# SUPERNOVA AND COSMIC RAYS

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## I. Introduction:

The Supernova (SN) is one of the most important and most complex phenomena in astrophysics. Detailed observations of SN require advanced techniques of astronomy and high energy astrophysics, but the theoretical explanation of SN involves virtually every branch of physics. Supernovae, however, offer more than a challenging physics problem because SN are involved in the origin of most of the heavy elements, are the birthplaces of neutron stars, pulsars and probably black holes, control the structure of the interstellar medium, may be responsible for the birth of new stars (and possibly our own solar system), and, of greatest concern in this paper, are involved either directly or indirectly in the origin of the galactic cosmic rays.

Supernova were first observed as "guest stars", objects that appeared as new bright stars in the night sky only to disappear after a number of months. Recorded SN sightings go back at least as far as the ancient Chinese, and there have been several historical SN in our galaxy: Tycho (1572 AD), Kepler (1604 AD), and the Crab (1054 AD). Of course, there are many identified supernova remnants, among them Cassiopeia A which probably exploded $\sim$1700 AD but was not reported. Unfortunately, there have been no modern supernova in our galaxy, but $\gtrsim$ 100 SN have been observed in external galaxies. The optical observations of SN along with detailed studies of supernova remnants (SNR) remain the principal source of experimental information on the SN phenomenon.

It is impossible to review all aspects of supernovae within the space limitations of this paper. Rather a brief general overview will be presented, focussing on recent developments, followed by a discussion of the relationship between SN and galactic cosmic rays. I apologize at the outset to the many people whose papers will not be discussed, but I will attempt, where possible, to refer to papers or review articles through which the primary references may be obtained.



*G. Setti, G. Spada, and A. W. Wolfendale (eds.), Origin of Cosmic Rays, 39–50.*

## II. The Life of a Supernova -- A Brief Review

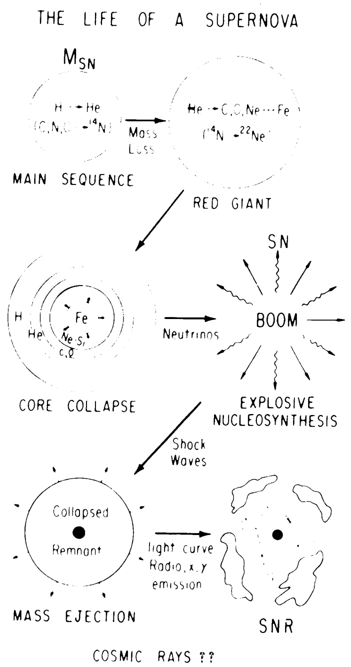


Fig. 1: Evolution of a typical Supernova

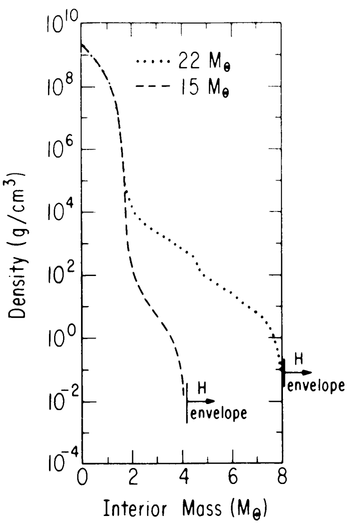


Fig. 2: Density profile for two stars following pre-supernova evolution

Supernovae are believed to be the death-throes of massive stars, occurring after the cessation of thermonuclear reactions. The life-cycle of a typical SN is illustrated on figure 1. The pre-supernova star evolves normally through the main sequence to the red-giant stage. Thermonuclear reactions then proceed at an ever increasing rate, converting the He to C and O and then burning these products, in turn, until the iron peak is formed. This leaves a star composed of the major alpha-particle nuclei, $^{12}$C, $^{16}$O, $^{20}$Ne, $^{24}$Mg, etc. and the iron peak in an approximate shell structure or "onion-skin" model as illustrated in the third panel of the figure. Gravitation then takes over and the core begins to collapse, increasing in temperature and density. Neutrinos are produced and carry away energy. The details of what happens next are still unclear, but somehow the star explodes, ejects the overlying layers of processed matter, and leaves a condensed remnant. The shock wave from the explosion moves through the mantle and heats the matter, initiating nuclear reactions (explosive nucleosynthesis) and providing the visual light display. The mantle itself expands and interacts with the local interstellar medium (ISM), eventually coming to rest as a supernova remnant. It is at these later stages that cosmic rays may be accelerated.

