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THE Ba II STAR HR 774

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ABSTRACT

Abundances are derived for the Ba II star HR 774 relative to the K2 II star π^6 Ori. The metal-to-iron ratios are very similar to those obtained by Warner. A possible underabundance of iron is discussed.

I. INTRODUCTION

Chemical abundances in the stars represent one of the most important sources of data on which modern theories of stellar evolution and the origin of the elements are based. The Ba II stars have received special attention because they show abnormally high abundances of those elements which may be attributed to one specific nuclear process, the *s*-process.

The first Ba II star to be analyzed for its abundance was HD 46407 (Burbidge and Burbidge 1957). More recently Warner (1965) analyzed nine Ba II stars, including HD 46407. Danziger (1965) also made abundance determinations for two of the stars studied by Warner. HR 774, the second brightest of the Ba II stars, has been studied only recently (Nishimura 1967), undoubtedly because of its location at +81° declination.

There are now two completely independent abundance studies of HR 774. Our data come entirely from the blue-violet region of the spectrum, while those of Nishimura were obtained in the red and infrared. Two different comparison stars were used, ϵ Vir by Nishimura and π^6 Ori in the present study. In spite of these and other minor differences in technique, the agreement of the results is excellent. In every case where the final result depended on six or more lines, one could hardly hope for better agreement.

II. OBSERVATIONS AND REDUCTIONS

Three Kodak IIaO plates at 9.4 Å mm^{-1} were obtained at McDonald Observatory on HR 774 and the K2 II comparison star π^6 Ori. We are indebted to P. C. Keenan for the suggestion of π^6 Ori for use in the present analysis. The calibration spectra were exposed on plates cut from the same piece of glass as the stellar spectra and developed simultaneously. No indications of the Eberhard effect were noticed.

The plates were traced with the Yerkes microphotometer, using a magnification of about 100 from the plate. A number of apparently unblended profiles were selected to establish the usual relation between line depth and equivalent width. Our technique essentially follows Warner (1964) with two exceptions. We assumed that all of our profiles were triangular, and we made all of our measurements with respect to the local continuum near the line in question. Corrections for depression of the local continuum were then made using Thackeray's rule (cf. the discussion by Moore, Minnaert, and Houtgast 1966).

The consistency of the results from plate to plate of the same star was considered satisfastory. The stronger lines agreed to about 12 per cent. For the weaker lines, the mean deviation from the mean was about 40 per cent, with occasional differences up to a factor of 2 for the very weakest lines. On one of the three plates of HR 774, the equivalent widths were systematically smaller than on the other two by 10 per cent with no noticeable dependence on the strengths of the lines.

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In order to obtain an estimate of the reliability of our measurements in an absolute sense, we compared our log F's for HR 774 for Fe I with Warner's measurements for HD 83548. This comparison revealed systematic differences which depended on both wavelength and line strength. The differences were sufficiently large (about 0.1 dex) for the strongest lines to prohibit a realistic determination of the damping constant, which depends on the absolute value of the line strengths of the strongest lines (see below). The turbulent velocity depends on the absolute value of the intermediate-strength lines, for which the agreement was excellent. It could be that both measurements are systematically too large, but there is no good way to investigate this possibility until line strengths in these stars are measured at much higher dispersion.

UBV photometry was available for π^6 Ori, but we were unable to find photometric measurements of HR 774. At our request, John Neff made photoelectric measurements of HR 774 on the intermediate-band system of Morgan and Neff (1964). We wish to thank Dr. Neff for obtaining these measurements for us.

