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# ABUNDANCES OF TRACE ELEMENTS IN HR 465: EVIDENCE FOR THE *r*-PROCESS

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#### ABSTRACT

Abundances have been derived for eight elements in HR 465 near the r-process peaks at tellurium and osmium. Elements on the peaks are decidedly enhanced relative to those in the nearby "troughs." If we add to this information the presence of uranium, a strong case can be made that the abundances in HR 465 reflect a substantial amount of r-processing.

Subject headings: abundances, stellar — nuclear reactions — peculiar A stars — stars, individual

#### I. INTRODUCTION

The r- and s-processes are the classical  $B^2FH$  (Burbidge *et al.* 1957) methods for building up the elements beyond the iron peak. The analyses of stellar spectra have shown fairly convincing evidence for the results of s-processing (see Warner 1965, Danziger 1966). Stellar evidence for the r-process has been much more fragmentary.

Perhaps the best evidence for the occurrence of the *r*-process is found in the solarsystem abundances. Seeger, Fowler, and Clayton (1965) have shown how it is possible to subtract out the *s*-process contribution. When the resulting abundances are plotted as a function of mass number A, they clearly show three peaks characteristic of the theoretical *r*-process calculations and provide convincing evidence for the *r*-process.

The *r*-process has been frequently mentioned in connection with the abundance anomalies observed in Ap stars (see, e.g., Fowler *et al.* 1965, Guthrie 1969, and many others). Our line identification work in the exceptional Ap star HR 465 (Hartoog, Cowley, and Cowley 1973) showed that the two *r*-process peaks associated with neutron shell closings at N = 82 and 126 were very likely present. The identification and abundance determination for uranium (Cowley and Hartoog 1972) was further strong evidence for the *r*-process, since uranium cannot be made by the *s*-process.

In the present study abundances were derived for Pd, Te, Ba, Er, Yb, Hf, Os, Pt, and Hg. These elements are all located near the peaks or troughs associated with shell closings at N = 82 and 126 (with the exception of Er). The new abundances were derived differentially with respect to Aller's (1972) determinations. A few control calculations which were made using the complete model-atmosphere technique were in satisfactory agreement with the differential method.

We display the evidence for r-processing in HR 465 using a plot like that of Seeger, Fowler, and Clayton for the solar-system abundances. We have been forced to plot our abundances versus Z rather than A, since the isotopic data are unavailable, and we are unable to subtract the s-process contributions for the same reason. Nevertheless, the r-process peaks at tellurium and osmium-platinum do emerge, relative to the neighboring elements which fall in the "troughs" of the theoretical calculations.

#### **II. DETAILS**

Many line identifications and abundances were available from previous work (see Aller 1972). The identifications were rediscussed by Hartoog and Cowley (1972) and

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## TABLE 1 DATA FOR ABUNDANCE DETERMINATIONS

