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NEW WAVELENGTHS FOR ASTRONOMICAL SPECTROSCOPY: APPLICATION TO Ap STARS*

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ABSTRACT

Many of the strong unidentified lines in Ap stars such as HR 4816, which are not especially rich in rare earths, may be identified with *predicted* lines of first and second spectra of iron-peak elements, notably of chromium. The wavelength tables of Kurucz and Peytremann are shown to provide the basis for a significant breakthrough in line identification and abundance work. A selected region from the spectrum of HR 4816 is discussed, and it is shown that most of the strong previously unidentified lines may be satisfactorily explained. Numerous spectroscopic conundrums are shown to be resolved by the presence of blends. Although many of these lines are absent from laboratory wavelength lists, their strengths may be predicted from the Kurucz-Peytremann semiempirical *gf*-values.

Subject headings: line identifications — stars: peculiar A

I. INTRODUCTION

It has been recognized for a long time that certain astronomical objects represent more powerful spectroscopic light sources than any yet constructed in a terrestrial laboratory. Among the better known examples of this fact are the forbidden lines that are emitted from gaseous nebulae and the solar corona. However, many permitted lines of neutral iron, so identified in the solar spectrum (Moore, Minnaert, and Houtgast 1966), do not appear on any published listing of Fe I lines excited in the laboratory.

In all of these cases, identifications were first made on the basis of the atomic energy levels, which had either been located by "other" lines, or, in the instance of the coronal lines, predicted with the help of atomic theory.

In the field of stellar spectroscopy, little systematic work has been done to identify features in early stars with the help of predicted wavelengths of lines that have not been observed in the laboratory. The impetus for the present study was provided by Dworetsky (1971), who showed that a fairly large number of features in the manganese stars HR 4072 and χ Lup could be explained as predicted lines in Fe II and Cr II.

The work of Kurucz and Peytremann (1975) provides the basis for a significant breakthrough in the problem of line identifications in stellar spectra. This monumental work lists wavelengths, both observed and predicted, *and* transition probabilities, which are essential as a means of assessing the actual contribution of a line to a stellar feature. The tables thus provide an indispensable supplement to the standard reference volumes for stellar line identifications: the *Multiplet Table* of Moore (1945), the *MIT Wavelength Tables* (Harrison 1939), and *NBS Monograph No. 145* (Meggers, Corliss, and Scribner 1975).

The rich spectra of Ap stars in the magnetic sequence are replete with lines that have not been satisfactorily identified. Indeed, the modicum of success achieved by Dworetsky in demonstrating the presence of predicted Cr II and Fe II lines in the (relatively) sparsely lined manganese-star spectra was an almost sure indication that the technique would prove to be of fundamental importance in the magnetic Ap star sequence. It is perhaps surprising that it has taken so long to apply this method in detail. The following remarks may explain the stellar spectroscopist's hesitancy to pick up this tool, and allay reservations concerning its careful use in future work.

In the traditional methods of line identification (cf. Moore 1954), the concept of a multiplet played a key role. This is primarily because the relative intensities of lines within a multiplet are only weakly dependent on the excitation conditions of most spectroscopic sources. The standard procedure to check out a possible identification is to see if "other" lines in the same multiplet are present with about the right strength. This powerful and valid procedure will always remain of great importance in line identification work; in the case of Ap stars, however, its usefulness may be exhausted before many of the lines are identified. This happens for several reasons: (1) Serious blending distorts stellar line intensities from predictions based on multiplet membership. (2) Often there is only one strong line in a multiplet. (3) The very concept of a

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multiplet (in LS coupling) breaks down as a result of perturbations of the LS coupling terms.

Even in Dworetsky's brief listing of "new" predicted multiplets, there are some strange-looking transitions, with $\Delta L = 2$, $\Delta S \neq 0$. One may certainly be permitted to ask if it is reasonable to expect lines from such a transition in a star, or whether the coincidences observed are merely due to the plethora of wavelengths that may be generated by subtraction of energy levels.

