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Observational Results from SN1987A and their implications on Theoretical Modelling of Supernovae

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In the approximately one year since the explosion of the Supernova 1987A in the Large Magellanic Cloud, a large amount of work, both observational as well as theoretical, has been undertaken. Stan Woosley, a prolific worker in the field has summarized the situation in the following way: "Accurate data, especially regarding the bolometric light curve, was initially difficult to obtain, and a proliferation of models occurred, many of them mutually inconsistent. Few, if any, are in good accord with data as we now know it. For the most part, theoreticians were greatly influenced by what they happened to be working on at the time and by a great haste to publish". In the ensuing time, more reliable and cross-checked data have been gathered and theoretical understanding has been substantially advanced. In this presentation I shall discuss the relevance of a few crucial observations on SN1987A to Supernova models and their theoretical understanding.

Important Observational Results from SN1987A:

Most observations, as far as their theoretical understanding are concerned can be classified in three categories: (1) Pre

Supernova evolution, (2) Collapse and neutron star formation and (3) Lighting up in the post-explosion stage.

In the first category, broadly speaking, belong: (a) the identification of the progenitor star Sanduleak-69° 202 with a blue supergiant star; (b) the fainter "plateau stage" compared to a typical type II supernova; (c) the short time span between the neutrino "sighting" and the first optical sighting and an upper limit to the brightness of the star some 106 minutes after core collapse; (d) the high enrichment of Nitrogen and Oxygen ejected material of the pre-existing circumstellar shells. In the second category come: (e) the detection of a burst of neutrinos a few hours prior to the optical brightening of the SN, their energetics, numbers and arrival times; (f) Observation of Infra Red lines characteristic of low ionization state of Cobalt and Nickel, their line widths and the inferred velocity and position of these elements in the core. The third category includes: (g) the exponentially decaying light curve of the Supernova after 120 days and its implication towards the amount of radioactive Ni^{56} and Co^{56} synthesized and mixed in the core; (h) analysis of late light curves towards the amount of H-rich envelope when the star exploded; (i) hard x-ray emission and gamma-ray line emission and the extent of radioactive element mixing in the core. The implication of the second category of observations as well as parts of the last category are being discussed by others in this Volume.

Sanduleak-69° 202 and Pre Supernova Evolution

Prior to the identification of the progenitor star of SN1987A, type II supernovae were generally presumed to arise from red supergiant stars (Weaver et al. 1978), even though there were theoretical models which had these stars evolve to blue supergiant under certain conditions (Brunish and Truran,1982a,b ;Arnett 1977). The identification, structure and evolution of the presupernova star are important for at least two different reasons: (1) presupernova stellar structure determines the character of the core collapse, bounce and shock formation, and shock propagation; (2) the post-explosion light curve, as the shock propagates through the outer envelope and circumstellar matter, is determined by the structure of the pre-existing star and its history among other things.

Various observations that have bearing on the nature of the presupernova star of SN1987A point towards a substantially more compact nature of the star than is expected of a red supergiant. The fact that the star was blue (spectral class B3I, with an effective temperature in the range 15,000 to 18,000° K) along with its apparent magnitude m_V=12.36 (Wallborn et al. 1987) and distance measure of 18.5 and extinction 0.5 (hence a luminosity $4.0^{+2}_{-1}\ \times10^{38}$ erg/s) imply that its radius was in the range $(3\pm1)\times10^{12}$ cm. In comparison, a typical red supergiant star of 15 $M_\odot$ with near solar metallicity would have a radius of 3.8×10^{13} cm (Weaver et al. 1978). This has further implications towards the class of acceptable models. The last optical sighting of the progenitor star was made between February 23.059 (UT) and February 23.101. There was no enhanced emission at that time from the star. The neutrino burst recorded by the IMB collaboration (Bionta et al. 1987) (and within one minute by Kamioka collaboration; Hirata et al. 1987) took place at Feb. 23.316 UT, signifying the core-bounce and formation of the neutron star. Between 182.8 minutes to 185.8 minutes after the neutrino burst, the supernova was recorded on film at V = 6.0 and 6.2 by McNaught. Soon, by about 24.455 UT, (i.e within 1.139 d) the supernova brightened to m_V=4.8. In between, at UT 23.39 (i.e. 106.5 minutes after IMB), there was an observation of the same field by A. Jones who noted that there was no supernova present at that time although he discovered it easily next night with the same instrument. This suggested that the object was fainter than 7.5 at UT

