A RETROSPECTIVE INTRODUCTION

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"It takes little talent to see clearly what lies under one's nose, a good deal of it to know in which direction to point that organ." W. H. Auden

Listening to the sequence of fine talks that have made up this Joint Discussion, I have been impressed by the veritable flood of new observations that bear on the question of the abundance ratios in the oldest stars. The flood is marked by depth and diversity, as 'noses' are being pointed in highly profitable directions. As an example of depth, I would note the extensive investigations reviewed by Andy McWilliam of the chemical compositions of *very* metal-poor stars where [Fe/H] $\simeq$ -3 marks the upper end of the range defining the class. To characterize diversity, I draw attention to the analyses of quasar absorption line systems so ably discussed by Limin Lu who showed that the abundance ratios for the gas in such high z systems resemble ratios found from Galactic metal-poor stars. Of course, to many at this Joint Discussion the wealth and diversity did not come as a surprise. Indeed, I suspect that many of us pursue the topic of the composition of the first generations of stars because of the wealth and diversity of observational constraints that may now spawn a unified interpretation. Hopefully, the marvellous talks given here will pull in a few new minds - young and old - to ponder nucleosynthesis in very young galaxies and in our Galaxy in particular.

1. Insights into Evolution

"Truth is Catholic, but the search for it is Protestant." W. H. Auden

Comprehensive measurements of abundance ratios are undertaken to provide novel insights into the evolution of stellar systems and stars. I think it fair to say that this is the primary reason why we strive to measure abundance ratios. Several speakers have alluded to applications of abundance ratios. A few examples must suffice to illustrate this well known point.

- **Red giants.** High-resolution spectroscopy, as reviewed by Bob Kraft, of red giants in globular clusters provides evidence of compositional changes attributed to deep mixing beyond the modest levels predicted by the first dredge-up of standard stellar models. Luminosity dependent evolution of the carbon and nitrogen abundance including the $^{12}C/^{13}C$ ratio point to mixing. Changes in sodium and aluminium abundances point to contact between the convective envelope and deep hot regions in which the Ne-Na and Mg-Al H-burning cycles operate.
- **Mass transfer and binaries.** Among very metal-poor stars, there appears to be a rather high frequency, as Tim Beers discussed, of very carbon-rich stars. It is tempting to identify these as members of a binary system in which the initially more massive star evolved to become a carbon AGB star before losing mass at a copious rate. Transfer of mass to the companion produced the now C-rich dwarf star. Is this the complete story for the very metal-poor C-rich stars?
- **Chemical Evolution of Stellar Systems.** Stars by their nucleosynthesis and mass loss exert the controlling influence on the evolution of the chemical composition of a system. If we understand stellar nucleosynthesis theoretically or empirically, we may learn a lot about evolution of a stellar system from a study of abundance ratios. In this context, stellar system ranges from open clusters, globular clusters, to galaxies of all kinds including intra-galactic gas. In the case of our Galaxy and other nearby galaxies, we may use abundance ratios to

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probe evolution of sub-systems in the galaxy: for example, the halo, disk, and bulge. Roger Cayrel discussed the evolution of the halo. Michael Rich reviewed the compositions of stars in our bulge. At the very lowest metallicities, [Fe/H] ≤ -3, evidence of a Population III may turn up – a population of objects that were the first sources of nucleosynthesis after the Big Bang and which seeded the primordial gas before galaxies were formed.

2. Occam's Razor

"It is vain to do with more what can be done with less." William of Occam

This admonition has certainly been accepted by many who have tried to relate abundance ratios to a model of the Galaxy's evolution. In turn, the acceptance has been encouraged by the seemingly simple evolution of the abundance ratios.

