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ON THE ABUNDANCE OF EUROPIUM

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ABSTRACT

The inclusion of the effects of hyperfine splitting can significantly lower the abundance estimate of Eu from singly ionized lines which lie on the flat portion of the curve of growth. In the 21 cool Ap stars studied by Adelman and the five Am stars studied by Smith the Eu abundance was reduced by 0.4 dex on the average. In individual cases the reductions were as great as 0.9 dex. This makes the Eu abundance comparable to that of its neighboring rare earths Sm and Gd in the Ap stars and less than Sm and Gd in the Am stars, but still substantially overabundant with respect to solar values.

Subject headings: abundances, stellar — hyperfine structure — metallic-line stars — peculiar A stars

I. INTRODUCTION

Abundance analyses of the cool Ap stars and Am stars have often indicated that europium is the most abundant rare earth. In his recent survey of the abundances of 21 cool Ap stars Adelman (1973*a*) found that on the average Eu was more abundant by 0.4 dex than the next most abundant rare earths, Sm and Gd. This result violates the well-known odd-even effect in cosmic abundances, as do the results found by Smith (1971) for the Am stars where on the average Eu is *as* abundant as Sm and Gd. It is difficult to understand these abundances on the basis of the theories of Ap stars (Fowler *et al.* 1965; Brancazio and Cameron 1967; Michaud 1970; Havnes and Conti 1971) and with the subsurface-element separation-zone theory of Am stars (Watson 1970; Smith 1971).

II. THE EFFECT OF HYPERFINE SPLITTING ON THE CURVE OF GROWTH

Hyperfine splitting causes a spectral line to be split into a number of closely spaced components of unequal intensity. The spacing of the components is in general different for every line and for the same line in different isotopes of an element. Europium has two stable isotopes with mass number A, equal to 151 and 153. The spacing of the hyperfine components for these two isotopes was taken from Krebs and Winkler (1960) and is shown in figure 1 for $\lambda 4205$ of Eu II. The weaker hyperfine components have been combined with the stronger ones to simplify the calculations. The relative intensities were taken from Kopfermann (1958). Note that these intensities are independent of the electronic coupling scheme (Wybourne 1965) and appear to be in good agreement with the measured

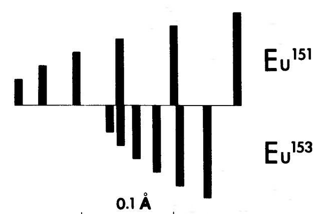

FIG. 1.—The hyperfine pattern of Eu II $\lambda 4205$ for both stable isotopes. The pattern of ^{153}Eu has been plotted reversed for clarity.

profiles of Krebs and Winkler (1960). The abundance of the two Eu isotopes is nearly the same in meteorites (Cameron 1968). Hauge (1972) found a similar ratio in the Sun from fitting the solar line profiles. The general question of the isotopic abundances of Eu in normal, Am, and Ap stars is an interesting one and requires additional attention. We have assumed that the two isotopes are equally abundant in Ap and Am stars.

To estimate the effect of hyperfine splitting on abundance determinations of Eu in Am and Ap stars, some sample curves of growth were calculated for a model atmosphere with a $\theta_{\rm eff} = 0.5$ and $\log g = 4.0$. The temperature distribution was taken from Mihalas (1966). In order to use existing computer programs, the line profiles were calculated in specific intensity by the weight-function method for three locations on the disk and then integrated over the disk to give the profile in flux, which was integrated to give the equivalent width. Figure 2 shows the results of these computations for $\lambda 4205$ with a microturbulence of $2\ {\rm km\ s^{-1}}$, $5\ {\rm km\ s^{-1}}$, and $8\ {\rm km\ s^{-1}}$. The hyperfine splitting acts like a "pseudomicroturbulence," by

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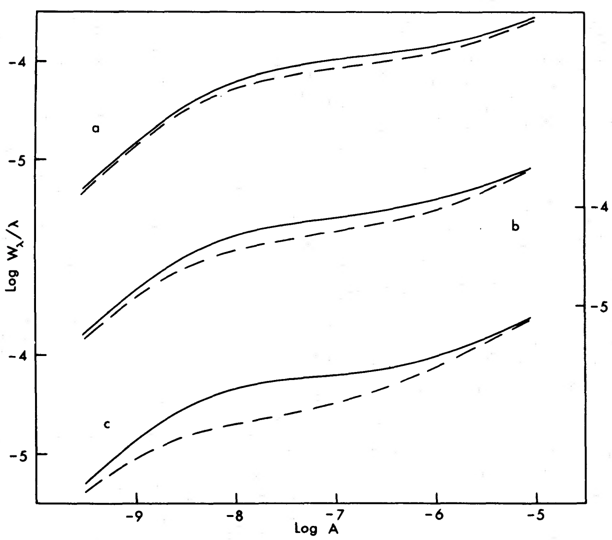

