flux per unit wavelength, and the wavelength scale is in the rest frame of M100. Unlabeled features in the synthetic spectrum are due to Fe II. From V.Trimble (1982)

are: the total absence of hydrogen lines; absence of hydrogen results in shortage of free electrons which reduces the continuum opacity in comparison to line opacity and therefore type I spectral lines are stronger than type II lines; line shapes can be fitted well by assuming that the line emitting gas is expanding with a speed proportional to its size. The elemental abundances do not agree either with solar abundances or with pure carbon detonation products. The temporal changes in the spectra can only be explained by a combination of temperature, velocity and abundance variations. The spectra imply excess of Iron and the spectral evolution and the light curve are found to be consistent with the radioactive decay of nickel to cobalt to iron.

There are three ways in which the energy released after the collapse can feed the light curve : (i) the instantaneous way in which most of the energy is dumped at the bottom of an extended envelope and then a shock carries it out; (ii) the gradual or the continuous way in which a pulsar in the core of the star continuously feeds the light curve, the third way, a combination of one and two in which about one solar mass of carbon through detonation or deflagration and the radioactive decay of Ni^{56} together can reproduce the light curve. The maximum of the light curve can be accounted by radiation from expanding gas of size $\sim 10^{15}$ cm. The contribution from radioactivity is on two time scales corresponding to 9 days half-life of $Ni^{56} \rightarrow CO^{56}$ and 111 days half-life of $CO^{56} \rightarrow Fe^{56}$. The other products of radioactivity like positrons and γ-rays may sustain the later part of the light curve. A testable prediction associated with the extended envelope way is a precursor of ultraviolet and x-rays which has not been identified so far. The amount of Ni^{56} which may vary from 0.25 $M_{\odot}$ to 1.4 $M_{\odot}$ is crucial in determining (i) the kinds of stars as progenitors, (ii) whether the core is massive enough to leave a neutron star, (iii) How many events a galaxy can tolerate without drowning in iron and (iv) compatibility with the observed spectrum.

Type II Supernovae

Light curves of type II supernovae are shown in Figure (3). One notices: a rather sharp maximum; a 30-60 days plateau in the final stages and interrupted decline. The peak luminosity varies from one supernova to another with a typical absolute magnitude $M_B = -19$. The variable fall in the luminosity indicates the action of absorption processes. In order to explain optical output of a typical type II supernova, one needs about 10^{51} erg deposited at the bottom of an extended envelope. This energy then moves outwards as a shock, heating and accelerating the gas. The modelling gives luminosity, photospheric radius and velocity of expansion as functions of time. The rising part of the light curve is explained by increasing brightness from expanding photosphere. Any plateau results from the arrested expansion due to cooling and recombination of hydrogen. The total light radiated is about 1% of the input energy; the rest appears as kinetic energy carried by circumstellar and interstellar material. The rapid drop in the light curve results from an almost complete recombination of hydrogen which ends bremsstrahlung. Continuous energy input from explosively synthesized Ni^{56}, as the shock enters the bottom of envelope can also make significant contribution to light curve through radioactive decay. A central pulsar is another likely candidate for feeding the light curve but may be inadequate for accelerating and heating of the gas. Type II supernovae have been observed in non-optical bands too. The ultraviolet emission originates from low density gas of mass 10^{-2} - 10^{-3} $M_\odot$ outside the photosphere. It fades on optical time scales. The gas velocities derived from UV lines are found to be smaller than those from optical lines. Radio emission is generally observed a month to a year after the optical (not so in SN1987A). Gas of mass 10^{-2} $M_\odot$ - 10^{-4} $M_\odot$ through nonthermal (synchrotron) and thermal processes can account for the radio luminosity of 10^{37} erg /sec. Observations at 6 cm, and 20 cm have revealed that radio curve is analogous to light curve. Newly formed pulsars do emit radio radiation but its survival through the photosphere, circumstellar material seems doubtful. Inverse compton scattering of optical and ultraviolet photons by the radio producing electrons can generate $2x10^{39}$ erg/sec in x-ray as has been observed.