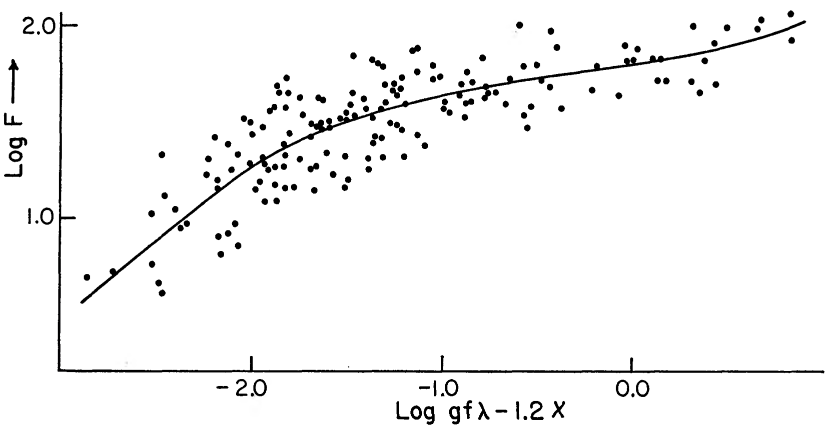

FIG. 1.—Fe I curve of growth for HR 774 using laboratory f-values

III. DIFFERENTIAL CONDITIONS IN HR 774 AND π^6 ORI

Three curves of growth for Fe I were plotted. First, for HR 774, we plotted log F versus $\log gf\lambda - 1.2\chi$ (Fig. 1). The gf-values were taken from Corliss and Warner (1964), with the normalization function removed (cf. Warner and Cowley 1967). The estimate $\theta_{\text{exc}} = 1.2$ is rather small, according to the results below, but the matter is of no consequence, since we make no further use of θ_{exc}. A mean curve was drawn through the points with the aid of the theoretical curve of growth of Hunger (1956) for a Schuster-Schwarzschild pure-absorption atmosphere. On the basis of this curve, it was possible to derive stellar f-values from HR 774, which were then used to construct a curve of growth for π^6 Ori. From this, it was possible to derive stellar f-values from π^6 Ori, which were used to construct a second curve of growth for HR 774, shown in Figure 2. In principle, one might "iterate" again, obtaining a second curve of growth for π^6 Ori based on the HR 774 line strengths, etc. However, it is clear from the similarity of the adopted curves in Figures 1 and 2 that the extra effort would not be worthwhile.

There is a much larger scatter in the curve of growth for HR 774 which uses laboratory f-values than in the one using stellar f-values. This result is well known, but it is generally attributed to errors in the laboratory oscillator strengths. A point-by-point comparison of some of the lines which scatter badly in the laboratory plot but fit well in the stellar plot reveals that a good deal of the scatter may be attributed to misidentifications, especially in the blending in of strong rare-earth lines in HR 774 with the Fe I lines. Our over-all impression is that there are many instances in which the principal contributor to a blend has not been properly chosen.

A general study of line identifications in Ba II stars extending the work of Warner (1963) would be a great aid to future abundance determinations. Such a study should be made at as high dispersion as possible and should extend over the entire accessible spectrum. Although equivalent-width measurements are generally not made shortward of λ4300, many *identifications* may not be made without information from this spectral region.

A value of $\Delta\theta_{\mathrm{exc}} = \theta(774) - \theta(\pi^6) = -0.04$ was derived from the Fe I curve of growth using the stellar oscillator strengths. The difference $\Delta\theta$ is of the same order as the probable error of its determination; the temperatures of the two stars must be very close. Values of the microturbulent velocity ξ_t and the damping parameter log $2a$ are given in Table 1.