FIG. 2.—The curve of growth for Eu II λ4205 with (*solid*) and without (*dashed*) the effects of hyperfine splitting for a microturbulence of (*a*) 8 km s^{-1}, (*b*) 5 km s^{-1}, and (*c*) 2 km s^{-1}.

raising the flat portion of the curve of growth. As a result, the inclusion of hyperfine splitting can lower an abundance determined from λ4205 by as much as 1.5 dex in extreme cases. On the linear portion and on the damping portion of the curve of growth hyperfine splitting is not significant for abundance determinations from the equivalent width. Of course, the line profile is always affected.

III. DISCUSSION

Hyperfine splitting is especially important for Eu II because of the unusual nature of its spectrum compared to that of the other singly ionized rare earths. Eu II has a few strong lines and a considerable number of very weak lines, with no lines of intermediate intensity. The strong lines can be easily identified in cool Ap and Am star spectra, but often are blended which makes good equivalent-width determinations difficult, and lie on the flat portion of the curve of growth where the equivalent width is relatively insensitive to the abundance and is most affected by hyperfine splitting. The very weak lines are extremely difficult to identify with any certainty. Other rare earths, especially Pr and Ho, have large hyperfine splittings, but the lines used for abundance determinations of these elements are usually weaker than the Eu II lines so that the hyperfine splitting is less important for abundance determinations. The remaining rare earths, such as Nd, Sm, Gd, and Dy have much smaller hyperfine splitting. Hence, the abundance of Eu in the cool Ap and Am stars is more difficult to determine than that of the other rare earths and has probably been overestimated.

In the cool Ap stars one must also consider the effects of Zeeman broadening. In order to estimate the relative importance of hyperfine splitting and Zeeman splitting one can compare the total widths of the respective patterns. Table 1 gives for each strong Eu II line in the photographic region the multiplet number, the wavelength, the transition, the mean separation z of the σ components in terms of the normal Zeeman triplet, and the measured total width of the hyperfine pattern given by Krebs and Winkler (1960). Thus, if a typical surface magnetic field, H_s, of 3 kilogauss is present, the total width of the Zeeman pattern for λ4205 will be approximately 0.1 Å, a result which from table 1 is typical of all the strongest Eu II lines in the photographic region. For reference the full width of the thermal Doppler profile is about 0.03 Å. A comparison of these widths with the widths of the hyperfine patterns given in table 1 shows that, while for this typical magnetic-field strength, hyperfine splitting is more important than Zeeman splitting, both effects are of the same order of magnitude, and therefore, both must be considered. A detailed treatment of the combined effects of Zeeman splitting and hyperfine splitting for the typical magnetic field strengths found in cool Ap stars is complex (see, i.e., Kopfermann 1958). However, as a first approximation one may treat the Zeeman broadening following Adelman (1973*a*) as a "pseudoturbulence" which broadens each

TABLE 1

DATA ON THE ZEEMAN AND HYPERFINE PATTERN OF STRONG Eu II LINES

				HYPERFINE WIDTH (Å)	
MULTIPLET NO.	λ	TRANSITION	z	^{151}E	^{153}Eu
1................	3819.67	$^9S_4$–$^9P_5$	1.50	...	...
	4129.73	$^9S_4$–$^9P_4$	1.97	0.171	0.076
	4205.05	$^9S_4$–$^9P_3$	1.62	0.238	0.106
2................	3724.94	$^9S_4$–$^7P_4$	1.87	0.155	0.069
	3688.42	$^9S_4$–$^7P_3$	2.12	0.153	0.068
4................	4435.58	$^7S_3$–$^9P_4$	1.88	0.223	0.099
	4522.29	$^7S_3$–$^9P_3$	2.12	0.163	0.072
5................	3971.98	$^7S_3$–$^7P_4$	1.38	0.165	0.073
	3930.50	$^7S_3$–$^7P_3$	1.96	0.140	0.066
	3907.10	$^7S_3$–$^7P_2$	1.67	...	...

hyperfine component. Thus, following Adelman and assuming that classical microturbulence is not present in the magnetic Ap stars and using the relation given by him we find that the Zeeman broadening of λ4205 in a 3 kilogauss magnetic field may be treated as a pseudoturbulence of about 3 km s^{-1}. The curves of growth in figure 2 show that at this turbulence the effect of hyperfine splitting can be substantial.