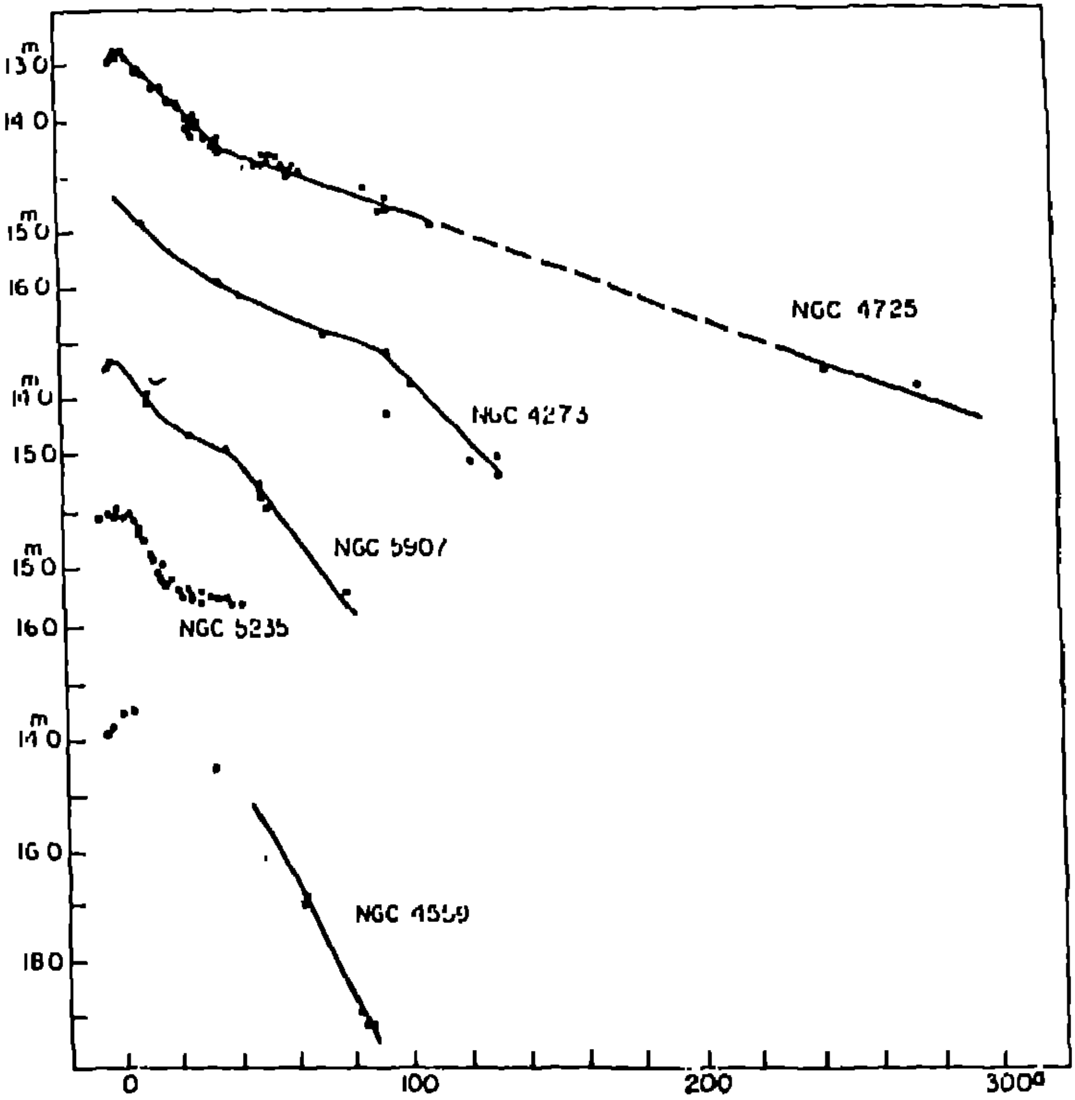

Fig.3. Photographic light curves of several type II supernovae. From I.S.Shklovsky (1968) in 'supernovae', London, John Wiley & Sons, p.8.

Infrared emission from type II has been observed in (2-20μ) range with a luminosity of 10^{42} erg/sec which is about a fortieth of the optical luminosity. Scattering by old and newly formed grains can account for the infra-red emission.

Type II spectra are shown in figure (2). One observes the preponderance of hydrogen lines, the defining characteristic of type II supernovae. In comparison to type I, the line strengths of elements other than hydrogen are smaller. The metallic abundances agree with solar and interstellar values. Total mass of the line forming gas is $\sim 0.2\ M_\odot$. Temporal changes in the spectra can be explained by invoking changes in density, temperature and expansion velocity of the gas.

Causes of Explosion

That the release of energy in a supernova has to do with the instability of the star, was realized a long time ago. The elders investigated the stability of a star and found that γ, the adiabatic index in the equation of state is the single most, deciding factor. The equation of state of a gas is given as

$$P = \rho^{\gamma}$$

where P is the pressure and ρ is the mass density. The gravitational energy density varies as $\rho^{4/3}$. If $\gamma > 4/3$, then pressure which is part of thermal energy density which tends to restore the original position after an adiabatic compression, will increase faster than the gravitational energy density and the star maintains its stability. For $\gamma < 4/3$ the gravitational energy density dominates and a volume element displaced towards the centre of the star will continue its motion, eventually attaining free fall. In normal hot ionized gases, $\gamma \sim 5/3$ and thus stars are stable. But at high energy densities, the particles become relativistic and $\gamma \simeq 4/3$ is approached. At $\gamma = 4/3$, the stability is decided by the mass of the stars. Chandrasekhar has shown that collapse becomes unavoidable after the fuel of the star is exhausted. This kind of collapse could lead to supernova explosion. There are two questions that need to be answered in order

