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STELLAR ROTATION, AND VIOLATIONS OF THE ODD-EVEN EFFECT IN THE MANGANESE STARS*

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ABSTRACT

Abundances of phosphorus and yttrium are examined in a number of slowly rotating Ap stars. It is argued that slow rotation is not a sufficient condition to establish the odd-Z abundance anomalies that are frequently observed for these elements. Implications for the diffusion hypothesis are discussed.

Subject headings: abundances, stellar — peculiar A stars — rotation, stellar

I. INTRODUCTION

In a recent paper, Cowley and Aikman (1975; Paper III) have called attention to several abundance anomalies in the manganese stars that appeared to be inexplicable in terms of nuclear astrophysics. Deviations from the odd-even abundance alternation at phosphorus, gallium, and yttrium appeared to conflict most strongly with nuclear predictions.

The high incidence of spectroscopic peculiarities among slowly rotating stars of types B, A, and early F is well established, and any theoretical explanation of the abundance anomalies is bound to gain in credibility if it can account for this observational result. If the abundance peculiarities in these stars are the result of diffusive separation (Michaud 1970), a plausible explanation of the correlation with stellar rotation can be made. It is quite reasonable to suppose that rapid rotation would break down the high degree of stability that is necessary to make the mechanism effective. The question naturally arises as to whether slow rotation alone is a sufficient condition for the abundance anomalies. The argument has recently been made that this *is* the case for the metallic-line A stars. In this paper we shall present arguments that slow rotation is not a sufficient condition for the odd-Z anomalies that appear in the manganese stars at phosphorus and yttrium.

Our assertion that slow rotation is not a sufficient condition for the odd-Z anomalies is based on the existence of a number of sharp-lined stars that do not show these effects. It is possible to make trenchant comparisons among stars with very nearly the same effective temperatures and surface gravities, some of which show the odd-Z anomalies and some of which do not.

II. THE COMPARISONS

An interesting contrast is presented by the stars ι Her and 3 Cen A. Fine analyses have been made of both stars (Kodiara and Scholz 1970; Hardorp 1968; see also the references cited in these papers). We have recently made line-identification studies in both stars on the basis of 2 Å mm^{-1} plates taken at the Dominion Astrophysical Observatory (DAO; one IIIa-J plate of ι Her) and at Kitt Peak National Observatory (KPNO; one IIIa-J plate and one 127-02 plate of 3 Cen—see Cowley and Hartoog 1975). Our identifications are in excellent agreement with the abundance work in the sense that all elements for which abundances have been given are present in the stars at very high confidence levels.

In Table 1 we give the atmospheric parameters for these stars taken from the abundance studies cited, along with four-color data from Lindeman and Hauck (1973). It is clear that the stars are very similar in atmospheric structure.

The similarities shown in Table 1 are in stark contrast to the abundances of phosphorus and gallium. Lines of P II are enormously strong and plentiful in 3 Cen A, leading to an excess with respect to the solar system of about 100. On the other hand, we were unable to make a positive identification of sulfur in this star. Hardorp's upper limit to the S abundance is roughly a tenth the solar value.

In ι Her the situation is reversed. Sulfur is identified at a very high confidence level, while phosphorus is weak or absent. A summary of the results of our element identification study for these two stars is given in Table 2. The notation and technique have been discussed by Hartoog, Cowley, and Cowley 1973; Cowley, Hartoog, and Cowley 1974; and Paper III). Briefly, H/N is the ratio of the number of coincidences (here with a tolerance of ± 0.06 Å) to the number of lines sought; f is the probability that the coincidences are due to chance, and s is the confidence level in

TABLE 1

PHOTOMETRIC AND ATMOSPHERIC PARAMETERS FOR ι HERCULIS AND 3 CENTAURUS A

Parameter	ι Her	3 Cen A
T_{eff} (K)........	20,200	19,350
$\log g$..........	3.75	3.87
$b - y$.........	−0.064	−0.062
c_1.............	0.294	0.251
β.............	2.661	2.668

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TABLE 2

SOME RESULTS OF ELEMENT IDENTIFICATIONS IN ι HERCULIS AND 3 CENTAURUS A

Parameter	ι Her	3 Cen A
Wavelength region (Å)....	3729–4650	3827–6717
P II:		
H/N..................	0/28	39/68
s.....................	−1.2	43.6
f.....................	1.00	< 0.005
S II:		
H/N..................	19/22	1/60
s.....................	17.1	0.2
f.....................	< 0.005	0.58
Ga II:		
H/N..................	1/4	4/10
s.....................	1.3	8.6
f.....................	0.27	< 0.005

standard deviations ("sigmas"). The parameter s for P II in 3 Cen is the largest that we have obtained so far, for any element, in any star!

