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RESOLUTION OF THE PRASEODYMIUM ABUNDANCE ANOMALY IN THE Ba II STARS

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ABSTRACT

Previous abundance analyses of Ba II stars have usually yielded large excesses of praseodymium over its rare-earth neighbors. Several of these analyses have been revised to include the effect of hyperfine structure in the spectrum of Pr II. The revised abundances show excellent agreement with predictions of the *s*-process.

Subject headings: abundances, stellar — Ba II stars — hyperfine structure — nucleosynthesis

I. INTRODUCTION

The character and origin of anomalous abundances inferred from the spectra of peculiar stars are important issues in the study of stellar evolution and the chemical history of the Galaxy. Current thought is generally guided by the framework of the work of Burbidge *et al.* (1957), which assigns the production of elements heavier than iron to neutron addition mechanisms, the *r*- and *s*-processes.

For the *s*-process, one expects that for atomic weights between neutron magic numbers $\sigma_A N_A \simeq \sigma_{A-1} N_{A-1}$, where σ_A is an average neutron-capture cross-section averaged over a suitable Maxwell-Boltzmann distribution for a nuclide of atomic weight A. Even near neutron magic numbers, however, the σN product is predicted by *s*-process theory to be a smoothly varying function of A. This smooth variation was reported for the solar-system abundances of Suess and Urey (1956), by Clayton *et al.* (1961), and later in revised form by Seeger, Fowler, and Clayton (1965). This later work shows drops in the σN curve at neutron magic numbers which these workers were able to reproduce by calculations using a simple exponential representation for neutron exposure.

It was proposed by Burbidge and Burbidge (1957) that the observed overabundances of rare earths in Ba II stars are the result of nuclear processing of material inside the star beyond the prenatal composition assumed to be reflected in the spectra of normal stars. If this additional processing were by slow-neutron capture, the abundance *excess* of heavy elements ($A > 56$) should show a smooth variation with respect to A, a variation whose exact shape would be determined by the physical details of the exposure. The extensive study of Warner (1965) (hereinafter referred to as W) gives evidence for such a smooth variation in nine Ba II stars, except for a pronounced excess of Pr (praseodymium) appearing in all but one star. Theoretical calculations of both *r*- and *s*-process abundances show that Pr should actually be *less* abundant than its neighbors with even Z, as is found in the solar system.

The overabundances of europium with respect to nearby rare earths that have been found in Ap and Am stars have recently been shown to be in error due to the effect of hyperfine structure (Hartoog, Cowley, and Adelman 1974). We present a similar analysis of Pr II abundance determinations in the Ba II stars.

II. CALCULATIONS

Curves of growth were computed in LTE for Pr II $\lambda\lambda$4405, 4408, and 4510 for a representative K0 II–III atmosphere. The atmosphere was derived with the $T(\tau_0)$ relation from the flux-constant $T = 4000°$ K, $\log g = 2.0$ grid model of Carbon and Gingerich (1969), assuming $\log g = 1.4$. Curves of growth were also calculated for the $\log g = 2.0$ atmosphere; the deduced logarithmic-abundance corrections were very nearly the same except near $\log W_\lambda/\lambda = -4.2$ where the difference reached a maximum of about 0.2. For λ4405, curves of growth were calculated with and without hyperfine structure for microturbulent velocities $\xi_t = 2.0$, 3.5, and 6.0 km s^{-1}; as expected, the abundance effect was greatest for $\xi_t = 2.0$ and least for 6.0. We do not show these curves of growth because of their strong similarity to those shown by Hartoog *et al.* (1974). The quantity $\xi_t = 3.5$ was chosen as the most representative value for the Ba II stars (Cowley 1968; Tech 1971). The hyperfine structure flag-pattern width for the Pr II lines varies from 156 to 276 mÅ (see table 1); relative intensities were

TABLE 1

FLAG-PATTERN WIDTHS FOR Pr II LINES

λ (Å)	$\Delta\lambda_{\rm Flag}$ (mÅ)
4368.33	191
4405.85*	198
4408.84*	167
4449.87	180
4477.26	201
4510.16*	210
4535.92	124
4628.75	250
4664.65	145
4672.08	177

* Lines for which curves of growth were calculated.