Element	λ	× <sub>l</sub>	log gf	Abundance log H = 12.0	Element	λ	× <sub>ℓ</sub>	log gf	Abundance log H = 12.0
Pd I Gd II Fe I	3404.60 3407.56 3399.34	.81 1.31 2.20	0.30 0.80 0.55	<5.8 <6.1	Ba II Nd II	<b>455</b> 4.03 4556.14	0.00 0.06	0.17 -2.22	<3.0
Pd I Nb TT	3516.94 3510.26	0.96	0.07	<6.4	Er II Dy II	3441.15 3441.45	0.05	-0.64 -0.53	5.3
Pd I Fe I	3553.08 3554.92	1.45	0.54	7.2	YD II Sm II	3694.19 3693.99	0.00	-0.82 -0.96	3.9
Te II Gd II	3406.79 3407.56	11.49 1.31	0.0*	8.8	Hf II ND II	3399.80 3399.71	0.00 1.82	-0.74 0.00	<4.8
Te II	3442.25	9.27	0.0*	<7.0	Hf II Er II	3505.23 3505.07	1.03 0.89	-0.05 -0.32	3.3
Fe I	3445.15	2.20	0.56	7.7	Hf II Dy II	3644.36 3645.41	0.79 0.10	-0.57 0.28	4.6
Te II Dy II	34 <b>55.</b> 12 3460.97	11.02 0.0	0.0* -0.10	<8.3	Hf II	3793.37	0.38	-1.20	
Te II Ti II	3521.11 3520.25	8.82 2.05	0.0* 0.15	7.6	Os II	3604.48	1.44	-1.0*	< 4.6
Te II Gd II Dy II	3918.53 3916.51 3914.86	10.76 0.60 0.54	0.0* 0.06 -0.78	8.0 7.2	Sm II Pt II Sm II	4046.45 4047.16	0.49 4.52 0.18	-0.21 -1.0* -1.18	5.8
Te II Fe I	3975•93 3977•74	10.83 2.19	0.0* -0.28	7.6	Pt II Sm II	4061.66 4064.58	3.63 0.33	-1.0* -0.76	5.7
Te II Fe I	4006.52 4005.25	8.82 1.55	0.0* -0.09	7.2	Hg II Dy II	3984.00 <b>†</b> 3983.67	4 <b>.3</b> 9 0 <b>.5</b> 4	-1.0* -0.34	5.1
Te II Ce II	4 <b>557.7</b> 8 4550 <b>.</b> 30	12.36 1.12	0.0* -0.90	6.7	* assume †stella	d log gf val r wavelengt)	lue		

Hartoog et al. (1973). The latter paper gives a complete discussion of the method and reliability of all of the identifications. The identification of Pd I was first proposed by Bidelman (1966). Tellurium deserves special comment because it, alone, defines the r-process peak associated with N = 82. The identification is based on a search for 31 strong lines from the list of Handrup and Mack (1964). With a tolerance of  $\pm 0.06$  Å, the probability that the coincidences are due to chance is 0.007 based on 1000 random trials (cf. Hartoog et al. 1973). The wavelengths in Handrup and Mack's compilation show differences up to -0.06 Å with an indication of systematic effects between systems of measurement. We have tried a variety of tolerances as well as a smaller laboratory line list. We conclude that the coincidences may not be attributed to chance. A line-by-line examination of the tracings of HR 465 supports this identification.

In the differential abundance calculations, we chose lines for the element in question that we believe are not blended. Usually this meant that no alternate identification was made by Bidelman in his original work, and that the profile appeared single. Frequently the strongest laboratory lines are unsuitable for the abundance determination for these reasons. We searched for a nearby line of *similar strength* belonging to

Adopted Abundances							
Element	No. of lines	$\log (El/H)$ $\log H = 12.0$					
Pd	3	6.4:					
Ге	8	> 8.0:					
Ba	1	< 3.0					
Er	1	5.3					
Yb	1	3.9					
Hf	4	4.2					
Os	1	53					

an element for which an abundance was determined by Aller (1972). We assumed that the product  $N_n g_n f_{nm}$  is nearly the same for both lines, where  $N_n$  is the number of atoms capable of absorbing the line. The mean atmospheric conditions adopted for HR 465 were log  $P_e = 2.5$ , and  $T = 10^4 \,^{\circ}$  K.

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Hg.....

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Detailed results of these calculations are given in table 1. For each line, we list immediately below it the comparison line used to derive the relative abundance. The abundances listed in the final column are an element-to-hydrogen ratio based on Aller's (1972) abundance for the comparison element. Several lines have abundances that were based on two comparison lines. The symbols > and < before an abundance mean that the strengths of the two lines used in the differential determination were not exactly equal.

