Plenary Session

Stan Woosley during his plenary review.

Chemical Abundances in the Universe:
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Nucleosynthesis Now and Then

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Abstract. Today we understand, to reasonable accuracy, the origin of most of the abundant elements in the sun and similar Population I stars. Given our relatively primitive ability to model supernova explosion mechanisms, stellar mass loss, and stellar mixing, this is a remarkable achievement. This understanding is possible, in part, because supernovae are highly constrained by their spectra, light curves and the sorts of remnants they leave. This same understanding extends to the major abundances seen in primitive metal-poor stars down to [Fe/H] > -4. In particular, one finds no compelling evidence for exotic energies or unusual stellar properties. There are exceptions, however. About half of the isotopes above iron, the *r*-process and the *p*-process with $A < 130$, still have an uncertain origin, both in the sun and in metal-poor stars. The abundances in the hyper-iron-poor stars ([Fe/H] < -4) also require a special explanation. We suggest that they represent the operation of a first generation of massive stars that produced almost exclusively C, N, and O and black holes, a generation in which 100 $M_\odot$ were abundant, but stars over about 150 $M_\odot$ and under 30 $M_\odot$ were almost absent.

1. Introduction - Making the Solar Abundances

Over fifty years have passed since the pioneering works of Burbidge *et al.* (1957) and Cameron (1957) inaugurated the quantitative study of stellar nucleosynthesis. During that time, substantial progress has been made in refining the measured abundances in the sun and similar stars, measuring and calculating the nuclear cross sections and rates needed to study nucleosynthesis, and calculating models of increasing realism for stellar evolution and explosion. Without replicating in any detail what already exists in the literature, the reader is referred to recent reviews by Kobayashi *et al.* (2006), Woosley & Heger (2007), and Limongi & Chieffi (2009). The results presented in these reviews are remarkably similar, despite using different codes, prescriptions for mass loss and convective mixing, and procedures for exploding and mixing the supernova.

There are several reasons why the answer is so robust. First, all calculations use similar nuclear physics, the critical rates having been, for the most part, determined in the laboratory. Second, they use similar explosion energies, typically around 1×10^{51} erg. This quantity, too, is highly constrained by observations, if not by current numerical simulations of core collapse. Fig. 1 shows the luminosity on the plateau (at 50 days) as a function of expansion velocity for a set of models and from observations of a variety of Type IIp supernovae. Luminosity is correlated with the velocity because the latter governs the advection of energy through the photosphere. The observed correlation is

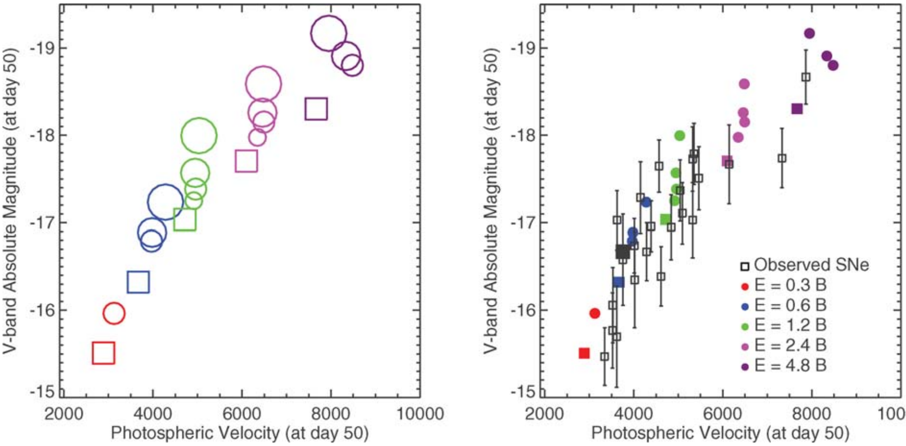

Figure 1. Constraining the kinetic energy of Type IIp supernovae. This figure, taken from Kasen & Woosley (2009), shows the correlation between the V-band plateau luminosity of a set of supernova models measured at 50 days and the expansion speed of the photosphere (left frame). In the right frame, the model results are compared with the observational data of Hamuy (2003). The models include five supernovae with masses from 12 to 25 $M_\odot$ (color coded in the web version) and two different metallicities for the 15 $M_\odot$ model (the square is for 15 $M_\odot$ with 0,1 solar metallicity). The higher mass models have larger radii and are the brightest in each cluster of points. The model presupernovae were exploded with five different choices of kinetic energy at infinity, 0.3, 0.6, 1.2, 2.4 and 4.8 $\times 10^{51}$ erg. Model data points tend to group by energy with the most energetic points on the right and least on the left. Data is most consistent with an explosion energy of $0.6 - 1.2 \times 10^{51}$ erg, though there are examples of explosions with higher and lower energies.

well fit by a range of explosion energies from 0.3 to 5×10^{51} erg, with most points falling in the range 0.6 to 1.2×10^{51} erg. The scatter due to main sequence mass and metallicity does not affect the result much.

