CHEMICAL EVOLUTION OF GALAXIES: ABUNDANCE TRENDS AND IMPLICATIONS

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ABSTRACT. Recent spectroscopic studies of the elemental abundance patterns associated with extremely metal deficient field halo stars and globular cluster stars are briefly reviewed. These metal deficient stellar populations have been found to be characterized by abundance patterns which differ quite distinctly from those of solar system abundances, but are consistent with the view that they reflect primarily the nucleosynthesis products of the evolution of massive stars and associated Type II supernovae. Guided by our current knowledge of nucleosynthesis as a function of stellar mass occurring in stars and supernovae, we identify some interesting constraints upon theories of the formation and early history of our Galaxy.

1. INTRODUCTION

Studies of galactic chemical evolution seek to explain the chemical compositions of the stellar and gaseous components of galaxies as a function of time. Critical theoretical input to such studies includes knowledge of: (1) the star formation rate (SFR) as a function of time; (2) the initial mass function (IMF), which can also in principle be time dependent; and (3) the composition of the matter returned to the interstellar medium from stars and supernovae as a function of stellar mass (and corresponding lifetime) and primordial composition. Observational constraints are provided by studies of the elemental and isotopic compositions both of our sun and other stars and of the gas and cosmic ray components of our Galaxy. Viewed in the context of models of stellar and supernova nucleosynthesis, this observational data can be used to guide and to constrain such models and to help us to identify the correct nucleosynthesis sites.

In this paper, we will be concerned with interesting abundance trends observed as a function of total metallicity [Fe/H]. We will review some anomalous abundance patterns observed in both metal deficient field halo stars and globular cluster stars, and then briefly examine some possible implications for nucleosynthesis and

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early galactic evolution.

2. 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 and Weaver 1986). For the purposes of the present discussion, we will confine our attention to several 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 phase of evolution; and (3) Type I supernovae, which are believed to be a consequence of the evolution of intermediate mass stars in binary systems. It is important to recognize the distinctly different production timescales for these sites of nucleosynthesis, as defined by their corresponding stellar evolutionary 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 $\tau < 10^8$ years, compatible with a halo collapse timescale.

Massive stars and associated Type II supernovae are known generally to synthesize nuclei from carbon to nickel. Detailed model predictions reveal, however, that carbon and the iron group elements are systematically underproduced in such events relative to oxygen and the neon-to-calcium elements (Hashimoto et al. 1989; Thielemann et al. 1990). This characteristic signature of nucleosynthesis in massive stars, as we shall see, is presumably reflected in the abundance patterns observed in metal deficient stars: $[O/Fe] \approx +0.5$ and $[Ne\text{-}Ca/Fe] \approx +0.5$. Nucleosynthesis studies (Truran and Arnett 1971) also indicate that reduced relative concentrations of odd-Z nuclei can be characteristic of explosive nucleosynthesis in stars of low metallicity, and this can also be reflected in abundances in metal deficient stars. Finally, it now also seems most likely that these massive stars represent the site of production of the r-process heavy elements (Truran 1981; Sneden and Pilachowski 1985). This identification, as we shall see, is strongly suggested by recent spectroscopic studies which reveal that the heavy-element abundance patterns in extreme metal-deficient stars have a distinctly r-process character. This conclusion also has important implications for nucleocosmochronology, since the interesting long lived nuclear chronometers ^{232}Th, ^{235}U, ^{238}U, and ^{244}Pu are believed to be formed in the r-process (Cowan et al. 1991a,b).

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) indicate that significant production of carbon, nitrogen, and the s-process heavy elements, in solar proportions, can be achieved in this environment. These nucleosynthesis products are then introduced into the interstellar medium (ISM) as a result of red-giant phase mass loss or planetary nebula ejection (Iben and

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Renzini 1984). The longer timescales of evolution of intermediate mass stars suggest that their nucleosynthesis products will begin to influence the interstellar gas abundances (from which subsequent generations of stars will be formed) only relatively late in the halo collapse phase. The dependence of the mechanism of s-process synthesis on the presence of primordial concentrations of seed iron-peak nuclei, on which neutron captures can proceed, suggests that the buildup of their abundance in the ISM will be somewhat further delayed. Since the abundances of the lighter s-process nuclei, through the abundance peak at strontium at mass number $A \sim 90$, can also be formed in the helium burning cores of massive stars, we might anticipate that the abundances of these isotopes can increase faster than those in the vicinity of the barium peak at mass number $A \sim 140$.