A. <u>Pre-Supernova Evolution</u>: This aspect of the evolution has been studied extensively with detailed evolutionary sequences both for complete stars and for helium cores of a variety of initial masses (see Arnett, 1977; Weaver, Zimmerman, and Woosley, 1978). Figure 2 shows the density profile for two stars. Note that both evolve similar cores, but the density gradient beyond the core is much steeper for the smaller star. Since each of the onion-skin shells is at roughly constant density, the 22M$_\odot$ star contains more processed heavy elements by a factor of $\sim$ 4. Integrating the amount of mass returned by each star of mass M over the mass distribution of stars in the galaxy, and over galactic history, Arnett (1978) has shown that the solar system abundances for the major isotopes are reproduced.

Stars may be divided into five mass ranges based upon their evolution and final state, as shown in Table 1. The lightest stars evolve so slowly that they remain on the main-sequence for the history of the galaxy. The next group contains stars that shed enough mass to become white dwarfs. Observations of young clusters suggest that an upper limit for this mass range is $6\pm2\ M_\odot$, with the uncertainty reflecting our lack of understanding of mass loss processes. For an onion-skin configuration, a star must be massive enough to ignite the carbon core formed during helium burning. For stars below $8\pm3\ M_\odot$, electron degeneracy pressure in the core can support the star from further collapse. Above $\sim8\ M_\odot$ carbon ignites non-degeneratively, and these stars evolve to the core collapse supernova discussed in this paper. Note that at the highest masses electron-positron pair formation in the oxygen core causes a change in the equation of state, leading to instability and explosion. The third line of the table shows a mass range which, fortunately, may not exist. If these stars do ignite carbon under degenerate conditions, a runaway results -- the carbon detonation supernova. This burns the entire core to iron which, if ejected, could lead to an "iron catastrophy."

TABLE 1: PRE-SUPERNOVA EVOLUTION

| MASS RANGE ($M_\odot$) | EVOLUTION | END-POINT |
|---|---|---|
| $\lesssim 1$ | main sequence only | - |
| $\sim 1$ to $6\pm2$ | mass loss | white dwarf |
| $6\pm2$ to $8\pm3$ | a) degenerate carbon core<br>b) pulsational mass loss | a) carbon det. supernova<br>b) white dwarf |
| $8\pm3$ to $\sim100$ | onion-skin structure | core collapse supernova |
| $\gtrsim 100$ | $e^+\ e^-$ pair production | pair formation supernova |

B. Collapse, Explosion and Mass Ejection: The fundamental problem facing the core collapse supernova model is the question of how to obtain an explosion with the ejection of the star's mantle. In recent years attention has focused on two classes of models: neutrino interaction models and hydrodynamic models. Neutrinos are the dominant energy loss mechanism for the core from carbon burning through the explosion. As the iron-nickel core collapses, temperature and density increase and neutronization occurs through $e^- + p \rightarrow \nu + n$ and $e^- +$ nucleus $\rightarrow \nu +$ nucleus'. This decreases the electron abundance, thus lowering the electron pressure and increasing the rate of collapse. At the high temperatures of the inner core, neutrino pair emission takes place. With the discovery of neutral currents in the weak interaction, the neutrinos take on added importance (see Freedman, Schramm and Tubbs, 1977). As collapse proceeds, the inner core, originally supported by electron pressure, evolves to a neutron gas. This implies a change in the effective adiabatic index, essentially a stiffening of the equation of state. The overlying matter falling into this stiffer core suffers a hydrodynamic 'bounce' with the formation of a shock wave.

How is the overlying material ejected? In the neutrino interaction model, the neutrinos streaming out of the core scatter from the mantle material transferring sufficient energy and momentum (it is hoped) to eject the mantle. However, detailed calculations show that the collapsing core of a massive star is <u>not</u> transparent to neutrinos, leading to a significant number of neutrino interactions before escape. This reduces the neutrino energy, and, since neutrino cross sections are proportional to $E^2$, reduces the effect of the neutrinos on the mantle. Further, the neutrinos are not emitted in a burst but are tied to the matter and come out over extended time periods. Calculations have obtained sufficient momentum transfer to slow or halt the infall of the overlying matter, but not an explosion. The hydrodynamic model offers an alternate approach, in which the reflected shock wave following the 'bounce' may drive off the mantle of the star. Recent spherical adiabatic collapse calculations by Van Riper (1978), assuming strong neutrino trapping and various equations of state, gave strong reflected shocks which steepened further in the star's density gradient (figure 2) providing ejection of the mantle. The results depend critically on the "elasticity" of the equation of state, giving a strong reflected shock only for adiabatic indices near 4/3. The typical energies in the explosion were a few times $10^{51}$ ergs, sufficient to power supernova light curves, and a dense remnant was formed.