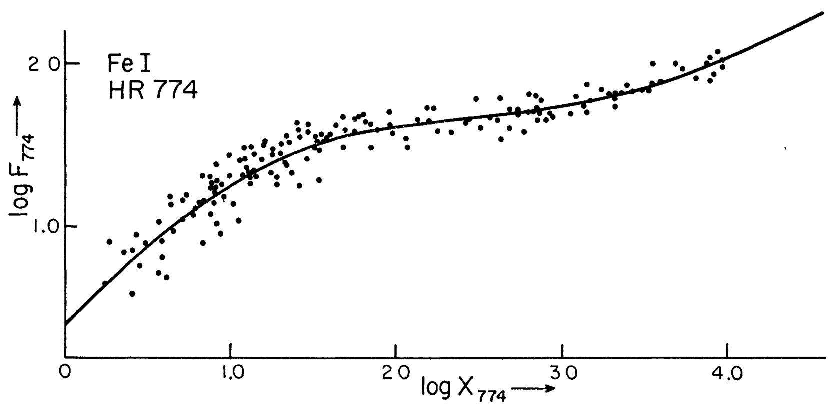

FIG. 2.—Fe I curve of growth for HR 774 using stellar f-values

TABLE 1

MICROTURBULENT VELOCITIES AND DAMPING PARAMETERS

	ξ_t	log $2a$
HR 774........	3.5	−2 0
π^6 Ori..........	4 8	−2.0

As we mentioned earlier, our strongest lines are undoubtedly subject to systematic errors, and for this reason the value of the damping constant cannot be accepted as realistic. (We obtain $\gamma \approx 4.6\ \gamma_{cl}$ by comparison with the Sun, where $\gamma \approx 25\ \gamma_{cl}$). *Differentially*, however, equality of the two values of log $2a$ implies near equality of the gas pressures in the two atmospheres, a result which is in good agreement with the differential electron pressure derived below.

We have also given reasons why considerably more faith can be put in the derived microturbulent velocities. Our result for HR 774 is in good agreement with the values of log v given by Warner and by Danziger, though it is somewhat smaller than that obtained by Nishimura from the red and infrared.

Differential θ's have been derived from the two photometric systems using relations between both color systems and spectral type. We derived our own ($B - V$, Sp.)-relation for luminosity class II stars, using data from Hoffleit (1964). There is an uncomfortable scatter, but the $B - V$ for π^6 Ori falls on the adopted mean relation. This mean relation is essentially that given by Harris (1963) for luminosity class III stars, shifted two-tenths of a spectral class earlier.

For HR 774 we used the tight relation derived by Neff for luminosity class III stars between spectral type and his index χ_1. This gave spectral type K2. A somewhat earlier spectral type would presumably have been derived if a spectral-type relation had been available for luminosity class II stars, but the resulting temperature would not have been much different. (A K1 II has nearly the same temperature as a K2 III). A value $\Delta\theta = -0.03$ was obtained, using Keenan's (1963) calibration of temperature versus MK type. The accuracy of the determination is, again, of the same order as $\Delta\theta$ itself—not as good as if both stars had been observed on the same photometric system.

The electron pressure is one of the most difficult parameters to establish observationally in stars or in the laboratory. A procedure that is commonly used is to adopt $\Delta\theta$ from one or from several sources, and then obtain log P_e from the neutral and ionized metals, via the Saha equation. The disadvantage of this technique is that it leans very heavily on the assumption of local thermodynamic equilibrium (LTE). Without LTE, none of the usual color indices from which $\Delta\theta$ (ionization) is frequently derived are in any way a measure of the radiation field at $\lambda < 2500$ Å which is actually responsible for the ionization.

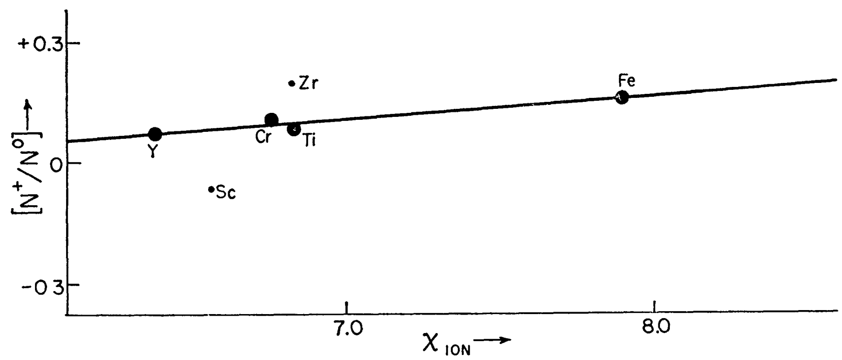

FIG. 3.—Differential ionization equilibrium in HR 774 and π^6 Ori

A second method is to attempt to obtain $\Delta\theta$ and log P_e *simultaneously*, from observations of several elements in two stages of ionization. This method is rarely used, because frequently only one or two elements are well observed in two stages of ionization. When the simultaneous determination can be made, it is more satisfying than the first method, since one has determined $\Delta\theta$ directly from the state of ionization.

