From Lithium to Uranium: Elemental Tracers of Early Cosmic Evolution
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Nucleosynthesis of pair-instability supernovae

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Abstract. The first generation of stars to form in the universe may have been very massive, and, due to the absence of initial metals, they could have retained most of their mass until their death and thus explode as pair instability supernovae. These supernovae encounter the late burning phases beyond carbon burning in an implosive/explosive way, leading to very powerful thermonuclear-powered explosions, up to a hundred times more powerful than ordinary supernovae. For primordial stars, these explosions also produce a peculiar abundance pattern, showing a strong odd-even pattern in the elemental abundances, a sharp drop-off of nucleosynthetic production beyond the iron group, and no *r*-process contribution. These results are greatly altered if only a small mass of 14N is dredged down into the helium burning core before the star becomes unstable. Such mixing could be a consequence of differential rotation or convective overshooting.

Keywords. Nucleosynthesis, stars: supernovae

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1. Introduction

The best currently available numerical simulations of the formation of the first stars in the universe (e.g., Nakamura & Umemura 1999; Bromm, *et al.* 2001; Abel *et al.* 2000; Abel *et al.* 2002), as well as theoretical expectations (Larson 2000) indicate the primordial stars may have been much more massive than present-day stars. Abel, Byan, & Norman (2002) and O'Shea *et al.* (2005) estimate a characteristic mass scale of 30–300 $M_\odot$. Once formed, such very massive stars may also retain a significant fraction of their initial mass, until their final collapse or explosion. Current estimates of mass loss rates for such primordial stars either due to line-driven winds (Kudritzi 2000; Kudritzki 2002) or due to pulsation-driven instabilities (Baraffe *et al.* 2001) indicate that a rather small mass loss is to be expected. If the stars retain enough mass to form a helium core of about 40 solar masses or more, the star encounters the electron-positron pair instability (an equation-of-state instability; Barkat, Rakavy, & Sack 1967; Bond, Arnett, & Carr 1984; Nadyozhin & Yudin 2004) after a radiative phase of central carbon burning. The star then rapidly collapses and encounters implosive/explosive neon, oxygen, and silicon burning. Below a helium core size of about 130 $M_\odot$ the released energy is enough to completely disrupt the stars, above that, photo-disintegration in the core softens the equation of state further and a collapse to a black hole results (Fryer *et al.* 2001). For helium cores below 63 $M_\odot$ the first pulse is not energetic enough to entirely disrupt the star; the envelope and parts of the helium core are ejected while the remainder falls back to form, again, a hydrostatic star that cools, contracts, resumes burning, and can re-encounters

