Chemical Abundances in the Universe:
Connecting First Stars to Planets
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The Nucleosynthetic Imprint of 15 - 40 $M_\odot$ Primordial Supernovae on Metal-Poor Stars

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Abstract. The first stars are key to the formation of primeval galaxies, early cosmological reionization, and the assembly of supermassive black holes. Although Population III stars lie beyond the reach of direct observation, their chemical imprint on long-lived second generation stars may yield indirect measures of their masses. While numerical models of primordial SN nucleosynthetic yields have steadily improved in recent years, they have not accounted for the chemical abundances of ancient metal-poor stars in the Galactic halo. We present new two-dimensional models of 15 - 40 $M_\odot$ primordial SNe that capture the effect of progenitor rotation, mass, metallicity, and explosion energy on elemental yields. Rotation dramatically alter the structure of zero-metallicity stars, expanding them to much larger radii. This promotes mixing between elemental shells by the SN shock and fallback onto the central remnant, both of which govern which elements escape the star. We find that a Salpeter IMF average of our yields for $Z = 0$ models with explosion energies of 2.4×10^{51} ergs or less is in good agreement with the abundances measured in extremely metal-poor stars. Because these stars were likely enriched by early SNe from a well-defined IMF, our models indicate that the bulk of the metals in the early universe were synthesized by low-mass primordial stars.

Keywords. cosmology: theory—early universe—hydrodynamics—stars: early type—supernovae: individual—nuclear reactions, nucleosynthesis, abundances

1. Introduction

Primordial supernovae (SNe) polluted the early universe with the first metals by $z \sim 20$ - 30. Although numerical models suggest that the first stars were 25 - 500 $M_\odot$ (Bromm *et al.* 1999, Bromm *et al.* 2002, Nakamura & Umemura 2001, Abel *et al.* 2000, Abel *et al.* 2002, O'Shea & Norman 2007), the Pop III initial mass function (IMF) is yet to be observationally constrained. The chemical imprint of Pop III SNe on low-mass second-generation stars may yield indirect measures of the primordial IMF. Remnants of the second generation are being sought in surveys of ancient extremely metal-poor (EMP) and hyper-metal poor (HMP) stars in the Galactic halo (Beers & Christlieb 2005, Frebel *et al.* 2005). HMP stars ([Fe/H] < -4) are thought to be enriched by only one or a few SNe. EMP stars ($-4 <$ [Fe/H]< -3) are more common and exhibit less scatter in their abundance ratios, implying that they form from gas enriched by a sample of SNe progenitors with a well-defined IMF.

Stellar evolution models suggest that 15 - 40 $M_\odot$ primordial stars die in core-collapse SNe and that 140 - 260 $M_\odot$ stars explode in pair-instability supernovae (PISN) with up to a hundred times more energy (Heger & Woosley 2002). Stars from 40 - 60 $M_\odot$ may end their lives as hypernovae (HNe), with energies in between those of conventional SNe and PISN (Nomoto *et al.* 2006). To date, numerical attempts to reconcile elemental

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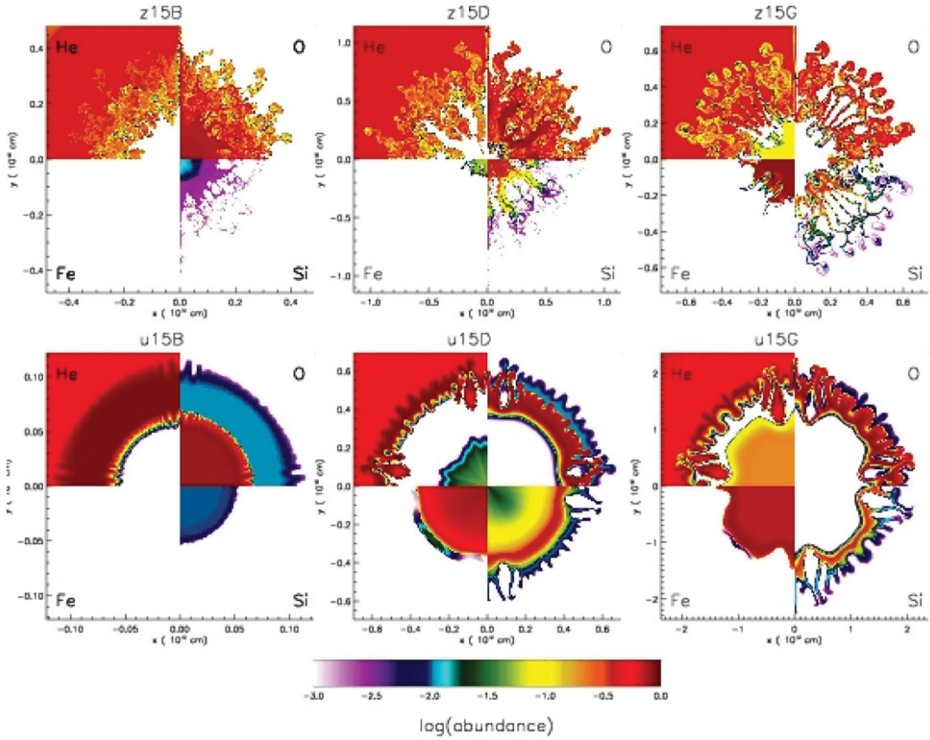