The presence of a group of lines in a stellar spectrum may often be established by unbiased statistical methods (cf. Hartoog, Cowley, and Cowley 1973). For individual lines, the Kurucz-Peytremann log gf-values make it possible to predict the strengths in a star, given an estimate of the abundance from lines whose identifications are (hopefully!) unambiguous.

This is not the place for a detailed discussion of the accuracy of the Kurucz-Peytremann semiempirical gf-values. For this, we refer the reader to Smith (1976) or Huber and Sandman (1977). However, it is necessary to remark, for the benefit of those unfamiliar with the details of the current work, that one must be prepared to accept uncertainties in the gf-values of the order of 0.5 dex as a matter of course. Occasionally, huge errors ($\sim$1–2 dex) occur. Sometimes one may anticipate the cases of largest uncertainty from the atomic structure of the levels involved in the line formation, but this is by no means straightforward, even for an experienced atomic spectroscopist. The working astronomer must simply keep these uncertainties constantly in mind. From a practical point of view, the uncertainties imply that out of a list of n "identifications," a certain fraction will be assigned incorrectly. This technique is too new for any kind of realistic estimate of what this fraction is. The present work indicates that for Cr I and II, the fraction is not prohibitively large.

The use of gf-values in line identification work was discussed by Tech (1971). These techniques can often provide an incisive answer to the question of whether at least the majority of a group of lines have been properly identified. However, the experienced stellar spectroscopist has often dealt successfully with these same problems with subjective and intangible criteria.

In the rest of this paper we shall first discuss the identification of lines, primarily of Cr I and II, in the spectrum of HR 4816 (HD 110066). We shall then turn to a discussion of specific blends in Ap stars, whose anomalous and puzzling behavior can now be explained on the basis of predicted lines of iron-peak spectra, lines which have never been observed in the laboratory.

II. PREDICTED LINES OF Cr II IN HR 4816

We generated a list of all Cr II lines that could be obtained by subtraction of the energy levels given by Sugar and Corliss (1977), subject only to the selection rule on parity and $\Delta J = 0 \pm 1$, $J = 0 \nrightarrow J = 0$. This list was then compared with the identification list of Bidelman (1976) for HR 4816. The preliminary comparison was auspicious; numerous previously unidentified stellar lines of moderate intensity and a few strong lines coincided to within ± 0.03 Å or better with lines on our list.

TABLE 1

COINCIDENCE TESTS OF PREDICTED Cr II LINES

H/N	p	S
Tolerance = ± 0.03 Å		
10/23	< 0.005	4.8
Tolerance = ± 0.06 Å		
17/23	< 0.005	5.6

In order to conclusively demonstrate the presence of previously unobserved Cr II lines, we selected "multiplets" on the basis of a coincidence of an unidentified line in HR 4816 with a predicted line. Each multiplet was "fingered" by the shortest-wavelength unidentified line within the range λλ3709–4750 whose intensity was ≥2 and whose position was within 0.03 Å of one of our generated wavelengths. The original "fingering" or pointer line was discarded, but the remaining lines in the multiplet were set aside for a statistical test. Altogether, some 26 multiplets were considered, with 115 lines, excluding the pointer lines. From these, a shorter list of 34 lines were prepared, for which log gf(Kurucz-Peytremann) $- 0.5\chi > 6.0$. Eleven of these lines have been observed in the laboratory. They were omitted from the final list of 23 predicted Cr II lines.

The 23 lines were tested for the significance of coincidences against wavelengths measured by A. Cowley on a Kitt Peak 2 Å mm^{-1} plate (cf. Cowley, Hartoog, and Cowley 1974). Table 1 gives the results of these tests, which were run for two tolerances for coincidence, ± 0.03 and ± 0.06. H/N is the number of coincidences, or "hits" out of N lines sought (here $N = 23$), p is the fraction of times H or more coincidences were found in 200 sets of 23 nonsense wavelengths, and S is, roughly, the significance of the result in standard deviations, assuming Gaussian statistics. A detailed discussion of this method is given by Hartoog, Cowley, and Cowley (1973).