The other major parameter in the explosion model is the "mass cut". After the shock goes through, what stays behind and what is ejected? This parameter is also constrained by observations, namely the mass of the gravitationally bound remnants left by the explosions. These are usually neutron stars for solar metallicity progenitors. Observations show that typical neutron star masses are around 1.35 $M_\odot$ (Thorsett & Chakrabarty, 1999). When corrected for neutrino losses, that mass limits the average baryonic mass inside the mass cut. Similarly, the constraint that very neutron-rich elements in the iron core not be frequently ejected limits the *minimum* mass inside the mass cut (Weaver *et al.* 1978). The mass cut must be outside the iron core. Finally, all groups average over some distribution of stellar masses, typically using a Salpeter initial mass function (IMF), and that tends to smooth out some of the variability at a given mass. Of course there is some residual uncertainty in the synthesis of many individual isotopes because of unknown reaction rates, sensitivity to conditions at the inner boundary, contributions from sources other than massive stars, etc., but, by and large, *elemental* abundances below krypton are well understood.

An important exception, however, is the r-process above A = 90 and the p-process between mass A = 90 and 130 (including the intriguing species ^{92}Mo). Fig. 8 of Woosley & Heger, in particular, which shows the isotopic yields from a generation of massive stars with solar metallicity and a Salpeter initial mass function, illustrates this inadequacy. For the r-process, the mechanism is generally agreed upon - the explosive expansion and cooling of nucleonic matter with a neutron excess (Hoyle & Fowler 1960). The favored site for years has been the neutrino-powered wind of a young (1 - 10 s) proto-neutron star (Woosley *et al.* 1994). Neutrinos drive mass loss composed of neutrons and protons with a ratio set by the fluxes and spectra of electron neutrinos and antineutrinos. Early on, the wind may actually be proton-rich and could contribute to the *p*-process (Pruet *et al.* 2006; Fröhlich *et al.* 2006). Later, the flux of antineutrinos is larger and the wind becomes neutron-rich, possibly producing the *r*-process.

Unfortunately, all realistic calculations since 1994 have failed to give a high enough entropy in the wind to make more than the lightest *r*-process isotopes, and it is now thought that the entropy in the study by Jim Wilson that was used then may have been unphysically high (Sam Dalhed, private communication). The entropy matters because decreasing density when the temperature is between 2 and 5×10^9 K, i.e., raising the entropy, results in fewer α-particles reassembling into heavy elements. If only a few reassemble, there are a lot of neutrons (or protons for the *p*-process) for each heavy seed, and a robust flow to heavy elements ensues. For the same reason, a short expansion time scale, i.e., a rapid freeze out from nuclear statistical equilibrium, also helps. If, on the other hand, most of the α-particles reassemble, the neutrons are incorporated into neutron-rich nuclei in the mass range 60 to 90 and the *r*-process does not even make it to the first peak. There is a potentially more serious problem in that the wind might not

