Nucleosynthesis in Metal-Free and Metal-Poor Stars

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Abstract. There have been a number of important recent developments in theoretical and observational studies of nucleosynthesis, especially regarding nucleosynthetic sources at low metallicities. Those selected for discussion here include the origin of $^6$Li, the primary production of $^N$, the $\alpha$-process, and the supernova sources for three groups of metals: (1) C to Zn with mass numbers $A < 70$, (2) Sr to Ag with $A \sim 90–110$, and (3) $r$-process nuclei with $A \sim 130$ and above.

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INTRODUCTION

Metals provide cooling in a star-forming gas, and the metallicity of the gas may be related to the initial mass function (IMF) of the stellar populations to be formed. In particular, it is considered that only massive stars can be formed from primordial gas with zero metallicity. Thus, metallicity can affect nucleosynthesis through its effects on the formation of different stellar populations as nucleosynthetic sources. The initial metallicity of a star also has important effects on its structure and evolution, and in the case of a massive star, on its explosion. These effects can influence nucleosynthesis during stellar evolution and explosions. Finally, the initial metallicity of a star can affect nucleosynthesis directly.

The above effects of metallicity on nucleosynthesis are illustrated nicely by the case of very massive stars (VMSs) of $\approx 130–300 M_\odot$ that give rise to pair-instability supernovae (PI-SNe). First of all, it is expected from recent simulations that due to the inefficient cooling by $H_2$ molecules, the collapse of metal-free gas clouds results in the formation of stars of $\sim 10–10^4 M_\odot$ (see e.g., [1, 2] for reviews of earlier works and [3, 4, 5] for more recent studies). Without rotation, these massive metal-free stars experience very little mass loss and end their lives with essentially their initial masses (e.g., [6]). A metal-free VMS of $\approx 130–300 M_\odot$ encounters the pair instability following core He burning. It implodes and then explodes as a PI-SN that disrupts the entire VMS [7]. These PI-SNe have a distinct nucleosynthetic signature: the gross underproduction of the elements of odd atomic numbers such as Na, Al, P, Cl, K, Sc, V, Mn, Co, and Cu [7, 8]. This is because the production of these elements requires a significant neutron excess but a metal-free VMS has no initial neutron excess and evolves too quickly to allow weak interaction processes such as $\beta^+$ decay to produce a significant neutron excess prior to its explosion.

The case of PI-SNe also nicely illustrates the interaction between theory and observations. The extensive data (e.g., [9]) on extremely metal-poor stars with $-4 < [Fe/H] = \log(Fe/H) - \log(Fe/H_\odot) < -3$ show that the abundances of the elements of odd atomic numbers relative to their neighboring elements in these stars are never as low as predicted for the products from PI-SNe. This suggests the following possibilities: (1) the VMS progenitors for PI-SNe cannot be formed from metal-free gas; (2) although such progenitors were formed and gave rise to PI-SNe, their nucleosynthetic contributions were overwhelmed by other sources that have less severe underproduction of the elements of odd atomic numbers; or (3) although metal-free VMSs of $\approx 130–300 M_\odot$ were formed, their initial masses were reduced during their evolution due to e.g., rotation [10]. Another interesting development is the recent report of possible detection of a modern PI-SN [11]. Clearly, further theoretical and observational studies are required in order to resolve whether VMS progenitors for PI-SNe can be formed at zero or any metallicity and how such stars evolve and make metals when more physical ingredients such as rotation are included in the model.

EFFECTS OF ROTATION ON NUCLEOSYNTHESIS IN METAL-FREE AND METAL-POOR STARS

While not easy to treat, rotation is a common property of stars and can have crucial effects on nucleosynthesis. To illustrate these effects, we discuss two examples: nucleosynthesis associated with jet-powered explosions of metal-free stars of $300–1000 M_\odot$, and primary production of N by massive as well as low and intermediate mass stars with rotation at low metallicities.

