Extreme Metal-Poor Stars in Ultra Low-Luminosity Dwarf Galaxies and the Galaxy

Andrew McWilliam (OCIW)

1. Reasons for Abundance Studies of Extreme Metal-Poor stars:

The study of Extreme Metal-Poor (EMP) Stars has already had a significant impact, and they offer the potential to understand and advance many areas of astrophysics, for example: supernova nucleosynthesis, population III stars, stochastic chemical evolution, the IMF, the formation of dwarf galaxies, and the cosmological growth of structure. However, progress is severely limited by the small number of EMP stars known (e.g., less than [Fe/H]=-4 only a handful are currently known).

2. Study nucleosynthesis from population III Supernovae

McWilliam et al. (1995, henceforth MPSS95) found an increasing ratio of [Co/Cr] with decreasing [Fe/H] in EMP stars between [Fe/H]~ -2.5 and -4.0; the ratio increases by ~ 1 dex over this range. This discovery has been confirmed many times. While there have been some suggestions that non-LTE effects may be responsible for the trend, recent non-LTE results from Bergemann, Pickering & Gehren (2010) showed that the overabundance of Co at low [Fe/H] is real, and should be increased with non-LTE corrections.

MPSS95 attributed the downward Co/Cr trend with increasing [Fe/H] to a cobalt-rich, chromium-poor, composition at early times (and low [Fe/H]), which was later diluted with material of solar iron-peak composition. McWilliam (1997), and McWilliam & Searle (1999), suggested that this early Co-rich composition could reflect nucleosynthesis products from population III SNe. If this is true, then the EMP iron-peak composition provides information on population III stars. It would be very interesting, and useful for cosmological questions, to understand the UV fluxes and masses of population III stars. It seems possible that this may be learned from the fossil record locked-up in EMP stars. In this regard, supernova nucleosynthesis models by Nomoto and collaborators found that Co abundance enhancements can be obtained in hypernovae explosions, which are characterized by high explosion energies.

Nucleosynthesis predictions for population III pair instability supernovae (henceforth PIS), by Heger & Woosley (2002), predict large odd-even abundance ratios in iron-peak elements. However, the predicted ratios are much more extreme than those actually observed in EMP stars. It is important to know whether any EMP stars can be found that show chemical signatures from the predicted PIS. If no evidence of the PIS signatures can be found it will be necessary for the theorists to understand why. Population III SNe presumably play a role in the cosmological growth of structure, which increases the value of finding population III in the fossil record of the composition of EMP stars.

2.1. Comparison with predicted yields for metal-poor Type II SNe

For EMP stars the large dispersion in neutron-capture abundances indicates that small numbers, even individual, SNe (at least for those elements with large dispersions). Thus, it is possible to compare and test predicted supernova yields with measured abundance ratios.

Elemental abundances in stars for some dwarf galaxies suggests stochastic chemical evolution and enrichment by a handful of Type II SNe, for example in the Her dwarf galaxy by Koch et al. (2008).

This stochastic chemical evolution is worthy of study alone, but it will also provide a tool for directly measuring the distribution of element yields from supernova events in the early Galaxy. Initially this will be important for constraining supernova yields, but it will also then inform on the progenitor mass function of these early supernovae.

This randomness in early contamination by population II supernovae should result in some EMP stars composed of relatively more population III material.

2.2. The r-process and the light neutron-capture elements

Because of the powerful coulomb repulsion of chraged particles with nuclei containing many protons, it is thought that the addition of neutrons onto heavy nuclei (which have no charge) is the main source of elements beyond the iron-peak (e.g., Burbidge et al. 1957). Neutron-capture has been categorized into two extremes: slow neutron-capture (s-process), for which all beta decays occur before the next neutron is added, and rapid neutron-capture (r-process), in which no decays occur until after all neutrons have been added. Much is known about stellar evolution and nuclear reactions occurring in stars that result in slow neutron-capture, but very little is known about the r-process; even the source of the r-process neutrons remains a mystery. What is known, is that the r-process neutron exposure events must occur in approximately one second. This short timescale suggests to some that the r-process occurs during core-collapse supernovae events.