C. Supernova Light Curves: The light curves of supernova are their visual "signature", and figure 3 shows 'typical' light curves (assuming any supernova is typical?) for type I and type II events, taken from observations collected by the Asiago Observatory (Barbon, Ciatti and Rosino, 1973). Both types show an initial peak in luminosity with the type II decreasing to an approximate plateau for several months, before a final decline. The type I, however, shows a long exponential tail which may persist for many months. The spectra of type I events show broad overlapping emission bands with little or no hydrogen emission. Type II's, on the other hand, clearly show the Balmer series in the first few weeks following maximum. Unfortunately, most supernova are discovered at or just past maximum light, so little is known about the pre-maximum epoch.

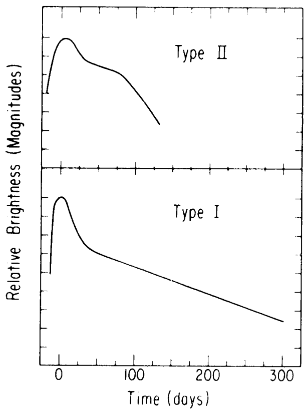


Fig. 3: 'Typical' SN Light Curves

Type II light curves have found an explanation, recently, in a shock wave model. Falk and Arnett (1977 and references therein) have followed the shock wave from core collapse into the star's mantle and envelope, tracking energy deposition, mass motions, radiative transfer, emissivity and opacity in a computer code combining numerical hydrodynamics and radiation transport. The peak in the light curve corresponds to the eruption of the shock wave through star's envelope with the light from the hot gas being absorbed and re-radiated by an circumstellar shell, thereby spreading the peak. The rest of the light curve is explained by the time evolution of the material which becomes progressively more transparent so that light from the mantle and eventually from the core itself can be observed. No energy source other than the shock wave is needed, provided there is a massive mantle/envelope with a density structure similar to the 22 $M_\odot$

star in figure 2. Comparison of these calculations with the detailed observations of supernova 1969*l* in the galaxy NGC 1058 shows a remarkably good agreement.

The type I light curve has been explained recently by a mechanism involving radioactive decay. For a star whose density profile is similar to or even steeper than that shown for 15 $M_\odot$ on figure 2, the core collapse and explosion will process the inner 0.2-0.3 $M_\odot$ of mantle material to $^{56}Ni$ and eject it, provided the mantle/envelope does not stop the material. (This may require considerable mass loss during pre-supernova evolution.) Arnett (1979) has shown that the decay of the $^{56}Ni$ re-heats the matter after the peak so that the light curve decays initially as the $^{56}Ni$ mean life (8.8 days) until the γ-rays begin to escape, ~25 days past maximum. This is the transition to the exponential tail which is powered by the decay of $^{56}Co$ (half-life ~80 days). The $^{56}Co$ γ-rays escape, but the decay positrons provide the energy source. One important prediction of this model is that the γ-ray line emission from $^{56}Co$ should be observable over much of the exponential phase.

D. Explosive Nucleosynthesis: This nucleosynthesis takes place following the passage of the SN shock wave, which heats the mantle material Explosive processing has been studied extensively in parameterized calculations, employing detailed nuclear reaction networks, to determine the conditions of temperature, density, neutron excess and expansion time scale required for the calculations to reproduce the solar system abundance distribution. Figure 4 shows a sketch of a pre-supernova configuration for a 22 $M_\odot$ star. The values of $T_i$ indicated on figure 4 (in units of $10^9$ °K) are the temperatures derived from the parameterized studies for the carbon, oxygen and silicon shells to give the correct composition of the isotopes Ne-Si, Si-Ca, and the iron region, respectively (see summaries in Schramm and Arnett, 1973). Assuming that the different shells actually reach the temperatures indicated on figure 4, then the combination of pre-supernova evolution and explosive nucleosynthesis in massive stars does indeed form the majority of the stable isotopes through the iron peak.

