THE ASTROPHYSICAL JOURNAL, **254**:191–195, 1982 March 1

POSSIBLE IRON ABUNDANCE VARIATIONS AMONG SUPERFICIALLY NORMAL A STARS

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Received: 1981 May 15; accepted 1981 September 2

ABSTRACT

High-dispersion spectra of a sample of superficially normal late B and early A stars have been examined by the method of wavelength coincidence statistics (WCS). The sample was selected primarily on the basis of low projected rotational velocities. Two lists of approximately 70 strong and weak Fe II lines were used. The line intensities were predicted for 10,000 K. The WCS are influenced by $v \sin i$, effective temperature, and iron abundance in a predictable way. On the basis of WCS for stars having published fine analyses, we suggest that several stars in our sample may be deficient in iron.

The kinematic properties of the sample indicate a young population. The iron-deficient stars may simply have sharper-lined spectra than the weak-lined A or Lambda Bootis stars which were recognized some time ago. Weak-lined stars may represent a sizable fraction of the late B and early A stars. We suggest that a part of their peculiar chemistry may arise from small ($\sim$0.3 dex, rms) abundance fluctuations in the interstellar medium. Other possibilities are mentioned.

Subject headings: stars: abundances — stars: early-type — stars: spectrum variables — stars: peculiar A

I. INTRODUCTION

Normal A stars play an important role in our overall understanding of chemically peculiar (CP) stars, which are so common on the upper main sequence.

According to the diffusion hypothesis, all CP stars may be explained in terms of chemical differentiation, *in situ*, from a primitive abundance pattern which is assumed by default to be that of the Sun. It is natural to assume the "normal" stars have this same, primitive, abundance pattern.

There has never been a hard observational basis for the assertion that all stars classified as late B or early A, with no noted peculiarities, do in fact have abundances within 0.1 dex of solar values, and there is mounting evidence that this is not so. We first call attention to the literature on the so-called λ Bootis stars. This chemically heterogeneous (Baschek and Searle 1969) group of objects with weak metal lines is generally accepted as being composed of A stars with underabundant metals. There was a special place in the nuclear theory of CP stars for the λ Bootis stars (Kodaira 1969), but they are not at present a part of the diffusion picture. Indeed, they appear to have been forgotten as a distinct class of A stars. Recent reviews of CP stars (Bonsack and Wolff 1980; Hack 1976; Baschek 1974) have not discussed them. Preston (1974) gives them only passing references, directing the reader to Sargent's (1967) paper. Thus, apparently, one must go to articles written prior to Michaud's (1970) presentation of the diffusion hypothesis in order to find a discussion of them.

In spite of their present "non-status" it is difficult to deny such objects. Baschek and Searle made a rather thorough study of them, concluding that the metals were indeed underabundant by a factor of about 3.

The work of Wolff and Preston (1978), Preston (1977), and Dworetsky (1974, 1976) provided the basis for Cowley's (1980) high-resolution survey of superficially normal stars. This work has been continued, and now includes some 33 stars with (nearly) normal spectra in the range B8 to A5, with $v \sin i$ less than ~ 25 km s^{-1} (see Table 1).

Because of the smaller $v \sin i$'s the spectra of these stars are simpler to analyze than the λ Bootis stars, where one is forced to work with strong lines. Sadakane (1981) has now analyzed two of these objects, and finds significant underabundances of a number of iron-group elements in addition to that of iron itself. In the case of HR 7338, the iron deficiency is about 0.7 dex, well outside the uncertainties of the analytic method (probably less than $\sim$ 0.3 dex).

