CHEMICAL EVOLUTION AND EXTREMELY METAL-POOR STARS

ANDREW MCWILLIAM
Observatories of the Carnegie Institution of Washington
813 Santa Barbara St., Pasadena, CA. 91101, U.S.A.
andy@marmite.ociw.edu

1. Introduction

Early abundance studies (e.g. Pagel 1968) showed that neutron-capture heavy elements ($Z > 30$) are present in halo stars, but deficient relative iron. Truran (1981) argued that at low [Fe/H] the chemical enrichment time scale was shorter than the lifetime of low-mass AGB progenitors, which are the main source of solar system heavy elements. He proposed that in the halo the heavy elements were produced by high mass stars, in type II supernova events (SNII), by rapid neutron capture nucleosynthesis (the r-process).

Spite & Spite (1978) investigated the trend of heavy element abundances with metallicity, from a small sample of halo stars. They found that at [Fe/H]~ -1.5 the halo [heavy element/Fe] ratio is approximately solar; but at lower [Fe/H] there is a roughly linear decrease of [heavy element/Fe] with declining [Fe/H]. Subsequent observations confirmed the general trend of heavy elements in the halo: [M/Fe]$\sim$0 down to [Fe/H]~ -2, followed by a linear decline in [M/Fe] to lower [Fe/H] (e.g. Gilroy et al 1988, Lambert 1987).

Additional evidence for the role of SNII in halo heavy element synthesis comes from the trend of [Eu/Fe] with [Fe/H]. Europium is an almost pure r-process element (Käppeler et al. 1989) and its abundance trend with metallicity is similar to the α element trend (e.g. O and Mg made in massive stars). The element ratios show an increase in [M/Fe] as [Fe/H] decreases from 0 to -1; below this point [Eu/Fe] and [α/Fe] remain constant at $\sim +0.3$ dex. For α elements this behavior is thought to be due to the change in the relative contributions from type II SN and type Ia SN in the disk and halo (Tinsley 1979). The trend for Eu also indicates production by massive stars (e.g. SNII). Near [Fe/H]~ -2.5 Eu appears to decline relative to [Fe/H] (like other heavy elements, but unlike the α elements). This abundance trend has been used to constrain the numerous proposed astrophysical sites of the r-process (e.g. Mathews & Cowan 1990).

Evidence for a dispersion in heavy element abundances at low metallicity was first uncovered by Griffin et al. (1982), who found one star, HD 115444, with a huge excess of Eu. Gilroy et al (1988) claimed a dispersion in [heavy element/Fe] for metal-poor halo giants, as did Gratton & Sneden (1990, 1991) and Ryan et al (1991). However, this was not universally accepted: Baraffe & Takahashi (1993) compared the results for individual stars from different studies, and found that the observed dispersion was consistent with the measurement errors. Also, Gratton & Sneden (1994) found no dispersion in [Sr/Fe] for their study of halo stars with [Fe/H]$= -3$ to -0.5 dex, and concluded that measurement errors in the earlier works were responsible for the apparent dispersion.

2. Extremely Metal-Poor Stars

2.1. HEAVY ELEMENT ABUNDANCES

In our study (McWilliam et al 1995, MPSS95) we analyzed spectra of 33 halo red giants from the sample of Beers et al (1992, BPS), with [Fe/H] ranging from -4 to -2. The measurement uncertainty of the abundance analysis was evaluated by use of a Taylor series expansion, propagated from the S/N of the spectra. We found a 2.5 dex range in [Sr/Fe] (Figure 1), and a typical abundance uncertainty near ± 0.2 dex; this confirmed previous claims of an intrinsic abundance dispersion, and was consistent with the early heavy element abundance trends.