It is of importance to note that the increased wavelength tolerance leads to an even more highly significant result, since the accuracy with which a symmetrical feature of moderate strength (line depth $\gtrsim 0.2$) can be measured is probably better than ± 0.01 Å. The reason why most stellar wavelengths do not agree with their laboratory positions is that they are perturbed by blends. However, especially in the less well-studied atomic spectra, the laboratory positions are not accurate, and this should be kept in mind with regard to predicted lines.

III. APPLICATION TO UNIDENTIFIED LINES

Now that we have demonstrated the presence of predicted lines of Cr II in HR 4816, let us turn to the

TABLE 2

STATISTICS OF THE REGION λλ4328–4404 OF HR 4816

Number of features measured for wavelength.........	208
Number of unidentified features.....................	101
Number of features with intensities ≥2..............	68
Number of unidentified features with intensities ≥2...	15

question of the importance of such lines in line-identification studies. In order to give a quantitative estimate, we give some figures in Table 2 concerning identifications from the region λλ4328.83–4404.76 of Bidelman's list for HR 4816. In our opinion, this work was carried out with great care, and is of equivalent quality and reliability to any similar published or unpublished study. However, the reader should note that the material was in fact not published, and is used here with Dr. Bidelman's kind permission.

It is not surprising that a large fraction of the weaker features are unidentified. We shall concentrate here on the stronger features with intensities ≥2. Between one-fifth and one-quarter of these were originally unidentified. Of these, the strong line λ*4330.22 is certainly primarily Ti II-94, but this identification is not in good accord with the data in the Multiplet Tables for Ti II multiplet 94, for which the wavelength given is λ4330.264. A discrepancy of 0.04 Å is much too large for a line as strong as this stellar feature. However, the MIT Tables give λ4330.243, reducing the discrepancy, and show this line to be more intense than others in the multiplet. Ironically, a subtraction of energy levels gives λ4330.204, so both the wavelength and relative intensity of this line were probably influenced by the physical conditions in the laboratory light source used.

Four of the features in Table 3 might (in hindsight) have been identified with weak Cr I lines from the study of Keiss (1953). The presence of such weak Cr I lines could undoubtedly have been established by traditional line-identification procedures, but only with an incongruous expenditure of effort. It is, however, a simple matter to make *calculations* of Cr I line strengths in HR 4816, based on the Kurucz-Peytremann *gf*-values. In this way, the plausibility of the identifications suggested in the last column of Table 3 has been established.

The measured stellar wavelengths (λ*) given to three decimals are from Cowley, Hartoog, and Cowley (1974); those given to two decimals are from Dr. Bidelman's wavelength list.

Equivalent widths for HR 4816 are given in column (2), while column (3) contains the logarithm of the abundance of the element (or elements) suggested for the identification which would be necessary to produce the measured equivalent width. Since our purpose here is to establish the credibility of the identifications and *not* to determine abundances, we have not made a great effort to optimize the model ($T_{\rm eff}$ = 9000 K, $\log g$ = 4.0, ξ_t = 2.0) or to assess the relative contribution of blends precisely. The assumed *gf* values were in all cases simply adopted from Kurucz and Peytremann (1975).

We do not pretend that all of the features in Table 3 have been completely explained—λ*4368.141 is particularly recalcitrant—but it is clear that great progress has been made. The Cr I and II lines give abundances which are usually in reasonable agreement with

TABLE 3

STRONG, PREVIOUSLY UNIDENTIFIED LINES IN THE REGION λλ4328–4404 OF HR 4816 (HD 110066)