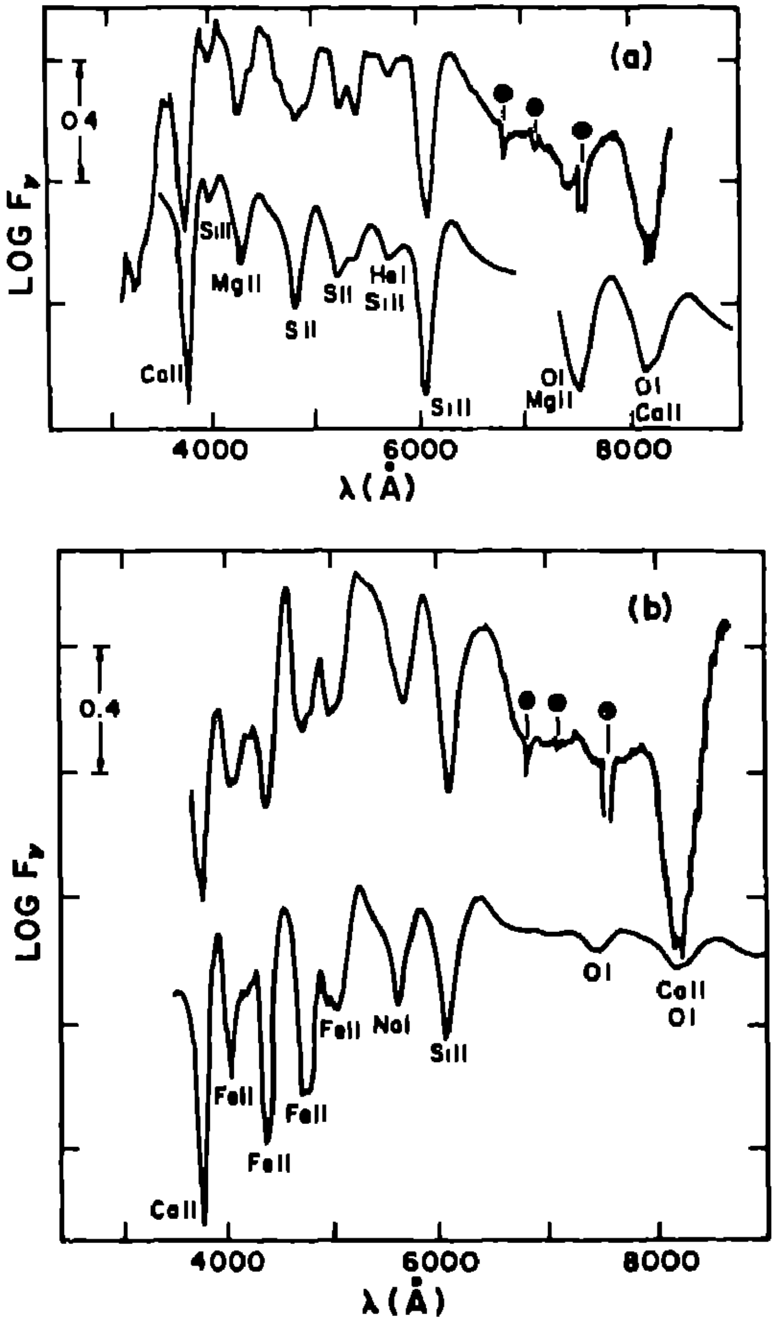

Fig.4. Observed spectra (upper lines) and synthesized fits (lower lines for the type I SN 1981 in NGC 4536: (a) at maximum light, and (b) 17 days postmaximum. The two fits respectively have T = 17000 K and 8000 K; V = 12000 Km/Sec and 11000 Km/Sec. Terrestrial lines are indicated in the observed spectra. From V.Trimble (1982).

to understand a supernova explosion: (i) what are the actual mechanisms for reducing γ below 4/3 and (ii) how does an original collapse turn into an explosion? Nuclear burning of nuclei of given atomic number needs a certain temperature. Nuclear burning of higher atomic number nuclei needs higher temperature. Until this temperature is reached, the density keeps increasing due to gravitational compression and the matter becomes degenerate. The burning of degenerate fuel is explosive in nature. This can be understood by recalling that in normal nuclear burning, the following sequence of events occur: High burn rate results in increase in pressure which causes expansion that cools the gas and therefore burning slows down; this leads to contraction, then heating and back to high burn rate, thus providing a self regulating system. Under degenerate conditions, the pressure comes from degenerate electrons and not from thermal energy density. As the burning proceeds, the material does not stop contracting and therefore gets hotter and hotter, leading to very fast explosive burning. Eventually when the thermal pressure overtakes degeneracy, an ejection takes place. Thus the collapse and the explosion are nothing but the fall and the rise of γ.