J. Andersen (ed.), Highlights of Astronomy, Volume 11A, 49–52.

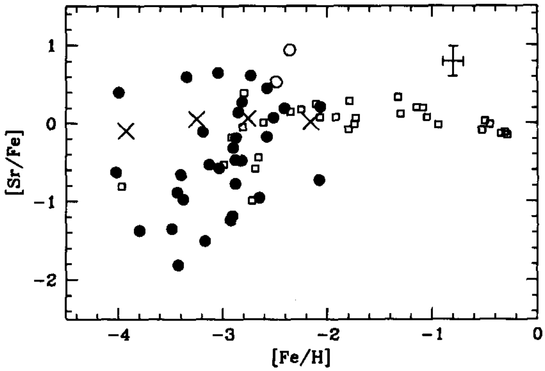

Figure 1. [Sr/Fe] as a function of [Fe/H]. Filled circles from MPSS95, open squares from Gratton & Sneden (1990, 1991). Open circles indicate CH stars, which do not reflect their original composition. Crosses show the mean [Sr/Fe] values for bins 0.5 dex wide in [Fe/H]; note that the average [Sr/Fe] ratio is approximately independent of [Fe/H].

The intrinsic heavy element dispersion cannot be due to AGB nucleosynthesis, such as seen in population I barium stars. The most compelling reason for this is that the heavy elements in these stars exhibit a nearly pure r-process abundance pattern (Figure 2), whereas AGB nucleosynthesis is achieved via the s-process. Also, the frequency of population I barium stars is too low to explain the halo [Sr/Fe] dispersion. The primordial origin of the dispersion is also supported by a similar [Sr/Fe] dispersion found in halo dwarfs (Ryan et al. 1996).

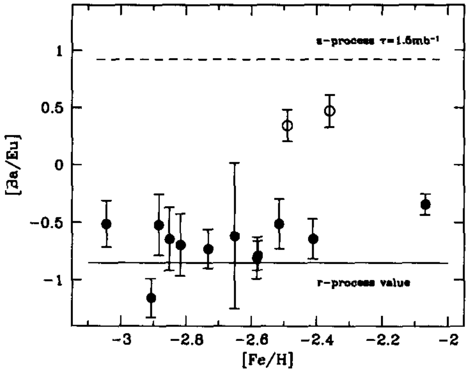

Figure 2. [Ba/Eu] for stars in the MPSS95 sample (McWilliam 1997). Open circles indicate CH stars, which are affected by AGB nucleosynthesis and do not reflect their primordial composition.

The observed 300-fold range in [Sr/Fe] seen in Figure 1 sets the minimum range of Sr/Fe yield ratios from the progenitor SN. The observed dispersion also requires that homogenization processes at these low metallicities were insufficient to mask the abundance patterns from individual SN events. Furthermore, since the largest [heavy element/Fe] ratios are approximately 20 times the asymptotic halo values, the SN producing these large ratios must be correspondingly rare. The dispersion in Figure 1 shows that homogenization did occur by [Fe/H]~ -2.5 dex.

These observations suggests a stochastic model of chemical evolution, in which stars were born from isolated regions. In each region the SN events were drawn from a random sampling of the SN yield function. As the number of SN events increased the composition approached the average value, with complete homogenization when the full range of SN yields was sampled. The stochastic model is supported by a number of observations:

1. The trend of decreasing dispersion in Sr/Fe with increasing [Fe/H].
2. The average [Sr/Fe] ratio is roughly constant; although the number of stars with high Sr/Fe ratio is small.

3. The presence of stars with highly unusual chemical composition: CS 22892-052 with a large excess of heavy elements, CS 22949-037 which is apparently deficient in iron-peak elements by ~ 1 dex, and CS 22897-008 which has an unusually high [Sr/Ba] ratio.
4. The shape of the observed [Sr/Fe] function between [Fe/H]=−2.5 and −3.0 can be matched with a stochastic model (Searle & McWilliam 1997).