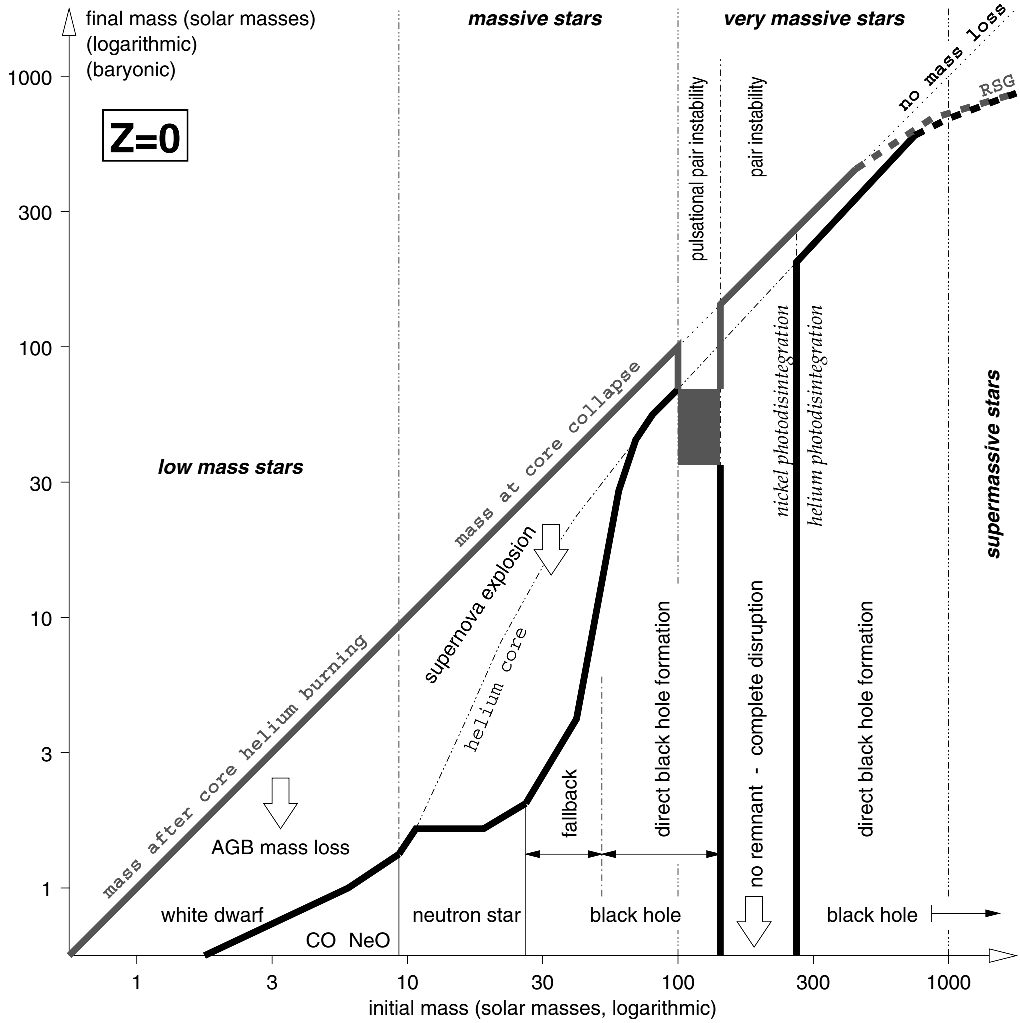

Figure 1. Initial-final mass function of non-rotating primordial stars. The *x-axis* gives the initial stellar mass. The *y-axis* gives both the final mass of the collapsed remnant (*thick black curve*) and the mass of the star when the event begins that produces that remnant. We distinguish four regimes of initial mass: *low mass stars* below $\sim 10\,\mathrm{M}_\odot$ that end as white dwarfs; *massive stars* between $\sim 10\,\mathrm{M}_\odot$ and $\sim 100\,\mathrm{M}_\odot$; *very massive stars* between $\sim 100\,\mathrm{M}_\odot$ and $\sim 1000\,\mathrm{M}_\odot$; and *supermassive stars* (arbitrarily) above $\sim 1000\,\mathrm{M}_\odot$. Since no mass loss is expected before the final stage, the grey curve follows the line of no mass loss (*dotted*). Exceptions are $\sim 100 - 140\,\mathrm{M}_\odot$ where the pulsational pair-instability ejects the outer layers of the star before it collapses, and above $\sim 500\,\mathrm{M}_\odot$ where the stars become red supergiants may lose mass (Baraffe, Heger, & Woosley (2001)). In the low-mass regime asymptotic giant branch (AGB) mass loss due to self-enrichment of the envelope leads to the mass loss and CO or NeO white dwarf result. "Massive stars" are defined as stars that ignite carbon and oxygen burning non-degenerately and do not leave white dwarfs. The hydrogen-rich envelope and parts of the helium core (*dash-double-dotted curve*) are ejected in a supernova explosion. The defining characteristic of *very* massive stars is the electron-positron *pair instability* after carbon burning. This begins as a pulsational instability for helium cores of $\sim 40\,\mathrm{M}_\odot$ ($M_{\mathrm{ZAMS}} \sim 100\,\mathrm{M}_\odot$). For higher masses, the pulsations become more violent, ejecting any remaining hydrogen envelope and an increasing fraction of the helium core itself. An iron core can still eventually form in hydrostatic equilibrium in such stars, but it collapses to a black hole. Above $M_{\mathrm{He}} = 63\,\mathrm{M}_\odot$ or about $M_{\mathrm{ZAMS}} = 140\,\mathrm{M}_\odot$, and on up to $M_{\mathrm{He}} = 133\,\mathrm{M}_\odot$ or about $M_{\mathrm{ZAMS}} = 260\,\mathrm{M}_\odot$) a single pulse disrupts the star. Above $260\,\mathrm{M}_\odot$, the pair instability in non-rotating stars results in complete collapse to a black hole.