Figure 1. Distribution of He, O, Si, and Fe in $Z = 0$ (top) and 10^{-4} $Z_{\odot}$ (bottom) 15 $M_{\odot}$ stars after RT-driven mixing has ceased. $Z = 0$ stars, which die as large red giants, show much more mixing than $Z = 10^{-4}$ $Z_{\odot}$ stars, which die as smaller blue giants. Mixing increases with explosion energy, which is 0.6, 1.2, 2.4 B from left to right across the panels.

abundances from these explosions with those measured in metal-poor stars have met with only limited success (Umeda & Nomoto 2002, Umeda & Nomoto 2003, Umeda & Nomoto 2005, Tominaga *et al.* 2007, Tominaga 2009, Joggerst 2009). In particular, the odd-even nucleosynthetic yields predicted for PISN have yet to be detected in HMP or EMP stars. Furthermore, HMP stars exhibit skewed [C/Fe] ratios, implying that carbon abundances in some stars were enhanced either by a binary companion or by formation in chemically stratified environments. These observations highlight the difficulty with directly equating elemental yields from one generation with the chemical abundances of the next: intervening hydrodynamical processes such as mixing within the SN explosion itself or mass transfer between two stars may complicate the uptake of elements between generations.

2. Models and Results

We have performed a suite of two-dimensional calculations of 15 - 40 $M_{\odot}$ Pop III SNe to determine the effect of progenitor rotation, mass, metallicity, and explosion energy on the nucleosynthesis and propagation of heavy elements into the early IGM. Our simulations were implemented in two stages. First, one-dimensional SNe profiles were computed in the KEPLER code to calculate explosive nucleosynthetic burning. These profiles were then mapped onto a two-dimensional RZ grid in the new CASTRO hydrodynamics code and evolved out to radii at which Rayleigh-Taylor (RT) mixing ceased and the star was

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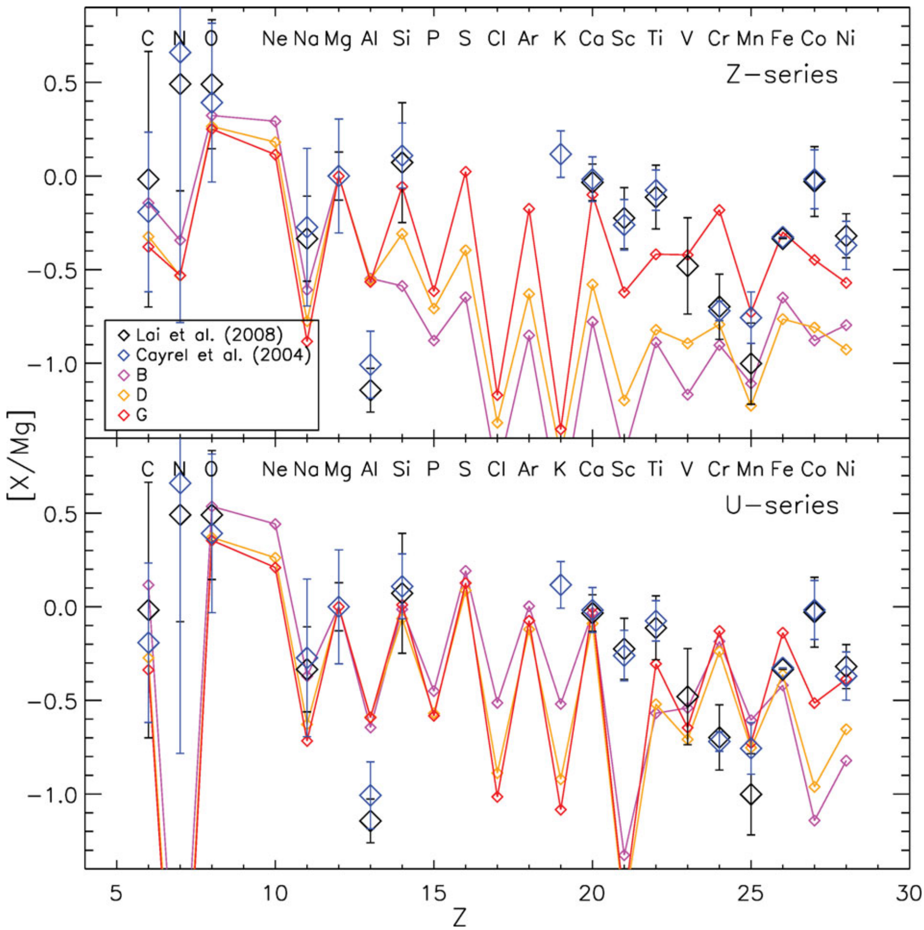

