Extremely Metal-Poor Stars: The Local High Redshift Universe

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1. Motivation

Extremely metal-poor (EMP) stars can only have formed early in the history of the Galaxy, and represent the local equivalent of the high redshift universe. With them, we can study the early supernovae, the early chemical evolution of the Galaxy, and the history of star formation in the Milky Way. By analogy we can learn about those epochs of galaxy formation in the distant past that are currently at such high redshifts that they are beyond the reach of even the largest existing telescopes, a technique some call "near-field cosmology".

While H, He, and some Li came out of the Big Bang, all other elements were formed in stars, and were dispersed by supernovae and stellar winds into the gas from which subsequent stellar generations formed. The ejecta from supernovae played the most important role in the early Universe. SN models have many parameters, including the history of the progenitor star (initial mass, mass loss history, internal nucleosynthesis history prior to the explosion, etc), the details of the explosion (energy, ejected mass, mixing) etc. There are vigorous groups pursuing the details of these models both theoretically and computationally in the US and abroad. But there are so many free or poorly known parameters that these efforts are best guided by observations of metal-poor stars.

2. What we learned during the past decade

We learned that EMP stars[1] (i.e. those with [Fe/H] < -3) are rare.

We learned that ultra-metal poor stars with [Fe/H] < -4 are extremely rare.

The main source of candidate EMP stars until recently was the HK Survey (Beers, Preston & Shectman 1985, 1992), based on objective prism plates with low dispersion spectra of millions of targets. These plates were searched by eye to isolate several thousand candidates for stars of very low metallicity, but no star from that survey surpassed CD –38 245, at [Fe/H]~ -4.0. It was only after the Hamburg/ESO survey database, a deeper digital database with larger sky coverage, became available that HE0107–5240 with [Fe/H] ~ -5.3 (i.e. a star composed of gas with n(Fe)/n(H) 1/200,000 that of the Sun) at $V \sim 15.2$ mag was discovered by N. Christlieb and collaborators in 2002. Since then arduous efforts to check perhaps ten thousand stars have resulted in the discovery of two more such stars, HE1327–2326 (Frebel et al 2005) and HE0557–4840 (Norris et al 2007). All three of these were found in the Hamburg-ESO Survey, but essentially all the best candidates from this survey, which covers 6400 sq deg of the southern Galactic pole region to a

[1] We follow the nomenclature suggested in the review article of Beers & Christlieb (2005).

depth of $B \sim 17.5$ mag, have already been examined, and no more such stars have been found in this database.

The extreme scarcity of ultra-metal poor stars leads directly to constraints on either the initial mass function or mixing of enriched stellar ejecta from the first stars throughout the gas within a dark matter halo in the early Universe, or both of these.

We discovered that a surprisingly large fraction of the most metal-poor stars are highly carbon-enhanced.

The nucleosynthesis pattern seen in many of these stars, both among C, N, and O and among the elements past the Fe peak formed by neutron capture, matches that expected from a low mass AGB star (e.g. Cohen et al 2006; Aoki et al 2007). Such stars could result after mass transfer within a binary system when a more massive former primary passed through the AGB phase.

By measuring abundances in the surviving star, we have an almost pristine record of nucleosynthesis in an EMP AGB star, information that is not obtainable by other methods because metal-poor AGB stars responsible for galactic chemical evolution (those with $M > 1.1\ M_{\odot}$) have all died by now. Observational studies combined with modelling have shown the importance of very metal-poor AGB stars for the production of Pb, as reviewed by Busso, Gallino & Wasserburg (1999), and explored the origin of the seeming disappearance of the *s*-process in such stars at the lowest metallicities (Cohen et al 2006; Aoki et al 2007). The number of stars that have been polluted by AGB stars has been used to study in the IMF of very metal-poor stars in the low-to-intermediate mass range (see, e.g. Lucatello et al 2005; Komiya et al 2007).

We discovered that three of the stars known with [Fe/H] below -4.7 are very highly carbon-enhanced. Is this a clue to their nucleosynthesis history or the result of binary mass transfer ?

We will need to monitor the radial velocity of these stars for a decade or more to check for binarity. Furthermore, one might ask if these stars initially had such low Fe-metallicity, or whether they were formed from material from a SN with a peculiar explosion, possibly with an anomalous mass cut, so that the Fe-rich layers were not ejected.

We established cosmochronology using radioactive decays as a technique to provide direct age measurements for the Galaxy. This was enabled by detection of features of uranium in a metal-poor star in 2001 by Cayrel and collaborators.