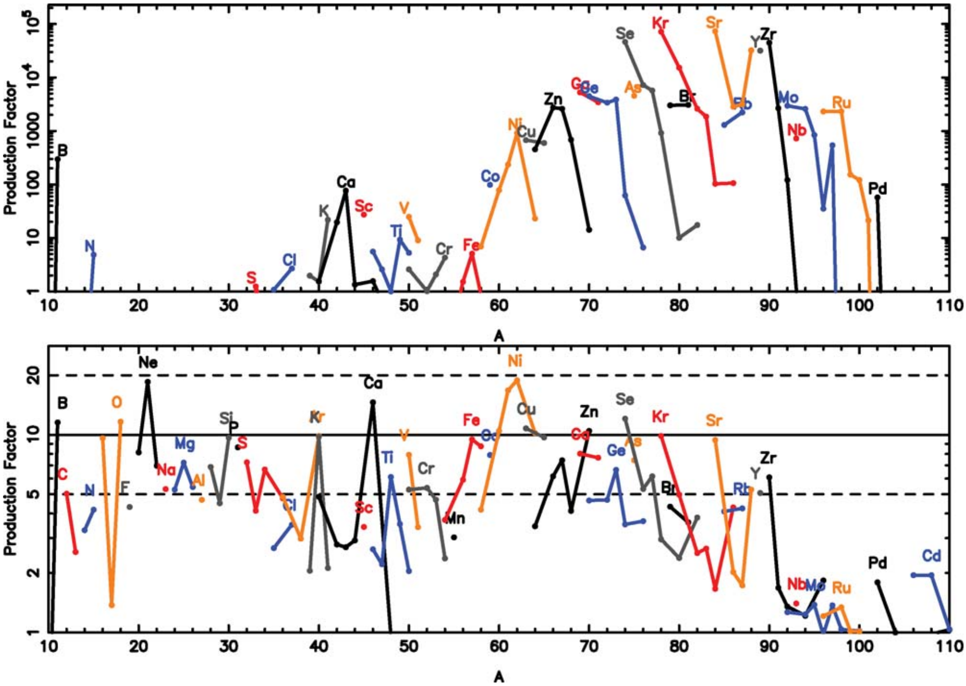

Figure 2. Nucleosynthesis in a 15 $M_\odot$ supernova including the contribution of the neutrino wind. The upper panel shows production factors, $X_i/X_{i,\odot}$, for just the wind. The production factors are large but the amount of mass involved is small. Synthesis below A = 60 and above A = 105 is negligible. This figure, taken from Roberts *et al.* (2009), integrates over the complete ten second history of the wind as the neutrino luminosities and spectra evolve. The bottom panel shows this nucleosynthesis combined with that from the rest of the supernova, properly normalized. Standard values for the neutrino physics give a yield that is not grossly out of line with nucleosynthesis in the rest of the supernova. However, the model completely fails to produce the *r*-process except for the closed shell isotopes of ^{88}Sr, ^{89}Y, and ^{90}Zr. Instead it produces the light p-process elements ^{78}Kr and ^{84}Sr.

only *not* make the r-process, but could grossly overproduce a few tightly bound nuclei with a closed neutron shell at N = 50, ^{88}Sr, ^{89}Y, and ^{90}Zr (Hoffman *et al.* 1996).

The current situation is illustrated in Fig. 2. This calculation takes the neutrino fluxes and spectrum from Woosley *et al.* (1994), but uses a modified version of the Kepler code (Weaver *et al.* 1978) to compute the hydrodynamics. Post-Newtonian corrections to gravity are included and the wind typically has a final entropy $S/N_A k \sim 120$ as opposed to about 400 in the Wilson calculation. Modern neutrino cross sections are included and the composition of the wind is calculated using a large reaction network. Of particular import are weak magnetism corrections to the neutrino-nucleon interactions (Horowitz 2002). The wind is included in the explosion of a 15 $M_\odot$ star (1.2×10^{51} erg) and the total nucleosynthesis determined, i.e., the wind is integrated over its entire duration and its contribution is plotted with the nucleosynthesis from the rest of the star.

Fig. 2 shows the results when weak magnetism is included. The effect of this correction is to make the wind more proton-rich at earlier times when there is larger mass loss and to diminish the large overproduction of ^{88}Sr, ^{89}Y, and ^{90}Zr, which is otherwise seen. The good news is that the wind doesn't overproduce anything. It successfully makes the light p-process isotopes ^{78}Kr and ^{84}Sr along with ^{88}Sr, ^{89}Y, and ^{90}Zr. The bad news is that it makes nothing heavier. A caveat is necessary here, however. The fluxes and spectra of neutrinos were calculated in a model that ignored weak magnetism and hence the results are internally inconsistent. In a revised model the neutron excess may be a bit larger, but it is still doubtful that any appreciable r-process will result.

So there is a problem making the observed r-process. There are three possible solutions. First is that the neutrino spectra may be greatly revised in a fortuitous way so as to produce a much larger neutron excess. Flavor mixing might help do this, but the difference in the average energies of μ-, τ-, and e-neutrinos is not as great as it used to be. Of course if the electron-neutrinos magically disappeared and the anti-neutrinos did not (so that $\bar{\nu}_e + p \rightarrow n + e^+$ greatly dominated over $\nu_e + n \rightarrow p + e^-$), the problem would be solved. Or, there may be other ways of increasing the entropy in the wind to high values or decreasing the dynamical timescale. Magnetic fields and rotation are one possibility (Qian & Woosley 1996; Metzger *et al.* 2007) yet to be demonstrated. Vibrations from the newly formed neutron star are another (Qian & Woosley 1996; Burrows *et al.* 2007; Otsuki *et al.* 2008).