Detailed chemical abundance studies of EMP stars have revealed significant facts about the r-process: 1. The r-process over-abundances of the rare r-process rich EMP stars indicates that r-process supernovae elements must be at most 1/20 to 1/40 of all supernovae. 2. The r-process pattern above barium appears to be universal. Remarkably, the r-process rich EMP stars, which must contain the ejecta from a single r-process event only, have heavy element abundance patterns that are identical to the solar r-process pattern. 3. Two EMP stars show unexpectedly high thorium and uranium abundances. If this is shown to be real, it would prove that there is variability in the r-process. 4. The light neutron-capture elements near Z=38 (strontium) show variability relative to the heavier nuclei, indicating that there is an additional nucleosynthesis source for the elements near strontium. First discussed by

McWilliam (1998) and Johnson & Bolte (2002) many believe that this second source is due to a weak r-process (e.g., Wanajo & Ishimaru 2005), but the actual source of the abundance dispersion near strontium remains unknown.

One use of the r-process rich stars has been as a cosmo-chronometer; time since r-process nucleosynthesis can be measured for the EMP stars by comparing abundances of Th and U with those of stable r-process elements (e.g. Eu.)

Perhaps the two most pressing questions in nuclear astrophysics today are:

What is the source of the r-process? and

What is the source of the light neutron-capture element dispersion in EMP stars?

3. THE ROLE OF ULTRA-LOW LUMINOSITY DWARF GALAXIES

EMP surveys (e.g., Christlieb 2003; Beers, Preston & Shectman 1992) have already searched roughly one quarter of the Galactic halo (beyond $|b|$ 30deg) down to B$\sim$17.5 to obtain the extant sample of known EMP red giant stars. Thus, future surveys within the Galactic halo are unlikely to produce a large increase in EMP red giant stars. While there is a large reservoir of Galactic EMP dwarf stars, the dwarfs show very weak, or undetectable, lines from neutron capture, due to atmosphere effects. For this reason, progress in the questions outlined above is unlikely to be made with dwarf stars.

Thus, it is likely that progress will require a large sample of EMP red giant stars beyond the Galactic halo. Recent surveys have identified ultra-low luminosity dwarf galaxies near the Milky Way. Spectral analysis of stars in these galaxies show that they frequently contain EMP stars (e.g., Simon et al. 2010).

Planned large scale surveys, including the Dark Energy Survey (DES) PANSTARRS, and LSST, are expected to reveal hundreds of new low-luminosity dwarf galaxies within the Local Group. From this pool of dwarf galaxies we can expect to find a large number of EMP stars. The timescale for these surveys is 5 to 10 years. Thus, this is an area where a quickly built, efficient, high resolution spectrograph on Gemini will be able to compete with the best spectrograph/telescope combinations in the world today. The large number of anticipated targets assures that this will be a major undertaking, with plenty of room for all groups to make a significant contribution; no one institution will be able to observe all the targets. Success will depend on number of night allocated to the project, and efficiency of the spectrograph/telescope combinations.

Abundance ratios of EMP stars, can be used to reveal the average mass of the stars that synthesized their meterial, and thereby constrain the IMF. This is especially interesting for the ultra-low luminosity dwarf galaxies, which may have only experienced very few SN events after population III. In particular, Kroupa & Weidner (2003) suggested that the high mass end of the IMF is set by the mass of the galaxy. Thus, this Integrated Galactic IMF (IGIMF) would show a deficit of high mass stars in low mass galaxies. Abundance ratio diagnostics in low-mass galaxies can test this IMF idea.

Massive star yield predictions (e.g. Woosley & Weaver 1995; Maeder & Meynet 2002) show a strong dependence of the synthesized [C/O] ratio in the ejecta with progenitor mass; more massive stars produce more hydrostatic oxygen, for a lower [C/O] ratio. The ratio also depends on stellar winds at metallicities above [Fe/H]~ -1 (e.g., see Meynet & Maeder 2002; Cescutti et al. 2009).

Supernova nucleosynthesis predictions (e.g., Woosley & Weaver 1995; Nomoto et al. 2006) show that Mg is greatly overproduced in stars with progenitor masses above $\sim$30 $M_\odot$, and the [Mg/Ca] ratio increases with increasing progenitor mass.

The [C/O] ratios are often difficult to measure in EMP stars due to the nature of the spectral lines in cool stars. Also, the red giant phase dredge-up reduces the carbon abundance, so that both C and N must be measured in order to estimate the primordial [C/O] ratio. The [Mg/Ca] ratio does not suffer from these difficulties, and can be readily measured in EMP stars. Koch et al. (2008) found enhanced [Mg/Ca] in the 2 giants of the Her ultra-low luminosity dwarf galaxy, which suggested nucleosythesis by massive stars. The question remains: was this because of the IMF skewed to massive stars, or due to stochastic sampling of the IMF? To answer this is will be necessary to sample the composition of many ultra-low luminosity dwarf galaxies.

