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Research Note

A New Interpretation of the Heavy Element Abundances in Metal-deficient Stars

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Summary. Observations of element abundances in extremely metal-deficient stars are reviewed. Particular attention is given to trends in the abundances of the neutron capture products yttrium, barium, and europium. The variations in [Y/Fe] and [Ba/Fe] with [Fe/H] are found to defy simple explanation in the context of current theories: the conventional interpretation of these abundances as resulting from *s*-processing may be incorrect. We suggest, rather, that the observed trends follow in a natural and straightforward manner from the assumption that the Y and Ba in the most extreme metal-poor stars represent products of *r*-process nucleosynthesis. Implications for galactic evolution and nucleosynthesis are briefly discussed.

Key words: abundances, stellar – nucleosynthesis – galactic evolution

I. Introduction

Studies of element abundances in the oldest and most metal-deficient stars in our galaxy are extremely important. They serve as tests of nucleosynthesis theories and of models of chemical evolution, and can provide critical inferences concerning timescales for halo evolution and possible variations in the initial mass function with stellar population. The role of secondary elements is of particular interest in this regard: their dependence upon the concentrations of elements formed in prior generations of stars implies more pronounced variations of their abundances with time over galactic history. Furthermore, their very existence in unevolved stars of low total metal content demands that at least two prior generations of stars have contributed to nucleosynthesis. The most recent and complete discussion of many of these questions known to this writer is that due to Tinsley (1979).

Existing abundance determinations for nuclei from carbon to iron in extreme metal-deficient stars are largely compatible with the view that they are formed, in relative amounts consistent with solar system abundances, as a result of explosive charged-particle nucleosynthesis. Supernovae involving more massive stars provide the expected astrophysical setting. The trends in carbon and oxygen abundances reviewed by Tinsley (1979) are consistent with this picture. Observed excesses in [O/Fe] for halo stars are understandable in the context of published studies of the nucleosynthesis yields from massive stars (Arnett, 1978). Data on nitrogen are not available for the most metal-poor stars, [Fe/H] <-2, and therefore trends are not clearly established. Mild relative depletions of the odd-*Z* elements lighter than iron may be anticipated (Truran and Arnett, 1971).

Observed trends in the abundances of designated *s*-process nuclei are viewed by Tinsley (1979) as inconsistent with conventional theories. This question will be addressed in Sect. II. It is proposed that the heavy element abundance patterns observed in the most metal-deficient stars are attributable to the *r*-process. Implications for galactic evolution and nucleosynthesis are considered in Sect. III. Our conclusions follow.

II. Interpretation of Heavy Element Abundances

The fact that there exist real and systematic depletions in the abundances of *s*-process elements relative to iron in stars of low [Fe/H] was emphasized by Pagel (1968). Discussions of this problem have since been presented by a number of researchers (Peterson, 1976; Truran and Iben, 1977; Spite and Spite, 1978; Tinsley, 1979). Through the years, information concerning the abundances of the *s*-process elements has accumulated for a slowly increasing number of extremely metal-deficient stars. The data currently known to this writer are summarized in Table 1. The depletions of the *s*-process elements Sr, Y, Zr, Ba, La, and Ce relative to iron in stars of low [Fe/H] are apparent. For comparison, the abundance patterns in two CH stars, HD 26 and HD 201626, are also shown. These stars are often viewed as Population II counterparts of the Ba II stars; the observed enrichments of the *s*-process elements relative to iron are interpreted as evidence for *in situ* *s*-process nucleosynthesis.

The very presence of *s*-process nuclei in the oldest, most metal-deficient stars would hold important implications for galactic evolution. The most straightforward interpretation would be that these represent *at least* third generation objects: first generation (pure hydrogen and helium) stars formed the elements carbon-to-iron by charged particle reaction mechanisms, while second generation processing yielded *s*-process elements which in turn were incorporated into the presently observed metal-poor stars. Even so, the production of these heavy *s*-process elements on a very rapid timescale – compatible with the dynamic timescale of the galactic halo – seems essential. Truran and Iben (1977; see also Truran, 1980) pointed out that the detailed characters of the *s*-process abundance patterns in the most extreme metal-deficient stars, showing depletions in barium relative to strontium-yttrium-zirconium, are consistent with their having been produced during core helium burning in massive stars (Lamb et al., 1977). The shorter lifetimes of these more massive stars make this an attractive alternative.