23.39. This upper limit has been used by Arnett (1987) and Woosley (1988) to derive a measure of the initial radius and test the consistency of the light curve and the claimed detections of neutrino signal by Mont Blanc experiment with the two others, i.e. IMB and Kamioka. The interval of time between core collapse (neutrino burst) and the rapid optical rise is a measure of the initial radius divided by the average hock velocity. The Jones limit therefore sets a minimum initial radius for the supernova star (2-3 x 10^{12}cm) which is close to the radius calculated for Sanduleak-69°202, a Blue supergiant star. The rise in luminosity with time, which has to be consistent with the Jones limit, constrains the initial radius modulo the explosion energy (which in turn is fixed by later photometric observations). An important aspect of this analysis of the Jones limit is that it is very hard to reconcile the claimed detection of neutrino-events by Mont Blanc taken as the start of the shock more than four and half hours before the IMB/Kamioka detection and the later development of optical brightening. Acceptance of Mont Blanc events as the zero of the time would require unusually low energy of explosion or unusually massive Hydrogen envelope of the star which are ruled out on observed properties of SK-69° 202 and the later powering of the light curve by radioactive decay of Co^{56}. In contrast, a variety of reasonable models are able to accommodate acceptable fits to various observed results if IMB/Kamioka events are taken to be the origin of shock propogation (see Arnett (1987) and Woosley (1988)).

Hydrogen lines have been seen in the spectrum of SN 1987A which lead to its classification as a type II supernova. But in many ways it is found to be not so typical a type II supernova. For example, in the so-called "plateau" phase it had a luminosity about ten times fainter than a typical type II explosion and also the supernova brightened considerably within a few weeks. In addition, extremely rapid spectral development led to the appearance of characteristic line-profiles of expanding envelope.These P-Cygni profiles appeared in 1-2 days which normally takes roughly 10 days to appear. Again all these observational differences can be tied together if the initial state from which the supernova expanded was considerably more compact than the "ordinary" type II SNe. The peak in the luminosity at the plateau stage has a sample scaling with the initial radius as this is connected with the adiabatic decompression of the internal energy:

$$L_p \sim R(o) < v^2 >$$

where R(o) is the initial radius and v^2 is the square of the expansion velocity scale.

Following hydrogen recombination, the luminosity rises, mostly due to energy from radioactivity that diffused out. In the absence of any such extra input of energy, the light curve would have declined after hydrogen recombination. Among the possible sources of input other than radioactivity, Ostriker (1987) had suggested that there could be a central pulsar. Although a pulsar is not ruled out (in fact a neutron star must be present as evidenced by the detection of neutrino-burst signifying gravitational collapse), it is now known from a study of later (t>120 days) decline of the light curve that radioactive decay of Co^{56} must have been the source of energy input. This in turn produces a limit as to what the energy input from a (possible) pulsar can be and hence how fast the neutron star can be rotating at birth (Arnett and Fu (1988) gives $\lesssim 2\times10^{39}$ erg/s and P $\gtrsim 2\times10^{-2}$ sec).

With the recognition that a small sized progenitor star could explain many of the observational features, several workers addressed themselves to the question as to what conditions made the star appear blue. The envelope structure and the size of the star does not change much between the carbon ignition and immediate presupernova stages since the nuclear burning proceeds at a quicker pace than the rate at which the star's envelope has a chance to relax and achieve thermal equilibrium. Therefore the position of the star on the Hertzsprung-Russel diagram at or beyond the carbon-ignition stage does not change much till the star explodes (see Weaver et al. (1978)). Blue supergiants evolving to an exploding supernova have been considered earlier by Arnett (1977), Brunish & Truran(1982 a,b) and recently by Hillebrandt et al. (1987), Arnett (1987) and Woosley et al. (1988). It was found by Brunish and Truran that for a 15 $M_{\odot}$ star, the radius of the star at carbon burning strongly dependent upon the metallicity between $z = 0.001$ and $z = 0.01$ (from 2.6×10^{12} cm to 6×10^{13} cm).