λ* (1)	W_λ (mÅ) (2)	log *A* (log *H* = 12) (3)	Suggested Identification (4)
4330.22......	72	5.4	.24 Ti II-94 (λ from MIT Tables)
4332.980.....	48	8.2	.93 Cr II
		8.3	.95 Cr II
		8.3	.98 Mn II
4355.09......	48	9.0	.04 Cr II+
4356.637.....	57	7.5	.62 Cr I
		7.5	.68 Mn II
4357.15......	46	8.0	.16 Cr II
4359.007.....	53	..	.98 Cr I†
4368.141.....	129	>9.5	.17 Cr II+
4368.613.....	34	9.3	.63 Cr I+
4371.035.....	97	≳10.5	.98 Fe I+
4374.570.....	75	1.5	.46 Sc II-14
		8.7	.61 pCr II-179
4374.815.....	74	5.8	.83 Ti II-93
4380.781.....	81	10.0	.78 Cr I+
4382.529.....	79	9.0	.50 Cr I
4384.092.....	53	8.8	.08 Fe II (Dworetsky 1971)
4389.234.....	32	8.9	.26 Cr I
		9.0	.24 Fe I-2

† This line is not in the Kurucz-Peytremann list and therefore no *gf*-value is available for it. It arises between levels (31028.33–53963.05 cm^{-1}) of Sugar and Corliss (1977).

the results of Adelman (1973*a*), who obtained 8.6 for the chromium abundance in this star. Perfect agreement between his value and ours is not to be expected because of the differences in our models and systems of *gf*-values and uncertainties in the *gf*-values; nevertheless, strong support for the proposed identifications is obtained. The two Ti II lines in Table 3 give log (Ti/H) = 5.6, which may be compared with Adelman's value of 5.6. Of the features in Table 3 involving iron, only λ*4384.092 appears to be dominated by a line due to iron alone, viz., Fe II λ4384.08, a line originally predicted by Dworetsky (1971). The derived iron abundance for this line alone is 8.8; Adelman found 9.1 for iron.

IV. RESOLUTION OF SEVERAL SPECTROSCOPIC PARADOXES

In a perceptive discussion of stellar line-identification work, Tech (1971) points out that the extra effort necessary to identify some particularly refractory feature may not be justified unless the line is considered to be of "strategic importance." We shall discuss a number of such cases below. A general pattern running through all of these cases is a conflict between the results of our statistical element-identification surveys (cf. Cowley 1976), and an assessment based on an examination of the spectra themselves. Each of the instances discussed represents, in our opinions, a line of strategic importance to the understanding of the chemically peculiar stars.

a) *The Uranium Feature of λ3859.6*

Cowley, Aikman, and Fisher (1977) discuss four stars for which there is statistical support—usually only with marginal (95–99% confidence)—for the identification of U II. However, in their atlas of the λ3859 region, it can be seen that a moderately strong stellar feature near the expected position of U II λ3859.57 is common among the CP stars of the magnetic sequence. They noted the capricious behavior of the stellar wavelengths, and suggested the presence of an unidentified blend, but neither they nor other workers who had studied this question (cf. Adelman 1971, 1973*b*; Jashek and Jaschek 1974; Cowley and Adelman 1975) had been able to suggest a candidate for the blending line.

The Kurucz-Peytremann compilation lists four predicted lines which, together with U II λ3859.57, are capable of explaining all of the observations, with the possible exception of a peculiar profile in β CrB. Relevant data is listed in Table 4.

Equivalent widths of the stellar feature λ3859.6, as reported by Adelman (1971) or Cowley, Aikman, and Fisher (1977), range from 23 to 124 mÅ. Obviously, with one stellar feature, it is not possible to find unique abundances for Sc, Cr, and Mn. A number of representative calculations have been made, based on our standard $T_{\rm eff} = 9000$ K $\log g = 4$ model with $\xi_t = 2$ km s^{-1}. Two of these are reported in Table 4, and resulting equivalent widths are given in the last row of the table.

The primary contribution to the equivalent widths in these calculations is chromium, although Sc II and Mn I make some contribution to the larger equivalent width.

It is clear that the iron-peak blend has the potential for explaining the entire λ3859.6 blend, at least in some stars, and the important question is, can it do so in all? The crucial cases to look at are the stars where the U II identification has some statistical support: HR 465, HD 2453, HD 101065, and HD 221568.

The best case is HR 465. Here, the λ3859.6 feature is strongest in the rare-earth-maximum phase where the iron-peak spectra and chromium in particular are generally weak. Moreover, HR 465 is undoubtedly hotter than 9000 K, and this reduces the relative importance of lines of Cr I.

