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The chemical enrichment in the early Galaxy

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Abstract. Observations of metal-poor stars are crucial for our understanding of the chemical enrichment in the early Galaxy. In particular, chemical abundance ratios in these objects provide detailed insight into the properties and nature of the previous generation of stars. The goal of this talk was to provide an overview of the field, highlight the tremendous progress over the past few years, and offer an outlook on where we can expect new progress to be made.

Key words. early universe Galaxy: formation Galaxy: halo nuclear reactions, nucleosynthesis, abundances stars: abundances

1. Introduction

The oldest and most chemically primitive stars in our Galactic halo contain the nuclear ashes of the very first generation of stars that formed after the Big Bang. Understanding the evolution, nucleosynthesis, and physical processes that occurred in that first stellar generation remains a major goal of modern astronomy. Studying the chemical compositions of the most metal-poor stars offers the most promising avenue to understand the nature of the first stars and chemical enrichment in the early Galaxy.

The goal of this review talk was to convey three key aspects to the general audience. First, metal-poor stars are extremely rare, and tremendous effort is required to find these objects. Second, there is great diversity in the chemical compositions among metal-poor stars. Finally, the large range in chemical compositions requires great diversity in the properties (e.g., rotation, mass, mass-cut, explosion energy) among the first generations of stars (e.g., AGBs, SNe Ia, SNe II). (See Beers & Christlieb 2005 and Frebel & Norris 2015 for more detailed reviews on metal-poor stars.)

2. Twenty years of progress

Iron is the canonical measure of stellar metallicity because its relative abundance is high and there are many absorption lines in the visible spectra of FGK type stars. In many instances, abundance ratios are presented relative to iron, e.g., [X/Fe], and plotted against metallicity, [Fe/H]. As cautioned by N. Prantzos during question time, it is worth remembering that there are two sources of iron (SNe II and SNe Ia) and that the iron abundance in a star may not be the best chemical indicator of relative age.

In Figure 1, we plot the [Ca/H] distribution function along with [Mg/Ca] vs. [Ca/H]. This figure includes the majority of data published up to 1996. In addition to the comments from N. Prantzos, the choice of using Ca rather than Fe is motivated by the fact that the most Fe-poor star has a calcium measurement but only an iron limit of [Fe/H] < -6.53 (Nordlander et