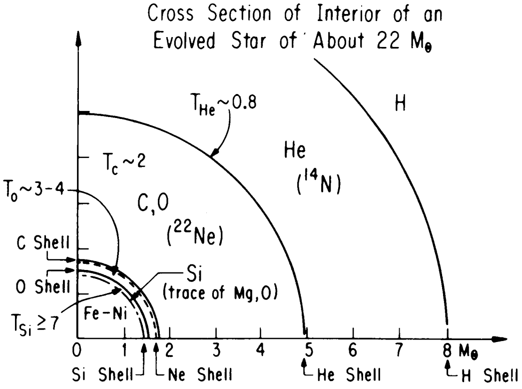


Fig. 4: Onion-skin configuration indicating burning shells, nucleosynthesis products and temperatures required for explosive processing.

Recent calculations, however, modify this simple picture. Weaver and Woosley (1979) find that the carbon region in their 25 $M_\odot$ star does not attain the required temperature but that explosive processing occurs in the neon rich region. Wefel et al (1980) find a large overproduction of the isotopes in the atomic mass range A = 69-77 from neutron reactions during explosive carbon burning,

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suggesting that explosive carbon burning cannot take place in most supernova events. Arnett and Wefel (1978) showed that the isotopes Ne-Si can be formed during pre-supernova evolution in high temperature, convective carbon burning shells, such as are shown on figure 4. Thus, the division between pre-supernova and explosive nucleosynthesis remains a gray area which contains many important problems (and probably a few surprises as well).

The role of massive star SN in producing the upper 2/3 of the periodi table is still unclear. The synthesis of these elements relies mainly on neutron capture reactions on, historically, a s(slow) or r(rapid) time scale relative to beta decay times. The rare proton rich species bypassed by neutron capture reaction are not included here (see Woosley and Howard, 1978). The bulk of the s-process isotopes are formed in lower mass stars (3 - 8 $M_\odot$) via thermal instabilities in high temperature shell burning. Each flash sweeps fresh material into the shell burning region where neutrons are liberated and subsequently captured by iron peak elements before the material is convected out of the shell (Truran and Iben, 1977). Although limited s-process environments do occur during the evolution of massive stars, the majority of the s-process material is not produced here.

The r-process requires intense neutron fluxes and short time-scales, as described by Norman and Schramm (1979). Such conditions might be found in the core of massive stars near the 'mass cut', the division between material which will be ejected and the matter that remains in the core, but the physics of this region is not well understood. Alternatively, an r-process event may occur in the helium burning shell if the shock wave heats the material to $T_{He} \sim 0.8$, as indicated on figure 4 (see also Thielemann, Arnould, and Hillebrandt, 1979), although such heating is still questionable. No completely acceptable site for an r-process event has yet been identified, but massive star supernova still remain the best prospect.

Massive star evolution provides both a supply of neutrons and heavy elements to capture the neutrons (seeds). Thus, neutron capture reactions are expected to be important. The seeds are the iron peak elements with which the star was originally endowed. The neutron excess resides in $^{22}$Ne formed during core helium burning via $^{14}N(\alpha,\gamma)\ ^{18}F(\beta^+)\ ^{18}O(\alpha,\gamma)\ ^{22}Ne$ from the $^{14}$N made from the initial carbon and oxygen in the star by CNO-cycle hydrogen burning. The evolution of these elements is indicated on figures 1 and 4. Investigations of neutron capture episodes are incomplete with only core helium burning and explosive carbon and explosive helium burning studied in some detail (see discussion in Wefel et al, 1980). It may turnout that the combined effects of neutron captures during pre-supernova and explosive evolution can reduce, substantially, the requirements placed upon the classical s- and r-processes.

E. Supernova Remnants (SNR): Following the explosion, the ejected mantle/envelope material expands with velocities between $10^3$ and $10^4$ km/sec, impinging upon the local interstellar medium (ISM). The SN material decelerates and eventually instabilities break the expanding shell into pieces. A reverse shock wave forms and propagates into the ejecta creating further turbulent motions. At this stage substantial mixing probably takes place, and, if a magnetic field is present, it can be drawn out into filiamentary structures by the instabilities. (For further details see Chevalier, 1977).