TABLE 1

PROPERTIES OF LATE B AND A STARS

Star	HD	Sp	$v \sin i$ (km s^{-1})	(H/N) × 100	$(b-y)_0$	U	V	W
23 Cas	4382	B8 III	25	32	−0.058	+12	−10	−5
HR 562	11905	B8 III	7	38	−0.061	+8	−8	−8
68 Tau	27962	A2 V	8	76	+0.00	+40	−23	+4
μ Lep	33904	Hg-Mn	20	40	−0.052	+17	−21	−10
36 Aur	40394	B9.5p	12	74	−0.03	+19	−8	+2
64 Ori	41040	B8 V	<5	62	−0.058	−13	−7	−3
γ Gem	47105	A0 V	7	81	+0.004	−15	−5	+2
α CMa	48915	A1 V	16	83	−0.007	−15	−0	−11
21 Lyn	58142	A1 V	15	51	−0.005	+27	−6	+7
HR 2844	58661	B8 III	27	7	−0.06	+24	−26	+7
κ Cnc	78316	Hg-Mn	6	76	−0.063	+20	−16	+5
θ Leo	97633	A2 V	18	56	+0.003	+4	−14	+2
95 Leo	103578	A3 V	5	80	+0.041	−6	+5	−20
22 Com	109307	A5 III	8	58	+0.01	+7	−12	0
HR 5422	127304	A0 Vs	7	74	−0.015	+8	−11	−4
HR 6127	148330	A1 V	10	60	−0.010	+5	+2	−8
28 Her	149121	B9.5 III	6	79	−0.029	+16	−4	−24
η Oph	155125	A2 V	12	56	+0.028	+3	+9	+2
HR 6506	158261	A1 V	10	73	−0.008	+28	−19	+8
38 Dra	169027	A0 V	23	16	−0.04	−80	−21	+7
α Lyr	172167	A0 V	17	19	+0.001	+16	−6	−8
HR 7098	174567	A0 Vs	7	72	−0.011	−11	−9	+1
HR 7338	181470	A0 III	5	77	+0.003	+20	−7	−5
46 Aql	186122	B9 III	<3	91	−0.055	+13	−30	+6
HR 7512	186568	B8 III	16	45	−0.038	+1	−12	+6
κ Cep	192907	B9 III	25	45	−0.016	+4	−25	−7
ν Cap	193432	B9.5 V	15	43	−0.016	+2	−6	−5
HR 7878	196426	B8 IIIp	6	63	−0.057	+1	−32	+4
HR 8094	201433	B9 V	13	49	−0.048	+7	−27	−9
HR 8226	204754	B9.5 V	12	21	−0.053	+10	−8	−1
HR 8348	207840	B8 III	20	37	−0.06	+24	−9	+14
21 Peg	209459	B9.5 V	<4	81	−0.017	+2	−4	−6
o Peg	214994	A1 V	7	79	−0.009	−5	+6	−8
HR 8873	219827	B8 III	7	62	−0.055	+13	−9	−10

II. STARS NEAR A0 WITH SHARP-LINED SPECTRA

Table 1 gives spectral types, colors, and space motions (km s^{-1} relative to the Sun) of 34 late B and early A stars. With few exceptions, the stars have been assigned MK types by Cowley *et al.* (1969, hereafter C^2J^2) or Cowley (1972). The type for 38 Dra is from Adelman and Sargent (1972), while that for HR 6127 is from Bonsack (1974). The latter star may be a spectrum variable (Ziznovsky 1980). Some of the stars are known to be chemically peculiar in the traditional sense of overabundances. Two well-studied mercury-manganese stars, μ Lep and κ Cnc, are included as "fiducial" points for the hotter stars such as 64 Ori. Others, such as 46 Aql and HR 562, were discovered to be peculiar only by observations beyond the MK domain (see Wolff and Wolff 1974, 1976).

The unreddened $(b-y)_0$ indices are from Philip, Miller, and Relyea (1976). In a few cases these are supplemented by Geneva photometry (Rufener 1977). The reddening-free parameters X of Cramer and Maeder (1979, 1980) were converted to effective temperatures using an empirical relation which they give. These temperatures were transformed into $(b-y)_0$ using the theoretical colors of Relyea and Kurucz (1978). For 38 Dra, we converted the effective temperature of Adelman and Sargent (1972) into $b-y$ via the theoretical colors. The inferred values of $(b-y)_0$ are given in Table 1 to two decimals.

Cowley and Aikman (1980) have shown that abundance estimates can be obtained from the kind of wavelength coincidence statistics (WCS) which have been performed for all of these stars. These estimates were judged to be uncertain by typically a factor of 3. One chief uncertainty is the dependence of the visibility of weak lines on $v \sin i$. This is illustrated in Figure 1, where the percentage of coincidences on strong Fe II lines is plotted versus $v \sin i$. The $v \sin i$'s were taken from the references given by Cowley and Aikman. When published values were not available, visual estimates were made by interpolating between published "standards." These estimates are not intended to be definitive, but the horizontal error bars for HR 7512 are believed to be liberal. The vertical bars for HR 7512 and HR 7878 are made by adding and subtracting twice the square root of the variance of the number of concidences on the Monte Carlo nonsense wavelengths (see below).