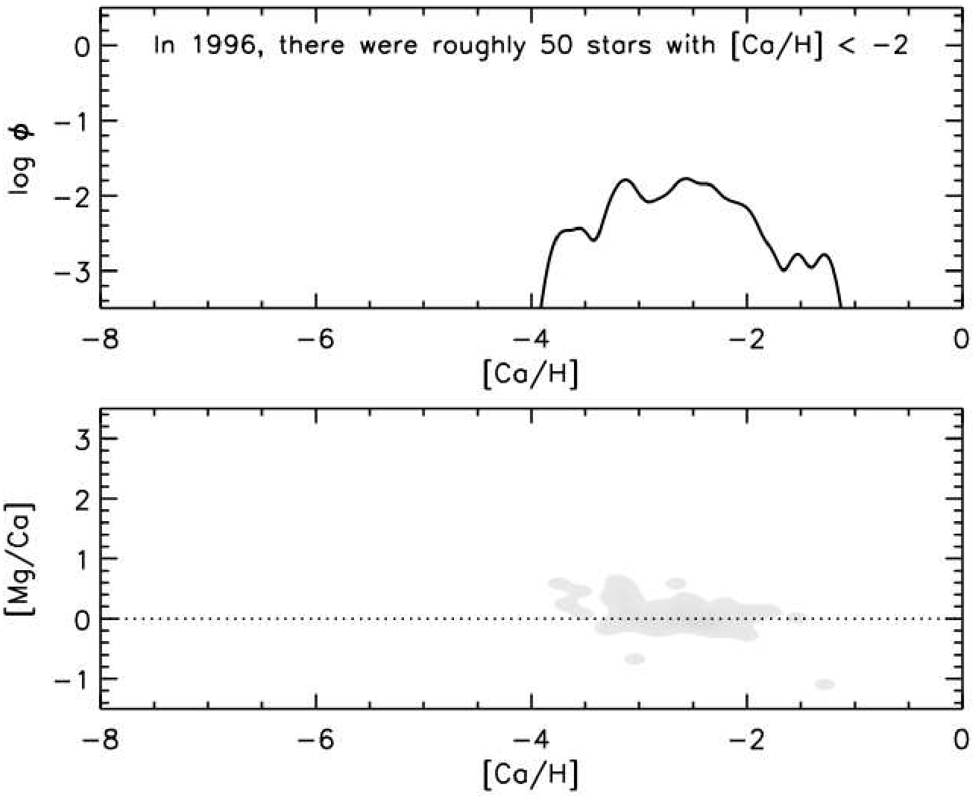

Fig. 1. The upper panel shows the generalized histogram of the calcium distribution function on a logarithmic scale. The lower panel is [Mg/Ca] vs. [Ca/H] in which each data point is represented as a two-dimensional generalized histogram. The data used to generate this plot were taken from McWilliam et al. (1995) and Ryan et al. (1996).

al. 2017). In 1996, there were approximately 50 stars with published Mg and Ca abundances in the metallicity regime [Ca/H] < −2.

In Figures 2 and 3, we again plot the [Ca/H] distribution function along with [Mg/Ca] vs. [Ca/H]. This time, we include all stars from the SAGA database (Suda et al. 2008) with Mg and Ca abundances published in 2005 or earlier and 2014 or earlier, respectively. Below [Ca/H] = −2, there were approximately 900 stars by 2014, i.e., a roughly 20-fold increase since 1996.

These three figures illustrate the enormous progress has been made over the past two decades due to wide-field surveys, high-resolution spectrographs on 6-10m class telescopes, and the efforts of numerous teams around the world (e.g., Cayrel et al. 2004; Barklem et al. 2005; Lai et al. 2008; Aoki et al. 2013; Cohen et al. 2013; Norris et al. 2013; Roederer et al. 2014; Bonifacio et al. 2015; Hansen et al. 2015).

3. Discovery and diversity

While the rate of discovery has increased, the simple fact remains that metal-poor stars are rare. The halo contains about 1% of the stellar mass of our Galaxy such that for a random sample of 1000 stars, only 10 will belong to the halo. The observed metallicity (iron) distribution function for the Galactic halo has a peak near [Fe/H] = −1.6 and a width of ~0.6 dex. So halo stars with [Fe/H] < −3 represent