In the absence of rotation, metal-free stars of $300–1000 M_\odot$ collapse into black holes at the end of their
lives without ejecting any material. With significant rotation, an accretion disk may form around the black hole produced by the core collapse of such a star and the jet associated with the disk may power an explosion. The nucleosynthetic products ejected by jet-powered explosions of metal-free stars of 500 and 1000$M_\odot$, respectively, were studied in [12] assuming a range of opening angles, velocities, energies, and amounts of ejecta for the jets. It was found that the yield patterns for particular sets of jet parameters (especially models B-1 and B-2 in [12]) are in agreement with the abundance ratios [O/Fe], [Ne/Fe], [Si/Fe], and [S/Fe] observed in metal-poor stars of low to high masses with reasonable initial rotation and the heavy elements usually attributed to their lower mass loss rates and greater compactness resulting from processes in the surface region. A scenario where this depletion is achieved approximately in the H burning shell, where N is produced by the CN cycle. Adequate mixing may be induced if a star starts on the main sequence with the amount of rotation comparable to that observed in present-day stars. The transport of the newly-synthesized C into the H burning shell is especially efficient for rotating metal-poor stars because their lower mass loss rates and greater compactness result in steeper angular velocity gradients, which in turn cause more mixing due to the shear instability [17]. Calculations of evolution and nucleosynthesis in metal-poor stars of low to high masses with reasonable initial rotation show that stars of $\sim 5–7M_\odot$ have the largest absolute N yields and the dominant sources for primary N when weighted by the Salpeter IMF are stars of $\sim 2–5M_\odot$ [17, 18]. These results can account for the general trend for the evolution of the N/O ratio with metallicity [18, 19], in particular the high N/O ratios at low metallicities for which massive stars were the predominant sources for N through primary production enhanced by rotationally-induced mixing. Further, rotation can induce severe mass loss from extremely metal-poor stars of high masses due to the enhanced surface metallicity following the dredge-up of newly-synthesized metals [10]. This suggests that extremely metal-poor VMSs may suffer so much mass loss that they could not produce PI-SNe. Finally, in addition to N, the abundance ratios of C, O, Na, Mg, and Al relative to Fe achieved in the envelope of rotating metal-poor stars of $\sim 2–7M_\odot$ are in accordance with the ratios observed in non-evolved carbon-enhanced metal-poor stars [10].

**NUCLEOSYNTHESIS AT LOW METALLICITIES**

Now we turn to a general discussion of nucleosynthesis at low metallicities, which covers the sources for the fragile $^6\text{Li}$, the intermediate-mass elements from C to Zn, and the heavy elements usually attributed to the s-process and the r-process.

**Sources for $^6\text{Li}$**

The Spite plateau [20] of $\log \varepsilon(\text{Li}) = \log(\text{Li/H}) + 12 = 2.05 \pm 0.15$ at $[\text{Fe/H}] < -1.5$ is well established from observations of metal-poor stars in the Galactic halo by different groups. It is widely accepted that this Li represents the $^7\text{Li}$ produced in the big bang. However, for the baryon-to-photon ratio measured by the recent cosmic microwave background experiment WMAP (e.g., [21]), the theory of standard big bang nucleosynthesis (SBBN) predicts $\log \varepsilon(^7\text{Li}) = 2.65 \pm 0.10$ (e.g., [22]), which is higher than the Spite plateau by $\sim 0.5$ dex. As $^7\text{Li}$ is destroyed at relatively low temperature, a plausible explanation of this discrepancy is that the surface abundances of this isotope in metal-poor stars have been depleted by processes in the surface region. A scenario where this depletion is achieved approximately independent of e.g., the surface temperature of stars was discussed in [23].

Accepting that the Spite plateau results from nearly uniform depletion of the primordial $^7\text{Li}$, we are facing another problem with the origin of $^6\text{Li}$ detected in stars on the plateau. The presence of $^6\text{Li}$ introduces a slight additional asymmetry into the intrinsically asymmetric line profile of $^7\text{Li}$ and the spectral analysis to extract
the $^6\text{Li}/^7\text{Li}$ ratio is rather difficult. Nevertheless, at least the detection of $^6\text{Li}$ in HD 84937 has been confirmed by several groups (e.g., [24, 25, 26]). The measured isotopic ratio $^6\text{Li}/^7\text{Li} = 0.052 \pm 0.019$ [28] is orders of magnitude larger than the value $^6\text{Li}/^7\text{Li} \sim 10^{-5}$ resulting from SBBN. A more recent observational study of 24 metal-poor halo dwarfs has detected $^6\text{Li}$ in 9 stars at the $\geq 2\sigma$ significance level and suggests a $^6\text{Li}$ plateau of log $^6\text{Li}$ $\approx 0.8$ corresponding to $^6\text{Li}/^7\text{Li} \approx 0.05$ [27]. As $^6\text{Li}$ is much easier to destroy than $^7\text{Li}$, this implies that there must be sources at low metallicities that can produce $^6\text{Li}$ much more efficiently than SBBN.