Models of Type I Supernovae

Modeling predicts that stars with 4-8 $M_\odot$ mass can explode through carbon detonation and carbon deflagration, stars with mass 8-10 $M_\odot$, which have lost their hydrogen-rich envelopes are susceptible to oxygen deflagration, and helium stars of mass $\lesssim$ 4 $M_\odot$ undergo explosive ignition of carbon and oxygen. A star near Chandrasekhar mass limit with degenerate carbon core has a helium burning shell. Carbon, the product of helium burning is added to the core whose mass then exceeds the Chandrasekhar mass limit. The core contracts. Conditions for degenerate burning of carbon set in. The core explodes and the resulting shock can completely disrupt the core. This process is known as carbon detonation. The kinetic energy requirements of type I supernovae are satisfied. About 0.5 to 1.0 $M_\odot$ of Iron peak elements are produced. Complete disruption leaves no neutron star. If on the other hand, the core is too dense to suffer complete disruption, neutron star remnant is possible as well as some of the iron can remain locked thus saving the explosion products from having too much iron. However, more detailed modeling casts doubts on the formation of a strong enough shock. Instead of the shock, if the heat is carried outwards by convection and conduction and fresh fuel is pumped in due to Rayleigh-Taylor instabilities the material is said to have undergone deflagration. Perhaps it is a combination of detonation, deflagration and rapid transport processes that is needed to account for the complexity of the supernovae phenomena. It is known that Chandrasekhar limiting mass is higher for a hot and rotating star. With the loss of angular momentum, eventually the star will exceed the Chandrasekhar mass limit and undergo collapse. Since, loss of angular momentum needs a long time, this may be one reason for associating type I Supernovae with old stars. Explosion in binary stars can be triggered when the accreting white dwarf grows until it (i) collapses by electron capture, (ii) ignites helium off centre, resulting in detonation, (iii) ignites carbon off centre resulting in detonation or deflagration disrupting the whole star. A merger of a white dwarf core with the degenerate core of the companion star can also initiate collapse and detonation. In conclusion helium envelope masses of $\sim 0.5\ M_\odot$, an optically emitting region of 10^{11} - 10^{13} cm and half $M_\odot$ core of Ni^{56} are the ingredients that make type I supernova.

Models of Type II Supernovae

A type II supernova requires about 10^{51} ergs at the base of $\gtrsim 5\ M_\odot$ envelope of solar composition and supergiant structure. The likely candidates include single stars of 4-7 $M_\odot$ mass, capable of developing nondegenerate carbon-oxygen cores of mass exceeding Chandrasekhar limit. Nuclear burning proceeds until core evolves into a Chandrasekhar mass of iron supported by degenerate electrons. The exponent γ can go below 4/3 when (i) electron capture ($e + p \rightarrow n + \nu_e$) results in the production of neutrons and neutrinos, and in the withdrawal of pressure support of electrons, (ii) photodisintegration of iron ($Fe^{56} \rightarrow 13\alpha + 4n$), (iii) Surrounding Silicon shell continues to burn adds more Fe, Ni to the core which exceeds the Chandrasekhar mass limit and collapses and (iv) the neutrino pair emission from the hot core drains energy out of the core.

After the collapse occurs due to one or more of these reasons, the core heats up and eventually the thermal pressure wins and γ increases back to 5/3, the pressure being due to neutrons. The hydrodynamic bounce can create a shock. If the mass of core inside the bounce region exceeds 1.1 $M_\odot$, a neutron star comes into existence. In this scenario, most of the energy released is either carried by shock or by neutrinos. Shocks are favored by softer equation of state. Shocks gain energy from the infalling matter and lose it by neutrino emission. It appears doubtful if the shocks can reach envelope with enough useful energy. The numerical modeling is pursued for the first few milliseconds of the collapse and therefore the life and times of shock remain unknown. Neutrinos, on the other hand have become a hot favourite of the modelers because it is now realized that neutrinos can efficiently deposit energy due to their coherent scattering with the nuclei. The ejection of material can be facilitated through convection caused by Rayleigh-Taylor instabilities where light neutrinos are trapped under heavy Baryons of outer core and mantle. The basic need is the strongly coupled hydrostatic core, the shocked mantle and the neutrinos; hoping all this will essentially enhance the neutrino transport rate and result in a usable deposition of energy. Well, in order to account for the complexity and variety of supernovae phenomena, one has to use all one has and more.

Supernova 1987A is an year old. It has been observed in almost all bands. Modelers and observers are working hand in hand to give us a comprehensible picture. Let me make a birthday wish for SN 1987A: May it be blessed with a functioning pulsar, Amen!

Acknowledgement

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