The third possibility is that one gives up on supernovae as the dominant production site of the heaviest r-process isotopes. The leading alternate contender is merging neutron stars, where the large neutron excesses and rapid expansion time scales occur naturally. The historical problem with this site is not that it can't make the r-process, but that it makes to much of it, and too infrequently (Argast *et al.* 2004). It may be worth revisiting this issue though, with a more modern view of binary neutron star formation and evolution, including the effects of kicks, multiple pulsar velocity distributions, etc. The early history of the Galaxy may also have been more complex than in the Argast *et al.* mode, with mergers, a time-variable IMF, etc.

However it is resolved, the fact is that the production of the r-process has been a problem for a long time. It would be good to see some real progress.

2. Metal-Poor Stars

The stars that were born with far less than their solar complement of heavy elements may have had a different history from their modern counterparts. Even if the initial mass function was the same, their mass loss history was probably different. Line-driven and grain-driven mass loss, in particular, would have been less, and consequently stars born

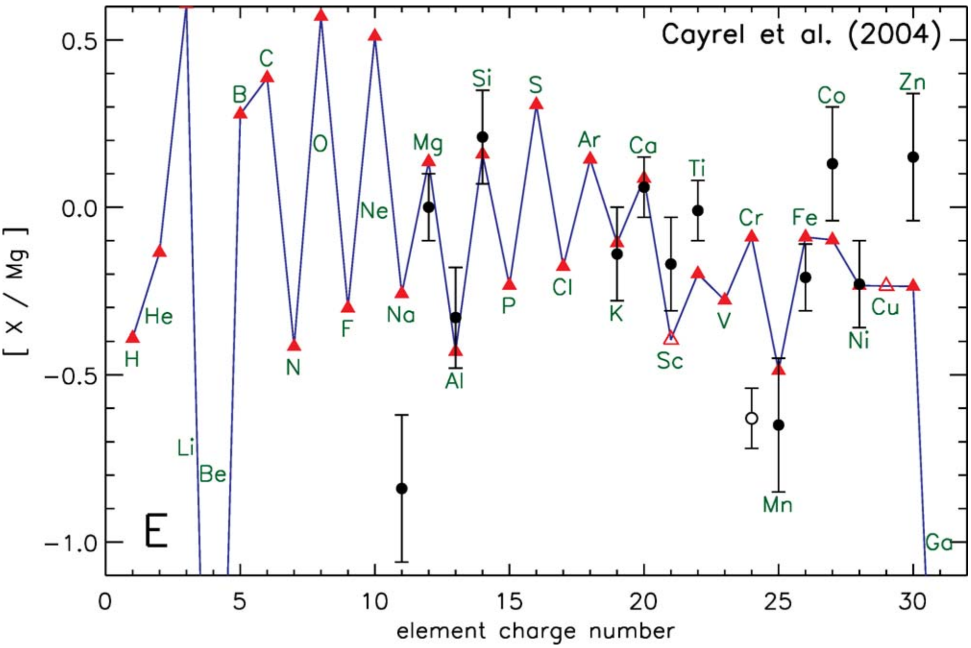

Figure 3. Model abundances vs. the metal poor data set of Cayrel *et al.* (2004). The model grid consists of 120 zero metallicity stars in the mass range 12 to 100 $M_{\odot}$. Each star was exploded with an energy of 1.2×10^{51} erg and moderately mixed. Model data was averaged over a Salpeter IMF. Since these stars included no *s*-process or neutrino wind contribution, Sc and Zn may be underproduced. This figure is taken from Heger & Woosley (2009).

with the same mass as today would have died with higher masses (Eldridge & Vink 2006, Meynet & Maeder 2005). These larger mass stars would have been more tightly bound and harder to explode (Woosley *et al.* 2002). They may also have been more compact and prone to fall back and diminished mixing (Church *et al.* 2009). Together, these facts suggest a more massive population of presupernova stars, but at the same time, less efficient ejection of their heavy elements.

