Where Did the First Generation of Stars Form in the Universe?

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Abstract The first generation of stars in the universe are expected to contain no heavy elements beyond helium, and are considered "metal-free" Population III stars (or Pop III). These metal-free stars in the early universe are predicted to have hard ionizing photon spectra and unique element yields from their supernovae, leaving signatures through the reionization of the intergalactic medium and the metal enrichment of gas in the early universe. Here, we examine the metal abundances in a variety of systems in the nearby universe, from very metal-poor Galactic halo stars to ultra-faint dwarf spheroidal galaxies, and compare them with the latest theoretical models of massive stars with and without rotation. We find new abundance trends of interest in a variety of individual elements spanning metallicity values of [Fe/H] from about -2 to -5. We also compare our results with the abundances found in the very metal-deficient nearby dwarf irregular galaxy Leo P, which was recently discovered in the Arecibo ALFALFA survey. We comment on the similarities and differences between abundance trends in gas-rich dwarf galaxy systems like Leo P versus gas-poor ones like the ultra-faint dwarf spheroidals, and on the possibility of such systems hosting populations of the first stars.

Introduction

The evolution of cosmic metal abundance provides a key window into the star formation history of the universe, and how this varies with time or different environments. This project primarily focuses on comparing observations of a large number of metal abundances in local gas-poor faint dwarf spheroidal (dSph) galaxies and extremely metal-poor (EMP) stars in the Galactic halo with the theoretically predicted yields from massive first-stars models with and without rotation. We compare our results with recent Arecibo ALFALFA, KPNO and LBT/MODS observations of a nearby gas-rich metal-poor dwarf irregular galaxy Leo P, and discuss the implications for the sites of primordial star formation.

Figures 1a-1d: A comparison of relative metal abundances between EMP stars and dSph galaxies for C, Ca, O, and Mg.

Figure Legend

- □ EMP star data (Cayrel et al. 2004)
- ✕ dSph galaxy data (see references)
- □ WW95 Metal-poor SN models, $E_{SN} = (1.3 - 2.5)\times10^{51}$ erg
- □ WW95 Metal-free SN model, $E_{SN} = 3.0\times10^{51}$ erg
- □ Keller et al., 2014, [Fe/H] < -7.1