Two of the best known SNR's are the Crab Nebula and Vela remnant, both of which contain pulsars. The Crab shows pulsed emission from radio frequencies to high energy gamma rays. On-the-other-hand, Cas A, represents a relatively young SNR ($\sim$300 years) which is not dominated by pulsar emission. Optically, Cas A contains high velocity (5-10 thousand km/sec) clumps of material along with much slower "quasi-stationary flocculi". The spectra of the fast knots show that they are composed of heavy elements, O, S, Ar, Ca, with almost no hydrogen or helium. The flocculi, however, show mainly H, He, and N with the latter two elements enhanced relative to solar proportions. Cas A may be explained as a 10-30 $M_\odot$ star that underwent significant mass loss (40-60%) prior to the explosion. The fast moving knots are material processed through explosive oxygen burning, and the flocculi sample material from near the hydrogen burning shell (c.f. figure 4) where N and He are overabundant relative to H. Thus, SNR provide an important tool for comparing the theory to observations. Cas A is one well-studied case, but other SNR's need to be exploited.

The expanding SNR compresses the ambient ISM which eventually forms into clumps or clouds. Inside the SNR shell the medium is hot and rarefied. Thus, after the SNR comes into pressure equilibrium, the ISM around it consists of a large region of hot tenuous gas surrounded by denser clouds. If the supernova rate is high enough, the entire ISM evolves to a multi-component medium in which hot, tenuous gas ($10^{-2}$ atoms/cm$^3$, $10^{5-6}$°K) occupies 70 to 80% of the volume with denser (10-100 atoms/cm$^3$) clouds, each surrounded by a "warm" halo, composing the rest of the ISM (McKee and Ostriker, 1977).

The interaction of supernova blast waves with cold clouds may be the push necessary to begin the collapse of such clouds to form new stars and planetary systems, possibly including our own solar system. This idea has been stimulated by the discovery of material of anomalous isotopic composition in meterorites. In particular, the demonstration that $^{26}$Al ($T_{1/2} \sim 7\times10^5$ years) must have been active in the early solar nebula places a supernova event within a few million years of the birth of the solar system (see review by Schramm, 1978, and other articles in that volume). Further, it may be that the dynamics and composition of regions of active star formation, such as OB associations, are dominated by supernova from rapidly evolving massive stars. In such a scenario, the local ISM could have a composition enriched in supernova produced heavy elements, including r-process isotopes, from which may derive isotopic anomalies, metal-rich stars, and possibly the galactic cosmic rays.

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## III. Cosmic Rays and Supernova:

The three main connections between cosmic rays and supernovae are the energy requirement, acceleration mechanism, and the detailed composition. The cosmic rays have an energy density in the galaxy (assuming uniformity) of $\sim$ 1 ev/cm$^3$. However, cosmic rays leave the galaxy after a mean residence time of 10-20 million years (Garcia-Munoz, Mason, and Simpson, 1977), requiring replenishment to maintain a constant energy density. For a supernovae rate of $\sim$0.1 per year and $\sim10^{51}$ erg/SN, the cosmic rays can be maintained if $\sim$1% of the SN energy is converted to energetic particles. This energy requirement was presented in detail by Ginzburg and Syrovatskii (1964) and with Ginzburg's rule (1=10 in astrophysics) has survived changes in supernova rates, cosmic ray confinement times and volumes, and SN energies.

Supernovae also offer a unique situation for charged particle acceleration, and, in fact, observations of synchrotron emission from both SNR's and pulsars is direct evidence that high energy electrons <u>are</u> accelerated. Observations of gamma rays with a spectrum characteristic of $\pi^o$ decay would provide evidence for proton acceleration as well. Models for galactic cosmic rays are constrained by the question of 'adiabatic losses'. In attempting to leave the expanding SNR, the cosmic rays interact and generate hydromagnetic waves which transfer energy from the particles to the medium. In the worst case, several orders of magnitude of particle energy may be lost before the SNR expands and cools sufficiently to damp the waves and allow the particles to escape. There is, however, some disagreement about the inevitability of this energy loss (see discussion by Schwartz and Skilling, 1978), but the problem is alleviated if particle acceleration does not begin until <u>after</u> several years of SNR expansion. Such a time delay is supported by measurements of the Co/Ni ratio in cosmic rays. The data imply that the electron capture isotope $^{57}$Co ($T_{1/2}$ = 271 days) decayed prior to acceleration giving a <u>minimum</u> delay between nucleosynthesis and acceleration of 1-3 years.

