ABUNDANCE CLUES TO EARLY GALACTIC CHEMICAL EVOLUTION

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ABSTRACT. High S/N spectroscopic studies of the abundance patterns characterizing extremely metal-deficient halo field stars and globular cluster stars have served to provide significant clues to and increasingly stringent boundary conditions upon the chemical evolution of the halo population of our galaxy. Guided by our current knowledge of nucleosynthesis as a function of stellar mass occurring in stars and supernovae, we identify some interesting constraints that these combined observational and theoretical considerations impose upon theories of the early history of our galaxy.

1. INTRODUCTION

Abundance determinations from analyses of stellar spectra have, historically, played a critical and defining role in the development of nucleosynthesis theory. The early recognition of the fact that there exist halo stars in our galaxy with metal contents less than one hundredth that of solar system matter provided support for the view that heavy element synthesis has occurred predominantly in galactic sources. The detection of technetium (an element having no stable isotopes) in the atmospheres of red giant stars (Merrill 1952) further confirmed that nucleosynthesis mechanisms are indeed operating in stars, triggering an epoch of theoretical activity in stellar and supernova nucleosynthesis that has persisted over more than a quarter century. Recent observational studies utilizing high S/N spectroscopy are continuing in this tradition. Some observational and theoretical considerations relevant to the interpretation of the anomalous abundance patterns characterizing certain classes of peculiar red giants, carbon stars, barium stars and R Corona Borealis stars have been reviewed in the paper by D. Lambert in these proceedings. In this paper, we will concentrate on the anomalous abundance patterns observed in metal deficient field halo stars and globular cluster stars and examine their implications for

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models of stellar and supernova nucleosynthesis and galactic chemical evolution.

2. FIELD HALO STARS AND EARLY GALACTIC EVOLUTION

One area in which high S/N spectroscopic studies have yielded significant returns is that involving the abundances observed in extreme halo population stars and their implications for the early chemical and dynamical evolution of the Galaxy. We will briefly review both the predictions of nucleosynthesis theory and the existing observational data regarding extremely metal deficient stars and show how these serve to constrain modeling of stellar activity during the halo collapse phase (see also Truran 1983; Truran and Thielemann 1986; Truran 1987).

2.1 Nucleosynthesis Expectations

Nucleosynthesis predictions are now available for both the stable phases of stellar evolution and the matter ejected in supernova events (Truran 1984; Woosley 1987). For the purposes of this discussion, we confine our attention to the following interesting elements or classes of nucleosynthesis products: carbon, nitrogen, oxygen, the elements from neon to calcium, the iron-group nuclei, the _s_-process heavy elements, and the _r_-process heavy elements. We also identify the interesting ranges of stellar mass with which specific nucleosynthesis products are found to be associated: (1) the mass range $M \geq 10\ M_{\odot}$ of the massive star progenitors of Type II supernovae; (2) the mass range $1 \leq M \leq 10\ M_{\odot}$ of intermediate mass stars for which significant nucleosynthesis occurs during the asymptotic giant branch phase of evolution; and (3) Type I supernovae, which are believed to result from the evolution of intermediate mass stars in binary systems. We note a crucial distinction in the production timescales for these nucleosynthesis sources as defined by their corresponding stellar lifetimes: intermediate mass stars evolve on timescales $\tau \geq 10^8$ - 10^9 years, while massive stars $M \geq 10\ M_{\odot}$ evolve on timescales $\tau \leq 10^8$ years compatible with a halo collapse timescale.

Massive stars and associated Type II supernovae are known generally to synthesize nuclei from carbon to nickel (Woosley 1987). Detailed model predictions indicate, however, that carbon and the iron group elements are underproduced in such events relative to oxygen and the neon-to-calcium elements. This characteristic signature of nucleosynthesis in massive stars, as we shall see, is presumably reflected in the abundance patterns observed in metal deficient stars: [O/Fe] ≈ + 0.5 and [Mg,Si,Ca/Fe] ≈ + 0.5. We also assume that these massive stars provide the site of formation of the _r_-process heavy nuclei, this being associated perhaps with the ejection of highly neutronized matter from the vicinity of the mass cut in supernovae which leave neutron star remnants (Truran 1984; Hillebrandt 1978; Truran, Cowan and Cameron 1985).