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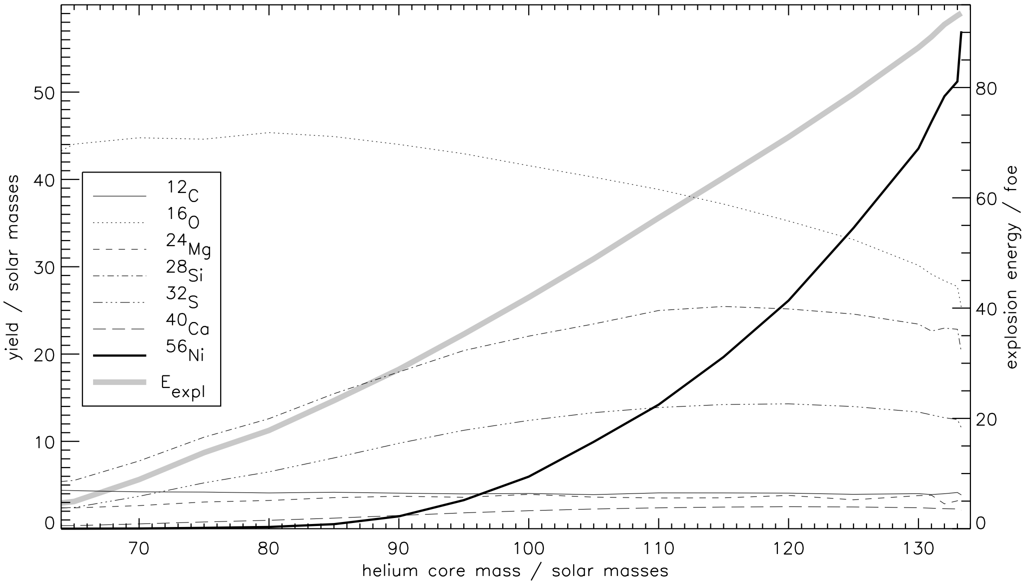

Figure 2. Yields of the dominant elements (*left scale*) and explosion energies (*thick gray line, right scale*; one "foe" is 10^{51} erg, about the explosion energy of a typical modern supernova) as a function of helium core mass. The range shown corresponds to main sequence masses of $\sim 140-260\,\mathrm{M}_\odot$. Helium cores of lower mass do not explode in a single pulse and those of higher mass collapse into black holes (see Figure 1)

the pair instability. Several pulses follow on time-scales of hours to thousands of years, depending whether the cooling is dominated by neutrinos or photons, until the star has built up a sufficiently massive iron core that likely also collapses to a black hole. The limits between this transitions are clearly defined and well understood (Ober, *et al.* 1983; Heger & Woosley 2002; Heger *et al.* 2003; Figure 1).

2. Nucleosynthesis

The yields from pair-instability supernovae from non-rotating primordial stars are dominated by alpha nuclei. In Figure 2 we show the bulk yields of these isotopes as a function of initial helium core size of the star (corresponding to an initial mass range of about $140\,\mathrm{M}_\odot$ to $260\,\mathrm{M}_\odot$. While most of the lighter isotopes change only by a few, at most, from the least massive to the most massive pair instability supernovae, ^{56}Ni, which later decays to ^{56}Fe, increases from essentially nothing to almost $100\,\mathrm{M}_\odot$ (Heger & Woosley 2002). That is, the iron-to-oxygen ratio in the yields of these stars, e.g., varies by several orders of magnitude, i.e., is very sensitive to the initial mass of the star - a fact that is often overlooked in chemical evolution models of the early universe. Note that also the explosion energy ranges from a few 10^{51} erg to almost 10^{53} erg. The yields from these supernovae have a steep drop-off in production beyond the iron group, have essentially no *s*-process contribution, and also no *r*-process contribution.

In Figure 3, Panel A, we show the elemental production factor (average abundances of eject divided by solar abundances) for a $100\,\mathrm{M}_\odot$ helium core, corresponding to an initial mass of about $200\,\mathrm{M}_\odot$. This star exhibits a strong odd-even abundance pattern (elements with odd charge number are produced at a far lower level than elements with even charge number, compared to the solar ratio of these elements). The elemental abundance figure is good for comparison with observations, but hides that most of the neutron-rich isotopes