Figure 2. IMF averages of yields compared to observations of EMP stars from Cayrel et al. (2004) and Lai *et al.* (2008). Higher-explosion energy rotating $Z = 0$ stars reproduce EMP abundances well if 15 $M_\odot$ stars are included.

expanding homologously. We computed thirty-six such models, covering 3 masses (15, 25 and 40 $M_\odot$), 3 explosion energies (0.6, 1.2, and 2.4 Bethe, where 1 B = 10^{51} erg), 2 metallicities ($Z = 0$ and $10^{-4} Z_\odot$), and 2 rotation rates (Joggerst *et al.* 2009).

We find that rotation induces mixing between the helium core and the base of the hydrogen shell, which creates C, N, and O that incites CNO burning at the bottom of the hydrogen shell. This dramatically increases the rate of energy production in zero-metallicity stars and puffs up their outer layers. It also changes the interior structure of the star, leading to a uniformly mixed He-H layer outside the CO core in the $Z = 0$ models. Including even a small amount of angular momentum in the models effectively turns compact blue zero-metallicity stars into red giants. Once rotation is introduced, however, we find that the degree to which the progenitor expands is relatively insensitive to its magnitude. Rotation has less of an effect on stars with low metallicities (Heger & Woosley 2009).

Since rotating zero-metallicity stars are an order of magnitude larger in radius than stationary ones, the SN ejecta expands through an extended stellar envelope, which allows RT instabilities more time to develop and promotes mixing between adjacent shells. The delay also enhances fallback of Fe and Ni onto the compact remnant, in

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some cases preventing any of it from escaping into the IGM. Because the structure is relatively insensitive to the magnitude of the rotation once it is present, so is the degree of mixing and fallback. Less mixing occurs in our $Z = 10^{-4} Z_\odot$ models because the progenitors expand less with rotation. As expected, fallback decreases and mixing increases as explosion energy rises, but at a given energy fallback increases and mixing decreases with increasing progenitor mass. We show the former two trends for 15 $M_\odot$ $Z = 0$ and $10^{-4} Z_\odot$ stars in Figure 1.

3. Conclusion

One of our models, a zero-metallicity 15 $M_\odot$ 2.4 B SN, reproduces the abundances of the HMP star HE0557-4840 well, but none of the others match HE0107-5240 or HE1327-2326 exactly, which have higher C, N, O, and Na abundances and can be explained by models with more exotic explosion mechanisms. Simulations of jet-driven explosions in 40 $M_\odot$ Pop III stars have successfully reproduced the abundances of HE0107-5240 and HE1327-2326 (Tominaga *et al.* 2007). However, as we show in Figure 2, a Salpeter IMF average of the elemental yields of our models are a good match to the abundances found in the much larger sample of EMP stars in the Cayrel et al. (2004) and Lai *et al.* (2008) surveys. These abundances likely originated from a population of early SN progenitors with a well-defined IMF that was built up over a relatively narrow range of redshifts, and are therefore more representative of primordial SNe than the one or two singular events that imprinted HMP stars. Our models suggest that rotation and mixing in 15 - 40 $M_\odot$ primordial SNe can account for the majority of metal production in the early universe.

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