The symbols used in Table 2 are those used in numerous papers on WCS (see Cowley 1976). Briefly, H/N is the ratio of coincidences, or hits at ± 0.06 Å, to the

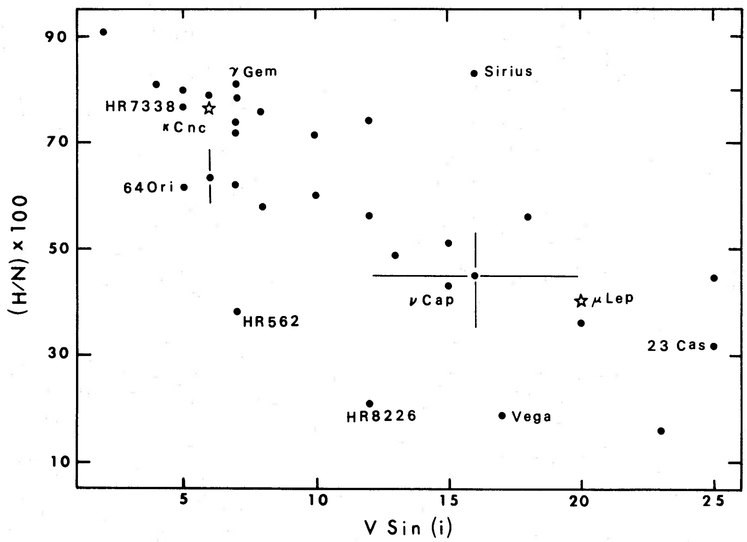

FIG. 1.—Percentage coincidences on a set of Fe II lines versus $v \sin i$. Open star symbols indicate hot mercury-manganese stars with normal or mildly enhanced iron abundances. The remaining stars are superficially normal. The known deficiency, normality, and excess of iron in Vega, ν Cap, and Sirius are clearly illustrated. Several other stars may be deficient in iron. HR 562 and HR 8226 are suggested candidates for iron deficiencies, and several of the other stars may also be iron poor.

number of lines sought. The parameter p gives the probability, based on 200 Monte Carlo trials, that the H hits occur by chance, while S, roughly speaking, is the significance of the hits in standard deviations.

The data for Figure 1 were taken from Table 2. Coincidence statistics are given for two Fe II lists. Set C, used in Figure 1, consists of the strongest Fe II lines in the region of the stellar spectra for a temperature of roughly 10,000 K. For all of the Fe II lines in the tabulation of Kurucz and Peytremann (1975) we computed an intensity parameter, defined as $\log (gf) - 0.5\chi$. In Set C this parameter is in the range (-3.2 to -5.4) while in Set D the range is (-5.7 to -6.3).

If we are careful to consider stars with similar line widths and effective temperatures, we may estimate relative abundances, at least qualitatively, from data of this kind. Consider, for example, the stars Sirius, Vega, and ν Cap. Abundances studies (Kurucz and Furenlid 1979; Dreiling and Bell 1980; Sadakane and Nishimura 1979, 1980; Adelman 1980) indicate that iron is overabundant by about a factor of 3 in Sirius, underabundant by about same factor in Vega, and normal in ν Cap. The relative positions of these three stars in Figure 1 are in good agreement with this. Similarly, the iron abundances found by Adelman and Sargent (1972) for the old disk population star 38 Dra, and by Allen (1977) for the stars 23 Cas and HR 2844 (off the figure, to the lower right) are consistent with their positions in Figure 1, although the quantitative abundance differences found are each arguably solar within the uncertainties. Since these results were obtained by independent workers, it is gratifying to see that our qualitative assessment, based on uniform material, supports the abundance work so clearly.

While virtually all of the stars in the sample give highly significant ($p < 0.005$) results with the stronger lines, the