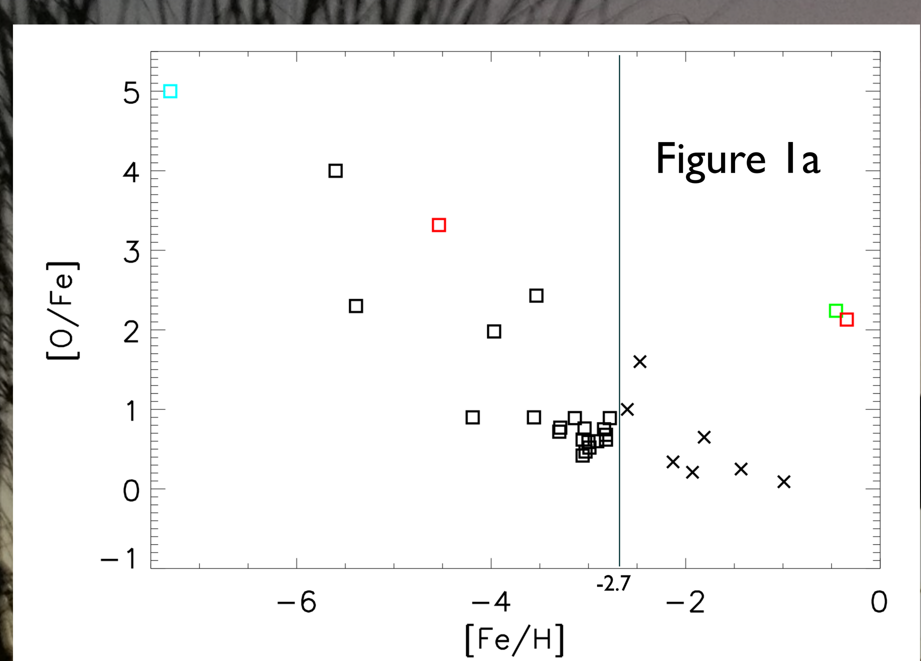
Analysis & Results

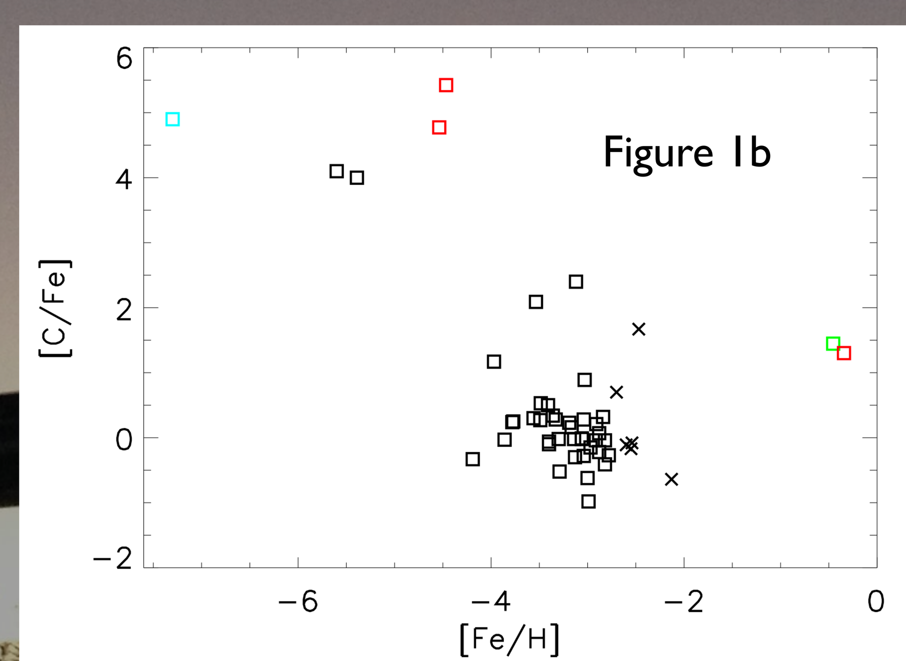
We compiled a database of metal abundances of 64 dSph galaxies (Kirby et al. 2010) and compared these with the abundances of 48 EMP halo stars (Cayrel et al. 2004). We also compared these with the theoretical yields from metal-free and metal-poor stars from the models by Weaver & Woosley (1995; WW95). Values of [Fe/H] = - 2.7 mark the approximate boundary between the data on dSph galaxies and EMP stars, shown in Figure 1a.