HD 221568 (Osawa's star) is probably the next best case for U II. Cr I is quite weak on DAO 9975 (cf. Cowley, Aikman, and Fisher 1977, Fig. 3*A*). The strong Cr I line λ3858.89 is very weak; compare its strength with that on DAO 10192 of the same star. Our identification program confirms the presence of both Cr I and Mn I on DAO 9975, but only at the 99.5 and 97% confidence levels, while among those stars which we describe as "chromium-manganese, rare-earth-moderate," Cr I and Mn I are identified at the 4–6 σ levels.

We shall not discuss HD 2453. The relevant data is given by Cowley, Aikman, and Fisher (1977). No line is measured in HD 101065 that is either U II λ3859.57 or an obvious blend of it and Fe I λ3859.91. Higher resolution spectra of this star are needed before one can realistically discuss the marginal identifications (cf. Cowley *et al.* 1977).

In summary, the predicted lines completely account for the ubiquitous presence of λ3859.6 in magnetic Ap stars, and, at least in our opinion, *strengthen* the case for presence of U II in the "lanthanide-rich Ap stars."

TABLE 4

IRON-PEAK CONTAMINANTS OF λ3859.6

λ(predicted)	Spectrum	log *gf*	χ	log (abundance) log $H = 12$	
3859.59........	Cr I	−1.48	3.39	8.5	8.8
3859.62........	Sc II	+0.10	4.01	3.0	3.5
3859.66........	Mn I	−2.92	3.37	8.0	8.5
3859.68........	Cr I	−2.40	2.54	8.5	8.8
W_λ (mÅ).....				48	77

b) *The "Fake"* Nd II *Line,* λ*4303.58*

This line is important because it is the strongest Nd II line listed in NBS Monograph 145, and it is present in considerable strength in stars which we have described as having a Nd-Sm anomaly—i.e., a remarkable weakness of the Nd II and Sm II spectra *relative to* La II, Ce II, Eu II, and Gd II. Our statistical analysis convinced us that there was a definite "hole" at these two lanthanides (cf. Cowley 1976), yet the presence of λ4303.58 made the validity of this classification seem doubtful.

The stellar line is almost certainly a line of Cr II predicted by Dworetsky (1971) and Kurucz and Peytremann to be at λ4303.566. If we use our standard 9000 K, $\log g = 4$ model and $\log gf = -2.52$ given by Kurucz and Peytremann, then a chromium abundance of 8.5 gives a 79 mÅ line. Since Cr II is very strong in β CrB and HR 7575, the prototype stars having Nd-Sm anomalies, this λ4303.58 paradox is, at least in our opinion, resolved.

The strategic significance of this particular line is related to the origin of the Ap abundance anomalies themselves. Once we grant that the Nd-Sm anomaly is real, and not just a manifestation of errors in our analysis, we have a piquant problem for the theoretician. We know of no theoretical scheme that has been proposed to explain this particular anomaly. Yet it could contain the key to the entire question of Ap star anomalies.

c) *The "Fake"* Ho II *Line at* λ*3810.7*

This line has an interesting history. It was originally misclassified as due to Ho I (cf. Meggers, Corliss, and Scribner 1961), and may thereby account for the tentative identification of Ho I in some stars. The stellar line is quite strong (~110 mÅ in HR 4816 with respect to the local continuum). It has been correctly identified by Adelman (1974) with a Cr II line which appears *weakly* in the study of Kiess (1951) but is not in the MIT or Multiplet Tables. Since Kiess was able to classify this line ($a^2S_{1/2}$–$z^2D^o{}_{3/2}$) it is not "predicted" in the sense of being unobserved in the laboratory! However, the Kurucz-Peytremann *gf*-values make it clear that this line is expected to be strong in Cr-rich stars such as HR 4816.

d) *The Blend at* λ*3848.0* (Tm II?)