The situation is further complicated by other forms of mass loss and by primary nitrogen production. Low metallicity stars may still lose their mass by rotational instabilities (Meynet, Ekström, & Maeder 2006). Rotation also enhances the possibility that the outer part of the convective core will mix with the hydrogen shell during core helium burning (Ekström *et al.* 2008). When this happens large amounts of nitrogen are produced at the base of the envelope and a super-charged hydrogen burning shell causes a previously zero-metallicity blue supergiant to expand and become a red supergiant. Carbon dredge up increases the grain opacity and the possibility of mass loss. Also, mass loss as a luminous blue variable may lead to envelope removal in very massive stars, just as it is doing today in Eta Carina.

Fortunately, the nucleosynthesis, except of nitrogen, is much more sensitive to what happens in the helium core than the hydrogen envelope (so long as the helium core explodes - see next section). It is thus worth exploring whether the same sorts of models that give good agreement with the major solar abundances might also work well at low metallicity.

Fig. 3 shows the model yields from Heger & Woosley (2009) compared with the observations of metal-deficient stars ([Fe/H] ∼ -3) by Cayrel *et al.* (2004). Considering that only model stars with zero metallicity were included in the fit, hence ignoring the *s*-process and the neutrino wind, the agreement is quite good. The overproduction of Cr probably reflects a difficulty with atomic physics and ionization stage (Sobeck et al. 2007, Lai *et al.* 2008). The observed abundance of Na is prone to large non-LTE corrections. In any case, it would be difficult to make less Na than in zero metal stars with no s-process and little CNO cycling. Potentially more problematic are the underproductions of Co and Zn. In the present calculation, both are due to the α-rich freeze out in the innermost zones that are ejected. Variations in the location of the mass cut and the way the explosion is simulated (thermal energy vs. piston) could change their production appreciably. Zinc might also be partly produced in the neutrino wind (Hoffman *et al.* 1996, 1998; Wanajo et al. 2009). All in all, the fit is as good as the previous one was to solar abundances and additional efforts to remedy a two-sigma difference do not appear warranted.

Indeed, better agreement is obtained with the observational data set of Lai *et al.* (2008) who studied 28 metal poor stars with [Fe/H] between -2 and -4 (13 were $<$ -2.6). In that paper the same stellar model set from Heger & Woosley (2009) was employed, but mixing and explosion energy were allowed to float so as to obtain the best fit. The best fit was obtained with an explosion energy of only $6 \times 10^{50} (M/20)^{-0.5}$ erg and a low value of mixing. This low energy its decline with mass tends to emphasize the contribution of low mass supernovae below 30 $M_{\odot}$. The rest made black holes that swallowed much of their nucleosynthesis. The good fit included Sc, Cr, Co, and Zn, but mysteriously overproduced Cu. This is still not understood, but it would be very difficult to produce the Co, Ni, and Zn abundances seen in the observations without making a comparable production of Cu. All four are made in the α-rich freeze out.

An additional product of stellar evolution at low metallicity is the compact remnants they leave. Even if low metal stars of high mass lose their envelopes because of rotation, LBV outbursts, and red giant winds, the Wolf-Rayet stars they leave behind are likely to have both a larger typical mass and a lower mass loss rate than for solar metallicity stars. Wolf-Rayet mass loss depends sensitively upon the *iron* abundance down to low values of [Fe/H] (Vink 2005). It is thus likely that the first stars produced more black holes and black holes of a higher average mass than the stars dying today. Zhang *et al.* (2008) predict an average black hole mass of 8.5 ± 7.6 $M_{\odot}$ produced about 50% of the time. This is to be compared with 3.8 ± 1.0 $M_{\odot}$ produced 9% of the time for solar metallicity stars. In both cases, the numbers assume a maximum neutron star mass of 2.0 $M_{\odot}$. The maximum black hole mass depends on the explosion energy but is unlikely to be larger than the biggest helium core that does *not* experience the pulsational pair instability, about 40 $M_{\odot}$.

Since these simple considerations suggest an increasing frequency of black hole formation with decreasing metallicity, the comparative paucity of black hole candidates in the SMC (Liu *et al.* 2005) is a mystery.