One possible mechanism for producing $^6\text{Li}$ at low metallicities relies on cosmic rays. Some of the primordial $^4\text{He}$ nuclei ($\alpha$-particles) can be accelerated into energetic cosmic rays by shocks from e.g., structure formation and SNe. The fusion of the $^4\text{He}$ nuclei in the cosmic rays and those in the general medium produces $^6\text{Li}$ through e.g., the reaction $\alpha + \alpha \rightarrow ^6\text{Li} + d$. By considering a cosmological component of cosmic rays possibly accelerated by the first stars, it was shown that the $^6\text{Li}$ plateau could be produced (e.g., [28]). In general, cosmic-ray production of $^6\text{Li}$ can proceed through both fusion of $\alpha$-particles and spallation of C, N, and O nuclei by protons and $\alpha$-particles. It is expected that the fusion channel dominates at low metallicities. At metallicities close to the solar value, the $^6\text{Li}$ abundances are dominated by contributions from cosmic-ray spallation, which is the only channel to produce Be. The ratio $^6\text{Li}/\text{Be} \approx 6$ from meteorites is characteristic of the relative production of these two nuclei by spallation. This ratio is much lower than the value $^6\text{Li}/\text{Be} \approx 40$ observed in HD 84937 [29], which is consistent with the dominant additional contributions to $^6\text{Li}$ from fusion of $\alpha$-particles at low metallicities.

The main reaction for producing $^6\text{Li}$ in SBBN is $\alpha + d \rightarrow ^6\text{Li} + \gamma$, which is a very inefficient electromagnetic quadrupole reaction (the dipole of the reacting nuclei vanishes as they have the same charge-to-mass ratio). On the other hand, the production of $^6\text{Li}$ can be greatly enhanced in non-SBBN. For example, the hadronic decay of supersymmetric particles produce energetic nuclei, which in turn can produce $^3\text{H}$ and $^3\text{He}$ through spallation of $^4\text{He}$. If such decay occurs $\sim 10^5$ s after the big bang, $^6\text{Li}$ can be produced through reactions such as $\alpha + ^3\text{H} \rightarrow ^6\text{Li} + n$ and $\alpha + ^3\text{He} \rightarrow ^6\text{Li} + p$. In fact, for the appropriate particle properties, it is possible to enhance the production of $^6\text{Li}$ and destroy $^7\text{Li}$ simultaneously without affecting the yield of D very much (e.g., [30]). In this case, the Spite plateau of $^7\text{Li}$ and the accompanying plateau of $^6\text{Li}$ observed in metal-poor stars would be interpreted simply as the true primordial abundances produced by non-SBBN without alteration by stellar processing or additional contributions from other sources. The above non-SBBN scenario is attractive in that it solves two problems of the Li isotopes at the same time. However, the required physics input, while plausible, is not yet established.

**The $s$-process**

The main $s$-process producing $^{88}\text{Sr}$ and heavier nuclei occurs in giant branch (AGB) stars. In the current model, a $^{13}\text{C}$ pocket is formed via the reaction sequence $^{12}\text{C} + p \rightarrow ^{13}\text{N} + \gamma$ followed by $^{13}\text{N} \rightarrow ^{13}\text{C} + e^+ + \nu_e$ after a small quantity of protons are mixed into the region between the He and H burning shells. Neutrons produced by the reaction $^{13}\text{C} + \alpha \rightarrow ^{16}\text{O} + n$ are then captured by Fe seed nuclei to make $s$-process nuclei ($s$-nuclei). As the efficiency of the neutron source is considered to be independent of the initial metallicity of the AGB star but the abundance of Fe seed nuclei directly depends on this metallicity, large neutron-to-seed ratios are achieved in metal-poor AGB stars [31]. Therefore, major production of Pb is expected from the $s$-process at low metallicities.