In the works of Arnett (1987) and Hillebrandt et al. (1987) where the evolution is computed with only a reduced metallicity (compared to solar) and no mass-loss is involved, the star stays in the blue region throughout the post-carbon ignition phase. Although lower metallicity (e.g. the metallicity $Z = Z_0/4$ to $Z_0/3$, appropriate for LMC) reduces the opacity and would tend to make the envelope of the star less extended (thus making it appear blue) the effect is not so simple. Changing the metallicity changes the extent of the convective core, and modifies the energy generation rate and opacity during the core Hydrogen burning and H-shell burning stages. The presupernova radius has been shown to be highly sensitive to the core luminosity beyond a critical value (Woosley, Pinto and Ensman, 1988). Beyond this luminosity, the radiative envelope becomes a fully convective red supergiant envelope, and therefore the sensitivity to overall metallicity arises.

On the other hand, observations of 30 Doradus region where SN 1987A took place, show the existence of many red supergiants. Therefore it is likely that either a fraction of the massive stars explode in the red supergiant phase (in contrast to SN 1987A) or these stars spend a long time in the red supergiant phase and then somewhat before they explode (effectively around central carbon ignition) they make the transition to the blue. If the latter alternative is followed, then in the HR diagram these stars undertake a blue to red to blue path. Observations on SN 1987A, in particular the existence of nitrogen-rich, low velocity ($v<200$ km/s) gas -presumed to be a circumstellar shell, point towards the latter alternative, since this observation (due to Kirshner et al. 1987) indicates that the progenitor Sk$-69^{\circ}202$ underwent a lot of mass loss (Maeder 1987; Nomoto et al. 1987). This is easier in the extended red supergiant phase. The anomalous and highly enriched N/C and N/O ratios that are observed may exist naturally in massive stars that have passed through the red supergiant phase. During core hydrogen burning, the convective central zone shrinks, leaving behind a large Nitrogen to Carbon ratio. If at a later stage this Nitrogen enriched material is dredged up to the surface by convection then it can be subsequently lost to a circumstellar envelope. This is possible in a red supergiant (RSG) phase even without mass-loss especially near the tip of the RSG branch where it has a deep convective envelope and enhancement of N/C ratio over a factor of 2 to 10 is possible. A star which stays in the Blue part of the H-R diagram throughout and has a different envelope structure is not expected to undergo substantial enhancement of products of CNO processing deep in the interior unless other effects like rotational mixing are brought into play.

Woosley (1988) has pointed out the importance of the accurate determination of the factor by which the N/C ratio exceeds the solar value. N/C enhancements can be as large as 80 (Casatella, 1987) or down from 30 to 10 (Kirshner as quoted by Woosley (1988)). Enhancement factors over 10 indicate a degree of mass loss from the system. If there is heavy mass loss, the mass of the envelope retained would be smaller and the dilution of the CNO enriched material by the envelope which is dredging up the material to the surface would be less. Ratios of N/C 80 times or even 30 times solar are achieved only if the star loses almost all its envelope. The works of Maeder (1987) and Wood and Faulkner (1987) suggest that the nitrogen enhancement in the circumstellar medium and the blue nature of the progenitor are related only if a few tenths of a solar mass of envelope was retained on the star when it exploded. Other observational results combined with theoretical calculations discussed below tend to suggest that mass loss of that great a magnitude would not be supportable; hence the blueness of Sk -69° 202 taken together with the Nitrogen enhancement in the envelope imply a cause that is at least partially due to lower metallicity (though not entirely due to it).

Supernova light-curves and mass of the envelope at explosion

The post Helium-burning nuclear evolution has little sensitivity to the mass or state of the Hydrogen envelope. The luminosity of the star is determined by its Helium-core mass since the H-burning shell contributes little at the time of the SN. M_{HC} does not change much beyond central carbon depletion. A luminosity of $\sim 1.3 \times 10^5$ $L_{\odot}$ requires (from evolutionary calculations) that Helium core mass is $6M_{\odot}$ for an overall metallicity of $Z=Z_{\odot}/4$. The luminosity of SK $-69^{\circ}202$ is nearly 10^5 $L_{\odot}$ with D=55 kpc and visual extinction $A_V \sim 0.6$. Observations and theoretical calculations of various authors imply (see Woosley,1988) that at the time of explosion the star had a Helium core mass of $6 \pm 1 M_{\odot}$.
(Incidentally, the Helium core mass at central C-depletion, upon which the luminosity of the progenitor depends so sensitively, is dependent on a variety of physics inputs, among which are the algorithm of energy transport by time-dependent convection, composition, nuclear reaction rates etc. These are currently under investigation by several groups to arrive at a physically optimal and self-consistent approach.) This in turn implies a mass of the star on the main-sequence to be $M_{ms} \sim 20$ $M_{\odot}$ (19 ± 3 $M_{\odot}$; see Nomoto et al. (1987) and Woosley