3. The Ultra-Iron-Poor Stars

The two most iron-poor stars, HE0107-5240 with [Fe/H] = -5.3 (Christlieb *et al.* 2002, 2004) and HE1327-2326 with [Fe/H] = -5.4 (Frebel *et al.* 2005, 2008; Aoki *et al.* 2006) have characteristic abundances that differ greatly from the low metallicity samples of Cayrel *et al.* and Lai *et al.* In particular, the iron group and α-elements, calcium and titanium, have much lower abundances than the lighter elements, C, N and O, while Na, Mg, and Al are intermediate. In some ways these stars resemble the "carbon-enhanced metal poor stars" (CEMP stars), a substantial fraction of which show evidence for contamination from a binary companion (e.g., Komiya *et al.*, 2007). However, so far, these two stars show no evidence for binary membership or for the s-process.

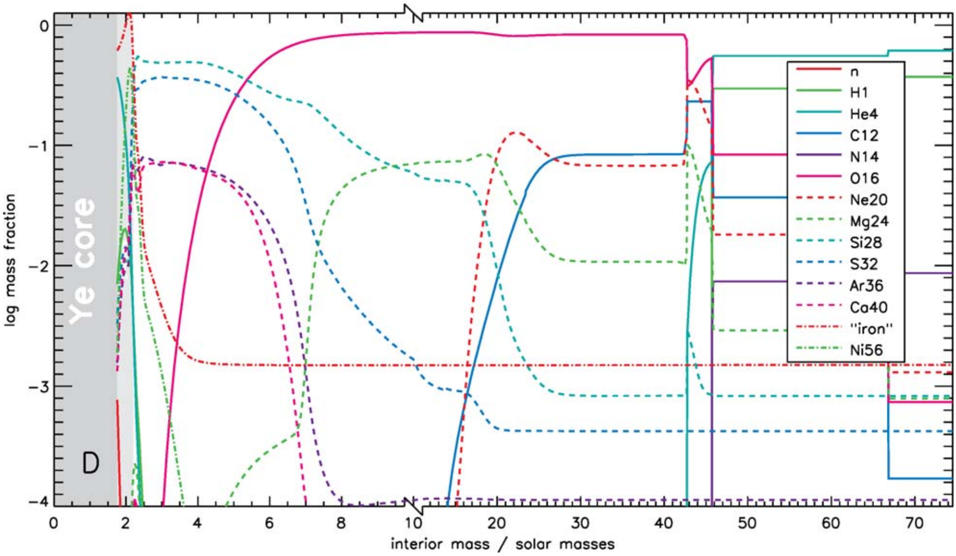

Figure 4. Nucleosynthesis in pulsational pair-instability supernovae. This presupernova star was derived from a 110 $M_\odot$ mass main sequence star that lost only a portion of its hydrogen envelope before dying. The star experienced two violent supernova-like "pulsations" before its final death, the first of which ejected all of the hydrogen envelope and a few $M_\odot$ of the helium core. At its final death, the star consists of 45 $M_\odot$ of helium and heavy elements. It is likely that this entire core will collapse to a black hole, so the nucleosynthesis is the material outside of 45 $M_\odot$, i.e., C, N, O and Ne. Figure taken from Woosley *et al.* (2007).

Several explanations have been offered (Tumlinson 2007). The earliest was that these stars represent the nucleosynthetic products of one or a few supernovae of large mass that experienced little mixing and a large amount of fallback (Umeda & Nomoto, 2003; Iwamoto *et al.*, 2005). More recent calculations by Heger & Woosley (2009) support this conclusion, but multi-dimensional calculations of the mixing by Joggerst *et al.* (2009) suggest that quantitative agreement may be difficult. The large ratio of O/Mg, in particular, is hard to achieve.

It has also been suggested that the ultra-iron-poor stars, like the CEMP stars, may have acquired their light element enhancements only at their surfaces from a companion that passed through an AGB phase (Suda *et al.* 2004), but the lack of evidence for binary membership or *s*-process enhancement is troubling. On the other hand, Tumlinson (2007) has emphasized that the depletion of lithium seen in HE1327-2326, favors the binary mass-transfer hypothesis.

Meynet *et al.*(2006) have proposed that the large CNO abundances reflect the mass loss from a massive population of stars (around 60 $M_\odot$) that lost their envelopes through rotational mass shedding and then collapsed to black holes to avoid a large production of heavier elements. Frebel *et al.* (2008) find, however, that the elements other than nitrogen are produced in inadequate quantities in this model. In short, there doesn't seem to be any single explanation that satisfies everyone.