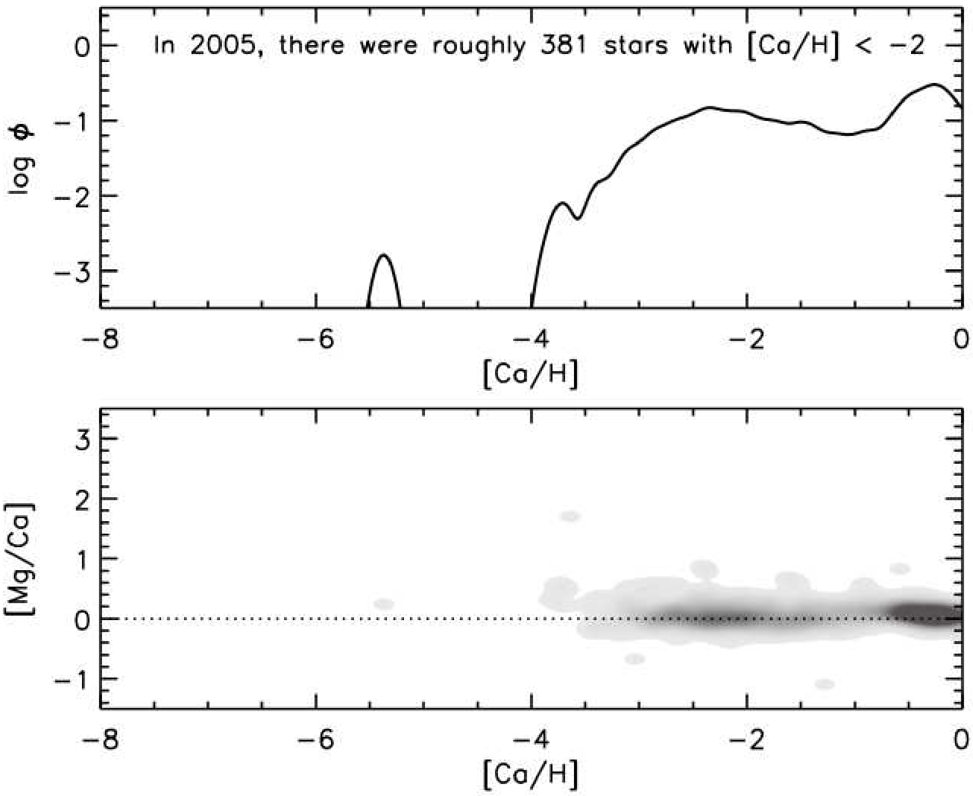

Fig. 2. Same as Figure 1, but including all data from the SAGA database (Suda et al. 2008) up to 2005. The grey-scale represents the density on a linear scale.

about 1% of the halo population. The numbers of stars with abundance less than a given metallicity decreases by a factor of 10 for each factor of 10 decrease in metallicity. So for a random sample of 100,000 field stars, roughly 1,000 will belong to the halo of which approximately 500, 50, and 5 will have metallicities [Fe/H] < −1.5, [Fe/H] < −2.5, and [Fe/H] < −3.5, respectively.

Among the various techniques to identify metal-poor stars discussed in Frebel & Norris (2015), photometric surveys are arguably the most promising due to the large sky coverage and depth. The SkyMapper (Keller et al. 2007) and Pristine (PIs E. Starkenburg and N. Martin) surveys both use narrow-band filters centered on the Ca II H and K lines and will eventually cover 20,000 and 3,000 square degrees in the southern and northern hemispheres, respectively. The commissioning survey with SkyMapper led to the discovery of the most Fe-poor star known (Keller et al. 2014; Bessell et al. 2015; Nordlander et al. 2017) as well as a 120 star sample (Jacobson et al. 2015).

Chemical abundances in the most metal-poor stars exhibit a large range for many elements. For example, Figure 3 indicates that while there is a dominant population with [Mg/Ca] = 0, that abundance ratio varies by four orders of magnitude. For many other elements (e.g., C, N, Sr, Ba), a large range in element abundance ratios [X/Fe] and/or element-to-element abundance ratios [X/Y] is also evident. It is encouraging that inhomogeneous chemical evolution models (e.g., Kobayashi & Nakasato 2011) are increasing in sophistication and predict large dispersions in element