TABLE 2

WAVELENGTH COINCIDENCE STATISTICS FOR Fe II LINES

Star	Set C			Set D		
	H/N	p	S	H/N	p	S
23 Cas	22/69	<0.005	15.9	2/60	0.43	0.4
HR 562	27/71	<0.005	9.2	4/60	0.58	−0.1
68 Tau	54/71	<0.005	17.8	13/59	0.02	2.5
μ Lep	27/67	<0.005	16.8	5/57	0.04	2.5
36 Aur	51/69	<0.005	24.6	13/58	0.005	5.5
64 Ori	44/71	<0.005	20.5	17/59	0.125	1.4
γ Gem	51/63	<0.005	19.6	15/60	0.005	4.1
α CMa	48/58	<0.005	24.9	8/54	0.025	2.6
21 Lyn	35/69	<0.005	16.0	8/58	0.01	2.6
HR 2844	4/55	<0.025	2.5	0/54	1.0	−1.1
κ Cnc	44/58	<0.005	26.1	5/54	0.11	1.7
θ Leo	40/71	<0.005	19.2	7/61	0.05	1.9
95 Leo	57/71	<0.005	18.0	13/59	0.03	2.2
22 Com	41/71	<0.005	13.3	11/61	0.02	2.2
HR 5422	52/70	<0.005	17.6	13/59	<0.005	3.9
HR 6127	42/70	<0.005	17.1	5/59	0.43	0.3
28 Her	55/70	<0.005	23.9	13/59	<0.005	4.5
η Oph	40/71	<0.005	22.0	8/59	0.02	2.5
HR 6506	52/71	<0.005	23.1	9/59	0.01	2.4
38 Dra	11/69	<0.005	6.2	3/59	0.25	1.0
α Lyr	13/70	<0.005	5.9	4/59	0.23	1.1
HR 7098	50/69	<0.005	20.1	12/58	<0.005	3.6
HR 7338	53/69	<0.005	22.4	9/60	0.02	2.4
46 Aql	61/67	<0.005	23.6	22/57	<0.005	8.5
HR 7512	31/69	<0.005	15.4	7/60	0.03	2.4
κ Cep	30/67	<0.005	19.0	3/57	0.32	0.8
ν Cap	30/69	<0.005	19.2	3/58	0.38	0.6
HR 7878	41/65	<0.005	18.5	7/58	0.08	1.8
HR 8094	35/71	<0.005	15.6	3/59	0.70	−0.3
HR 8226	14/67	<0.005	9.3	1/57	0.80	−0.4
HR 8348	25/68	<0.005	15.3	5/58	0.08	1.9
21 Peg	57/70	<0.005	16.2	18/59	<0.005	3.6
ο Peg	56/71	<0.005	21.7	18/59	<0.005	5.9
HR 8873	44/71	<0.005	22.6	7/58	0.005	2.6

list of weaker lines, Set D, allows additional discrimination. However, stars with larger values of $v \sin i$ or high temperatures give significances with this set only if they have exceptionally strong Fe II. Examples of such stars are 46 Aql and 36 Aur.

Peculiarities in 36 Aur were noted by C^2J^2, who called attention to Fe II 4005 Å. Perhaps this star should not be considered "superficially normal," but we shall not exclude it from this following discussion, because it does not have a particularly rich line spectrum. Similar remarks could be made for a number of stars in Table 1.

III. ADDITIONAL METAL-POOR STARS IN THE SAMPLE

We believe that Figure 1 and Tables 1 and 2 strongly suggest that some of the stars not already analyzed for abundances may also be sub-solar in their iron. The most promising candidates are HR 562 and HR 8226. The stars 64 Ori and HR 7878 may also be iron poor. The $(b - y)_0$ values show that these objects are among the hotter stars in our sample. They are in a temperature domain where double ionization of iron is surely of influence, but we do not yet have reliable abundances for any of the stars in this temperature range. For this reason, we included the hot manganese stars μ Lep and κ Cnc to serve as fiducial marks.

According to Heacox (1979, $\xi_t = 3$ km s^{-1}), Allen (1977), and Kodaira and Takada (1978), the abundance of iron in μ Lep is respectively 7.7, 7.4, and 7.9 (log H = 12). For κ Cnc, the corresponding results are 7.9, 7.6, and 7.6. Dworetsky (1971) states that κ Cnc has an iron abundance 0.3 dex above the solar value. Another useful reference point is 23 Cas, for which Allen reported an iron abundance of 7.5. If we adopt 7.5 as the solar value (Holweger 1979), we see that these reference stars all have either solar iron or mild enhancements.

A comparison of WCS and $v \sin i$'s of HR 562 and HR 8226 with those of μ Lep and 23 Cas makes it clear why we suggest they are underabundant in iron.

HR 562 is itself a mercury-manganese star discovered in the survey of Wolff and Wolff. Its spectroscopic and binary properties were studied by Aikman (1976), Hube (1970), and Wolff and Preston (1978). The MK type assigned by C^2J^2, B8 III, is known to spectroscopists to contain a high percentage of manganese stars. There is, moreover, precedent for iron deficiencies in these stars (Cowley 1981).

Fekel (1979) has made a detailed study of the multiple system 64 Ori. The entries shown in Table 2 are for the single-lined phase. At the double-lined phase, which we have also analyzed, the two sharp-lined components appear nearly identical on casual inspection. However, WCS shows that there are unmistakable differences between the two stars, one component having decidedly lower significance for the hits on most atomic spectra, including Fe II.