While the $s$-process may occur in AGB stars of higher masses, the dominant sources for $s$-nuclei are low-mass AGB stars of $\sim 1–3\,\odot$ when the Salpeter IMF is taken into account. As low-mass stars have long evolution timescales, the $s$-process contributions to the general interstellar medium (ISM) are negligible at low metallicities, say $[\text{Fe/H}] < -1.5$. However, in a binary system consisting of two metal-poor stars of low but different masses, the primary star of higher mass would go through the AGB phase in due time and contaminate the surface of the unevolved secondary star with AGB products through mass transfer. The secondary star would then be observed to have extremely high enrichments of $s$-nuclei and other AGB products, especially Pb and C, but very low abundances of non-AGB products such as Fe. A number of these so-called Pb stars have been observed and their abundance patterns of Zr, La, Cé, Pr, Nd, Sm and Pb can be fitted by calculations based on the above $s$-process model (e.g., [32]).

There are also a number of metal-poor stars observed to have extremely high enrichments of C and Pb but their overall abundance patterns of Ba and above appear to be a mixture of $s$-process and $r$-process products (e.g., [33, 34, 35]). It was proposed that these so-called $s+r$ stars were initially the secondary members of binary systems. The primary member of such a system first went through the AGB phase, transferring $s$-nuclei and other AGB products onto the surface of the secondary member. The white dwarf left behind by the AGB evolution then accreted back some of the material and collapsed into a neutron star. The ejecta from this accretion-induced collapse (AIC) event contaminated the surface of the sec-
Nucleosynthesis in massive stars

The dominant sources for the intermediate-mass elements from C to Zn at low metallicities are massive stars of \( \sim 10-100 M_\odot \), which give rise to Fe core-collapse SNe at the end of their evolution. The elements from C to Al are mainly produced by hydrostatic burning during the pre-SN evolution, and the elements from Si to Zn are mainly produced by explosive burning associated with the propagation of the SN shock through the shells above the Fe core. While the production of all these elements has some importance dependence on the initial metallicity of the SN progenitor through e.g., mass loss, pre-SN density structure, and details of the explosion, the yields of individual elements are broadly similar over a wide range of metallicities and have been calculated by several groups (e.g., [39, 40, 41]).

Mass cut, fallback, and mixing

The ranges of explosion energy \( E_{\text{expl}} \) and ejected \( ^{56}\text{Ni} \) mass \( M_{\text{Ni}} \) inferred from observations of light curves suggest that Fe core-collapse SNe fall into three categories (e.g., [42]): (1) normal SNe with \( E_{\text{expl}} \approx 10^{51} \) erg and \( M_{\text{Ni}} \approx 0.07 M_\odot \), (2) hypernovae (HNe) with \( E_{\text{expl}} \sim (2-60) \times 10^{51} \) erg and \( M_{\text{Ni}} \sim 0.2-0.6 M_\odot \), and (3) faint SNe with \( E_{\text{expl}} < 10^{51} \) erg and \( M_{\text{Ni}} < 0.01 M_\odot \). Normal SNe produce neutron stars and are associated with progenitors of \( \leq 20 M_\odot \). For higher masses, Fe core collapse produces black holes and gives rise to HNe if the progenitor has sufficient rotation to induce a jet-powered explosion or to faint SNe otherwise. However, the detailed explosion mechanisms remain unknown in all three cases and different groups have employed different parametric approaches to model the explosion and the associated production and ejection of nucleosynthetic material. A commonly adopted parametrization is the mass cut, the material inside which is assumed not to be ejected. If the shock is not sufficiently powerful to eject all the material above the mass cut, the fallback of some of this material results in the formation of a black hole. In this case, the material eventually ejected contains some mixture of the shocked material in the inner layers and the fallback material from further out. This fallback and mixing requires another parametrization.