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Table 1. Observed abundance patterns

Star	Ref.	[Fe/H]	[Sr/Fe]	[Y/Fe]	[Zr/Fe]	[Ba/Fe]	[La/Fe]	[Ce/Fe]	[Eu/Fe]
ζ^1 Ret	a	−0.37	−0.25	−0.29	−0.23				
TW Cap	b	−0.72	−1.08	−0.88	−1.18	−0.38		−0.48	
W Vir	c	−1.03	−0.77	−1.27	−1.27	−0.87		−0.87	
HD 161817	d	−1.11	+0.24	−0.19	−0.14	−0.05			
HD 86989	e	−1.24	−0.42	−0.76	−0.14	−0.56			
HD 94028	f	−1.28		−0.10		+0.0			
HD 109995	d	−1.44	−0.62	−0.10	−0.41	−0.55			
HD 108177	f	−1.5		0.0		+0.1			
HD 2665	g	−1.6		−0.3		−0.4			0.0
BD+26°3578	f	−1.9		−0.2		−0.2			
HD 19445	f	−1.9				−0.3			
BD+39°4926	h	−2.1	−1.28	−0.82					
HD 165195	f	−2.1		−0.2		−0.7			+0.4
HD 184711	f	−2.3		−0.5		−0.7			+0.1
HD 140283	f	−2.4		−0.4		−0.8			
HD 128279	f	−2.5		−0.2		−0.4			+0.3
HD 84903	f	−2.6		−0.6		−0.8			+0.3
HD 122563	f	−2.6		−0.3		−0.7			−0.4
HD 26	i	−0.67		+0.30	+0.60	+1.30	+1.20	+1.20	
HD 201626	i	−1.45		+0.30		+1.10	+1.30	+1.10	

References:

a) Danziger (1966)
b) Anderson and Kraft (1971)
c) Barker et al. (1971)
d) Kodaira et al. (1969)
e) Peterson (1976)
f) Spite and Spite (1978)
g) Koelbloed (1967)
h) Kodaira et al. (1970)
i) Wallerstein and Greenstein (1964)

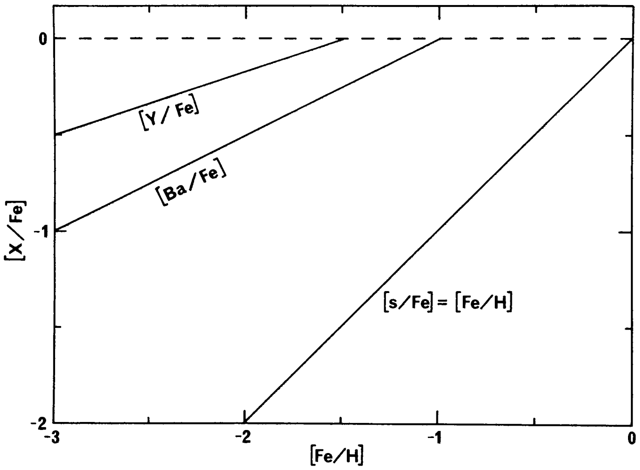

Fig. 1. Observed trends in the variations of [Y/Fe] and [Ba/Fe] with [Fe/H] are illustrated. The theoretical relation [s/Fe] = [Fe/H], where "s" designates some arbitrary s-process nucleus, is shown for comparison

The evolution of the heavy element abundance patterns nevertheless presents a challenge. The trends in [Y/Fe] and [Ba/Fe] with [Fe/H], revealed largely by the studies of Spite and Spite (1978), are illustrated schematically in Fig. 1. For comparison, the "theoretical" curve for the evolution of secondary elements defined by the relation [s/Fe] = [Fe/H] is also shown. Tinsley (1979) has emphasized this apparent discrepancy between the theoretical and observed behavior. We have recently performed calculations of the early chemical evolution of the galaxy which indicate that, when account is taken of various possible sources both of s-process nuclei and of iron, these trends may generally be understood. In particular, the anomalous heavy element patterns in the most metal-deficient stars are assumed to be provided by ejecta of massive stars; on a longer timescale, the contributions from the intermediate mass stars (Truran and Iben, 1977; Iben and Truran, 1978) dominate and a solar abundance pattern for the s-process elements results. That the yttrium and barium ratios to iron become solar when iron itself is still depleted, $[Fe/H] \leqq -1$, may in principle be understood on the assumption that the dominant contributions to the iron abundance in the galaxy are due to stars of lifetimes longer than those of the stars in which most of the s-process elements are produced.

While an understanding of these trends is achievable, for plausible if somewhat limiting assumptions concerning nucleosynthesis yields for iron and s-process elements, it is the purpose of this letter to emphasize that there exists a viable alternative interpretation of the heavy element ($A > 60$) abundances in extreme metal-deficient stars: *they are r-process products.* The fact that a neutron capture process characterized by a relatively long timescale is required to explain the heavy element abundance patterns in the Sr–Y–Zr and Ba abundance peaks in solar system matter has led virtually all workers to assume these to represent s-process products wherever they are seen. This assumption may be inappropriate for the most metal deficient stars. The results obtained by Spite and Spite (1978) for europium, an element whose abundance in nature is dominated by its r-process component, indicate that the Eu/Fe ratio is essentially solar even for $[Fe/H] \sim -2.6$: r-process synthesis has certainly occurred.