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Intermediate mass stars provide important contributions to heavy element abundances in the galaxy particularly as a consequence of the occurrence of thermal pulses in their helium burning shells on the asymptotic giant branch. Estimates of nucleosynthesis yields from asymptotic giant branch stars (Iben and Truran 1978; Renzini and Voli 1981) specifically suggest that significant production of carbon, nitrogen, and the s-process elements, in solar proportions, can be achieved in this environment. The longer timescales of evolution of intermediate mass stars suggest that their nucleosynthesis yields will begin to influence the interstellar gas abundances only relatively late in the halo collapse phase.

Type I supernovae are believed to be the major contributors to the abundances of the iron group nuclei in our galaxy. Calculations of explosive nucleosynthesis associated with carbon deflagration models of Type I supernovae (Thielemann, Nomoto, and Yokoi 1986) arising from binary evolution predict that sufficient iron-peak nuclei are formed to explain both the powering of the light curves of Type I supernovae by the decay of ^{56}Ni and ^{56}Co and the observed mass fraction of iron in galactic matter. The production timescale is expected to be compatible with the lifetimes of the intermediate mass stars which characterize these binary systems.

2.2 Composition Trends in Field Halo Stars

Existing observations of the abundances in the most metal deficient field halo stars have recently been reviewed by Spite and Spite (1985). Interesting trends from the point of view of nucleosynthesis may be briefly summarized as follows. For CNO nuclei, both [C/Fe] and [N/Fe] are found (Laird 1985) to be approximately constant and compatible with solar for a sample of disk and halo stars which span a range in [Fe/H] from -2.45 to +0.5. In contrast, high oxygen to iron ratios [O/Fe] ≈ + 0.5 are found to characterize the halo stars. Similar trends are evident for the intermediate mass elements Mg, Si, and Ca, which are found to be enriched relative to Fe by approximately 0.5 dex (Luck and Bond 1985; Gratton and Sneden 1987).

Further interesting trends have been identified in the heavy element region. The data clearly establishes the existence of deple-tions in the abundances of the designated s-process elements Sr and Ba, relative to iron, in stars of low Fe/H (Spite and Spite 1978; Luck and Bond 1985; Gratton and Sneden 1987). In point of fact, both theory (Truran 1981) and observation (Sneden and Pilachowski 1985) now seem strongly to suggest that these heavy element abundance patterns charac-teristic of extreme metal deficient stars are dominated by r-process contributions. On the theoretical side, it is recognized that it is a natural consequence of r-process synthesis that the resulting ratios Ba/Sr, Sr/Er and Ba/Er should deviate from those of solar system matter, in a manner compatible with those observed for metal deficient stars. The heavy element abundance pattern for the extremely metal deficient star HD 110184, determined from the high S/N spectroscopic analysis of Sneden and Pilachowski (1985), indeed strongly suggests that the r-process contribution dominates in this object. This is again compatible with our assumption that massive stars represent a site of r-process nucleosynthesis.

We note finally that the data also give evidence for the presence of a mild odd-even effect involving the products of explosive nucleosynthesis: specifically, elements containing odd numbers of protons (e.g. Na, Al, and Sc) seem perhaps to show somewhat greater relative deficiencies than neighboring even-Z nuclei in extremely metal deficient stars (Luck and Bond 1985; François 1986a,b; Gratton and Sneden 1987). Such an odd-even effect in Z has indeed been predicted by calculations of explosive nucleosynthesis (Truran and Arnett 1971) for stars of low metallicity. Unfortunately, the uncertainties in the data are such that a definite trend is not unambiguously established.

2.3 Discussion

The trends in elemental abundance patterns in the extreme halo population stars in our galaxy are thus seen to be quite consistent with the predictions of nucleosynthesis theory for the ejecta of normal stars of masses $\geq 10\ M_\odot$ and associated Type II supernovae. These massive stars, of lifetimes $\leq 10^8$ years compatible with a halo collapse timescale, are the major galactic sources of oxygen, the elements from neon to calcium and the r-process heavy elements, while carbon, nitrogen, the iron peak nuclei, and the s-process heavy elements are produced in stars of lower masses and longer lifetimes. The "anomalous" abundance features characterizing extremely metal deficient stars (e.g. the high O/Fe, Mg/Fe, Si/Fe, and Ca/Fe ratios and the strikingly r-process-like heavy element abundance pattern) may thus be understood in a straightforward manner. One cannot strictly rule out contributions to the abundances of the most extreme metal deficient halo stars from such more exotic sources as supermassive stars or a Population III, but neither is there any compelling evidence to suggest that such sources may have contributed significantly.