If slow rotation were a sufficient condition to establish the odd-Z anomalies at phosphorus and gallium, it is reasonable to ask why they do not appear in ι Her, which has an equally low value of $v \sin i$. One possible answer to this question is that ι Her could be a rapidly rotating star seen pole-on. This contingency cannot be excluded; on the other hand, a variation of the P/S ratio appears among other sharp-lined manganese stars.

The variations in identification results for phosphorus and sulfur among 14 manganese stars are assembled in Table 3. All of the stars have been studied on 2.4 Å mm^{-1} plates taken either at KPNO or DAO. The list is in approximate order of temperature, as determined from the colors of the stars as well as determinations of Mihalas and Henshaw (1966) and Dworetsky and Vaughan (1973). The identifications that are considered clearly positive are italicized. Values for phosphorus in π^1 Boo are given in parentheses because two of the five stronger P II lines were not measured.

There can be no doubt that the detectability of both P and S (cf. ι Her) is easiest in the hottest stars because of the high excitation potentials of the lines of both elements. We must not, therefore, confuse confidence of detectabilities (i.e., small f's, large s's) with abundances, which remain to be determined for most of these stars. Moreover, all of the lines in question are weak in the cooler stars, and detectability is undoubtedly influenced by stellar rotation, plate grain, the density of the exposure, etc.

The star ι CrB is the coolest star in which P II lines are found. We measured equivalent widths of 8.7, 5.2, and 3.8 mÅ for λλ4602, 4588, and 4499, which yield an abundance of 6.4 for phosphorus (log H = 12.0). These figures are very uncertain and preliminary, but they suggest that the phosphorus odd-Z anomaly is less pronounced in ι CrB than in 3 Cen A, where Hardorp (1966) found ~7.5, or in κ Cnc, where Aller (1970) found 7.9 for the phosphorus abundance.

An interesting pair of stars that differs greatly in the P/S ratio is κ Cnc and HD 200311 which was studied by Adelman (1974). HD 200311 is a sharp-lined, hot, magnetic Ap star. Table 4 gives a summary of the photometric properties of these stars, from which it can be seen that the atmospheric structures must be quite similar. We again have the situation in two peculiar stars where we can identify phosphorus without sulfur in one, and sulfur without phosphorus in the other, and it is not possible to introduce the "pole-on" concept in a way that would allow us to conclude that the star with sulfur has normal abundances.

Although HD 200311 shows rare earth lines, which are atypical of the manganese stars, it has gallium, platinum, and mercury in common with them. It is an entirely open and interesting question, whether the variable P/S ratio seen in these two stars is just another example of the phenomenon illustrated in Table 3 among the (nonmagnetic) manganese stars, or whether the magnetic field of HD 200311 plays some decisive role, as may be the case with the rare earths. What *is* clear is that no solution to the abundance

TABLE 3

ELEMENT IDENTIFICATIONS OF PHOSPHORUS AND SULFUR IN FOURTEEN MANGANESE STARS

	P II			S II		
STAR	H/N	s	f	H/N	s	f
3 Cen A	*39/68*	*43.6*	*< 0.005*	0/28	−1.2	1.00
κ Cnc..........	*19/26*	*16.3*	*< 0.005*	1/22	0.0	0.72
HR 7664.......	*14/28*	*10.0*	*< 0.005*	2/22	1.2	0.23
μ Lep..........	3/26	1.8	0.10	1/22	0.3	0.51
υ Her..........	3/28	0.8	0.26	*6/22*	*4.2*	*< 0.005*
53 Tau.........	2/28	−0.2	0.67	5/22	2.6	0.015
φ Her..........	2/28	−0.6	0.82	*11/22*	*5.5*	*< 0.005*
π^1 Boo.........	(6/28)	(3.8)	(< 0.005)	*8/22*	*6.1*	*< 0.005*
46 Dra A	*13/28*	*4.6*	*< 0.005*	2/22	−0.7	0.83
HR 1800.......	4/28	1.0	0.24	*7/22*	*4.4*	*< 0.005*
HR 205........	1/28	0.0	0.62	1/22	0.5	0.36
46 Dra B.......	3/28	−0.8	0.83	4/22	0.7	0.32
ι CrB..........	*10/28*	*4.7*	*< 0.005*	2/22	0.5	0.55
HR 4072.......	4/32	1.4	0.15	7/24	2.4	0.03

TABLE 4

DATA FOR κ CANCRI AND HD 200311

Parameter	κ Cnc	HD 200311
Wavelength region (Å)....	3778–4635	3761–4913
Dispersion..............	2.4	4.5
$b - y$..................	−0.040	−0.044
c_1......................	0.548	0.470
β......................	2.722	2.715
P II:		
H/N..................	19/26	2/33
s.....................	16.3	−0.9
f.....................	< 0.005	0.88
S II:		
H/N..................	1/22	12/25
s.....................	−0.02	4.9
f.....................	0.72	< 0.005

differences is to be found in the rotational velocities alone.