As an example, we describe the parametrization of the mass cut, fallback, and mixing adopted in the calculations of [41]. For normal SNe, the mass cut is chosen to give \( M_{\text{Ni}} = 0.07 M_\odot \). For HNe and faint SNe, in addition to an inner mass cut \( M_{\text{cut}} \) (initial), another parameter \( M_{\text{mix}} \) (out) is introduced to set the outer boundary of fallback. The material between the inner mass cut and this boundary is assumed to be fully mixed. A fraction \( f \) of the mixed material is assumed to be ejected and the rest is accreted onto the black hole. With appropriate choices of \( M_{\text{cut}} \) (initial), \( M_{\text{mix}} \) (out), and \( f \), it was shown that (1) the overall abundance patterns of C to Zn observed in metal-poor stars with \( -2.7 < [\text{Fe}/\text{H}] < -2.0 \) can be explained by the sum of the contributions from normal SNe and HNe with progenitors of 10–50 \( M_\odot \); (2) the overall patterns observed in extremely metal-poor stars with \( -4.2 < [\text{Fe}/\text{H}] < -3.5 \) can be explained by the ejecta from individual HNe, and (3) the overall pattern observed in CS 29498–043 with [Fe/H] \( \sim -3.5 \) can be explained by the ejecta from a faint SN. However, there are also important deficiencies of the models: the calculated abundance ratios of N, K, Sc, Ti, Mn, and Co relative to Fe are too low compared with observations. As discussed in the section on the effects of rotation, primary production of N is greatly enhanced when rotation is explicitly included in models of metal-poor massive stars. On the other hand, the underproduction of K, Sc, Ti, Mn, and Co can be remedied by modifying e.g., the electron fraction \( Y_e \) of the material undergoing explosive nucleosynthesis.

Effects of neutrinos

The electron fraction \( Y_e \) specifies the neutron-to-proton ratio of the material and plays a crucial role in nucleosynthesis. The conversion between neutrons and protons can only proceed through the weak interaction involving neutrinos. The death of massive stars can be considered as a neutrino phenomenon. When the Fe core of such a star collapses into a protoneutron star, a great amount of gravitational binding energy is released in \( \nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \) and \( \bar{\nu}_\tau \) with average energies of \( \langle E_\nu \rangle \sim 10-20 \) MeV. Typical luminosity of the initial neutrino emission is \( L_\nu \sim 10^{52} \) erg/s per species. In the case of normal SNe, neutrino emission with \( L_\nu \sim 10^{51} \) erg/s
per species lasts for \(\sim 10\) s. With such intense neutrino fluxes, the neutron-to-proton ratio of the material close to the protoneutron star is modified by the reactions \(\bar{\nu}_e + p \rightarrow n + e^+\) and \(\nu_e + n \rightarrow p + e^-\). The corresponding \(Y_e\) relevant for explosive nucleosynthesis then depends on the competition between these two reactions, which in turn depends on the differences in \(L_{\nu}\) and \(\langle E_{\nu}\rangle\) between \(\bar{\nu}_e\) and \(\nu_e\) (e.g., [43, 44, 45]).

During the first \(\sim 1\) s after the onset of Fe core collapse, the neutrino emission characteristics give rise to \(Y_e > 0.5\) in the material immediately above the protoneutron star. This results in greatly-enhanced yields of \(^{45}\)Sc, \(^{49}\)Ti, and \(^{64}\)Zn due to the production of their more proton-rich progenitor nuclei; \(^{49}\)Cr, \(^{45}\)V, \(^{49}\)Mn, and \(^{64}\)Ge [46, 47]. It was shown that the inclusion of neutrino effects on \(Y_e\) brings the calculated abundance ratios Sc/Fe and Zn/Fe in accordance with observations of metal-stars with rich (i.e., from \([\text{Fe/H}] < -3\)) into the abundance ratio of neutrons to heavy nuclei greatly exceeds \(\sim 10\) when all charged-particle reactions cease to occur at a temperature of several \(10^9\) K due to the Coulomb barrier, then the \(\alpha\)-process smoothly merges with the \(r\)-process as the heavy nuclei produced by the former rapidly capture neutrons at lower temperatures. This is the neutrino-driven wind model for the \(r\)-process (e.g., [52, 53, 54, 55, 56]). However, based on the studies by several groups [45, 57, 58], while it is quite plausible that the physical conditions in the wind are sufficient for producing the \(r\)-nuclei up to \(A \sim 130\), it is very difficult to obtain the conditions required for producing the heavy \(r\)-nuclei with \(A > 130\) (e.g., [59, 60, 61]).