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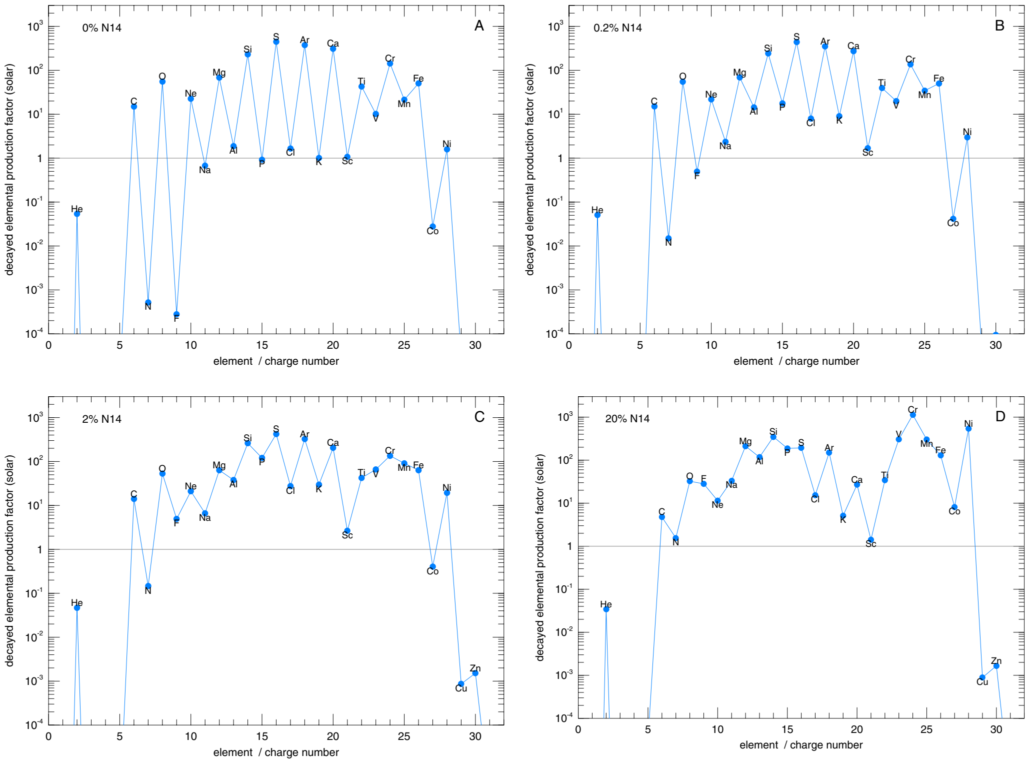

Figure 3. Elemental decayed production factor relative to solar abundances of 100 $M_\odot$ helium cores for different degrees of assumed enrichment by ^{14}N due to mixing of the helium core and the hydrogen envelope. The initial helium core enrichments of ^{14}N are: 0 % (Panel A), 0.2 % (Panel B), 2% (Panel C), and 20 % (Panel D).

of the element are far under-produced compared to the dominant alpha nuclei isotopes. Though some ultra metal-poor stars show extreme ratios of CNO isotopes to iron, such a strong odd-even pattern as predicted by our models has not been found in any objects, including the ultra metal-poor stars of our galactic halo (e.g., Depagne *et al.* 2002; Cayrel *et al.* 2004; Frebel *et al.* 2005) which may be the most pristine and closest in chemical enrichment to the first generation of stars.

3. Mixing and Nucleosynthesis

Hydrogen burning in primordial massive stars cannot be powered by the CNO cycle on initial abundances of these elements because there are none (except a very small ^{14}N mass fraction of $\sim 10^{-12}$ (Brian Fields, private communication). Since hydrogen burning by the pp-chains is not efficient enough to balance the energy losses of the star from the surface, the star contracts till it reaches a central temperature beyond 10^8 K where ^{12}C is produced by the triple alpha reaction and the CNO cycle can start (Ezer & Cameron 1971). Just a small mass fraction of 10^{-9} is produced initially, and the hydrogen burning proceeds at these rather hot and dense conditions. After core hydrogen depletion the same is true for the hydrogen-burning shell outside the helium-burning core.

Since these conditions for hydrogen burning are close to those of helium burning, the entropy rises only very gently at the edge of the helium core while more metal-rich stars usually develop a rather steep rise in entropy at the edge of the helium core. It has long been known that the unique setup of primordial stars may allow mixing of the carbon