For the Galaxy, this evolution is historically portrayed as the evolution of a ratio [X/Fe] versus [Fe/H] where X is an element of interest. When halo and disk stars are combined in such a plot, the resulting relation is generally smoothly varying and exhibits little scatter in [X/H] at a given [Fe/H] over the metallicity range readily explored, say [Fe/H] ≥ -2. This assertion is borne out by, for example, the reviews by Wheeler, Sneden & Truran (1989) and Lambert (1989). Iron is a product of both Type II and Type Ia supernovae. Then, from the evolutionary point of view, a key element to contrast with iron is one produced primarily synthesised by Type II supernovae but not Type Ia supernovae. Oxygen is the ideal example but unfortunately despite a variety of spectroscopic indicators of the oxygen abundance (permitted and forbidden O I lines, and molecular OH ultraviolet and infrared lines) uncertainties continue to becloud the run of [O/Fe] in metal-poor stars. As a substitute, the so-called α-elements - Mg, Si, Ca, and suprisingly Ti - are taken.

The run of [α/Fe] with [Fe/H] is considered constant at about + 0.35 for [Fe/H] ≤ -1 and to decline smoothly for higher metallicities reaching 0.0 at about the solar metallicity (i.e., [Fe/H] = 0). There is, it has been said, little to no 'cosmic' scatter about the mean relation. For example, McWilliam (1997) reviews measurements of [α/Fe] of halo stars and concludes "the full range of measured [α/Fe] ratios is well represented by $+0.37\pm0.08$." This seems to overlook McWilliam et al.'s (1995a,b) results for stars with [Fe/H] $\leq$ -3.5 showing a large scatter in [α/Fe]. Ryan, Norris & Beers (1996) report increased scatter starting at a slightly higher metallicity.

The standard simple interpretation of the run of [α/Fe] with [Fe/H] would delight William of Occam: the ratio in halo stars reflects the composition of processed material from Type II supernovae, and the decline about [Fe/H] = -1 is due to the additional contribution of ejecta from Type Ia supernovae with a much lower α/Fe ratio than the Type II SN. The halo [α/Fe] ratios are in fair agreement with those expected of Type II supernovae originating from metal-poor massive stars (Timmes, Woosley & Weaver 1995).

Exploration of *very* metal-poor stars adds a scatter to the smooth run of [α/Fe] vs [Fe/H] established for [Fe/H] $\geq$ -2 (McWilliam et al. 1995a,b; Ryan et al. 1996). In part, the scatter likely arises because the very metal-poor stars formed out of gas contaminated by ejecta from just one to a few Type II supernovae. In particular, the yield of iron from Type II supernovae is very dependent on the 'mass-cut' between the neutron star and the ejecta. This mass cut may be dependent on individual properties of supernovae while the yield of α-elements is likely less dependent on local properties and certainly on the location of the mass-cut.

A goal in studying the most metal-poor stars is to try and extrapolate stellar compositions to the birth of the Galaxy and so obtain observational constraints on the proto-Galaxy's composition. Was the proto-galactic gas mixed with ejecta from a pre-galactic population of stars, the so-called Population III?

3. A Few Impressions

As an observer of this sequence of talks, I was left with a few striking impressions and questions. A distillation follows:

- **Accuracy of Abundance Data.** Very little was said on this topic! My immediate impression was that this was regrettable but certainly understandable given the pressure of time. One may readily list potential sources of error, especially those pernicious systematic errors- e.g., model atmospheres, non-LTE effects, basic atomic data, stellar parameters. Several sources of error and uncertainty may be reduced with a well designed differential analysis, a point perhaps not adequately made today.

  The key seems to be to convey to the audience a fair impression of the accuracy of abundance data without suppressing mention of potential sources of error. I am reminded at this point of Evan Skillman's (1997) impression that "the confidence in abundances derived from nebular spectra is vastly different between people that work in the field and those that do not, in the sense that people that work in the field hold nebular abundance measurements to be quite reliable while outsiders consider them suspect." "For those of us in the field, there is nothing more interesting than a small bit we don't understand". Skillman avers that outsiders, however, may view the nebular abundances with suspicion because undue emphasis is given by "people in the field" to errors and uncertainities. Amen!