Our observations included six elements in two stages of ionization. The range in χ_{ion} was only 1.5 eV, but we decided nonetheless to attempt the simultaneous differential determination, according to the relation

$$\left[\frac{N^+}{N^0}\right] = -[P_e] - \Delta\theta\chi_{\text{ion}} - \tfrac{5}{2}[\theta] .$$

We use the usual "bracket" notation (Helfer, Wallerstein, and Greenstein 1959). Total number densities were derived using the relative displacements of the curves of growth. The differential temperature dependence of the partition functions is negligible.

In the final determination, the points for Zr and Sc were given very low weight because of the number of points involved and their location on the curve of growth. The adopted mean relation was drawn through the four large points of Figure 3. In this way we obtained

$$\Delta\theta_{\text{ion}} = -0.04 , \quad \Delta \log P_e = +0.13 .$$

Because of the excellent agreement of this value of $\Delta\theta$ with the earlier determinations, we have adopted the above parameters in the determination of relative abundances. The mean differential conditions in HR 774 and π^6 Ori seem well determined.

Table 2 gives the mean physical conditions adopted for use in deriving abundances. The absolute values given here are not of great importance, since they are used only differentially. From the data in Table 2 we derived a value $[\kappa] = +0.08$ for the logarithmic opacity difference in the two atmospheres, using the tables of Bode (1965).

IV. DERIVED ABUNDANCES

In Table 3 we give the derived element-to-hydrogen ratios relative to π^6 Ori. The number of lines used in the abundance determination gives some idea of the reliability of the results, although the strength of the lines is also an important (and sometimes subtle) factor. For comparison, we also list the results of Nishimura along with the number of lines employed by him in the red and infrared.

It should be pointed out that Nishimura's results are relative to the star ϵ Vir, so that any differences in Nishimura's results and ours *could* be due to differences in the chemical composition of ϵ Vir and π^6 Ori. However, the excellent over-all agreement for all elements for which six lines or more were available leads one to believe that the abundances in both comparison stars are the same. For the well-determined cases of Ti, V, Cr, Fe, Co, and Ni, the average value of |Nishimura − Cowley| is 0.043 dex, or 10 per cent.

TABLE 2

ADOPTED MEAN PARAMETERS

	θ	$\log P_e$
HR 774	1 30	−1.27
π^6 Ori	1.26	−1.40

Barium itself does not appear in Table 2, because the resonance lines at λλ4554 and 4934 were too strong to be used on our plates. The [Ba/H] abundance may be estimated semiquantitatively from our red plates to be of the order of 0.8 dex. The over-all quality of our red plates was not considered high enough to justify including them in the present analysis.

V. DISCUSSION

A fairly plausible account of the abundances in the Ba II stars was given by the Burbidges. The material of these stars was originally the same as the Sun in chemical composition. At some stage in the stars' evolution, some of the material from the interior of the stars was subjected to neutron irradiation by a source of (slow) neutrons and then mixed with the surface layers. Warner showed that under these assumptions the excess heavy-element abundances could be explained on the basis of the addition of about 40 neutrons to the "seed" nucleus Fe^{56}. Since our abundances are in good agreement with those of Warner (note especially Pr), there is little that we can add to this over-all picture.

The value [Fe/H] of −0.18 for HR 774 deserves some attention. The accuracy of a differential iron-to-hydrogen determination is rarely much better than 0.2 dex, so that it is possible that the value −0.18 could be due to an error, say, in the opacity. However, the internal consistency of our own analysis, combined with the excellent agreement with the independent study by Nishimura, leads us to believe that a true underabundance of iron does exist for HR 774. We thus have an example of a star of intermediate type between the normal Ba II stars and the CH stars, which appear to be Population II analogues of the Ba II stars.

If one grants the reality of the [Fe/H] deficiency in HR 774, it then bears a relation to the ordinary Ba II and CH stars similar to that of α Boo to the normal giants and the halo red giants. Some of these stars are illustrated in Figure 4, in which we plot [Fe/H]