In search of the conditions for producing the heavy \(r\)-nuclei, there were attempts to modify the wind conditions by e.g., including the effects of a magnetic field above the protoneutron star [62] as well as proposals of alternative sites such as neutron star mergers (e.g., [63]) and the wind from the accretion disk around a black hole [64, 65]. Yet another approach is to seek guidance from observations. For example, the detection of the \(r\)-process element (\(r\)-element) Ba with \(A \sim 135\) in a number of stars with \([\text{Fe/H}] < -3\), especially the high Ba enrichments in several stars with \([\text{Fe/H}] < -3\), is crucial in evaluating neutron star mergers as the major source for the heavy \(r\)-nuclei. These events are much rarer (by at least a factor of \(10^3\)) than Fe core-collapse SNe. If neutron star mergers were the major source for the heavy \(r\)-nuclei, then enrichment in these nuclei would not occur until the ISM had already been substantially enriched in Fe by Fe core-collapse SNe [66, 67]. This is in contradiction to the observations of stars with significant to high Ba abundances but very low Fe abundances. Therefore, it appears very unlikely that neutron star mergers are the major source for the heavy \(r\)-nuclei.

Further guidance to the identification of the source for the heavy \(r\)-nuclei is provided by observations of a wide range of elements from C to Zn in addition to the heavy \(r\)-nuclei in a number of metal-poor stars. Data on the metal-poor stars CS 31082–001 [68], HD 115444, and HD 122563 [69] show that their abundances of the heavy \(r\)-elements differ by a factor up to \(\sim 10^2\). In contrast, these stars have essentially the same abundances of the elements between O and Ge (e.g., [68, 69]); [70]) is compared with HD 221170 ([\text{Fe/H}] = -2.2; [71]) and CS 31082–001 ([\text{Fe/H}] = -2.9) with BD +17°3248 ([\text{Fe/H}] = -2.1; [72]), data show that the stars in either pair have nearly the same abundances of heavy \(r\)-elements but the abundances of the elements between O and Ge differ by a factor of \(\sim 8\) and 6 for the former and latter pair, respectively. These results appear to require that the production of the heavy \(r\)-elements be decoupled from that of the elements between O and Ge. As Fe-core collapse SNe from progenitors of \(> 11M_\odot\) are the major source for the latter group of elements at low metallicities, this strongly suggests that such SNe are not the source for the heavy \(r\)-elements.

The elements between O and Ge are produced between the core and the H envelope by explosive burning during a core-collapse SN or by hydrostatic burning during its pre-SN evolution. Stars of \(\sim 8–11M_\odot\) develop degener-
ate O-Ne-Mg cores, at least some of which eventually collapse to produce SNe (e.g., [76, 77, 78]). Models of O-Ne-Mg core-collapse SNe show that the total amount of material ejected from between the core and the H envelope is only \( \sim 0.01-0.04 M_\odot \) [79, 80], much smaller than the \( \sim 1 M_\odot \) for Fe core-collapse SNe. Thus, O-Ne-Mg core-collapse SNe contribute very little to the elements between O and Ge. The decoupling between these elements and the heavy r-elements can then be explained by attributing the heavy r-elements to such SNe as argued in [73, 74, 75].

The attribution of the heavy r-elements to O-Ne-Mg core-collapse SNe is supported by the model proposed in [81]. In this model, the SN shock rapidly accelerates through the surface C-O layers of the O-Ne-Mg core due to the steep density fall-off in these layers. This gives rise to fast expansion of the shocked ejecta on timescales of \( \sim 10^{-4} \) s. Together with an entropy of \( \sim 100 \) units of Boltzmann’s constant per nucleon and an initial electron fraction of \( Y_e \sim 0.495 \) (e.g., for a composition of \( ^{13}\text{C} : ^{12}\text{C} : ^{16}\text{O} \sim 1 : 3 : 3 \) by mass), this fast expansion enables an r-process to occur in the shocked ejecta, producing nuclei with \( A > 130 \) through the actinides. To further test this model requires two lines of important studies: (1) calculating the evolution of \( \sim 8-11 M_\odot \) stars to determine the pre-SN conditions of O-Ne-Mg cores, especially the neutron excess and density structure of the surface layers; and (2) simulating the collapse of such cores and the subsequent shock propagation to determine the conditions of the shocked surface layers. As these layers contain very little mass, simulations with extremely fine mass resolutions are required to demonstrate the fast expansion of shocked ejecta that is the key to the production of heavy r-elements in the above model.