We conclude that slow rotation cannot be a sufficient condition for the phosphorus odd-Z anomaly.

We must leave the case of gallium for a future study. Wavelengths of only four Ga II lines are accurately known (Bidelman and Corliss 1962); two of these lines are actually close blends of Ga II lines, and another was described as hazy. The strongest line, λ4261.995, is close to Cr II λ4261.92. While we do not doubt the gallium identification in a number of stars, we ourselves have a number of results on gallium of marginal statistical significance. We would prefer to study these cases in more detail before commenting on the variability of gallium in the manganese stars. We turn, therefore, to the third odd-Z anomaly, yttrium.

Of the manganese stars for which abundances studies are available, ϕ Her shows the greatest yttrium odd-Z anomaly (see Table 5 and Paper III). It is interesting to contrast ϕ Her with the ultra–sharp-lined star 53 Tau, studied most recently by Strom (1969), where the Y/Sr ratio is within a factor of 2 of the solar value. There are several other important respects in which 53 Tau differs from ϕ Her as well as other manganese stars of similar temperature. It has no λ3984 (Hg II), nor is there any evidence for platinum. Although an abundance for gallium has been reported by several workers using a single Ga I line, we did not measure the line on a 2.4 Å mm^{-1} DAO plate, and we share the reservations of Auer *et al.* (1966) concerning the identification of λ4172 as Ga I. Scandium is normal in 53 Tau, while it is enormously enhanced in ϕ Her. On the other hand, the Mn/H ratio is higher in 53 Tau than ϕ Her, and may possibly represent an additional odd-Z anomaly (see Paper III).

In Table 5 we examine the yttrium anomaly. The statistical results are based on wavelength measurements of ~2 Å mm^{-1} plates. Data are given for a few of the hotter magnetic Ap stars as well as the four manganese stars. All of the stars have $v \sin i \lesssim$ 20 km s^{-1}.

It is apparent that the yttrium-to-strontium ratio is highly variable, ranging over more than four orders of magnitude in the data presented. Slow rotation alone is obviously unable to account for these observations.

In the three magnetic Ap stars, the Y/Sr ratio appears to be significantly less than the solar system value, while the rare earth cerium is overabundant by factors of the order of 10^2–10^3. In the manganese stars, both the second and third spectra of the lanthanides are characteristically absent. The atomic properties of yttrium, lanthanum, and cerium are remarkably similar. Their distinctive abundance patterns in the manganese stars on the one hand and in certain magnetic Ap stars on the other present a challenging problem to any theory based on the atomic properties of these elements.

III. DISCUSSION

The calculations of Michaud (1970) were of an exploratory nature. While more elaborate calculations have been made by Michaud and his co-workers (cf. Michaud 1973) for helium and mercury, the odd-Z elements have not been discussed since the original paper. So many complications were omitted from this study that it does not appear useful to compare the material in § II with the results of that paper without allowing for additional factors such as the age of the

TABLE 5

THE YTTRIUM ANOMALY

OBJECT	$T_{\rm eff}$ (K)	STATISTICAL RESULTS FOR Y II: H/N	s	f	Y/Sr ABUNDANCE RATIO
Magnetic Ap stars:					
HR 4854.........	10,550[1]	7/23	0.8	0.28[12]	0.001[2]
HR 465..........	10,610[3]	21/40	2.0	0.04[8]	
HR 4816.........	10,000[1]	5/23	−0.3	0.69[6]	0.007[2]
Manganese stars:					
ϕ Her............	12,500[11]	22/24	15.0	< 0.01[12]	60[11]
ι CrB............	11,000[9]	18/24	11.0	< 0.005[12]	10[5]
53 Tau...........	11,000–12,000[10]	4/24	2.0	0.06[12]	0.3[10]
HR 4072.........	9650[7]	23/25	11.0	< 0.01[6]	0.4[7]
Meteorites..........	...	...	...	...	0.18[4]

NOTES.—[1]Adelman 1973*a*; [2]Adelman 1973*b*; [3]Aller 1972; [4]Cameron 1970; [5]Cowley and Aikman 1975; [6]Cowley *et al.* 1974; [7]Guthrie 1966; [8]Hartoog *et al.* 1973; [9]Ross and Aller 1970; [10]Strom 1970; [11]Zimmerman, Aller, and Ross 1970; [12]This paper.

star, atmospheric turbulence, and the influence of magnetic fields.

The differences in chemical composition among Ap stars of the same subclassification have been emphasized by the Jascheks (1967). Our comparisons show that the phosphorus and yttrium odd-Z anomalies do not occur in every star that is *slowly rotating*. These anomalies in the manganese stars have a claimant need for an explanation that does not involve nuclear physics.

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