Cosmic ray acceleration may take place either inside the SNR or beyond its borders. Scott and Chevalier (1975) proposed a second order Fermi acceleration mechanism operating in SNR such as Cas A. The fast moving knots generate turbulent magnetic fields which act as scattering centers. Matter evaporated from the knots or swept up by the expanding SNR is accelerated, beginning $\sim$20 years following the explosion. Alternatively, particle acceleration by shock waves has been re-examined recently leading to an improved cosmic ray acceleration mechanism (see references in Blandford and Ostriker, 1978). In this "shock" model, particles at suprathermal energies are trapped by pitch angle scattering on either side of the shock and forced to make repeated transits across the boundary. The scattering centers are converging, giving particle acceleration by the efficient first order Fermi process. This "shock" model can operate anywhere, given a strong shock wave, and supernovae are probably the most prolific source of shock waves in the galaxy.

SN can provide both the energy input and acceleration for cosmic rays, but can they reproduce the cosmic ray composition? The elemental and isotopic composition of cosmic rays, both below and above the iron peak, is reviewed extensively in this volume (see chapters by Meyer, Reeves, and Fowler). Figure 5 shows a plot of the ratio of cosmic ray source abundances to solar system abundances (CRS/SS) as a function of the first ionization potential of the elements (see Casse and Goret, 1978). A similar plot versus the charge of the element would look like the dashed line, relative to the scale at the top of the figure.

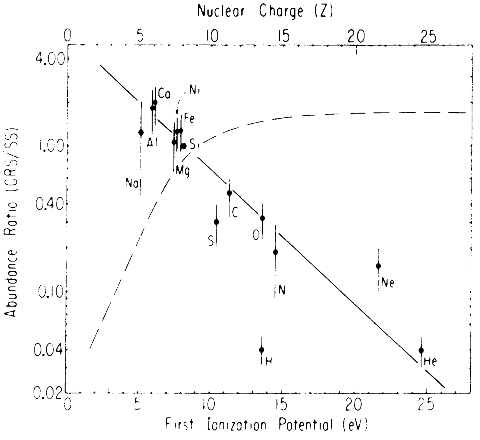


Fig. 5: Ratio of C.R. source to solar system abundances vs. first ionization potential. Dashed curve refers to scale at top and shows trend of a plot vs. Z.

The correlation between CRS/SS and first ionization potential suggests that a selective injection or preferential acceleration mechanism, based upon atomic properties of the elements, operates to modify the element distribution in the source region. This leads to the 'indirect' class of models in which the cosmic ray composition is derived by such preferential acceleration from material with approximately solar system composition. The models are indirect since acceleration can occur anywhere, and SN are involved only as the source of the accelerating shock waves.

'Direct' models begin with the correlation shown as a dashed line on figure 5 and attempt to explain the cosmic ray source composition from the SN itself. Hainebach, Norman, and Schramm (1976) worked out the details of one such 'direct' model in which the source composition resulted from pre-supernova evolution augmented by explosive nucleosynthesis and some mixing, prior to acceleration, with the ISM surrounding the star. They found that the abundances in a $\sim$15 $M_\odot$ star were much closer to galactic cosmic ray source material than were more massive stars. A 15 $M_\odot$ star is about the average SN by number, implying either that SN may each accelerate the same mass of material as cosmic rays or that the smaller stars evolve to SNR configurations that are more apt to accelerate charged particles.

The 'indirect' and 'direct' models are representative of the two extremes of SN involvement in the origin of cosmic rays. Clearly, many models are possible between these extremes. For example, a 'direct' model utilizing a 22 $M_\odot$ star, which produces abundances close to those in the solar system, combined with preferential acceleration may very well provide the cosmic ray source abundances. This highlights the need for further characterization of the cosmic ray source, such as has been obtained recently through isotopic measurements and studies of trans-nickel cosmic rays.