(1988)). Hence if there were no mass loss at all, the mass of the H-rich envelope would have been nearly $14M_\odot$. Thus the presupernova star could have an envelope of mass $10-15M_\odot$ with large He/H and N/C ratios in contrast to the original compositions of the main sequence star. We have seen in the previous section as to how a high value of N/C with respect to the Sun constrains the mass loss rate and the mass of the envelope retained. Now, the development of the light curve after the SN event, also constrains the envelope mass. This is true for both the very early light curve (i.e. near shock break-out time) as well as for the post-plateau brightening (especially near the peak).

For early light curve, if the envelope were to have a constant density, the outgoing shock reaches and breaks out of the surface of the star (Sedov solution is quickly attained by the shock) after a time:-

$$t_b = 2500 \text{ sec } (M_{env}/M/E_{51})^{1/2}$$

Thus, the shock breakout time is related to the mass of the envelope and energy of explosion. In more refined hydrodynamic models the envelope structure can be taken into account and the numerical calculations of brightening after a certain time interval following the IMB/Kamioka neutrino-burst can be compared with observed early ($t \lesssim$ 1-2 days) light curve. Woosley's models suggest that the shock wave excited the star between 40 to 120 minutes after core bounce with the most successful models giving t_b=6000 sec. This implies a combination of envelope mass and explosion energy stradling between $\sim 5\ M_\odot$ (0.65×10^{51} erg) on the low side to $M_{env} \sim 10M_\odot$ (1.4×10^{51} erg) on the high side, although somewhat lower and higher values are not ruled out on the basis of the relatively sketchy data in the early period. The energy cannot be too low either. The intermediate time (25d < t < 120d) light curve is also influenced by the mass of the envelope, because the energy released in the interior by the decay of radioactive nuclei has to diffuse out through the overlying material. But the light curve is also sensitive to other factors like explosion energy, opacity in the helium core, amount of energy released in recombination of ions etc.

The gamma-rays that are released in radioactive decay are quickly degraded to lower energy by Compton scattering and photoelectric transitions and ultimately this energy appears in the optical which scatter down to the photosphere. Ultimately however the core itself and of course the overlying matter becomes transparent, leading to the emission of high energy radiation from the Supernova.

Nomoto et al. (1987) and Woosley (1988) have run a series of hydrodynamic models to simulate the light curves and photospheric velocities as they developed from very early times to late times and have tried to restrict the envelope mass left at the time of explosion. Both groups find that reasonable agreement requires $M_{env} > 3M_{\odot}$. Envelopes less massive than this make light curves to rise to peak too early and too rapidly. One cannot reduce the mass below this too much by for example reducing the energy of explosion ($E<3x10^{50}$ erg) to obtain better fits, since in that case the layer which is rich in radioactive material would not have enough kinetic energy and would fall back and not give rise to the later exponential tail in the light curve. In low mass envelopes, because there is little "damping" effect, the slowest moving layers move out too fast compared to observations. The fact that low mass envelope models fail to accommodate later light curves is relevant in the context of the requirement of very low mass envelopes to simultaneously explain the blue nature of the progenitor star and the large N/C enhancements in the circumstellar envelope. The requirement of $M_{env} > 3M_{\odot}$ suggests that the progenitor returned from the red region of HR diagram to blue before losing most of its H-rich envelope.

In view of the "best fits" to the early and intermediate light curves (i.e. where the peak occurs, how fast is the rise to peak etc.) and the fact that x-rays, gamma-rays from the SN were detected relatively early, the best estimate of the envelope mass due to Woosley (1988) is near $5M_\odot$ (in the 5-10 $M_\odot$ range) with an explosion energy around 6×10^{50} ergs. A $10M_\odot$ envelope would require a higher explosion energy ($\sim 1.4 \times 10^{51}$ erg) and to explain the early appearance of x-rays a certain degree of clumping and/or mixing of radioactive material is required. The power output from the exponentially decaying optical light curve after 120 days, implies that a mass of $0.07M_\odot$ of Co^{56} was synthesised before or during the Supernova.