TABLE 3

ABUNDANCES

SPECIES	PRESENT STUDY		NISHIMURA	
	No of Lines	[El/H]	No. of Lines	[El/H]
Mg I	3	+0 05	...	...
Ca I	11	− .17	23	−0 1
Sc I	3	− .31	...	...
Sc II	2	− .56	...	...
Sc	...	− .4	9	− .1
Ti I	52	+ .03	...	...
Ti II	23	− .05	...	...
Ti	...	+ .01	29	0
V I	38	+ .05	45	+ .1
Cr I	50	− .05	...	...
Cr II	5	− .09	...	...
Cr	...	− .06	17	.0
Mn I	17	− .03	6	.0
Fe I	162	− .18	...	...
Fe II	12	− .18	...	...
Fe	...	− .18	121	− 2
Co I	18	− .11	14	.0
Ni I	29	− .12	48	− .1
Zn I	2	− .2	1	+ .8
Sr I	2	+ .6	8	+ .6
Y I	4	+ .23	...	...
Y II	5	+ .18	...	...
Y	...	+ .20	6	+ .2
Zr I	11	+ .25	...	...
Zr II	1	+ .34	...	...
Zr	...	+ .25	19	+ .3
Nb I	1	+ .5	...	...
Mo I	2	+ .1	.	. .
Ru I	2	+ .3	...	. .
La I	4	+ .43	. .	.
La II	1	+ .41	...	...
La	...	+ .43	14	+ 8
Ce II	12	+ .38	2	+ .5
Pr II	9	+ .88	1	+ .2
Nd II	11	+ .40	1	+ .9
Sm II	19	+ .28	...	...
Eu II	1	− .02	12	0
Gd II	8	+ .16	3	+0 5
W I	1	0.0	...	...

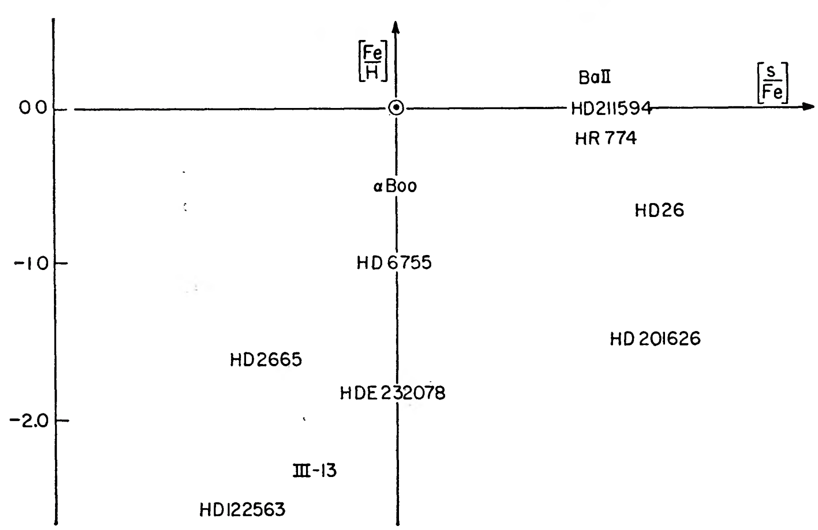

FIG. 4.—[Fe/H] versus [s/Fe] for several stars

versus [s-process/Fe]. We assume that all of the comparison stars have solar ($\odot$) abundances. Since we have plotted a single [s-process/Fe] ratio, which is a considerable simplification, we omit a scale on the abscissa—the diagram is semiquantitative. Table 4 lists some information about the stars in the figure.

The vertical spread among these stars is generally explained by enrichment of the interstellar medium, followed by star formation. The horizontal spread is a more recent result. It may be partially explained by the same basic hypothesis as the vertical spread, but also, if the excess s-process elements observed in the Ba II stars were formed in their interiors and mixed out to their surfaces, some stars should evolve to the right in Figure 4 during their lifetimes. We thus have the interesting possibility that α Boo may someday look like HR 774.

TABLE 4

DATA FOR FIGURE 4

Star	Type	Reference
HD 26	CH	Wallerstein and Greenstein (1964)
HD 2665	Halo red giant	Koelbloed (1967)
HD 6755	Halo red giant	Koelbloed (1967)
HD 122563.	Halo red giant	Pagel (1966)
HD 201626 . . .	CH	Wallerstein and Greenstein (1964)
HD 211594	Ba II	Warner (1965)
HDE 232078 . .	Halo red giant	Pagel (1966)
III–13	Halo red giant	Pagel (1966)
α Boo.	Metal-poor giant	Gratton (1954)

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