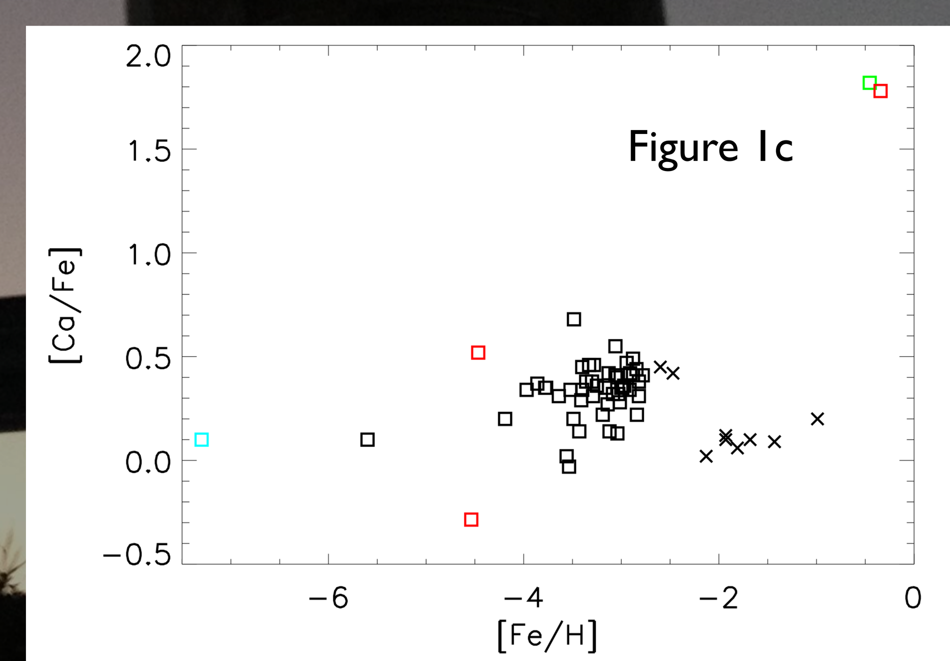
Many elements are found in common between the EMP star and dSph systems; we display only four cases here for C, Ca, O, and Mg (Figures 1a–1d). Also shown is the newly discovered ultra-iron-poor halo star from Keller et al. (2014). For any element X, the abundance ratios [X/Fe] versus [Fe/H] are plotted. In some cases, like oxygen (or zinc which is not shown here), there is a clear rise in [X/Fe] at lower [Fe/H], consistent with early enrichment of the alpha-elements from core-collapse supernovae. In other cases like magnesium and calcium, there are no obvious trends; however, the abundances remain intriguingly flat down to the lowest values of [Fe/H]. For a few cases, like carbon, the data points are somewhat scattered, other than the two anomalously over-enriched EMP stars at the lowest [Fe/H] values.

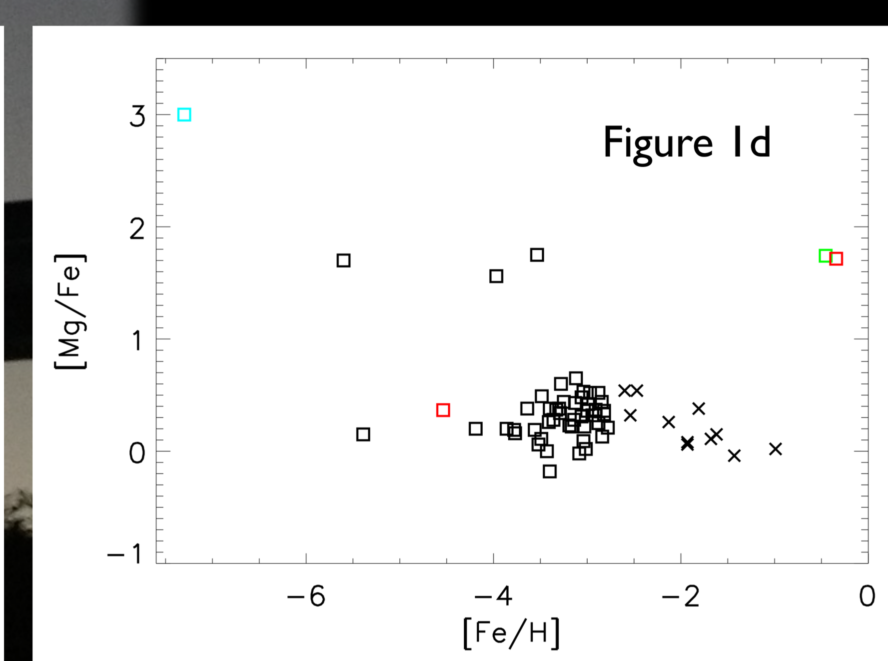
In addition to the data of EMP stars and dSph galaxies, the values calculated from the WW95 theoretical models are also included in Figures 1a-1d, with metal-poor models shown as red squares and metal-free models shown as green squares. Supernovae of varying kinetic energies models are shown in each case. Note that the metal-poor stars are a better fit in general to the data shown rather than the metal-free stars, although no one model is the best fit to most of the elements. The low KE models (model C in WW95) give slightly sub-solar [Fe/H] values along with overabundant [X/Fe] values relative to most EMP stars and dSph galaxies. Some metal-free models have anonymously low metal or Fe abundances, and therefore are well beyond the range of the plots shown. Last, Leo P is missing from this comparison in Figure 1 due to a lack of a measured Fe abundance. We address this in Figure 2, where we display [N/O] for EMP stars and Leo P. Note the close match in values between Leo P and the median of the EMP star data. We also show the theoretically predicted yields for a primordial 60 M_{sun} star with and without rotation (Meynet et al. 2006). This model under-predicts the observed [N/O] for metal-free or metal-poor stars (even when rotation is included), with the closest fit being rotating metal-free stars.