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The recent isotopic measurements important for SN models may be summarized as follows. At the cosmic ray source (relative to solar system abundances); (a)$^{22}$Ne/$^{20}$Ne is enhanced by $\sim$3, (b) $^{25+26}$Mg/$^{24}$Mg may be enhanced by $\sim$1.5-2 (but this needs verification), (c) iron is mainly$^{56}$Fe with $^{54}$Fe and $^{58}$Fe <10%, and (d) $^{40}$Ca/Fe is normal within $\sim$30%. An enhancement of the neutron rich isotopes of Ne and possibly Mg does not follow easily from indirect models unless the material being accelerated is itself abnormal in composition. Direct models can accommodate these enhancements either from the helium burned zone (see figure 4) or from a star with increased metal content. The dominance of $^{56}$Fe is comforting in either model and implies that the SN producing cosmic rays are no different from the rest in their behavior near the mass cut. The limits on $^{54}$Fe are beginning to be restrictive, but $^{58}$Fe could still be enhanced over its normal value (0.3%). The $^{40}$Ca/Fe ratio is interesting here because Ca has a significantly lower ionization potential than iron. An enhancement of a factor of $\sim$2 would be expected, and the normal ratio observed must be explained by indirect models.

The UH ($Z > 28$) cosmic rays sample the s- and r-process components of the source material. Current data favor an r-process source for the $Z > 70$ region, but this interpretation has been questioned. For the elements just above iron, $30 \leq Z \leq 40$, the data show a mixture of s- and r-process components, indistinguishable with current data from the solar system mix. Indirect models predict a solar ratio of s- and r-process material, but direct models predict an r-process dominance, since the bulk of s-process elements are <u>not</u> formed in massive stars. The exception is the region just above iron where neutron capture episodes can produce some s-process material (Wefel, Schramm and Blake, 1977). Therefore, the presence of s-process material at $Z > 70$ becomes the <u>key measurement</u>, involving the separation of the r-process peak at $Z \sim 78$ from the s-process peak at $Z \sim 82$. Current results favor direct SN involvement, but the data now being collected by the satellites Ariel-6 and HEAO-3 should provide definitive results.

The enrichment of cosmic ray sources in $^{22}$Ne, possibly $^{25,26}$Mg, and the r-process dominance for $Z > 70$ lead to the speculation that the stars responsible for cosmic ray production may be enriched in 'metals', i.e. $Z > 2$ elements. An enrichment by $\sim$3 implies enhanced abundances, at about the same level, for the neutron rich isotopes of Ne, Mg, Si, S and for $^{54}$Fe following the star's evolution. Such an enhanced metallicity cannot be present over the entire galaxy, but in local regions, such as regions of active star formation or OB associations, the ISM may be quite different. Rapidly evolving massive star SN can enrich the region such that later generations of stars are formed with higher metal contents. A similar scenario enhances the r-process isotopes, since these SN do not produce much s-process material. Acceleration of this local ISM as cosmic rays can take place via shock waves from second or third generation stars. The atomic properties of the elements may play a role in the injection/acceleration. The presence of the refractory elements such as Al, Ca, Fe in condensed grain cores rather than in the gas phase may present a constraint unless the shock wave vaporizes these grains prior to acceleration of the material (see discussion by Dwek and Scalo, 1980).

This scenario, of course, may be purely imaginary, but certain aspects can be studied experimentally. In the cosmic rays, precise measurements of the isotopic composition of Mg, Si, S, and Fe are needed along with a measurement of the exact ratio of s- to r-process material as a function of atomic number. Observationally, such regions should be identified and studied with particular attention paid to the element/isotope abundances. These regions of active star formation and cosmic ray production should be observable in gamma emission from cosmic ray interactions and in $\gamma$-ray lines from radioactive isotopes. Current $\gamma$-ray experiments in space may be able to supply the data.

## IV. Summary

Supernovae are one of the most important phenomena is astrophysics, and considerable progress has been made in recent years in understanding them. The pre-supernova evolution of massive stars continues to be studied in increasing detail, and the core collapse/explosion phase is now understood, at least to the point where reasonable physics in the hydrodynamic model does indeed provide an explosion with mass ejection. SN light curves, the dynamics of the expanding mantle, and the formation of SNR's have been explained and detailed comparisons of theory with experimental data are now possible. Acceleration mechanisms are available to produce the cosmic rays either directly from the SN matter or from a mix of SN debris and ISM. Recent cosmic ray isotopic data and element abundances for UH nuclei are providing increasingly stringent constraints on models for the synthesis of cosmic ray matter.

The present situation with respect to both theory and experiment is enormously exciting. Progress has been considerable, but much still remains to be done. Supernova certainly seem to be involved in the origin of cosmic rays, but exact models still elude our grasp. The decade of the 1980's promises to be a productive one for both supernova and cosmic rays.

## V. Acknowledgements

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