Gamma-ray and Infra-Red line observations & Ni-Co in the core

Line observations at two very different parts of the electromagnetic spectrum tell us significant things about the state of the core and the extent of mixing that has gone on there.

Hard x-rays in the (10-30KeV band) were detected for the first time on day 132 by the Japanese x-ray satellite Ginga (Makino 1987; Dotani et al, 1987) as well as by the Soviet Mir Space-borne Observatory (Sunyaev. et al. 1987). On the other hand gamma-ray lines were initially detected around 160 days by the Solar Maximum Mission (SMM) satellite (Matz et al. 1988). This was followed by detections of gamma-ray line fluxes by several groups, among which are GRAD (Lester et al. 1988) and Caltech and Lockheed groups as well as further results from SMM. The detected flux at 847 keV was rather high ($\sim 1.1 \times 10^{-3}$ photons/cm^2/sec) and early compared to expectations. In addition to this line, SMM also reported line flux at 1238 keV at a strength which corresponds to the laboratory branching ratio in the Co^{56} to Fe^{56} decay. This suggested that the emitting region is "optically thin" since otherwise the two lines would be absorbed to different extents, and their line ratios would be different from what is observed in the lab. The observed line strength is equivalent to uncovering approximately 1% of the total mass of Ni^{56} synthesized in the explosion, i.e., the total mass of 0.07 $M_\odot$ as interpreted from the exponential decay of the light curve.

The early detection of gamma-ray line flux and x-rays and the line ratio supports the suspicion that radioactive material is present in an extended and highly clumped distribution throughout the core and beyond. An alternative could have been to uncover material located deep inside at the required time by having high expansion velocity scale and/or low column density above the radioactive source by having a tenuous mass distribution at large radii. Fu and Arnett (1988) have looked into these possibilities, taking into account the early appearance and flux levels of hard x-rays as well. Their conclusion is that if the mass of the envelope and the velocity scale were to be chosen from the aggregate of theoretical and observational constraints, then a $0.07M_\odot$ radioactive source condensed within the helium core could not have produced the x-rays detected by Ginga so far. In the alternative assumption of an extended source with mixing of radioactivity beyond the He core, clumped sources of radioactive Co^{56} are uncovered which generates the detected level of hard x-ray flux. Fu and Arnett calculate that 4-5 clumps of radioactive Co each of mass $\sim 2 \times 10^{-4}$ $M_\odot$ reach a surface where the optical depth is about five between the time of x-ray to gamma-ray emergence. Thus, gamma-ray observations can be explained in this scenario as the "effervescence" of radioactive bubbles in the upper layers of the ejecta. These regions are being progressively more transparent partly because of the thinning of the surrounding media and partly because of the buoyancy of these bubbles. A good deal of mixing of the radioactive material outside of the helium core could have happened because of Rayleigh-Taylor instabilities which develop when a reverse shock wave propagates through the core and causes density inversion near the edge of the helium core and hydrogen-rich envelope (Nomoto et al, 1987, Woosley et al, 1987).

The evidence for mixing and penetration of radioactive material beyond the Helium core comes also from Infra-red line measurements. Comparison of spectrum of SN1987A in the 4 to 12.5 μm range taken by Kuiper Airborne Observatory (Rank et al, 1988) on 12th November 1987 and 21st April 1987 show the presence of Ni II and Ni III and perhaps Co II ions. The low ionization state of these elements implies a region of high density where there is efficient cooling. Thus these are from regions of SN near its core. A rough estimate of the velocity of IR-line emitting region from the frequency shifts is $\sim$ 1000 km/s (and could be as high as $\sim$ 2000 km/s). Supernova models where there is no mixing of explosive burning products would give a maximum velocity of the Co^{56} region usually much less than 500 km/s. Since higher velocities of expansion are reached at larger comoving distances (from rough homology arguments) a high velocity of the IR emitting region places it further outside the helium core.

Similar expansion velocity estimates (1300 ± 300 km/s) have been reported from the red and blueshifts of the 847 keV and 1238 keV gamma-ray lines by the GRAD experiment (Rank et al, 1988) and give further evidence towards mixing beyond the core.

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