It is analytic of the r-process that the resulting Y/Eu and Ba/Eu abundance ratios will be less than those of solar system matter: the defining short neutron capture lifetime (high neutron flux) ensures that the $N = 50$ and 82 neutron shell closures will be encountered in the neutron-rich regions off the valley of stability, yielding abundance peaks at somewhat lower mass numbers

(Seeger et al., 1965). A mild depletion of barium relative to strontium, yttrium, and zirconium is also likely. The heavy element abundance patterns characteristic of the most iron-deficient stars ([Eu/Fe]~ 0; [Y/Fe]~ -0.5; [Ba/Fe]~ 0.8) are therefore entirely compatible with their having an *r*-process origin. We of course assume that, on a timescale consistent with the evolution of the intermediate mass stars which produce the *s*-process elements, the concentrations of Y and Ba in galactic matter will reflect their contributions.

III. Implications for Galactic Evolution and Nucleosynthesis

The site of *r*-process nucleosynthesis has not yet been unambiguously established. Two promising but quite different environments have been examined. 1. The expansion and cooling of highly neutronized matter ejected from the vicinity of the mass cut in supernovae leaving neutron star remanants can be accompanied by the production of *r*-process nuclei (Truran et al., 1968; Cameron et al., 1970; Schramm, 1973; Hillebrandt, 1978). The *r*-process nuclei here represent primary nucleosynthesis products; calculations of chemical evolution (Truran and Cameron, 1971) indicate that only $\sim 10^{-6} M_\odot$ of matter processed in this manner need be ejected per supernova event to satisfy galactic requirements. 2. Shock heating of the helium layers of supernovae can also provide an environment compatible with *r*-process nucleosynthesis (Truran et al., 1978; Thielemann et al., 1979). In this case, the requirements of a $^{22}Ne(\alpha, n)^{25}Mg$ neutron source and of iron seed nuclei would imply that the *r*-process nuclei are secondary nucleosynthesis products. If the Y, Ba, and Eu concentrations in metal-deficient stars are to be explained in the context of this latter model, then the demands on galactic evolution would be substantially the same as for *s*-process nucleosynthesis.

For the purpose of our subsequent discussion, we will adopt the view that the *r*-process nuclei are primary nucleosynthesis products formed in supernova explosions associated with massive stars. This assumption has the advantage that it yields great simplicity in the interpretation of the abundance features we seek to explain. The incompatibility of the variations of [Y/Fe] and [Ba/Fe] with the theoretical relation [*s*/Fe] = [Fe/H] is now to be expected. One might even choose to argue, conversely, that the observed trends in heavy element abundances in metal-deficient stars demand their formation as primary nucleosynthesis products in an *r*-process setting.

Further simplicity emerges when we inquire as to the origin of the collective elemental abundances observed in the oldest stars. Since both the carbon-to-iron elements and the heavy elements here represent primary nucleosynthesis products, we may conclude that *a single prior generation of stars can have been responsible for the abundances observed in the most metal-deficient stars in our galaxy.* No reprocessing of matter through stars is required. The nature of this earlier stellar generation (Population III?), whether of galactic or pregalactic origin, remains a critical subject for future research. We can, however, impose the following general demands upon its character: 1. it must form products of explosive charged particle nucleosynthesis (through iron) and *r*-process nucleosynthesis in relative amounts roughly compatible with solar system abundances; and 2. the stellar mass function must differ in the sense that low mass stars of long lifetimes were not the dominant stellar component (Truran and Cameron, 1971), since pure hydrogen-helium stars have not been found.

IV. Conclusions

We emphasize the following general conclusions:

(i) The heavy element abundance patterns observed in the most metal-deficient stars in our galaxy may be understood in a simple and direct manner if the elements heavier than iron are assumed to represent products of *r*-process nucleosynthesis. The associated variations of [Y/Fe] and [Ba/Fe] with [Fe/H] are precisely what one would expect if the *r*-process nuclei represent primary nucleosynthesis products; this would be the case if they were formed as a consequence of the ejection of highly neutronized matter in supernova events.

(ii) Given this *r*-process interpretation of the heavy element distributions, it follows that the abundances observed in the most metal-deficient stars can be explained on the basis of nucleosynthesis contributions from a single prior generation of massive stars, either galactic or pregalactic in nature.

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