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COMMENTS ON THE IDENTIFICATION OF PROMETHIUM IN HR 465

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ABSTRACT

The general principles of line identification are discussed in connection with the identification of promethium in HR 465. It is shown that the Russell-Bowen formalism for the significance of wavelength coincidences is improper for most wavelength lists. An alternative procedure, due to E. Upton, is applied to HR 465, resulting in a 2 σ significance level for the wavelength coincidences alone. Coincidences in the character of the laboratory and stellar lines increase this significance to perhaps 2.8 σ (one chance in 200 of fortuitous occurrence).

This paper and its predecessor disagree primarily in optimism versus pessimism on a question which both agree cannot be conclusively resolved.

I. GENERAL REMARKS

Line identification work in stars must be based upon the intensities and character of the spectral lines as well as the wavelengths. The intensities that are available from laboratory studies can be extremely deceptive, but it is nevertheless folly to ignore them. A sure sign of a misidentification is the "presence" of weak lines when the strongest laboratory lines are absent.

The relative intensities within multiplets are an invaluable guide to identifications because these intensities are only weakly dependent on temperature and the laboratory estimates are far more reliable than from multiplet to multiplet. However, this method is less useful when the strongest lines in the laboratory spectrum are fairly weak in the star and when blending becomes a severe problem as in the case of HR 465. In any case the method was not available for Pm II because the analysis of the spectrum is not yet complete.

In the more complex spectra, especially the rare earths, the range of intensities tends to be smaller than, let us say, for calcium. When the strongest lines of an element are then weak, it becomes extremely difficult to establish an intensity correlation, even in the best of circumstances, as one may see from an examination of the weak-line portion of stellar curves of growth.

All of these factors entered full force in the matter of the identification of promethium in HR 465 (Aller and Cowley 1970, henceforth called Paper I). It was almost certain that the level of excitation in the star was greater than that in the laboratory study of Meggers, Scribner, and Bozman (1951), so that a meaningful intensity correlation was very difficult to establish indeed.

Nevertheless, what intensity data there is does indicate that the lines of laboratory intensity 80 or greater are stronger in HR 465 than those with $30 \leq I(\text{Lab}) < 80$. This may be seen from the percentage of coincidences which is greater with the stronger lines (73 percent versus 63 percent), and from the fact that it was possible to find the stronger lines $\lambda\lambda$4554.02 and 4529.23 on microphotometer tracings while a similar search for lines in the second intensity category was not always fruitful.

We have also examined the percentage of coincidences at ± 0.11 Å as a function of laboratory intensity for all of the lines in the list of Meggers *et al.* We find that only for the very weakest lines (intensity 1) does the observed percentage of coincidences fall below that expected for a random sample (cf. below). The correlation is by no means smooth, but in view of the general difficulty of this endeavor the most meaningful comparison is probably to subdivide the lines into two categories, weak and strong. When this is done, the observed percentages of coincidences support the identification.

The character of the spectrum is also worthy of examination. Many of the lines measured by Meggers *et al.* were noted as hazy, shaded to longer or shorter wavelengths. In Paper I, we called attention to the fact that out of six lines marked as peculiar in the laboratory, four were noted by Bidelman as possibly double in HR 465. Because of blending the probability that this would happen by chance is larger than one might expect—about one time in 10, according to our present methods of calculating probabilities of chance occurrences (see below).

In view of the difficulty of establishing a good intensity correlation, the demands upon the wavelength coincidences are larger. Our original work on the identification made use of a formulation due to Russell and Bowen (1929), which showed a very high level of significance could be attached to the coincidences.

Probably one of the most useful results to come out of exchanges of ideas with our scientific colleagues and adversaries about the promethium identification is concerned with the use of the Russell-Bowen formulae. Russell and Bowen determined the *a priori* probability of a wavelength coincidence under the assumption that the stellar lines were distributed at random throughout the wavelength interval examined. This assumption is certainly not valid in the case of the wavelength list for HR 465 or for the Rowland tables of solar wavelengths or probably for most other wavelength lists. The causes of this nonrandomness are a combination of instrumental resolution and psychological factors similar to those that were known in meridian-circle astronomy as personal equation. To the best of our knowledge, the importance of these effects in a statistical analysis of wavelength coincidences has not been previously recognized.