The strongest line of Tm II listed by Meggers, Corliss, and Scribner (1975) is λ3848.02, with intensity 8900. The next strongest line in the region we usually survey is λ3795.75 (intensity 7100), but this line is deep in the core of H10. Tm is an odd-*Z*, heavy lanthanide; only ytterbium and lutetium are heavier. The presence or absence of Tm II is of some importance, since we find that the intermediate and heavy lanthanides are difficult to identify with confidence in the majority of the CP stars using only the region λλ3650–4750. The important question is whether there is a precipitous drop in the abundances of the intermediate and heavy lanthanides, or whether these spectra are lingering just below the threshold of detectability. We *have* been able to identify Tm II, at least with marginal confidence, in some stars (e.g., HD 101065).

TABLE 5

IRON-PEAK CONTRIBUTORS TO λ3848.1

Sp	λ	log (abundance) 7000 K		8000 K		log H = 12 Solar
Ti I........	3848.03	7.0	7.0	5.0	7.0	4.9
V I........	3848.07	6.0	6.0	4.0	6.0	3.9
Cr I........	3848.08	6.0	7.0	8.0	6.0	5.6
W_λ (mÅ)		9	44	65	3	

Kurucz and Peytremann list three possible iron-peak contributors to the stellar feature near λ3848.0. These are listed in Table 5, along with some representative calculations for (scaled) model atmospheres with $\log g = 4.0$ and effective temperatures of 8000 and 7000 K. Cooler models are chosen here because our statistical surveys have found marginal evidence for Tm II in the Am stars 32 Aqr and τ UMa (94.5% and 97% confidence). Dy II is surely present in both of these stars. The body of the table lists assumed abundances leading to the equivalent widths in mÅ given in the bottom row. Solar abundances for Ti, V, and Cr are given in the final column. As in our previous calculation, we have simply adopted the *gf*-values for the lines in question from Kurucz and Peytremann.

Table 5 shows that only Cr I λ3848.08 is important for this feature. Its wavelength is significantly different from that of Tm II λ3848.02 that the measured stellar wavelength will contain information about the relative importance of the two putative contributors. Our measured wavelengths and equivalent widths are as follows: γ Equ λ*3848.047 (W_λ = 38 mÅ), 32 Aqr λ*48.037 (W_λ = 30 mÅ), τ UMa λ*48.065 ($W_\lambda \approx$ 30: mÅ).

Chromium abundances of ~6.0 have recently been determined by Allen and Cowley (1977) for γ Equ and 32 Aqr. If the *gf*-value is correct, these abundances and the wavelength measurements indicate that Cr I is only a partial contributor to the stellar feature. A recent study of the region λλ3086–3807 of γ Equ by Adelman, Bidelman, and Pyper (1978) concludes that Tm II is positively identified in γ Equ.

It appears, then, that Tm II and possible other intermediate and heavy lanthanides are indeed present in some CP stars, but that their spectroscopic properties are such that they are only marginally detectable if one uses only the region λλ3650–4650.

e) Pt II λ*4046.45*

Kurucz and Peytremann list Cr II λ4046.38 and Cr I λ4046.44. The latter line is probably unimportant, but the former may explain some of the data presented by Cowley (1977) on the occurrence of Pt II in the magnetic CP stars. In HR 6958, for example, the statistical program showed no evidence for Pt II, yet a 39 mÅ line was measured at λ4046.375. A predicted

Fe I line in multiplet 1075 must be considered in the synthesis of this feature in the cooler stars. We have not made calculations for this particular feature.

f) Hg II *λ3984*

A great deal of attention has been devoted to the isotopic abundances of Hg in mercury (-manganese) stars, based solely on this feature (cf. Cowley and Aikman 1975; White *et al.* 1976). All workers have searched, wih no success, for contaminants which would obfuscate the interpretation of the feature in terms of Hg isotopes. *The Kurucz-Peytremann list contains no likely candidates for this feature.*

There is, however, a predicted Fe II line at λ3984.064 which is virtually coincident with ^{204}Hg II λ3984.066. The transition does not look as though it should be strong $[3d^6(a^3P)4py^4P^o{}_{5/2}$–$3d^6(^5D)4d^6S_{5/2}]$; the lower excitation potential is 7.49 eV. Nevertheless, it clearly deserves further consideration. A calculation with an 11,000 K $\log g = 4$ model shows that a solar abundance of iron (+7.5, $\log H = 12$) would produce an 11 mÅ line of Fe II at λ3984.06 if $\log gf$ were as high as −1.5; an overabundance of iron of a factor of 10 would, of course, produce the same line strength with $\log gf = -2.5$.