Type Ia supernovae are believed to be the dominant contributors to the abundances of the iron group nuclei in our Galaxy. The currently preferred model for such outbursts involves the growth of a white dwarf to the Chandrasekhar limiting mass as a consequence of accretion in a close binary system. Calculations of explosive nucleosynthesis associated with carbon deflagration models of Type Ia supernovae (Thielemann, Nomoto, and Yokoi 1986) predict that sufficient iron-peak nuclei are formed to explain both the powering of the light curves due to the decays of ^{56}Ni and ^{56}Co and the observed mass fraction of iron in galactic matter. The production timescale is expected to be comparable to the lifetimes of the intermediate mass stars which characterize these binary systems. It follows that this input of iron-peak nuclei into the ISM will be delayed relative to the input of the nucleosynthesis products of massive stars and Type II supernovae.

The nucleosynthesis expectations which follow from these considerations are clear: the earliest contamination of the ISM will involve the processed ejecta of massive stars ($M > 10\ M_\odot$), and will thus be characterized by high concentrations, relative to iron, of oxygen and the intermediate mass elements from neon to calcium, as well as by a heavy element abundance pattern that is consistent with r-process synthesis. These "anomalous" abundance patterns should therefore be expected to be reflected in the spectra of the most metal-deficient stars in our Galaxy.

3. COMPOSITION TRENDS IN FIELD HALO STARS

Existing observations of the abundances in the most extremely metal deficient field halo stars, recently reviewed by Spite and Spite (1985) and Wheeler, Sneden, and Truran (1989), reveal a number of interesting trends. High oxygen to iron ratios $[O/Fe] \approx +0.5$ are generally found to characterize the halo stars. Similar trends are evident for the intermediate mass elements Mg, Si, Ca, and Ti, which are again found to be enriched relative to iron by approximately 0.5 dex (Luck and Bond 1985; Gratton and Sneden 1987, 1990). In contrast, the abundances of both carbon and nitrogen, relative to iron, are compatible with solar abundances (Laird 1985). The data also give evidence for the presence of a mild odd-even effect involving the products of explosive nucleosynthesis: elements

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containing odd numbers of protons seem to show somewhat greater relative deficiencies than neighboring even-Z nuclei in extremely metal deficient stars.

In the heavy element region, the data now clearly establishes the existence of depletions 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). The theoretical interpretation of these trends as due to the fact that the heavy element abundance patterns characteristic of extreme metal deficient stars are dominated by r-process contributions (Truran 1981) has now been strongly confirmed by observations (Sneden and Pilachowski 1985; Gilroy et al 1988).

Collectively, these abundance patterns in metal deficient stars are therefore quite in agreement with those expected to be characteristic of the ejecta of massive stars (Truran 1983, 1987). It seems logical that this be so, since massive stars $M \gtrsim 10\ M_\odot$ of short lifetime $\tau \lesssim 10^8$ years can be expected to be the major source of nucleosynthesis on a timescale compatible with a halo collapse timescale.

4. COMPOSITION TRENDS IN GLOBULAR CLUSTERS

Similar elemental abundance trends are evident in the abundance patterns determined for globular cluster stars (Pilachowski, Sneden, and Wallerstein 1983; Gratton, Quarta, and Ortolani 1987; Gratton and Sneden 1990; Leep, Oke, and Wallerstein 1987; Wallerstein, Leep, and Oke 1987; Peterson, Kurucz, and Carney 1990). We note particularly the following features. Intermediate mass nuclei such as magnesium, silicon, calcium, and titanium (the "alpha" nuclei) are typically enriched, relative to iron, by up to approximately 0.5 dex, for clusters with values of [Fe/H] ranging from -2.52 to -0.81. Such relative enrichments are not, however, characteristic of other iron-peak nuclei like chromium and nickel. High O/Fe ratios are also encountered in some globular clusters, although there generally remain serious questions concerning the oxygen abundances in these systems. Finally, the heavy element ($A > 60$) abundance patterns in globular cluster stars (see Table 1) reveal anomalies in the ratios Zr/Fe, Ba/Fe, and Eu/Fe similar to trends observed in extreme metal deficient field halo stars, which have been determined to be r-process in nature. In particular, the systematically high values obtained for [La/Zr] for cluster stars, with a mean value +0.32, again seem suggestive of an r-process origin (Truran 1988). The fact that all of the heavy elements Zr, Ba, and Eu are systematically depleted relative to Fe for the studied cases is consistent, as well, with the suggestion of Mathews and Cowan (1990) that the r-process associated with massive stars $M > 10\ M_\odot$ which forms the heavy element pattern in the halo stars, preferentially operates in stars in the mass range $10 \lesssim M \lesssim 20\ M_\odot$.