The adopted abundances are given in table 2. For tellurium, we assumed  $\log gf = 0.0$  for all lines. This implies that the abundance is probably a lower limit. For Os, Pt, and Hg, we have taken the more realistic value of  $\log gf = -1.0$ . Dworetsky, Ross, and Aller (1970) give an astrophysical  $\log gf = -1.79$  for  $\lambda 3984$  of Hg II, which would raise our abundance by nearly an order of magnitude, and strengthen our case for *r*-process peaks. We present a conservative estimate. Log gf = -1.0 is also a conservative (i.e., large) estimate for the two platinum lines  $\lambda \lambda 4061.68$  and 4046.45. The former is an intersystem transition between levels which were (at least) given LS coupling designations by Shenstone (1938). The line at  $\lambda 4046$  is an apparent two-electron jump, possible only because of a mixing of configurations, and its oscillator strength is also likely to be small.

The Os II abundance is based on the one unblended line  $\lambda 3604.48$  which was identified by Bidelman. It is the strongest line of Os II. According to van Kleef (1960), the transition is  $5d^{6}({}^{5}D)6s {}^{4}D_{5/2}-5d^{5}6s(a {}^{7}S)6p {}^{8}P_{7/2}$ , and our transition probability is again not expected to be an underestimate.

Sources of gf-values for the remaining elements are the same as those used by Aller (1972), except for  $\lambda 4554$  of Ba II where we took  $\log gf = 0.17$  from Miles and Wise (1969).

The most realistic estimate of the uncertainties of the abundance determinations is probably obtained from an intercomparison of the individual determinations themselves. If we ignore the greater and less than symbols, we obtain, for example, for 10 tellurium determinations a rms deviation of 0.58 dex. Here the gf's were all guessed. If gf's are available, the uncertainties should be less. The rms for seven differential determinations of uranium was 0.28 dex (see Cowley and Hartoog 1972). These figures test the internal consistency of the method. Much larger errors are possible due to various systematic effects, but we do not expect that such errors would seriously perturb the relative overabundances of the elements on the *r*-process peaks.

### III. DISCUSSION

The new adopted abundances are listed in table 2. The column headed "No. of Lines" gives the number of lines on which the *abundance* determination is based. This number is, in general, considerably less than the number of lines used in the *identifica-tion* of an element. In figure 1, the abundances are plotted as a function of Z.

Figure 1 shows an enormous overabundance of tellurium. We have been unable to identify Sb, Sn, In, Cd, or Ag which lie to the left of this peak. Palladium is the first element shortward of Te for which we have an abundance. Xenon was not identified in HR 465; this could mean that Xe is less abundant than Te, or just that it is harder to identify because of the wavelengths and excitation potentials of its stronger lines. Further to the right of Te, barium is decidedly down in abundance as is lanthanum, which we were unable to identify positively (see Hartoog *et al.* 1973).

The rare earths, especially neodymium and samarium, make an additional maximum falling between the Te and the Os-Pt peaks. A similar hump in the rare-earth region is observed in the solar *r*-process abundances, although its maximum is more displaced toward the heavier rare earths than the maximum in HR 465. The following are seen in the results of Seeger *et al.*: (1) There are three well-defined maxima, one at Te, one in the rare earths, and one at Os-Pt. There maxima are defined with respect to the minima near Ba and La and Yb, Lu, and Hf. (2) The rare-earth maximum is quite high—comparable, in fact, with the tellurium peak.



FIG. 1.—Abundances (log H = 12.0) for selected elements in HR 465 as a function of Z. Circled elements are from Aller (1972). The abundances of U (Cowley and Hartoog 1972) and Fe (Aller 1972) are also indicated. The solid line represents the solar system abundances with the *s*-process subtracted out (Seeger *et al.* 1965). These solar-system values have been increased by 10<sup>3</sup> in order to be able to include them on the same graph.

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These features are in good qualitative agreement with our figure 1. Quantitative disagreements occur in the position of the rare earth maximum, and the relative heights of the Te and Os-Pt peaks. The latter property varies greatly in the various solutions of Seeger, Fowler, and Clayton, and does not seem serious.

In summary, the abundances in HR 465 are in remarkably good agreement with the results of theoretical r-process calculations. It is a moot question whether further theoretical work could bring the theory and observations into even closer accord.

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