Extremely Metal-Poor Stars

A White Paper Submitted for

High-Resolution Optical Spectroscopy

Gemini

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Introduction

How did the galaxies we see today form out of the remnant gas of the Big Bang? This unanswered question in modern astrophysics is central to the strategic astronomical roadmaps of the majority of Gemini member countries, and it is a key driver behind the next generation of extremely large telescopes. Specifically, the US decadal survey has listed the study of low-metallicity objects and how they can be employed to study the early Universe among their primary science goals. The formative moments in galaxy development can only be studied *directly* with large telescopes.

A complementary route is available through the study of extremely metal-poor (EMP; [Fe/H]<-3) stars. EMPs formed early in the history of the Galaxy. They offer us a tangible nearby sample of the high redshift universe. With a slew of new surveys to find EMP stars, this decade will see the consolidation of this field as sample size increases. This will in turn deliver on the promise of EMP stars to constrain the physics of the early Universe and the properties of the first stars. The candidate EMP stars to be found by up-coming surveys are predominantly bright (*V*<18.5). Therefore, 8m-class high-resolution spectrographs will be driving the growth of this field.

What can EMPs tell us about the early Universe?

Key observable 1: The Metallicity Distribution Function

Extremely metal-poor stars are extremely rare. The last two decades have seen three large-scale EMP surveys; firstly the HK survey (Beers, Preston & Shectman 1985, 1992), followed by the Hamburg/ESO survey (summarised by Schorck et al 2009) that were based on objective prism plates. Most recently we have seen the search for EMPs from the SDSS/SEGUE data (Beers et al 2010). Figure 1 shows the rapid decline in the metallicity distribution function (MDF) for the halo derived from the Hamburg/ESO survey.

We know of three stars with [Fe/H]<-4 (Christlieb et al 2002, Frebel et al 2005 & Norris et al 2007). It is precisely this EMP tail of the MDF that is a pivotable observable for constraining models of the formation and evolution of the Galaxy. Cosmological simulations suggest that the first stars formed in the central regions of subgalactic clumps of gas at redshift z~10-50. Such first stars are expected to be extremely massive. McKee & Tan (2008) predict typical masses for the first Population III (Pop III.1) of ~140Mo, with a possible range of ~60-320Mo. According to Heger & Woosley (2002), zero metallicity stars with masses 140<M<260 are expected to explode as pair instability SNe (PISN). Outside this mass range all stars end as black holes and yield to the interstellar medium no nucleosynthetic products. The end of Pop III.1 stars is the backdrop for the subsequent chemical evolution of the Milky Way.

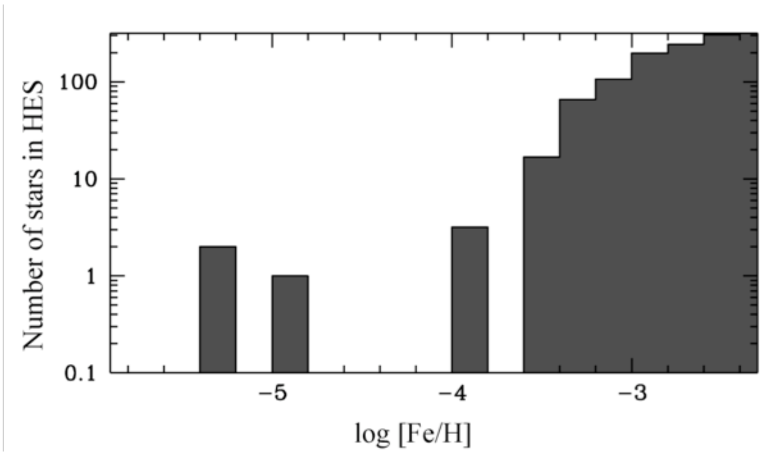


Figure 1. The number of extremely metal-poor stars known from the Hamburg/ESO Survey (scaled from Schorck et al 2009 to include both giant and dwarf stars)

Several groups have produced chemical evolution models for the Milky Way that take into account the hierarchical evolution of structure within LambdaCDM cosmology (e.g. Prantzos 2003, Salvadori et al 2007, Karlsson 2006). The resulting MDFs can be compared to that observed (Schorck et al 2009) to constrain the physical environment during galaxy formation. For example, in the absence of a critical metallicity for a transition from PopIII to `classical' (PopII) star formation, the number of EMPs is greatly overestimated. An extrapolation of the MDF in Figure 1 for [Fe/H]>-3.5 would predict the presence of 14 stars of [Fe/H]<-3.5 of which three are found. This posited `gap' of 3 sigma significance, has been interpreted as corresponding to the period of universal reionisation that occurred shortly after the first stars formed. Frebel et al (2009) shows the MDF of Figure 1 implies that the first stars were ~40-100Mo, and that only a small fraction died as PISN. By confronting cosmological simulations with observations we have the potential to constrain:

- The primordial stellar mass function,
- The critical metallicity for transition between PopIII to PopII,
- The role of reionisation on galactic evolution,
- The efficiency of early star formation, and,
- The efficiency of gas mixing in the early Galaxy

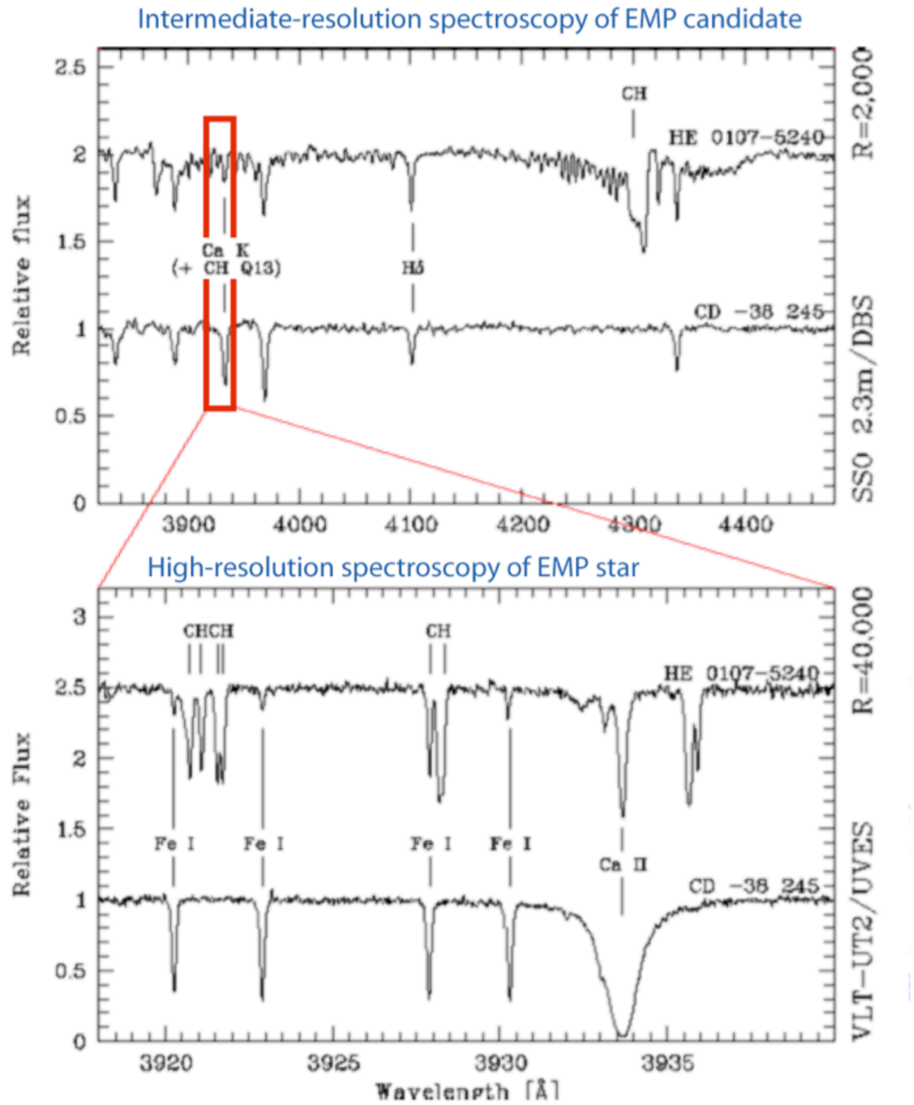
At present we are sample starved. To realize the potential of EMP stars to constrain the physical properties of the early Universe we need to increase the number of spectroscopically characterised EMP stars. Such a task is achievable with a high-resolution spectrograph on an 8m-class telescope.

Key Observable 2: Detailed Chemistry

As discussed above, the masses of PopIII stars differ fundamentally from PopII stars. In addition to a top-heavy mass function with 100Mo+ stars, a bimodal mass function that incorporates a range of intermediate masses has been suggested (Lucatello et al 2005, Komiya et al 2007). The detailed abundances of the most metal-poor stars are a direct way to constrain these models.

Barklem et al (2005) and Bonifacio et al (2009) have performed high-resolution spectroscopic analyses on a large sample of metal-poor stars. It is evident that there is an increasing frequency of stars with unusual chemical compositions towards lower metallicities. EMP stars are not the product of well-mixed gas that characterises the [Fe/H]>-2.5 halo (Tumilson 2010). Some stars exhibit large enhancements in rapid neutron capture (r-process) elements that indicate the enrichment by *individual* supernovae (Frebel et al 2005, Christlieb et al 2002, Cayrel et al 2004, Cohen et al 2007, McWilliam et al 1995).