3. GLOBULAR CLUSTER STARS

Observational studies utilizing high S/N spectroscopy now indicate that globular cluster stars exhibit abundance patterns similar to those of the extreme metal deficient field halo stars (Pilachowski, Sneden, and Wallerstein 1983; Gratton, Quarta, and Ortolani 1987). Significant observed trends include the following: (1) intermediate mass elements such as magnesium, silicon, calcium, and titanium are typically enriched relatively to iron by up to approximately 0.5 dex for clusters with values of [Fe/H] ranging from -2.2 to -0.9; (2) high O/Fe ratios are encountered in a substantial fraction of the observed clusters; and (3) the heavy element (A > 60) abundance patterns in globular cluster stars reveal anomalies in the ratios of Zr, Ba, and La to Fe similar to trends observed in the metal deficient field halo stars and again seem suggestive, in this writer's view, of an r-process origin. The situation with respect to the light odd-Z elements Na, Al, Sc and V can be quite complicated (François, Spite, and Spite 1987), but the evidence seems to suggest that these elements are relatively more abundant in the globular cluster stars than in the field stars.

The similarities in the abundance patterns characterizing globular cluster stars and extreme halo population field stars are strongly suggestive of a similar, if not common, nucleosynthesis origin. Their abundance distributions in both instances are quite consistent with the contamination of the gas from which they were formed by the ejecta of normal stars of masses $\geq 10\ M_\odot$, and associated Type II supernovae, on a timescale $\leq 10^8$-10^9 years. The question remains as to how this was accomplished. Possible explanations for these observed patterns include: (1) the primordial compositions of the gas from which both the globular cluster stars and the extreme metal deficient field halo stars formed reflect the contamination from a common earlier and elusive (Bond 1981) population III; (2) the first stellar generation was selectively polluted by massive stars and Type II supernovae formed first at the centers of massive collapsing clouds (Cayrel 1986); and (3) the globular cluster and extreme halo population stars were entirely *independently* contaminated by the ejecta of massive stars and Type II supernovae.

In this regard, the interesting question arises as to whether a self-enrichment model is possible for and appropriate to globular clusters. The physical conditions which are believed to have characterized the protogalactic gas (Fall and Rees 1985, 1988) imply a Jean's mass of the order of $10^6\ M_\odot$ consistent with expectations for protoglobular clusters. Cayrel (1986) argues that it is quite natural to expect star formation early in the history of the galaxy to have occurred in such objects. Could some of these clouds have survived to evolve to the globular clusters we observe today? Here again, perhaps, high S/N spectroscopic studies can provide critical input.

Specifically, an interesting possible test of whether a self-enrichment model is appropriate to globular clusters might be provided by a careful study of the abundance patterns in the most metal-rich clusters of $Z > 0.1\ Z_\odot$. Field stars of such metallicity exhibit patterns of abundances relative to iron which are consistent with those of solar system matter, since the nucleosynthesis contributions from the intermediate mass stars of relatively longer lifetimes have by this time enriched the interstellar medium in carbon, nitrogen, s-process elements, and iron-peak nuclei. Self-enrichment of a globular cluster must necessarily be realized on a much shorter timescale, hence the abundance patterns of stars in even the most metal-rich clusters should reflect only the contributions from the more massive stars.

If self-enrichment indeed occurred for the globular clusters, one might then expect even the metal-rich clusters to exhibit, to some degree, both the high O/Fe, Mg/Fe, Si/Fe, and Ca/Fe ratios and the r-process heavy element abundance pattern which are found to characterize the most metal-deficient field halo stars.

4. CONCLUDING REMARKS

My purpose in this paper has been to illustrate the manner in which increasingly sensitive spectroscopic studies can impact on one active and exciting area of astrophysical research. The abundance data thus obtained for both the extreme metal-deficient halo population stars and the stars in globular clusters is providing critical constraints on the nature of the stellar and supernova activity and associated nucleosynthesis contributions during the earliest phases of evolution of our galaxy. This allows at least a consistent model for the contamination of the gas in heavy nucleosynthesis products on a halo collapse (dynamical) timescale. We can anticipate that further detailed studies of this nature of the compositions of globular cluster stars, halo stars, and early disk population stars will provide important clues to the solutions of some of the many challenging problems which remain.

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DISCUSSION

M. SPITE May I remark that aluminum becomes underdeficient relative to iron as soon as the resonance aluminum lines are used to determine this abundance.

MAGAIN If one accepts that the resonance lines give a wrong abundance, one has to invoke non-LTE effects (or so). If non-LTE play a role, I have shown yesterday that they may also affect excited lines, and that nothing might be left of the odd-even effect. Maybe one should not invoke non-LTE effects only in the cases when observation disagrees with theory...