V. ON THE INCOMPLETENESS OF OUR KNOWLEDGE OF ATOMIC SPECTRA

Laboratory spectroscopists are well aware (Corliss 1978) that the spectra of many commonplace ions such as Ti I could be profitably reanalyzed with modern methods. The problem has been to find a justification for the expenditure of time and effort that such an undertaking would entail. The present study makes it clear that more extensive work in laboratory atomic spectroscopy would certainly be of use to the astronomer.

Our emphasis throughout this paper has focused on *wavelengths*, but it is clear that it would be of value to locate and classify many more *energy levels* in, for example, Cr I and II. We have generated our own lists of predicted lines of Fe II, Cr I, and Cr II using the data compiled by Reader and Sugar (1975) and Sugar and Corliss (1977). In a few cases, e.g., λ3984.06 of Fe II, lines of interest appeared on these lists that were not in the Kurucz-Peytremann Tables. In most instances, the reason the lines were missing from the latter tables is that one of the levels was incompletely specified in the basic atomic data; for example, no electron configuration was given. This made it impossible for Kurucz and Peytremann to calculate the transition probability by the semiempirical method for any line involving these levels. Moreover, the effects of these levels as *perturbers* could not be taken into account in calculations of transition probabilities, and this undoubtedly accounts for some of the major differences between the semiempirical calculations and laboratory measurements.

Predicted wavelengths are generated by Kurucz and Peytremann only through iron-group elements. For many spectra of trans–iron-peak ions it is palpably evident that our knowledge of the atomic spectra is not yet adequate for complete analyses of many stars. A few of the Ap stars are rich in the third spectra of the lanthanides, many of which are not completely analyzed, although much progress has been made since the pioneering study of Burbidge and Burbidge (1955) in which it was necessary to guess at both excitation and ionization potentials! Nevertheless, quite strong lines appear, for example, in the laboratory spectra of certain lanthanides (cf. Hussain 1973) and in the spectrum of HR 465, but it is not yet possible to assign these lines to a stage of ionization. Work on this problem is continuing in collaboration with Hannah Crosswhite of Argonne National Laboratory. Further details of this work will be published elsewhere, but we mention it here as an indication that we need to know much more about trans–iron-peak spectra before we can completely unravel the mysteries of CP stars.

VI. SUMMARY

The Kurucz-Peytremann Tables must take their place alongside the Multiplet Tables, the MIT Tables, and NBS Monograph No. 145 as basic references for line identification and abundance work. The stellar spectroscopist still requires more atomic data of all kinds—wavelengths energy levels, and transition probabilities—but the Kurucz-Peytremann work has enabled us to make a significant breakthrough in line identification work.

More than five years ago, George Preston called my (C. R. C.) attention to Dworetsky's work with predicted lines. I am grateful to Dr. Dworetsky for sending me a copy of his thesis, containing details of this work. We wish to thank Ingemar Furenlid for calling our attention to the usefulness of the Kurucz-Peytremann tables as a source of predicted wavelengths. Our own work draws heavily on the unpublished work of W. P. Bidelman and Diane Pyper. We thank Dr. Bidelman for this material, and also for comments on the present paper. S. J. Adelman, G. C. L. Aikman, and R. L. Kurucz were kind enough to read a preliminary version of this paper and have made a number of valuable suggestions. We are grateful for advice on various spectroscopic matters from Charles H. Corliss and Jack Sugar of the National Bureau of Standards. Thanks are due to Director van den Bergh and the staff of the Dominion Astrophysical Observatory for continued use of the facilities and various other courtesies. This research was supported by the National Science Foundation.

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