In the HR 465 wavelength list, the most obvious departure from randomness is an almost complete dearth of wavelength separations less than 0.1 Å. The Russell-Bowen formulation would predict many intervals smaller than this value. There is a similar paucity of large wavelength intervals, relative to the number that would be predicted from a random group of wavelengths with the same line density as HR 465.

The general effect of these two departures from nonrandomness is to tend to distribute the lines evenly in wavelength. Under such circumstances the probability of a wavelength coincidence is increased over the value that would be predicted for a random distribution of wavelengths.

The actual probabilities for the (nonrandom) wavelength list may be established empirically by a large number of trials, the so-called von Mises method. The basic assumption of the method is that if the promethium wavelengths are increased or decreased by a constant amount, the resulting wavelengths serve as a control set of wavelengths. Coincidences with this control set may then be compared with coincidences "on" wavelength. The use of this trenchant method was suggested to us by Dr. E. Upton of U.C.L.A. at the time when we first realized there were real difficulties in the Russell-Bowen method.

We have applied this test to the 153 promethium wavelengths discussed by Aller (1971). Independent, and somewhat more extensive, tests were made by Havnes and van den Heuvel (1972). The results of these tests are in agreement and clear. The significance level indicated by the assumption that the lines are distributed at random ($6\ \sigma$) is indeed much too optimistic. The present results indicate a significance level of $2\ \sigma$, or about one chance in 20 that the "on" wavelength coincidences may be attributed to chance. If this is combined with the analysis of the character of the lines, we have a probability of about one in 200 that both wavelength and character coincidences occur in a random sample of wavelengths.

II. COMMENTS ON THE PAPER BY WOLFF AND MORRISON

In our opinion Wolff and Morrison (1972) never get to the heart of the matter: that a nonrandomness in the stellar wavelength list precludes the use of the Russell-Bowen formalism. More recently, this question has been the subject of an independent study by Havnes and van den Heuvel (1972). Their discussion of the line statistics is almost identical with our own.

By and large, the discussion of Wolff and Morrison is argumentative and subject to rebuttal. For example:

1. We feel that the discussion of the 1966–1967 spectrum is of little relevance.
2. Their "simple empirical test" may be countered by repeating it with a tolerance of ±0.06 Å, which is perhaps a more appropriate tolerance. The results, which are shown in table 1, now favor the identification. (Our own statistical conclusions are based on an analysis of a larger data sample.)
3. The suggestion that the unstable element Tc should be present along with Pm depends upon certain assumptions concerning the relative abundances of the elements at the end of the nuclear processing which need not hold for HR 465.

We could continue line by line through their paper, but it does not seem appropriate to do so at this time.

We feel that the entire question of the identification of trace elements in stellar spectra is far more subtle than is usually supposed. Usually identifications are made or they are not made, and elements are classified as present or absent. For many elements this approach is far too simplistic. There should at least be an intermediate category which the theoretician may regard with due circumspection.

Surprisingly enough, we believe that Wolff and Morrison are in agreement with us that the promethium identification must be put into this intermediate category. The essential difference between us is that of optimism versus pessimism. To us, the positive factors seem very compelling. Nevertheless, there are a number of disturbing questions, some of which were raised by Wolff and Morrison. Although we are able to offer counter arguments, this does not mean that we feel they must be dismissed entirely. Only when the answers to these questions are completely understood, or when other incontrovertible evidence is found, can the identification be regarded as definitive. At one time we felt the wavelength coincidences alone gave such evidence, but the inapplicability of the Russell-Bowen formulation now precludes this conclusion.

Our present position is therefore about the same as it was when we wrote Paper I. The evidence is not inexorable, as we implied in the title, but it is highly suggestive. The possible presence of promethium in the 1960–1964 spectrum of HR 465 is a question with which astronomy must still contend.

TABLE 1

EMPIRICAL TESTS OF PROMETHIUM WAVELENGTH COINCIDENCES FOR 24 LINES

	Number of Coincidences	
	±0.11 Å Wolff and Morrison	±0.06 Å This Paper
Laboratory wavelength	16	13
Laboratory wavelength +1Å	18	9

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