- **Surveys.** This Joint Discussion has beautifully highlighted the need for surveys for candidates to be observed and analysed for their chemical composition. This applies to QSOs as well as to stars. A preeminent example is Tim Beers' search for ultra-metal poor stars which has been responsible - almost solely - for the continuing flow of data on compositions of stars with [Fe/H] $\leq$ -3. Perhaps out of this flow will come evidence for Population III, a pre-galactic or protogalactic generation of 'objects' be they stars of normal masses or super-massive objects. If this generation included stars of normal mass, we should find low mass main sequence objects of pure hydrogen and helium. Of course, super-massive objects will be detected only through their nucleosynthetic consequences for the protogalactic gas and the first generation of normal stars.

  Surveys of larger samples of less extremely metal-poor Galactic stars are likely to bear fruit, especially if the abundance analyses are undertaken with errors controlled and minimized by observations of control samples. Here, the recent work by Nissen & Schuster (1997) comes to mind. In their sample of stars with [Fe/H] between about -0.8 and -1.2, they found a group of stars deficient in [α/Fe] by about 0.1 dex with other anomalies (e.g., [Ni/Fe] about 0.1 dex below the normal value of 0.). These stars appear to share kinematic properties. This example may be an illustration of what awaits us when large samples are analysed to a precision of 0.05 dex or better. If the halo was built up by agglomeration of dwarf galaxies, globular clusters, and even smaller systems, abundance anomalies with respect to the traditional run of [X/Fe] with [Fe/H] are likely. Certainly, variations of [X/H] with age are expected but age estimates are essentially unobtainable for the surviving low mass stars.

- **Globular Clusters.** Chemical compositions of stars in Galactic globular clusters were ably reviewed by Bob Kraft with illustrations aplenty drawn from analyses based on high-resolution spectra acquired with the Keck telescope, as well as 3-4 meter telescopes. As a usually remote observer of the globular cluster scene, I am struck by two questions.
  - First, why do the stars of a given cluster with the glaring exception of ω Cen and the likely exception of M22 have the same metallicity? In well-observed clusters, the upper limit on the range in [Fe/H] is less than 0.1 dex while the cluster to cluster difference is about 1.5 dex at its extreme. Theoretical proposals to account for the mono-metallicity of globular clusters exist - see Brown, Burkert & Truran (1991,

1995) and Murray & Lin (1992). In these scenarios, the present stars are a second generation formed from gass polluted by ejecta from a first generation now lost from the cluster.

* Second, are the abundance anomalies for light elements (C to Al, say) among stars of a given cluster entirely the result of internal nucleosynthesis and mixing within individual stars or were they in part imprinted at the birth of the stars? Bob Kraft discussed this question which is often succintly phrased as 'evolutionary versus primordial' abundance anomalies. When a clear variation of an anomaly (say, the $^{12}C/^{13}C$ ratio) with the luminosity of the red giant is observed, it is plausible to attribute the anomaly to deep mixing by a giant's convective envelope. On the other hand, when abundance anomalies are seen on the subgiant branch or close to the main sequence (see, for example, Briley et al. 1996) , the more plausible explanation is surely that the gas from which stars formed was not chemically homogeneous. (And we should not forget the potential role of binary stars and mass transfer between the stars.)

In thinking about these questions, I am struck by the almost complete lack of field halo stars with anomalies like those seen among cluster stars. This to me is a pointer to a primordial ('environmental') contribution to these anomalies. Surely, gas enriched to the observed metallicity of a cluster by a now extinct population of stars may contain chemical inhomogeneities. The observed anomalies are indicative of H-burning by the CNO, Ne-Na, and Mg-Al cycles. It is an interesting question if the ejecta from stars formed of truly pristine gas, pure H and He with a dab of Li, can contain these anomalies when the star had no C,N, O etc. If not and if there is an enviromental component to the abundance anomalies, it would seem that either the present stars are third generation not second generation, as the above-referenced theories on cluster formation imply, or the gas was not pristine but was contaminated with C, N O etc. Alternatively, the abundance anomalies of main sequence stars may result from accretion of the ejecta of more massive second generation stars.