We constrained the sources of the majority of nucleosynthesis from the first generation of stars.

Simulations showed that the first star to form in a dark matter halo was massive enough to end its life as a pair-instability supernova (see, e.g. Abel, Bryan & Norman 2002). But the nucleosynthesis patterns in EMP stars (e.g. Carretta et al. 2002, Cayrel et al. 2004, Cohen et al. 2004) are clearly inconsistent with a major contribution from pair-instability supernovae, see also Tumlinson, Venkatesan & Shull (2004).

Very recent theoretical results focusing on the second star formed in a dark matter halo, which has been affected by the feedback from the first star (see, e.g. Greif & Bromm 2006) find that its mass function favors lower masses, thus achieving consistency with the observations. In a recent example of the power of abundances and supernova models to reveal the early Galaxy, Lai et al (2008) used the most up-to-date models of Heger & Woosley (2008) to show that the chemical inventory in very metal-poor stars was produced in lower mass ($< 15\ M_{\odot}$) supernovae.

We learned during this decade that the young Galaxy was fairly homogeneously mixed at surprisingly early phases.

In broad terms, it appears as if the early Galaxy was quite well mixed, with the abundance ratios for the elements through the Fe peak, ignoring C, N, O, Li and Be, being similar from star to star (see e.g. Cohen et al 2004; Cayrel et al 2004). However, the lowest metallicity stars known tend to deviate from this simple picture. Among the handful of stars we have identified at [Fe/H] $\lesssim -3.5$, there are several examples of stars with "peculiar" abundance ratios. The most obvious of these are the iron-poor stars (i.e. those with [Fe/H] $\lesssim -5$), but other stars feature extreme C, N, O and Mg abundances (CS 22949-037), very low [Si/Mg] and [Ca/Mg] ratios (HE 1424–0241, Cohen et al 2007) or very high [Ca/Mg] ratios (Lai et al. 2009, private communication).

The discovery and detailed study, accompanied by a program of laboratory spectroscopy, of a few extreme *r*-process-enhanced stars (Sneden et al 2003; Barklem et al 2005) has greatly improved our understanding of nucleosynthesis beyond the Fe-peak, where neutron capture processes dominate. Separation of the contributions of the various contributing processes became much clearer once these stars, with their very pure *r*-process heavy element abundance patterns, were identified and characterized.

3. Expectations for the Coming Decade

Finding and studying more stars at the lowest metallicities: The most important thing that we must do is to identify and study more of the most extreme stars, i.e. those with [Fe/H] < -4. It is clear (see e.g. Oey 2003; Salvarodi, Schneider & Ferrara 2007) that we should have found more [Fe/H] < -5 stars under reasonable assumptions about mixing with a Salpeter initial mass function than have been found to date; the extreme scarcity of such stars implies something is wrong with the input assumptions for such calculations. There are still considerable uncertainties in the models, and therefore identifying a bigger sample of stars at such low metallicities, of which only three are known at present, and studying them in detail, accompanied by theoretical simulations, is crucial.

Some of these stars, in particular those with peculiar abundance ratios, may well be examples of the elusive and long-sought stars that have been polluted by just one supernova, but their abundances are not a good match for current SN predictions. Accumulating a sample of ultra metal-poor stars big enough to determine the statistical properties of this class of stars and using them to understand supernova nucleosynthesis is a project that will require the next decade of surveys.

Understanding the C-rich Stars: Another area where preliminary work during the present decade still demands considerable effort is determining the origin of the extremely carbon-enhanced metal-poor stars. An alternative explanation for the high fraction of carbon rich stars among ultra metal-poor stars was recently offered by Hirschi (2007) who suggests that these stars have been polluted by winds from massive stars rotating far more rapidly than stars we see today. Untangling the nature of the carbon rich EMP stars, especially for the very small number of stars with [Fe/H] < -5, is a task that began during the past decade but one whose completion will require a lot more work in the coming decade.

The Next Generation of Databases: Databases from which candidates can be identified for the next decade will come from the SEGUE-1 and SEGUE-2 projects (part of SDSS–II and SDSS–III), and from the LAMOST survey telescope in China, which has a 4000 fiber multi-object spectrograph. The telescope and its instrument are currently being commissioned. The Australian SKYMAPPER survey will also provide numerous metal-poor candidates.