In conclusion, if ultra-low luminosity dwarf galaxies are the un-accreted population of systems that formed the Galaxy, the detailed composition, may reasonably constrain the IMF and UV fluxes of the massive stars responsible for their metals. Apart from the constraints on population III, chemical evolution, early star formation, and heavy element nucleosynthesis (discussed above), parameters on this population of early gralactic fragments would be useful to constrain current models on cosmological growth of structure.

4. REQUIREMENTS FOR EMP STAR STUDIES

- **High throughput:** Critical since EMP stars in ultra-low luminoisty dwarf galaxies are near V$\sim$19. Magellan 6.5m plus echelle spectrograph gives S/N$\sim$30, per extracted pixel, at R=20,000 for V$\sim$19 in 8–10 hours.

- **Spectral Resolution:** R=20,000 to 60,000 range. The MPSS95 EMP abundance study used R=20,000 with 4 pixel fwhm at S/N=30. This should be a minimum requirement. Since intrinsic line widths of RGB stars is equal to R=50,000, spectrograph resloving power much more than about R$\sim$60,000 does not improve line detectability[1].

- **Wavelength Coverage:** 3900-4600Å essential, 3700–9600Å preferred.

  Current world-class high resolution spectrographs, in particular the Magellan echelle (MIKE) have effectively complete coverage of the optical region, 3,400 to 9,600Å. This makes the spectrograph easy to use for any optical project, and more of a "workhorse" instrument.

[1] Of course, other projects, such as work on interstellar absorption lines, M giants, line profile fitting for isotopic abundances, and precision radial velocities, may benefit from spectral resolving power higher than this.

For EMP studies the blue region of the spectrum will be important, as this is where the measurable lines are, especially for the most metal-poor EMP stars. The wavelength range from 3900 to 4600Å is particularly critical. It would make sense to request high throughput down to the Balmer limit, at 3646Å. The Gemini silver coating is still useful at this blue wavelength.

- **Pixel Scale:** 4 pixel FWHM standard, 3 pixel fwhm for a higher resolution mode.

  Nyquist sampling is 2.22 pixels, but from personal experience a minimum of 3.0 pixels is preferred. In MPSS95 we found 4.0 pixel FWHM spectra very useful for EMP stars.

  If R=30,000 is selected as standard, with 4 pixel FWHM for 0.7 arc sec slit, then a 0.5 arc sec slit will obtained R=42,000 with 3 pixel FWHM.

- **Multi-Object Versus Single Object:** Single object/slit mode, with possible additional multi-fiber mode.

  The density of EMP stars in the Galactic halo and normal Local Group dwarf galaxies is too low to make significant multi-object efficiency gains, and would come at the cost of at least a magnitude in the faint limit of the telescope + spectrograph.

  For the ultra-low dwarf galaxies there are more stars, but they are very faint and will require the most efficient set-up to get any of them. Fibers will lose this faint limit if that is the only mode. In particular, the low blue throughput of the fibers would be a severe hinderance for EMP chemical abundances.

REFERENCES

Beers, T.C., Preston, G.W., & Shectman, S. 1992, AJ, 103, 1987
Bergemann, M., Pickering, J.C. & Gehren, T. 2010, MNRAS, 401, 1334
Cescutti, G., Matteucci, F., McWilliam, A., & Chiappini, C. 2009, å, 505, 605
Christlieb, N. 2003, Rev.Mod.Astron. 16, 191
Heger, A., & Woosley, S.E. 2002, ApJ, 567, 532
Johnson, J.A., & Bolte, M. 2002, ApJ, 579, 616
Kroupa, P., & Weidner, C. 2003, ApJ, 598, 1076
Koch, A., McWilliam, A., Grebel, E.K., Zucker, D.B., & Belokurov, V. 2008, ApJ, 688, L13
McWilliam, A., Preston, G.W., Sneden, C., & Searle, L. 1995, AJ,
McWilliam, A. 1997, ARA&A, 35, 503
McWilliam, A., & searle, L., 1999, Ap&SS, 265, 133
Meynet, G., & Maeder, A. 2002, å, 390, 561
Nomoto, K., Tominaga, N., Umeda, H., Kobayashi, C., & Maeda, K. 2006, Nuc.Phys. A, 777, 424
Simon, J.D. et al. 2010, ApJ, submitted (arXiv:1007.4198)
Wanajo, S.,, & Ishimaru, Y. 2005, IAU Symposium, 228, 435
Woosley, S.E., & Weaver, T.A. 1995, ApJS, 101, 181