Supernova nucleosynthesis theory, while making impressive progress (e.g. Heger & Woosley 2008), is still hampered by critical limitations: the physics of the explosion is unknown, the nucleosynthesis models are largely one dimensional, the amount of mixing, the mass cut of ejected material, and explosion energy are free parameters, rotation, rotational mixing and winds are not included. Thus, the comparison of theoretical SN yields with the detailed chemistry of EMP stars can provide a unique constraint on supernova nucleosynthesis and ultimately, the supernova explosion models.


Intermediate-resolution spectroscopy of EMP candidate

High-resolution spectroscopy of EMP star

Figure 2 Sifting through EMP star candidates is typically a two-stage process. First intermediate – resolution spectroscopy and then, if confirmed, high-resolution spectroscopy on 8m-class telescopes. In the example above the stars are CD-38 245 of [Fe/H]~-4 and HE0107-5240 a C-rich giant at [Fe/H]=-5.3 (from Christlieb et al 2002)

The most metal poor stars further distinguish themselves by exhibiting strong Carbon, Nitrogen and Oxygen overabundances. Indeed, ~20% of stars with [Fe/H]<-2 exhibit a 1-4 dex enhancement in Carbon relative to a scaled Solar value (Rossi et al 2005, Lucatello et al 2006). This fraction increases to 100% for stars with [Fe/H] < -4. Amongst metal-poor stars there is a clear correlation between carbon enhancement and the presence of s-process-element overabundances, such as for Ba. That correlation no longer persists (or at least is different in nature) for stars with [Fe/H] < -2.7, including all of the most iron-deficient stars known to date.

Explanations for carbon enhancement include self-enrichment, enrichment by supernovae (Whalen et al 2008), or the leading theory enrichment via pollution from a binary companion (either AGB – Lau et al 2009, or a rapidly rotating massive star – Hirschi 2007). However, the different scenarios are distinguished by abundance patterns (especially regarding neutron capture elements such as Ba and Eu), that can only be truly assessed by comparing high-quality and low-uncertainty abundance determinations, made possible by the use of high-resolution spectroscopy on 8-m class telescopes.

Untangling the nature of the carbon-rich EMP stars, especially those of [Fe/H]<-5 will require a large increase in the number of characterised objects in the decade to come.

An outstanding problem for concordance cosmology is that the relative abundances of Lithium isotopes seen in the atmospheres of EMP stars are not as expected (Melendez et al 2010). The conditions of the initial fireball determine these abundances. More low metallicity dwarf stars will be crucial to resolving this problem.

The Next Generation of EMP Star Surveys

The current decade will see the commencement of a series of photometric and spectroscopic surveys for EMP stars that will undoubtedly swell the numbers of candidate EMP stars. The SEGUE-2 dataset has already left us with a large number of candidate [Fe/H]<-2 stars (~25000). The SkyMapper Southern Sky Survey (Keller et al 2007) expects to provide a 100-fold increase in the numbers of [Fe/H]<-3 stars. Similar results may be expected from PanStarrs (Hodapp et al 2004) and the LAMOST (Li et al 2010) and HERMES multi-object spectroscopic surveys. The advent of LSST will enable the search to increasingly fainter EMP star candidates.

A workhorse 8m high-resolution spectrograph is required to turn EMP star candidates into confirmed EMP stars with elemental abundances. The process for isolation of EMP stars in the Hamburg/ESO program is illustrated in Figure 2. Candidates are first selected from low-resolution objective prism spectra. These are then examined with medium resolution spectroscopy. Having screened the majority of false positives, the EMP stars then progress to 8m-class telescopes.

It is important to emphasise that this decade will see the generation of a large set of relatively bright (*V*<18.5) candidate EMP stars that are accessible to 8m class telescopes for high resolution abundance study. For this reason, the majority of the headway to be made in this field in this decade will reside with 8m facilities as we expand the numbers of EMP stars.

The Gaia astrometric mission will have a major impact on stellar population studies of the Galaxy. This impact will largely be evident at *V*<18.5 where Gaia will produce accurate proper motions. It does not appear that Gaia will, however, return useful radial velocity measurements for *V*>15-16. This creates a great opportunity: to combine chemistry and radial velocities for EMP stars with Gaia proper motions (and parallax for a subset) to recover the full spatial kinematics of the inner and outer halo at [Fe/H]<-3.

Science requirements from a Gemini-based HRS

The requirements for a Gemini-based high-resolution spectrograph are straightforward:

- Wavelength coverage Lambda_min as low as possible, required to be below CaK (393.4nm), total coverage as wide as possible
- Throughput in blue as high as possible
- Resolution: minimum resolution mode optimal for fainter targets (19<V<20): R~15K, optimal for V<18.5-19: R~40K with an effective entrance aperture that corresponds to median seeing.
- Modest slit length, 10" spatially, to allow possibility of modest (~10 object) multi-fibre mode.

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