We are struck by the fact that no stars with extremely low CNO (commensurate with Fe in the ultra-iron-poor stars) have been discovered. The CEMP stars are a minor fraction of all metal-poor stars. It is thus surprising that the first two UMP (ultra-metal-poor) stars discovered are carbon-rich. One possibility is that the UMP stars actually reflect the composition of the galaxy (or its precursors) following the first generation of stellar nucleosynthesis. That is, they are not explained by one or a few events or by binary companions, but by the yields of all Pop III stars. The lack of iron constrains the IMF on both the top and the bottom. In particular there could have been few stars lighter than about 30 $M_\odot$ and few heavier than about 150 - 175 $M_\odot$. Lighter stars would have made supernovae like today with abundances like today. Heavier stars would have made copious heavy elements, especially iron, in pair-instability supernovae (Heger & Woosley 2002). Such an IMF has been suggested for other reasons by Tan & McKee (2004).

Between about 30 and 90 $M_\odot$ one might have the sort of evolution described by Meynet *et al.* Neutron stars and iron would occasionally be produced, but mostly the helium cores of the stars would collapse to black holes after losing their nitrogen-rich envelopes to winds. Above about 80 - 90 $M_\odot$, depending on rotation, one encounters the pulsational pair-instability supernovae (Heger & Woosley 2002; Woosley, Blinnikov & Heger 2007). The end point of such a star, 110 $M_\odot$ on the main sequence, is illustrated in Fig. 4. Prior to the time shown, all mass exterior to 45 $M_\odot$ has already been ejected by violent, supernova-like outbursts episodes. That mass was rich in CNO and Ne (Na was not followed in the calculation). Specifically, 0.84 $M_\odot$ of carbon, 0.22 $M_\odot$ of nitrogen, 1.9 $M_\odot$ of oxygen and 0.42 $M_\odot$ of neon was ejected in the pulses.

The remaining 45 $M_\odot$ core, at the time the star finally formed an iron core and collapsed, was very tightly bound, binding energy = 4.8×10^{51} erg outside the base of the oxygen shell. It will be very difficult to explode with neutrinos and the iron core itself, ~ 2.1 $M_\odot$, is not far from the maximum neutron star mass. Neutron star rotation with a period longer than 2 ms would also provide inadequate energy to eject most of the matter outside the iron core. The most likely outcome is that the whole core becomes a black hole.

Calculations in progress suggest that this sort of behavior might characterize all zero metallicity stars from 90 to 150 $M_\odot$, with the exact limits sensitive to the rotation rate and the uncertain characterization of convective overshoot and rotational mixing. If so, the first generation of stars may have left us chiefly CNO and a lot of black holes with masses around 40 $M_\odot$. The prediction then is that no UMP stars will ever be found that are not CNO rich and, conversely, no stars with much less CNO than the UMP stars will be found. The transition that happened between [Fe/H] = -5 and -3, namely the filling in of the IMF below 30 $M_\odot$, may have happened because of cooling due to light elements, not Fe. The little bit of iron that existed then came from a few stars near 30 $M_\odot$, or, more exciting, it may have come from a few pair-instability supernovae above 150 $M_\odot$. In the latter case, the odd-Z to even-Z abundances above Mg might show a distinctive non-solar pattern.

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References

Aoki, W. *et al.* 2006, *ApJ*, 639, 897

Argast, D., Samland, M., Thielemann, F.-K., & Qian, Y.-Z. 2004, *Astron. & Ap.*, 416, 997

Burbidge, E. M., Burbidge, G. R., Fowler, W. A., & Hoyle, F. 1957, *Reviews of Modern Physics*, 29, 547

Burrows, A., Livne, E., Dessart, L., Ott, C. D., & Murphy, J. 2007, *ApJ*, 655, 416

Cameron, A. G. W. 1957, Chalk River Report, CRL 41

Cayrel, R., *et al.* 2004, *Astro. & Ap.*, 416, 1117

Christlieb, N., *et al.* 2002, *Nature*, 419, 904

Christlieb, N., *et al.* 2004, *ApJ*, 603, 708

Ekström, S., Meynet, G., Chiappini, C., Hirschi, R., & Maeder, A. 2008, *Astro. & Ap.*, 489, 685

Eldridge, J. J. & Vink, J. S. 2006, *ApJ*, 452, 295

Frebel, A., *et al.* 2005, *Nature*, 434, 871

Frebel, A., Collet, R., Eriksson, K., Christlieb, N., & Aoki, W. 2008, *ApJ*, 684, 588