For a very simple-minded stochastic chemical evolution model, in which the iron yield is constant for all SN types and mixes with the same mass of ISM, the dispersion in the Sr/Fe number ratio is given by:

$$\sigma_n = \sigma_1/\sqrt{n} \tag{1}$$

Where n is the number of SN events contributing to the composition, and σ_n is the dispersion of the gas after n SN events. Of course σ_1 represents the Sr/Fe yield function from individual SN events, which the observations show is not Gaussian. Equation 1 indicates that if stars near [Fe/H]=−3.5 are composed of material from many SN events then the dispersion in supernova Sr/Fe yield ratios must be even larger than the presently observed values.

The model can be used to estimate the mass of the regions, which formed the stars with [Fe/H] between −4 and −2.5: Because the largest observed heavy-element/Fe ratio is ~20 times the asymptotic value, the frequency of the progenitor SN events can be no more than 1/20 of the total population. Since homogenization is observed to occur near [Fe/H]=−2.5 the full range of SN yields is approximately sampled by this metallicity, which occurs in at least 20 SN events. If each SNII produces ~ 0.1 $M_\odot$ of Fe, then in 20 events 2.0$M_\odot$ of Fe is produced; to dilute this to [Fe/H]=−2.5 requires 10^5–10^6 $M_\odot$ of hydrogen. Curiously, this is similar to the mass of giant molecular clouds seen in the Galaxy today. In this case a single SN event should result in material with [Fe/H]~ −3.8, which is close to the value of [Fe/H]=−4 predicted by Audouze & Silk (1995) from the physics of SN ejecta.

2.2. IRON PEAK ELEMENT ABUNDANCES

For Iron-peak elements MPSS95 found three new trends: a decline in [Cr/Fe] and [Mn/Fe] ratios and an increase in [Co/Fe] below [Fe/H]~ −2.5. This is additional evidence that chemical evolution below [Fe/H]~−2.5 was significantly different from the main population II component, and could be interpreted as evidence of population III or an early population II. Because the iron-peak ratios at low metallicity are not seen at higher metallicity the composition of stars in the MPSS95 sample cannot be due to a dilution of population II composition with pure hydrogen.

The unusual composition shows that SN iron-peak yield ratios must have a range, at least as large as the observations.

A viable chemical evolution model must simultaneously explain the tight correlation of the [Co/Cr] ratios (Figure 3) and the large dispersion in [Sr/Fe] (Figure 1). Three possible explanations are:

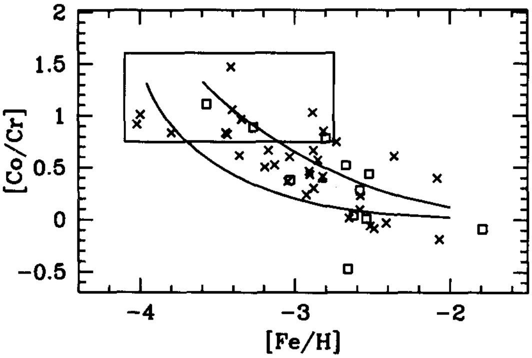

Figure 3. [Co/Cr] versus [Fe/H] from MPSS95. The loci indicate the composition path of material with high [Co/Cr] when diluted with normal iron-peak composition. The box indicates the approximate location of a primordial composition resulting from the first generation of SN.