To further compare the metal abundances in these systems, we show the mean values of [X/Fe] for 9 selected elements for the EMP halo star/dSph galaxy datasets and the Keller et al. (2014) star in Figure 3, as well as their corresponding standard deviations. Two theoretical models from WW95 are also shown for comparison. For EMP stars, the [X/Fe] values for most elements are between 0 and 0.5, except for oxygen and vanadium. Furthermore, the dSph galaxies' abundances are closely correlated with the EMP star abundances to within one standard deviation, except for calcium.









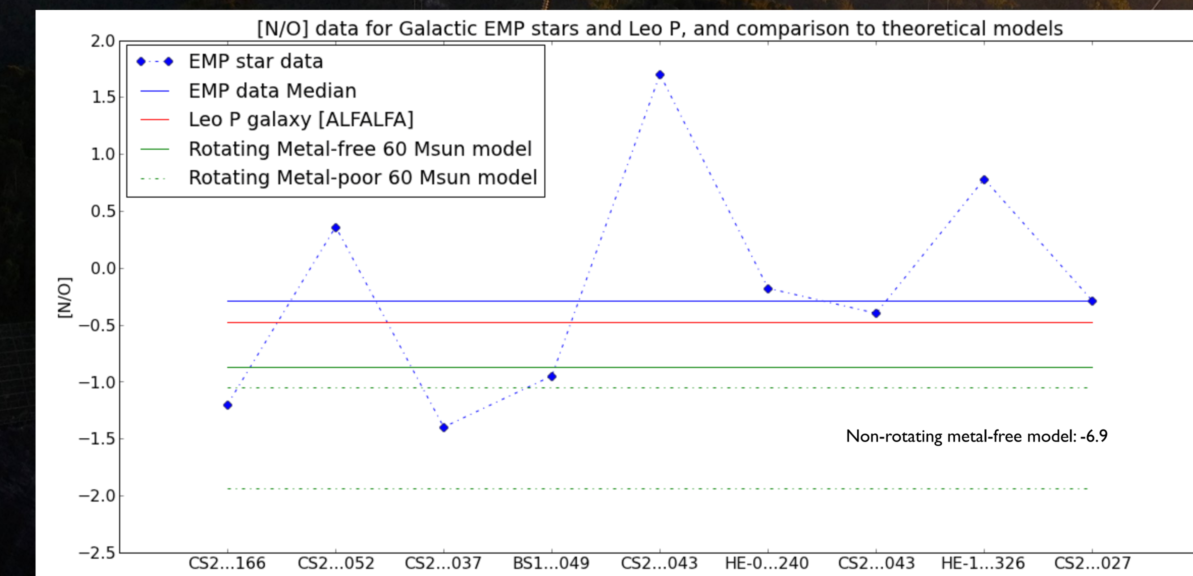


Figure 2 (left): Comparison of the [N/O] abundances across different systems and the theoretically predicted yields for a 60 M_{sun} star (Meynet et al. 2006). Note the close match in values between Leo P and the median of the EMP star data. The models under-predict [N/O] for metal-free or metal-poor stars, even with stellar rotation included.