The amount that the abundances of Eu will be lowered in any star by the inclusion of this effect depends on which lines were used in the abundance determination and where those lines are on the curve of growth. For example, Adelman (1973*b*) in his survey of cool Ap star abundances used λ4205, λ4436, and λ3907 of Eu II. The first two of these have the widest hyperfine pattern of the Eu II lines measured by Krebs and Winkler (1960), the third was not measured. Using curves of growth like those shown in figure 2 we have estimated corrections to the abundances determined from λ4205 and λ4436 for the 21 cool Ap stars studied by Adelman (1973*b*) and these corrections are given in table 2. Since a measured hyperfine width for λ3907 was not available and since this line is weak enough that in most cases in these stars the abundances determined from it should not be affected by more than about 0.1 dex, it was decided not to correct the abundances determined from this line. The corrected abundances from λ4205 and λ4436 were averaged with the abundance from λ3907 to give the mean Eu abundances given in the last column of table 2. The absolute abundances in individual stars may well be modified by future work. At the present time, it is probably more useful to consider average results. The mean Eu abundance of the 21 cool Ap stars is now −7.60 as compared to −7.19, determined by neglecting hyperfine splitting. For comparison the results of Adelman (1973*b*) for the mean Sm and Gd abundances are −7.50 and −7.64, respectively.

TABLE 2

ABUNDANCE CORRECTIONS AND NEW ABUNDANCES FOR SOME AP STARS

HD	Δ log Eu λ4205	Δ log Eu λ4436	New mean log Eu/H
2453	−1.15	−0.58	−6.56
5797	−1.50	−1.25	−7.14
8441	−0.1:	−0.2:	−7.52
12288	−0.05	...	−7.43
18078	−0.14	−0.05	−7.87
22374	−0.2:	−0.1:	−8.64
50169	−0.15	−0.03	−7.63
81009	−0.18	−0.1:	−7.39
89069	−1.10	−0.65	−7.21
110066	−0.79	−0.36	−6.76
111133	−0.11	−0.03	−7.57
118022	−1.25	−0.45	−7.02
137909	−0.24	−0.50	−5.94
137949	−0.60	−0.50	−7.23
165474	−0.70	−0.15	−7.43
176232	−0.55	−0.35	−9.26
191742	−1.10	−1.00	−8.15
192678	...	−0.03	−7.47
201601	−1.18	−1.10	−9.16
204411	...	0.0	−8.84
216533	−0.70	−0.13	−7.34
Mean			−7.60

TABLE 3

ABUNDANCE CORRECTIONS AND NEW ABUNDANCES FOR SOME AM STARS

Star	Δ log Eu λ4205	Δ log Eu λ4130	New mean log Eu/H
τ UMa	−0.60	−0.35	− 9.93
HD 103877	−0.70	−0.40	− 9.67
HD 161227	−0.28	−0.07	− 9.87
HD 174704	−0.65	−0.45	− 9.60
ξ Cep A	−0.20	−0.07	−10.20
Mean			− 9.85

For the Am stars, Smith (1971, 1973) used λ4130 and λ4205 to obtain Eu abundances. The hyperfine-structure pattern of the former line is about 2/3 of the latter line for each stable isotope. Table 3 gives estimated abundance corrections and new mean Eu abundances for the five Am stars analyzed by Smith (1973). The mean Eu abundance is −9.85 compared to −9.48, determined by neglecting hyperfine splitting. For comparison the results of Smith (1973) for the mean Sm and Gd abundances are −9.42 and −9.55, respectively.

The combination of hyperfine splitting and Zeeman effect will have important consequences if a diffusion mechanism operates in cool Ap stars. These effects both increase the equivalent widths of the Eu II and Eu III lines in the ultraviolet for a given abundance. Thus, these lines can more readily assist the radiative-driven diffusion of Eu in Ap star atmospheres to a much greater extent than if both the hyperfine and Zeeman splitting were small. In addition, those ^{151}Eu components which do not compete in the removal of flux with ^{153}Eu components will saturate after all other hyperfine components. This may lead to an increase in the ^{151}Eu/^{153}Eu ratio. Similar results may be expected in other elements which have isotopes with similar distributions of hyperfine splitting components.

Hence, the inclusion of hyperfine splitting in the Eu abundance determinations will lower its abundance relative to the other rare earths in many stars. Thus possible theoretical explanations of both the Am and Ap stellar-abundance anomalies need not predict an extreme abundance of Eu.

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