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TABLE 1. Globular Cluster Abundances: The Heavy Elements

CLUSTER	REF.	[Fe/H]	[Zr/Fe]	[Ba/Fe]	[Eu/Fe]	[La/Zr]
M71	2	-0.81		-.16		
NGC 362	1	-0.87		-.30		+.60
NGC 3201	1	-0.95	-.62	-.55	-.45	+.38
47 Tuc	1	-1.09	-.17	-.34	-.32	+.26
47 Tuc	2	-0.82		-.17		
M4	3	-1.20	-.20			
M4	2	-1.32		+.05		
M5	1	-1.09	-.36	-.30	-.25	+.26
M5	2	-1.42		-.32		
NGC 6752	1	-1.26	-.30	-.21	-.48	+.31
NGC 6752	2	-1.53		-.06		
NGC 4833	1	-1.34	-.06	-.23	-.19	+.13

Ref: (1) Pilachowski, Sneden, and Wallerstein (1983); (2) Gratton, Quarta, and Ortolani (1987); (3) Wallerstein, Leep, and Oke (1987).

DISCUSSION

The combined observational and theoretical results described in the previous sections allow a number of useful conclusions to be drawn regarding the earliest phases of galactic evolution.

The [O/Fe] ≈ +0.5 and [Ne-Ca/Fe] ≈ +0.5 trends and r-process heavy element abundance patterns observed in extreme metal deficient stars are unambiguous signatures of their massive star ($M > 10\ M_\odot$) progenitors. That these trends persist through [Fe/H] = -1, comparable to the abundances of the oldest disk stars, implies that this abundance level is achieved prior to the entry of the products of intermediate mass stars ($M \sim 1\text{-}10\ M_\odot$) of longer lifetimes ($\tau > 10^8\text{-}10^9$ years) into the gas. If it is further assumed that the IMF was not significantly different at that epoch, it must follow that this abundance behavior implies a very rapid collapse of the galactic halo.

The similarities we have identified 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 seem clearly to reflect the fact that the gas from which they were formed had been contaminated primarily by the ejecta of normal stars of masses $> 10\ M_\odot$, and associated Type II supernovae. Such can readily occur on a timescale $< 10^8\text{-}10^9$ years, compatible with a halo collapse timescale. There are, however, several manners in which this might be accomplished: (1) The primordial

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concentrations in the gas from which both the metal deficient field halo stars and the globular cluster stars formed reflect the contamination from a common earlier stellar population (Population III: Bond 1981). (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; Fall and Rees 1985). Presumably, the present day globular clusters (the spheroidal component) may represent the surviving clusters from this era. Note here again that the massive star $M > 10\ M_\odot$ sites of nucleosynthesis are compatible with cluster formation and self-enrichment on timescales $\lesssim 10^7$ years. Models for such self-enrichment have recently been discussed by Brown, Burkert, and Truran (1990a,b).

The firm identification of the site of the r-process with massive stars allows one better to define the production history of the important nuclear chronometers ^{232}Th, ^{235}U, ^{238}U, and ^{244}Pu. Scrutiny of the heavy element ($A > 60$) abundance patterns can potentially allow even tighter constraints to be imposed on the star formation and nucleosynthesis history of the early galaxy. Mathews and Cowan (1990) and Mathews et al (1990), for example, interpret the trends in the growth of the europium - a rise relative to iron at $[Fe/H] \approx -2.5$ - as evidence for the fact that lower mass Type II supernovae represent the most likely r-process site.

The identification of the globular clusters with halo evolution (structure, metallicity, and timescale), together with our conclusion that the halo collapse occurred on a rapid timescale, would seem to suggest a relatively narrow spread in ages for the spheroidal component of our Galaxy's globular clusters. This appears to be inconsistent with the conclusion of VandenBerg et al (1990) that the more metal-rich globular clusters show a significant spread in age, of order 3-4 Gyr. Future investigations of the detailed abundance patterns in globular cluster stars will hopefully be able to guide us to an understanding of this problem.

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