- **Mass Cut between Massive and Intermediate Mass Stars.** Massive stars die as Type II supernovae. Intermediate (and low) mass stars evolve to become asymptotic giant branch stars and die by shedding their outer envelope to leave the stelar core as a white dwarf. Elements beyond the iron-peak are synthesised by these stars: r-process nuclides in Type II supernovae (probably) and s-process nuclides in AGB stars. The mass cut is presently put at 8-10$M_\odot$ based on observations of white dwarfs in open clusters. To my knowledge there is no quantitative understanding of the mass cut.

  Mass loss is likely a determining factor. Since mass loss rates driven by radiation pressure on dust grains or gas are metallicity dependent, one may wonder if the mass cut is metallicity dependent too. If it is, the production ratio of r/s nuclides will vary with metallicity. Is this an observable effect by careful characterization of appropriate [X/Fe] vs [Fe/H] relations? Such an exercise must recognise that the character of the s-process itself evolves with [Fe/H]: the total exposure to neutrons increases with decreasing metallicity. In this connection, it would be useful to test the oft made assumption that the r-process provides a solar distribution of r-process nuclides irrespective of the metallicity of the supernova.

- **Unification!** 'Unification' in astronomical parlance is usually applied to Seyfert galaxies, AGNs and assorted other odd things. Here, I appropriate the word to recall the resemblance between the abundance ratios of the oldest Galactic stars and of the absorption line systems revealed by the high-z QSOs. To first-order the resemblance is no surprise; nucleosynthesis by Type II supernovae is a universal phenomenon! By using red-shift and a cosmological model, it is possible now to plot abundances against a clock: [X/H] versus time is surely more informative than [X/Fe] versus [Fe/H]. Of course, the gaseous disks (presumably) that are sampled by QSO lines of sight belong to a family of galaxies unlike the stars in our Galaxy that *now* at least belong to a single galaxy. The sampling of a galaxy population is likely to compromise the simplicity of abundance versus clock plots. Particularly valuable information will be provided if the galaxy responsible for an absorption line system can be identified by deep imaging.

4. An Introductory Retrospection

The name of the English poet and man of letters, W. H. Auden, has appeared above. I was introduced to his works by an imaginative master at the grammar school who was faced with an unhappy group of senior schoolboys specialising in science but required by the edict of the headmaster to take 1 hour of English a week. Oh how we grumbled at the time! But that hour a week has led to many happy hours of reading in the subsequent 40 years.

A memory of the school classroom came back recently when I read an account of a visit by W. H. Auden to Dartmouth College. The then elderly Auden was entertained before delivering an address. "When he arrived at the auditorium where he was to deliver a paper on Romanticism, he tripped over the top step while mounting to the stage and his typescript spilled across the platform. Putting the pages back in correct order was of course beyond him. So, with his Oxford aplomb, he pulled them together out of order and read whatever page came to the surface. The audience thought the essay had many fine insights but was a bit lacking in structure, though charming." (Hart, 1997)

There is a sense in which we are following in Auden's faltering footsteps. Abundance ratios of the oldest stars provide us with a chemical history of the Galaxy. The pages of the history book are not ordered by metallicity. Nonetheless, we have provided 'fine insights' into the Galaxy's early evolution. In the case of the QSO absorption line systems, we may feel that the pages are numbered by z but we may doubt that they have come from a single book rather than a library of volumes.

Present activities as highlighted in this Joint Discussion augur well for the future. Contemporary ideas about the early evolution of galaxies may be vindicated as the abundance analyses of stars and gas, near and far, are extended in depth and breadth. Perhaps, as history shows, present ideas will prove to be off the mark. But let's leave the last word to W. H. Auden:

His boneless worm-like ancestors would be amazed
At the upright position, the breasts, the four-chambered heart,
The clandestine evolution in the mother's shadow.

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