1. Metallicity-dependent iron-peak yields (MPSS95). As the metallicity increased from [Fe/H]=−4 to −2.5 the Co, Cr, and Mn SNII yields slowly changed. This model requires many generations of SN events, and may be inconsistent with only 20 SNII events required by [Fe/H]= −2.5.
2. SN iron-peak yields are tightly correlated with explosion energy (Ryan et al. 1996). The most energetic SN events, with high [Co/Cr] yield ratios, mix their ejecta with more pure hydrogen than low-energy (low [Co/Cr]) SN events. This naturally leads to a trend of [Co/Cr] with [Fe/H], but suffers from the difficulty imposed by the small observed dispersion in [Fe/H] at a given [Co/Cr]. Figure 3 suggests that the dispersion in mixing of SN ejecta with pure hydrogen is approximately 0.3 dex.
3. The clouds evolved in isolation, with no exchange or addition of new material, and the ejecta of the first generation SN (formed from zero metallicity gas) was characterized by a high [Co/Cr] ratio (Searle & McWilliam 1997). In this model the second generation stars form over a large [Fe/H] range, but with high [Co/Cr] ratios (indicated by a box in Figure 3). Subsequent SN ejecta were characterized by normal [Co/Cr] ratios, and "diluted" the first generation ejecta, as indicated by the loci in Figure 3. The dilution loci form a bottle neck, with a fairly small dispersion in [Fe/H] at [Co/Cr]~0.5 dex.

Note that #3 is consistent with the stochastic model, and small numbers of SN events, used to understand the [Sr/Fe] dispersion. This mechanism is astonishingly similar to the results of Ostriker & Gnedin (1997) who predicted population III in primordial gas clouds with star formation from cooling by H_2 gas, followed by re-ionization and a subsequent cooling for population II. The mass of the star-forming clouds in their model was 10^6–10^7 $M_\odot$, and reached a metallicity of [Fe/H]~−3.7.

3. Summary

- Supernovae element yield ratios show a large dispersion.
- Stars near [Fe/H]=−3.5 may reflect the composition of individual SN events, born in clouds of mass 10^5–10^6 $M_\odot$. If not, then stars with [Fe/H]≤−5 should exist, with a larger [Sr/Fe] dispersion than seen in the most metal-poor stars presently known.
- The chemical composition of stars below [Fe/H]=−2.5 reflects either an early population II or population III, consistent with the population III predictions of Ostriker & Gnedin (1997).
- Improved abundance measurements from superior spectra and an increased sample of extremely metal-poor stars would be useful for testing these ideas.

References

Audouze, J., & Silk, J. 1995, *ApJ*, **451**, L49
Baraffe, I., & Takahashi, K. 1993, *A&A*, **280**, 476
Beers, T.C., Preston, G.W., & Shectman S.A. 1992, *AJ*, **103**, 1987
Gilroy, K.K., Sneden, C., Pilachowski, CA, & Cowan, J.J. 1988, *ApJ*, **327**, 298
Gratton, R.G., & Sneden, C. 1990, *A&A*, **234**, 366
Gratton, R.G., & Sneden, C. 1991, *A&A*, **241**, 501
Gratton, R.G., & Sneden, C. 1994, *A&A*, **287**, 927
Griffin, R., Griffin, R., Gustafsson, B., & Vieira, T. 1982, MNRAS, *198*, **637**
Käppeler, F., Beer, H., & Wisshak, K. 1989. *Rep. Prog. Phys.*, **52**, 945
Lambert, D.L. 1987, *Astron. Astrophys.*, **8**, 103
Mathews, G.J. & Cowan, J.J. 1990, *Nature*, **345**, 491
McWilliam, A., Preston, G.W., Sneden, C., & Searle, L. 1995, *AJ*, **109**, 2736 (MPSS95)
McWilliam, A. 1997, *AJ*, in press
Ostriker, J.P. & Gnedin, N.Y. 1997, *ApJ*, **486**, 581
Pagel, B.E.J. 1968. In *Origin and Distribution of the Elements*, ed. L.H. Ahrens, pp 195–204
Ryan, S.G., Norris, J.E., & Beers, T.C. 1996, *ApJ*, **471**, 254
Ryan, S.G., Norris, J.E., & Bessell, M.S. 1991, *AJ*, **102**, 303
Searle, L. & McWilliam, A. 1997, in progress
Spite, M. & Spite, F. 1978, *A&A*, **67**, 23
Tinsley, B.M. 1979, *ApJ*, **229**, 1046
Truran, J.W. 1981, *A&A*, **97**, 391