**CONCLUSIONS**

In summary, there have been a number of important recent developments in theoretical and observational studies of nucleosynthesis, especially regarding nucleosynthetic sources at low metallicities. Those selected for discussion here include:

1. Observations show that there is a \( ^6\text{Li} \) plateau accompanying the Spite plateau of \( ^7\text{Li} \). The corresponding \( ^6\text{Li} \) abundances are orders of magnitude higher than what can be produced by SBBN. Whether this \( ^6\text{Li} \) was produced by non-SBBN or by fusion of the \( \alpha \)-particles in cosmic rays and those in the general medium remains to be investigated.

2. The rather high N/O ratios observed at low metallicities indicate contributions from rotating massive stars, in which the primary N production is greatly enhanced through rotationally-induced mixing.

3. The extremely high enrichments of C and Pb observed in metal-poor stars of binary systems indicate that the \( s \)-process at low metallicities occurs with large neutron-to-seed ratios in AGB stars and that the \( ^{13}\text{C} \) pocket is the most likely neutron source. However, current stellar models based on the \( ^{13}\text{C} \) pocket substantially underproduce Ba and a number of rare-earth elements when compared with some observations.

4. While the abundance patterns of C to Zn observed in some extremely metal-poor stars indicate contributions from individual HNe or faint SNe associated with progenitors of \( > 20 M_\odot \), the patterns observed in a large number of metal-poor stars can be accounted for by the sum of contributions from normal SNe and HNe. Although observations of metal-poor stars do not require contributions from PI-SNe associated with metal-free VMSs of \( \approx 130-300 M_\odot \), the recent report of possible detection of a modern PI-SN provides stimulus for further theoretical and observational studies of VMSs at all metallicities.

5. The material close to the protoneutron star produced in a core-collapse SN is subject to intense neutrino fluxes. The interaction with \( \nu_e \) and \( \bar{\nu}_e \) changes the \( Y_e \) of this material, thereby having important effects on the nucleosynthesis. In particular, the production of \( ^{44}\text{Sc}, ^{49}\text{Ti}, \) and \( ^{64}\text{Zn} \) in Fe core-collapse SNe is greatly enhanced by the proton-rich conditions of the inner ejecta resulting from the interaction with \( \nu_e \) and \( \bar{\nu}_e \). The neutrons produced by the reaction \( \nu_e + p \rightarrow n + e^+ \) in proton-rich material also give rise to a \( \nu p \)-process that can produce many nuclei beyond \( ^{64}\text{Zn} \).

6. The \( \alpha \)-process in neutron-rich neutrino-driven winds from a protoneutron star produced in either an Fe or an O-Ne-Mg core-collapse SN can easily produce the elements from Sr to Ag through charged-particle reactions. The production of \( r \)-nuclei with \( A \sim 130 \) is quite likely at least in the neutron-rich winds associated with some Fe core-collapse SNe. However, observations require that the production of the elements from C to Zn be decoupled from that of the heavy \( r \)-nuclei with \( A > 130 \). Therefore, the heavy \( r \)-nuclei must be attributed to O-Ne-Mg core-collapse SNe but not Fe core-collapse SNe. The rapid expansion of the shocked surface layers of an O-Ne-Mg core may be the key to the production of these nuclei. The SN sources for metals based on the above discussion are summarized in Table I.
Table 1. SN sources for metals

| Fe core-collapse SNe | O-Ne-Mg core-collapse SNe |
|---------------------|---------------------------|
| C to Zn (A < 70)    | yes                       |
| Sr to Ag (A ~ 90–110)| yes                       |
| r-process nuclei (A ~ 130) | yes for some? |
| r-process nuclei (A > 130) | no                   |

† from progenitors of > 11M⊙

‡ from progenitors of ~ 8–11M⊙

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