Fröhlich, C., Martínez-Pinedo, G., Liebendörfer, M., Thielemann, F.-K., Bravo, E., Hix, W. R., Langanke, K., & Zinner, N. T. 2006, *Physical Review Letters*, 96, 142502

Hamuy, M. 2006, *ApJ*, 582, 905

Heger, A. & Woosley, S. E. 2002, *ApJ*, 567, 532

Heger, A. & Woosley, S. E. 2009, *ApJ*, submitted, astroph 0803.3161

Hoffman, R. D. Woosley, S. E., Fuller, G. M., & Meyer, B. S. 1996, *ApJ*, 460, 478

Hoffman, R. D. Müller, B., & Janka, H.-T. 2008, *ApJ Lettr.*, 676, L127

Horowitz, C. J. 2002, *Phys. Rev. D*, 65, 043001

Hoyle, F. & Fowler, W. A. 1960, *ApJ*, 132, 565

Iwamoto, N., Umeda, H., Tominaga, N., Nomoto, K., & Maeda, K. 2005, *Science*, 309, 451

Joggerst, C. C., Almgren, A., Bell, J., Heger, A., Whalen, D., & Woosley, S. E. 2009, *ApJ, in press*, astroph 0907.3885

Kasen, D. & Woosley, S. E. 2009, *ApJ*, 703, 2205

Kobayashi, C., Umeda, H., Nomoto, K., Tominaga, N., & Ohkubo, T. 2006, *ApJ*, 653, 1145

Komiya, Y., Suda, T., Minaguchi, H., Shigeyama, T., Aoki, W., & Fujimoto, M. Y. 2007, *ApJ*, 658, 367

Lai, D. K., Bolte, M., Johnson, J. A., Lucatello, S., Heger, A., & Woosley, S. E. 2008, *ApJ*, 681, 1524

Limongi, M. & Chieffi, A. 2009, *Memorie della Societa Astronomica Italiana*, 80, 151

Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2005, *Astron. & Ap.*, 442, 1135

Metzger, B. D., Thompson, T. A., & Quataert, E. 2007, *ApJ*, 659, 561

Meynet, G. & Maeder, A. 2005, *Astron. & Ap.*, 429, 581

Meynet, G., Ekström, S., & Maeder, A. 2006, *Astron. & Ap.*, 447, 623

Otsuki, K., Burrows, A., & Matos, M. 2008, *Proceedings of the 10th Symposium on Nuclei in the Cosmos.* Available on line at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=53,

Pruet, J., Hoffman, R. D., Woosley, S. E., Janka, H.-T., & Buras, R. 2006, *ApJ*, 644, 1028

Qian, Y.-Z., & Woosley, S. E. 1996, *ApJ*, 471, 331

Roberts, L., Woosley, S. E., & Hoffman, R. D. 2009, in preparation for *ApJ*

Sobeck, J. S., Lawler, J. E., & Sneden, C. 2007, *ApJ*, 667, 1267

Suda, T., Aikawa, M., Machida, M. N., Fujimoto, M. Y., & Iben, I. J. 2004, *ApJ*, 611, 476

Tan, J. C. & McKee, C. F. 2004, *ApJ*, 603, 383

Thorsett, S. E. & Chakrabarty, D. 1999, *ApJ*, 512, 288

Tumlinson, J. 2007, *ApJ*, 665, 1361

Umeda, H. & Nomoto, K. 2003, *Nature*, 422, 871

Vink, J. S. & de Koter, A. 2005, *Astron. & Ap.*, 442, 587

Wanajo, S., Nomoto, K., Janka, H.-T., Kitaura, F. S., Ml̈ler, B. 2009, *ApJ*, 695, 208

Weaver, T. A., Zimmerman, G. B., & Woosley, S. E. 1978, *ApJ*, 225, 1021

Woosley, S. E., Wilson, J. R., Mathews, G. J., Hoffman, R. D., & Meyer, B. S. 1994, *ApJ*, 433, 229

Woosley, S. E., Heger, A., & Weaver, T. A. 2002, *Reviews of Modern Physics*, 74, 1015

Woosley, S. E. & Heger, A. 2007, *Physics Reports*, 442, 269

Woosley, S. E., Blinnikov, S., & Heger, A. 2007, *Nature*, 450, 390

Monique Spite, Paolo Molaro and François Spite.

Stan Woosley and Beatriz Barbuy.