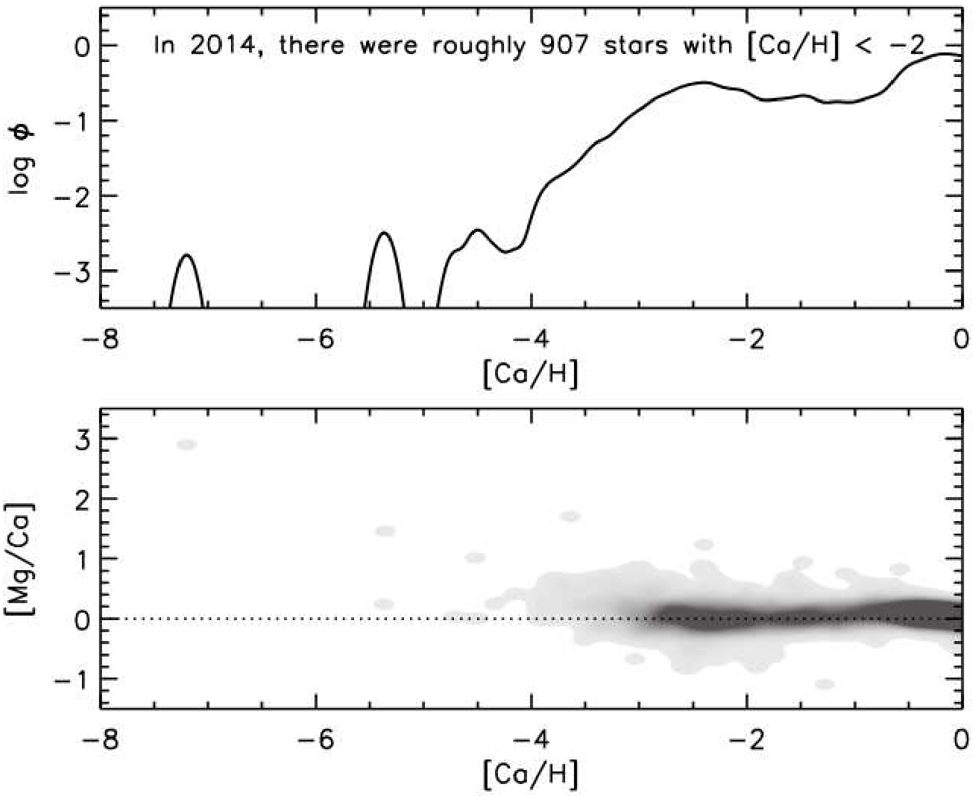

Fig. 3. Same as Figures 1 and 2, but including all data from the SAGA database (Suda et al. 2008) up to 2014.

abundance ratios. Of great interest will be the comparison between observations and simulations of multidimensional abundance distributions. Nevertheless, at present the large range in chemical abundance ratios require great diversity among the properties of the earliest generations of stars (e.g., Maeder & Meynet 2012; Cescutti et al. 2013; Norris et al. 2013; Karakas & Lattanzio 2014; Tominaga et al. 2014; Abate et al. 2015; Bisterzo et al. 2017).

4. Outlook

Understanding the nature of the first stars (and galaxies) and how they transformed the Universe is a key question driving the next generation of observational facilities. Therefore, the discovery and analysis of metal-poor stars will remain a major research area in the coming years. Given that the eight most iron-poor stars were all discovered after 2002, and that new photometric surveys like SkyMapper and Pristine are underway, it seems highly likely that many new metal-poor stars with [Fe/H] < −4 will be discovered and analysed in the coming years.

In addition to these larger sample sizes and more robust results from improved modelling of the stellar atmospheres (e.g., 3D and non-local thermodynamic equilibrium analysis by Nordlander et al. 2017), high precision differential analysis is one area which promises to provide new insights. For example, Reggiani et al. (2016) performed a differential analysis of G64-37 with respect to the standard star G64-12. For some elements (e.g., Al, Si, Ca, and Ti), the abundance errors for [X/Fe] were as low as ~0.01 dex (i.e., 2%). Their analysis revealed that for many elements, there were genuine abundance differences between these two stars. Additional high precision chemical abundance studies at low metallicities have the potential to provide important new insights into the chemical enrichment in the early Galaxy. For example, similarly high precision analysis of halo stars with [Fe/H] > -1.6 by Nissen & Schuster (2010) revealed that the halo hosts two populations with distinct [α/Fe] ratios and different kinematics. Fishlock et al. (2017) identified additional differences between the two populations when considering Sc and neutron-capture elements.

Some of the open questions that remain include:

(1) What is the shape of the metallicity distribution function for iron and other elements?
(2) What are the chemical abundance distributions?
(3) What is the fraction of carbon-enhanced metal-poor (CEMP) stars?
(4) What is the origin of the CEMP-no stars?

While these questions have been around for many years, we are now asking these questions at lower and lower metallicities. The answers to these questions will reveal important new insight into low-mass star formation at earliest times and the nature and properties of the first stars.

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