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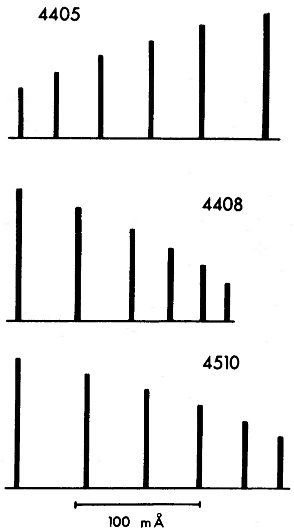

FIG. 1.—Relative intensities in the hyperfine patterns of the three Pr II lines for which curves of growth were calculated.

taken from Kopfermann (1958) where available or calculated according to Wybourne (1965). Note that two of the equations there (eqs. 5-109b and 5-109c) contain misprints. We need not give the corrected formulae since they may be found on p. 238 of Condon and Shortley (1959), making only the substitutions $LSJ \rightarrow JIF$. We give for reference the more compact expression for the line strength of a hfs component in terms of a Racah coefficient

$$S(\gamma JIF, \gamma' J' IF') = \text{const.}\, (2F' + 1)(2F + 1) W^2(J'JF'F; 1I)\,,$$

where *const.* is a constant for a given hyperfine multiplet. These formulae for *relative* intensities are valid irrespective of coupling scheme for the electronic states. Pattern intervals are from Kopfermann (1958) and the total widths are the laboratory measurements of White (1929). The weaker components were combined with the strongest six to give the familiar flag pattern (fig. 1).

For $\lambda\lambda$4405, 4408, and 4510 the abundance differences $\Delta \log \epsilon$ between the curves of growth with and without hyperfine structure can be easily plotted as a function of observed $\log W_\lambda/\lambda$. The resulting curves are roughly bell-shaped with a maximum at $\log W_\lambda/\lambda = -4.2$ of 1.6 ($\xi_t = 3.5$) for λ4405; for greater ξ_t the bell becomes smaller and the peak moves towards greater $\log W_\lambda/\lambda$. $\Delta \log \epsilon$ values for other lines were approximated by using the curve for the calculated line whose pattern width was most nearly equal to that of the line in question.

III. RESULTS

The abundance determinations of praseodymium in nine Ba II stars of W, Danziger (1965), and Burbidge

TABLE 2

PRASEODYMIUM OVERABUNDANCES

Star	Author*	[Pr/Fe]†	Net $\Delta \log \epsilon$	[Pr/Fe] (corr)†
HD 116713......	W	1.02	0.56	0.46
	D	1.4	0.39	1.01
HD 83548.......	W	0.34	0.41	−0.07
	D	1.0	0.12	0.88
HD 204075......	W	0.57	0.53	0.04
HD 46407.......	W	1.05	0.85	0.20
	B²	1.54	0.65	0.89
HD 178717......	W	1.19	0.75	0.44
HD 175674......	W	0.86	0.68	0.18
HD 92626.......	W	1.18	0.81	0.37
HD 183915......	W	1.10	0.61	0.49
HD 211594......	W	1.20	0.68	0.52

* W = Warner (1965), D = Danziger (1965), B² = Burbidge and Burbidge (1957).

† Uncorrected and corrected [Pr/Fe] for the Ba II stars.

and Burbidge (1957) were corrected by subtracting the average net $\Delta \log \epsilon$ for all the lines from the tabulated abundance values (table 2), where

$$\text{net}\, \Delta \log \epsilon = \Delta \log \epsilon(\text{Ba II star}) - \Delta \log \epsilon(\text{comparison})\,.$$

The equivalent widths used in W are published in Warner (1964). In addition, all results have been converted to a [Pr/Fe] scale for comparison with W. This correction is largest for the work of Danziger ([Fe] = 0.3), due to the known metal poverty of his comparison star, α Boo (Griffin and Griffin 1967).

The corrected abundances for praseodymium and the abundances for neighboring elements were used to plot $(y' - 1)\sigma N$ versus A (as in W), where $(y' - 1)$ is the *fractional overabundance* of s-processed species in the star,

$$(y' - 1) = (y - 1)(1 + r/s)\,,$$

$$\log y = [\text{El/Fe}] = \log(\text{El/Fe})_{\text{Ba II}} - \log(\text{El/Fe})_{\text{standard}}\,.$$

In principle what should be plotted are the s-process abundances of nearby elements at a given A; in practice, only one element (or isotope) contributes sensibly at each A, and the (r/s) factor corrects for any r-process contributions in the overabundances in the dominant species at each A.

For praseodymium and the adjacent elements barium, lanthanum, cerium, neodymium, and samarium, the $(y' - 1)$ of W have been reevaluated using his abundances, but consulting Seeger *et al.* (1965) for more recent values of r/s, the ratio of the solar-system isotope abundances formed by the r-process compared to the s-process. The σN are from the smooth theoretical curve in Seeger *et al.* (1965), which contributes to the exceptional smoothness of the corrected curves.