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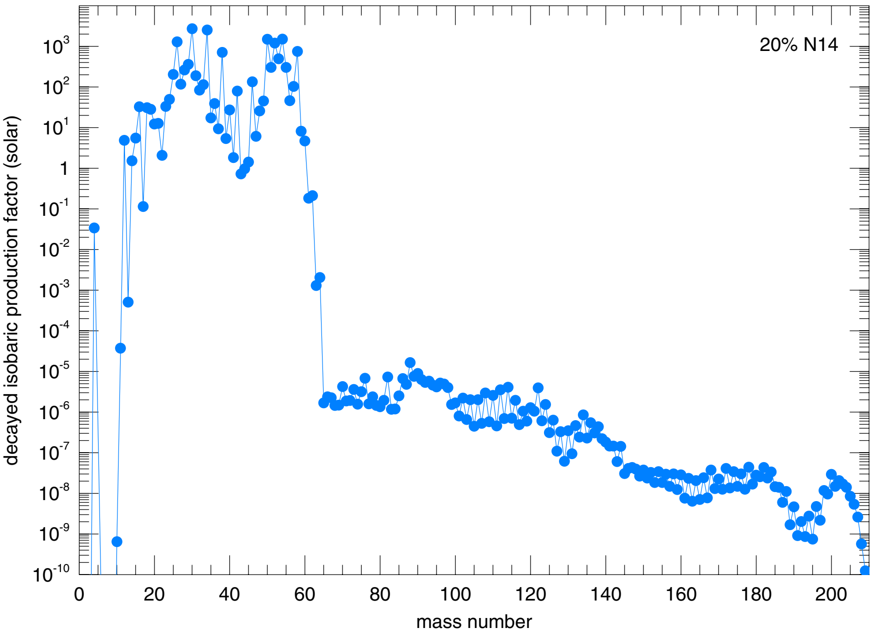

Figure 4. Decayed isotopic production factor relative to solar abundances for a $100\,M_\odot$ helium core (initial mass about $200\,M_\odot$) with $20\,\%$ ^{14}N enrichment.

and oxygen made in helium burning in the core with the hydrogen of the helium shell where the mass fraction of CNO isotopes is only of the order of 10^{-7}, though the exact magnitude of that mixing is not well modelled to date (Heger, Woosley, & Waters 2000; Marigo *et al.* 2001; Scannapieco *et al.* 2005). Such mixing could also be due to rotationally induced instabilities (e.g., Heger, Woosley, & Waters 2000; Meader *et al.*, this volume), again, the actual amount of mixing must be considered rather uncertain. For primordial stars even a tiny bit of mixing of C and O from the core with the hydrogen will make a big difference in the burning rate. Moreover, such an event will produce ^{14}N that can be converted in the core to ^{22}Ne - a primary neutron source.

For the results of the detailed nucleosynthesis plots presented here (Figures 3 and 4) we used the 1-d hydrodynamic stellar evolution code KEPLER (Weaver, Zimmerman, & Woosley 1986) and an extended adaptive nuclear reaction network (Rauscher *et al.* 2002) and the reaction rate library used in Woosley *et al.* (2004). In Figure 3, panels B-D we explore how enrichment of the helium core by primary ^{14}N production due to an assumed mixing with the hydrogen envelope changes the resulting nucleosynthesis. We performed three additional simulations where we added $0.2\,\%$, $2\,\%$, and $20\,\%$ of ^{14}N to the initial He core, then followed the evolution and nucleosynthesis of the stars through pair instability and explosion as in Heger & Woosley (2002). Figure 3B shows that $0.2\,\%$ of ^{14}N are sufficient to reduce the odd-even effect by an order of magnitude. The underproduction of scandium remains in all models; for the highest ^{14}N enrichments, Figure 3C and in particular Figure 3D, the neutronization becomes strong enough to push beyond the stable Cl, K, and Sc isotopes and a strong iron peak results, remarkably with a significant contribution of neutron-rich isotopes ($N > Z$), even before decay, i.e., make less ^{56}Ni. This would, e.g., also alter the brightness of supernovae from these stars (Scannapieco *et al.* 2005).

In Figure 4 we show the isotopic decayed production factor relative to solar for the same model as in Figure 3D. As expected, the alpha isotopes stick well out between

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$A = 20$ and 60. Remarkably, the production factor steeply drops at $A = 60$ to a s-process "strong" component floor ~ 8 orders of magnitude lower which, however, runs out all the way to bismuth. There is no "weak" s-process component (usually out to A=90; e.g., Woosley, Heger, & Weaver 2002) because of the missing initial iron seed. This is in contrast to the strong s-process found for metal-poor asymptotic giant branch stars (e.g., Travaglio *et al.* 2001) and further studies are needed to understand how their nucleosynthesis differs from the very massive Population III stars. We also do not find even a weak r-process-like component despite the significant neutron excess in the 20 % ^{14}N enriched model.

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