The first era of major surveys, which included the HK and HES efforts, resulted in the identification of a total of roughly 4000 stars with spectroscopically confirmed [Fe/H] < -2.0. The present-era large surveys, SDSS-I and SDSS-II (which included SEGUE-1) have added an additional 16,000 such stars to the total. By the time SDSS-III (which includes SEGUE-2) finishes, there should be a total of some 25,000 stars known with [Fe/H] < -2.0. By contrast, the numbers of stars with [Fe/H] < -3.0 will only rise to on the order of 1000, due to their extreme paucity. The numbers of stars with [Fe/H] < -3.5 will likely be in the tens of objects, but those below [Fe/H] $= -4.0$ may still only represent a scant handful. Other surveys in the current decade (LAMOST and SKYMAPPER) will hopefully swell these numbers by an order of magnitude or more. Deeper surveys of the future, such as LSST, will continue this upward trend to larger and larger numbers of candidate low metallicity stars.

The metallicity distribution function of very low metallicity stars, below [Fe/H] ~ -2.0, encodes the chemical history of the first billion years of the Milky Way's lifetime, and that of its satellite galaxies, which have been adding to the stellar content of the halo from the very beginning to the present. Detailed study of its shape, or deviations from continuity such as localized chemical peaks, and of course, its low-metallicity terminus point provide constraints on the nature of the Galaxy's assemblage, and the mass function of the earliest sub-Galactic building blocks (now destroyed) that may have been involved.

Moving Into the Outer Halo of the Galaxy: Recent work (Carollo et al 2007) based largely on analysis of tens of thousands of SDSS spectra suggests that it is highly desirable in such searches to reach far out into the Galactic halo beyond the "inner halo" (i.e. reach Galactocentric radius > 15 kpc) to improve the probability of finding such stars. These outer halo metal-poor stars also may be tracers to the formation of the Milky Way stellar halo. In addition to the observational evidence from SDSS, simulations in the hierarchical paradigm (see, e.g. Helmi 2008, and references therein) suggest many stars in this outer halo region came from systems different than those that formed the inner region of the Galactic halo. The chemical inventory of these stars would not then be expected to reflect the well-mixed ISM that seems to characterize the inner halo region. Combining chemistry with kinematics indeed predicts discoveries of stars down to [Fe/H] $= -7.3$ (Frebel et al 2009). In particular, an intriguing question is whether all dwarf galaxies (including the recently discovered ultra-faint dwarf galaxies) share a similar early star formation and chemical evolution history, regardless of whether they were later accreted by the Milky Way.

Instrumental Requirements for the Proposed Program: Extremely metal-poor stars have very weak lines, so that very high quality (both in terms of spectral resolution and signal-to-noise ratio) spectra are required. For example, 20 hours of integration on the VLT with the UVES spectrograph were required to determine the oxygen abundance in HE0107-5240 from the ultraviolet OH band. With high throughput, high dispersion spectrographs on more 10 m class telescopes we can map the evolution of abundance ratios from their values in EMP stars through [Fe/H] ~ -3 to their familiar values at the mean metallicity of the well-mixed local halo.

Success with the Hamburg-ESO Survey has demonstrated that the data products of a large survey are a good source of candidate metal-poor stars. Future surveys and better-informed mining of existing databases will provide larger and ever-fainter candidate lists, reaching into the outer Galactic halo. To exploit these new sources of EMP candidates will require new spectroscopic capabilities. An EMP search will need a wide field, highly multiplexed, high throughput, moderate resolution spectroscopic facility to find the most promising candidates. Our desire to probe the stellar component of the outer Galactic halo will ensure that new discoveries in the next decade will be fainter than the stars from the Hamburg-ESO Survey that pushed the limits of what was possible for high dispersion follow-up on 10 m-class telescopes. Many of the next generation of EMP candidates will require an ELT equipped with a high dispersion spectrograph with high efficiency throughout the optical wavelength regime for detailed follow-up. These requirements for a future EMP star search are much like what will be required for many other investigations that take the next generation of large surveys as their starting point.

Spectroscopic line density increases with decreasing wavelength. In cool metal-rich stars the domain $\lambda < 4000$ Å is too crowded for abundance analyses, but in ultra-metal-poor stars that same wavelength region often contains the only detectable transitions of some elements. Therefore an ELT must have capability for high-resolution spectroscopy down to the UV atmospheric cutoff, and, as a lower priority, we hope that facilites for abundance studies in the vacuum UV are a part of a future NASA space astronomy mission. Only with such facilities will we be able to probe, for example, the heaviest stable elements of the Periodic Table in low metallicity stars (e.g. Cowan et al 2005).