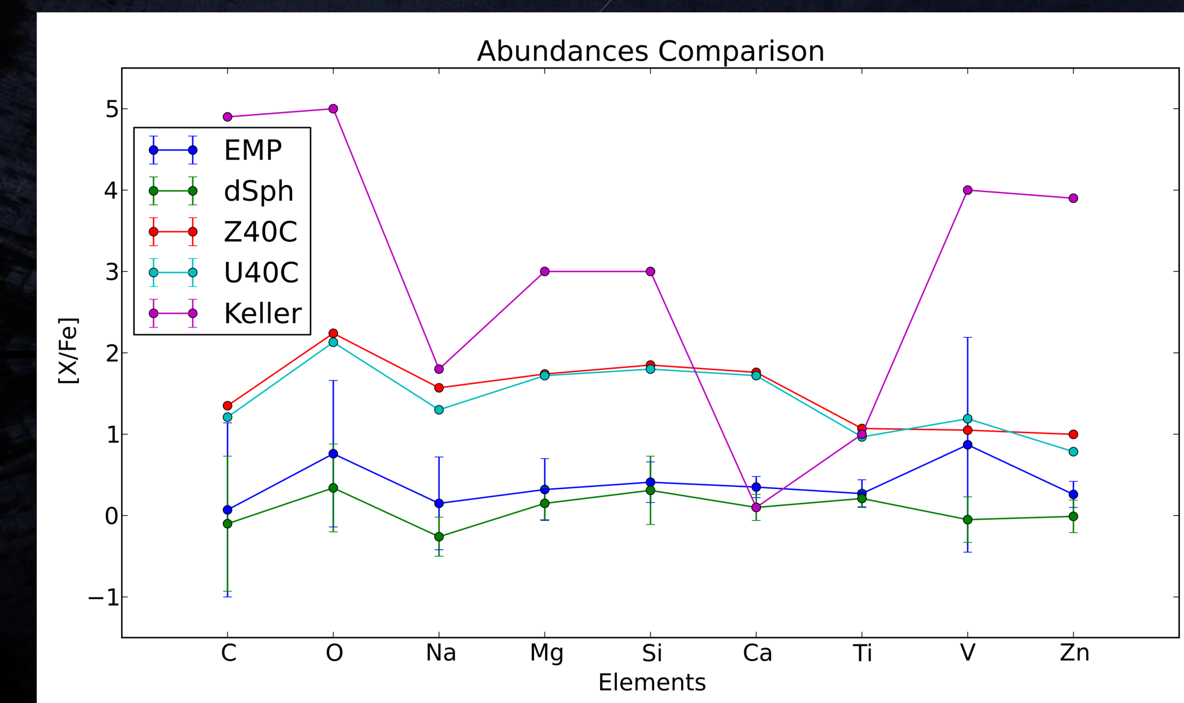


Figure 3 (left): Comparison of the mean values of the metal abundances for different elements averaged over all EMP stars and dSph galaxies. It demonstrates that the mean metal abundances in these two distinct systems are closely correlated, and within 1 standard deviation for all elements except calcium. This could have strong implications for the formation sites of the first stars in the early universe. Also shown are the theoretical yields for these elements from two WW95 models as well as the new ultra-iron-poor halo star. Note that these models are a poor fit for this halo star and the EMP star/dSph galaxy datasets.

Summary & Looking Ahead

The EMP halo stars are known to show metal abundance patterns that closely match the predicted output from primordial supernovae. Here, we have shown that many local dwarf galaxy systems show similar abundance trends as the EMP stars, and strikingly close mean values for many commonly measured elements. Including rotation in first-stars models could improve agreement with some metal content observations. A preliminary comparison of [N/O] abundances reveals that many gas-poor dSph galaxies as well as more gas-rich systems like Leo P could have hosted early stellar populations, and survived cosmological reionization through the present-day universe. More data on local galaxies, especially gas-rich dwarf systems, and their metal abundance patterns are needed to place more concrete limits on the formation sites and mass function of the first metal-free stars.

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