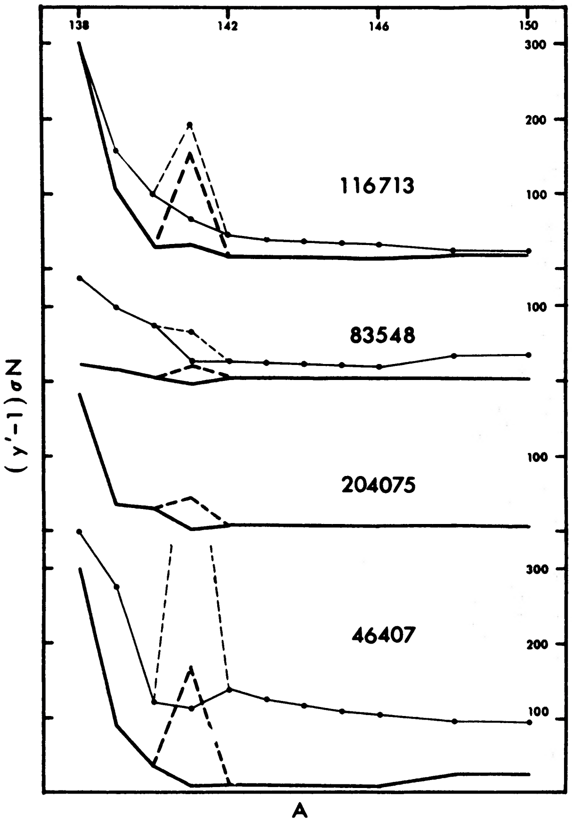

FIG. 2.—Overabundance σN curves for Ba II stars; identifying numbers are HD numbers. Dashed lines show praseodymium overabundance products before correction. Heavy lines are for W; light lines for HD 116713 and HD 83548 are for Danziger (1965); light lines in HD 46407 are for Burbidge and Burbidge (1957). Isotopes shown are ^{138}Ba, ^{139}La, ^{140}Ce, ^{141}Pr, $^{142-146}$Nd, ^{148}Sm, and ^{150}Sm.

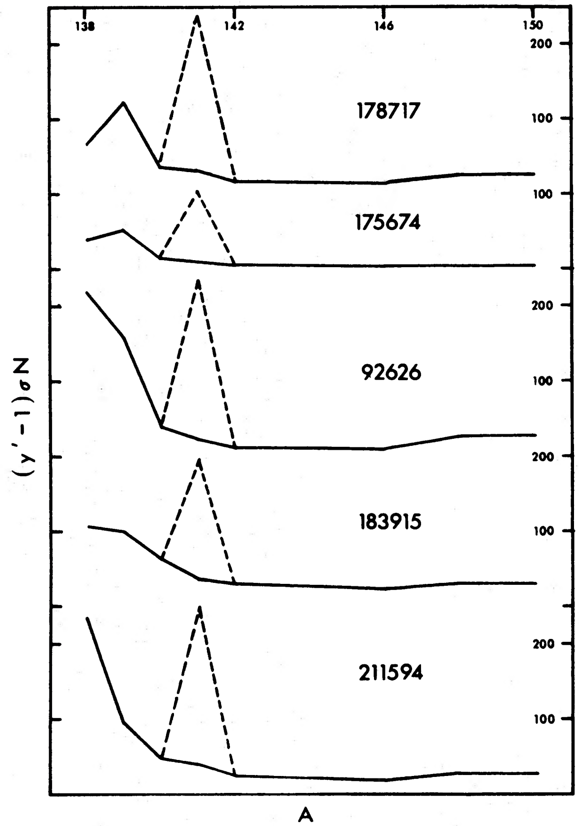

FIG. 3.—Same as fig. 2 for the remaining five Ba II stars

The assumptions implicit in this procedure are: (i) There has been *no* additional *r*-processing accompanying the extra *s*-processing. (ii) The use of these σN assumes that the conditions for the extra *s*-processing are at least roughly those assumed by Seeger *et al.* (1965), which are fit to solar system abundances. (iii) Any *p*-process contributions have been neglected. (iv) To make the element-isotope correspondence, the fractional *s*-process augmentations (y') for each *isotope* of a given element are assumed identical. This is consistent with assumption (ii) above.

In figures 2 and 3 are shown the amended W results as well as those of Danziger (1965) for HD 116713 and 204075 and Burbidge and Burbidge's (1957) for HD 46407. The systematic excesses of the Danziger results over Warner's are probably due to the metal deficiency of α Boo, whereas the disagreement with the Burbidges's results is attributed to systematic errors in the determination of the Burbidges's equivalent widths (this is fully discussed in W).

An analysis of HR 774 (Cowley 1968) was attempted but required otherwise unjustified adjustments ($\sim$0.5 km s^{-1}) in the microturbulence to be successful, so we do not show this here. The difficulties may be due to the use of a luminosity class II star as a standard, or to errors in the spectrophotometry.

IV. CONCLUSIONS

The inclusion of hyperfine structure splitting reduces the inferred praseodymium overabundances to or below the level of those of its rare-earth neighbors with even Z. The general smoothness and drop in the $(y' - 1)\sigma N$ curves from barium and lanthanum to cerium strongly resemble typical *s*-process abundance predictions; no "anomaly" in the *s*-process need be invoked to explain the strength of the praseodymium lines in the Ba II stars.

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