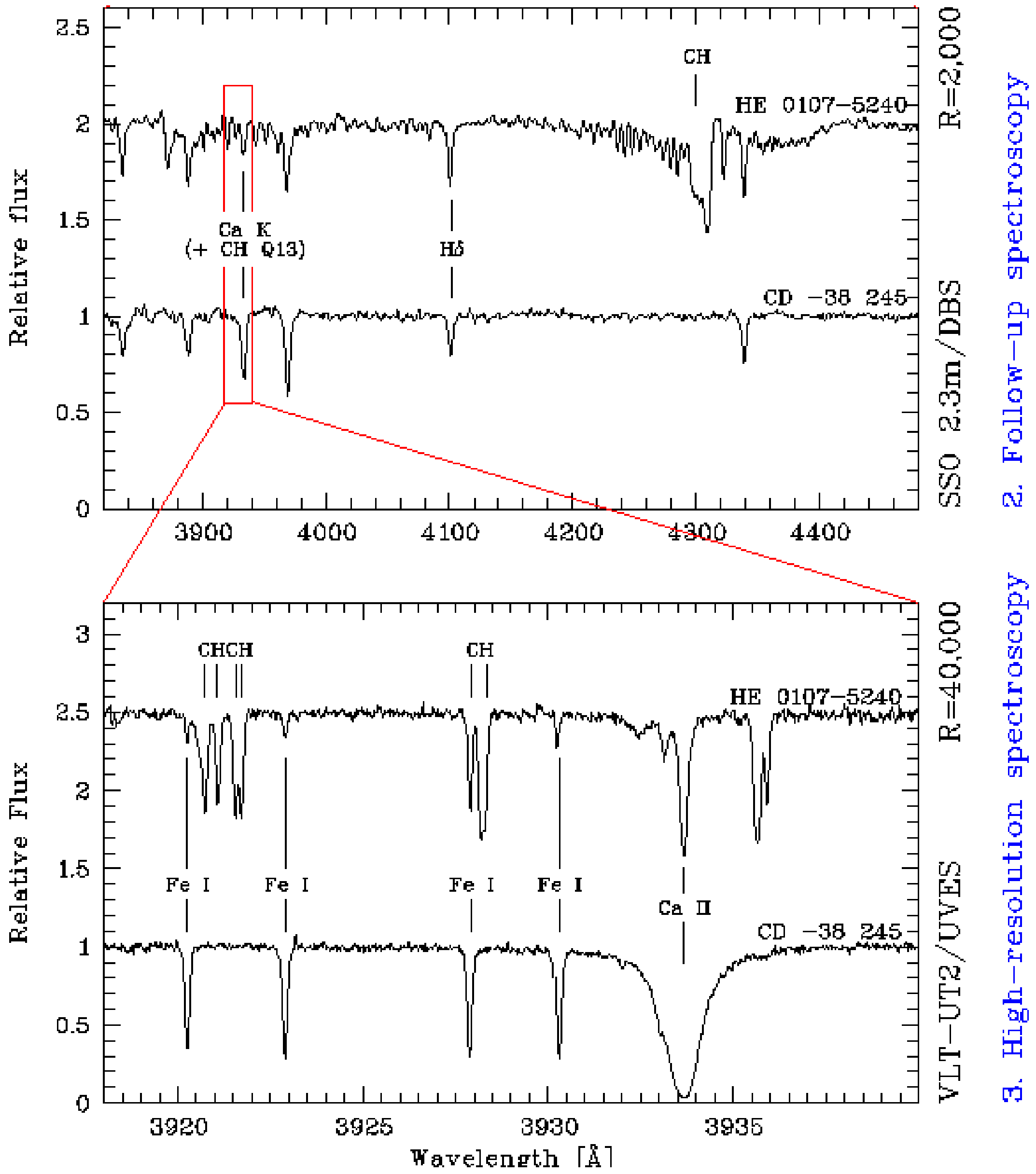

Fig. 1.— The two steps towards obtaining elemental abundances of extremely metal-poor stars: (1) moderate resolution spectroscopy (from SDSS for example); (2) high-resolution spectroscopy of confirmed candidates. The stars shown are CD –38 245, [Fe/H] ~ -4, the most metal-poor star known prior to 2002, and the C-rich giant HE0107–5240 with [Fe/H] -5.3. (Source: Christlieb 2002)

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