IV. DUPLICITY

Dr. M. M. Dworetsky has suggested that we make a further examination of the possible influence of duplicity on our results. The presence of light from a secondary star will weaken the spectral lines of the primary in all but a few unusual circumstances. Thus, if duplicity is ignored, systematic errors are introduced which will make the abundances appear to be lower in the primary star than they really are.

Equivalent widths in the primary spectrum will all be decreased by a factor of $1/(1 + S/P)$, where S and P are the intensities in the continua of the secondary and primary stars. If the abundances rest on weak lines, then the factor $(1 + S/P)$ should be applied to abundances which have been determined without considering the light of the secondary component.

Considerable information is available regarding the duplicity of the stars in Tables 1 and 2, but unfortunately no sources are complete. Batten, Fletcher and Mann (1978) have entries for 23 Cas (SB1), κ Cnc (SB1), 95 Leo (SB1), HR 6506 (SB1), and HR 7338 (SB2).

Possibly the most relevant fact is that HR 7338, the extreme iron-poor star analyzed by Sadakane (1981) was considered by Harper (1928) to be a double-lined binary. Petrie (1950) has estimated the magnitude difference in the two components to be 1.25 mag, which implies an upward correction to the abundance of 0.12 dex. This has been applied in our discussion above.

We agree with Harper, that the visibility of the secondary is very marginal. However, the secondary was readily detected by WCS using a radial velocity scan, and Ti II and Fe I were detected at very high confidence levels ($S = 7.3$, and 4.9 respectively), at a velocity of -57.6 km s^{-1} with respect to the primary. The epoch of our 2.4 Å mm^{-1} spectrogram is JD 2,443,709.8878.

We performed similar radial velocity scans, from -90 to $+90$ km s^{-1} for 23 Cas, HR 562, HR 2844, HR 6506, HR 8094, and 21 Peg. Apart from a few marginally significant results, expected by chance in the large number of trials that were made, the results of these scans were negative. This does not, of course, *prove* the absence of light from a secondary. Indeed, the presence of a secondary with very broad lines would be most difficult to detect by the techniques we have applied thus far.

The star HR 8094 (V389 Cyg) is probably a triple system (Bolton 1977). One of the stars has very sharp spectral lines, yet the presence of the other components thus far can only be inferred from the radial velocities. Gieseking and Seggewiss (1978) suggest that V389 Cyg may be a silicon star, but our material does not confirm that classification.

V. DISCUSSION

From the kinematics of the stars in Table 1, only 38 Dra, as already noted by Adelman and Sargent, appears to be old. Moreover, it was included in the present sample specifically as a result of that study. Generally, we are investigating fluctuations in the iron abundance among a young sample of stars.

Typical underabundances may be a factor of 2 or 3, exemplified by Vega. Sadakane's newest result is a much more substantial iron underabundance for HR 7338 (0.7 dex). We need to know how common these underbundances really are. In our sample of 31 stars (excluding 38

Dra), three have iron deficiencies of a factor of 2 or more which are already demonstrated by fine analyses, and we have suggested that several others may be deficient as well. If our sample is representative, 10 and perhaps 20% of what we once thought of as normal stars have weak mètal lines.

The presence of undetected secondary or tertiary stellar continua may reduce the actual fraction of iron-poor stars from the surprisingly large fractions mentioned above, but a very detailed study will be necessary to demonstrate that duplicity represents more than a perturbation on the systematics of such objects. For the present, we conclude that young, iron-poor stars represent a phenomenon relevant to the chemical history of the solar neighborhood.

It would not be easy to explain such ubiquitous underabundances by the same mechanism that accounts for the CP stars. A straightforward explanation for these objects is abundance fluctuations in the interstellar medium from which the stars formed. Other possibilities are separation of grains and gas, or a clumpy infall of nonsolar composition onto the galactic disk.

It is unlikely that a single mechanism will encompass both the metal-weak and metal-strong (CP) phenomena. Nevertheless, it is clear that primordial fluctuations of some elements, ranging up to an order of magnitude, can provide the observed diversity of abundances that is difficult to account for in terms of diffusion mechanisms alone.

It is a pleasure to acknowledge valuable discussions and/or correspondence with Drs. B. Baschek and J. G. Hills, and C. D. Scarfe. Dr. M. M. Dworetsky made a number of very useful suggestions. This research was supported in part by the U.S. National Science Foundation.

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