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REMARKS ON THE PROPOSED IDENTIFICATION OF PROMETHIUM IN HR 465

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ABSTRACT

Spectrograms of HR 465 obtained in 1966–1967 show that Pm II was not present at that time. A rediscussion of the observations made in 1960–1961 indicates that there is doubt that Pm was ever present.

Recently, Aller and Cowley (1970) reported that lines of promethium may appear in the spectrum of HR 465. Since the longest-lived isotope of Pm has a half-life of only 18 years, the question of whether or not this element is actually present is crucial. In particular, the presence of Pm would imply that at least some of the abundance anomalies of the Sr-Cr-Eu stars must be the consequence of nuclear reactions on the surface. The star HR 465 is a spectrum variable with a period of 22–24 years (Preston and Wolff 1970), and the identification of Pm was based on spectrograms obtained in 1960–1961, near the time of rare-earth maximum. In the present paper, we show that in 1966–1967, when the rare-earth lines were much weaker, lines of Pm II were not detectable in the spectrum of HR 465 and that it is doubtful that they were present even in 1960–1961.

In their analysis, Aller and Cowley separated the lines of Pm II according to laboratory intensity into two groups, one consisting of 11 strong lines and the other of 33 weaker ones. Ten of the 11 strong lines lie longward of λ3870 and are in the wavelength region covered by the spectrograms discussed by Preston and Wolff (1970). We have searched for the 10 lines on four of these spectrograms (ECZ 5157, ECZ 5254, ECZ 5415, and ECZ 5840), and we find that seven of the 10 lines are no longer detectable (equivalent width <10 mÅ). The three lines that are present, λλ3892.16, 3919.09, and 3998.96, are due primarily to Cr II (167), Cr I (23), and Zr II (16). Eighteen of the weak lines fall in the wavelength region included on our spectrograms. Features are definitely present at the positions of three of these lines and may be present weakly at the positions of three others. Two additional lines are masked by Hγ, and the remaining 10 are absent. Promethium was not observable in HR 465 in 1966–1967. If it was ever present, the oblique-rotator hypothesis implies that, like the other rare earths, it was confined to a limited region of the stellar surface.

A critical examination of the data available for HR 465 shows that it is doubtful that Pm was present even in 1960–1961. The primary argument offered by Aller and Cowley in support of their proposed identification is that the number of coincidences between lines of Pm and features in HR 465 is approximately twice as great as would be expected on the basis of chance. In order to determine whether or not the number of coincidences is in fact significant, we have applied a simple empirical test that was suggested, in a slightly different context, by Cowley and Aller (private communication). We have increased each of the Pm II wavelengths by 1 Å and looked for lines within 0.11 Å (the wavelength tolerance used by Aller and Cowley) of these arbitrary wavelengths. For HR 465, we have used the list of line identifications prepared by Bidelman (private communication), from measurements of the spectrograms used by Aller and Cowley. We have only the portion of Bidelman's list that includes the region λλ3898–4730. If we exclude the two lines masked by Hγ, then 24 of the 44 Pm II lines discussed by Aller and Cowley fall in this region, and 16 are within 0.11 Å of features included in Bidelman's list. (Aller and Cowley identified several of the remaining lines on microphotometer tracings made from Bidelman's spectrograms. Since we do not have such a tracing, we will base our discussion solely on Bidelman's list of lines.) For the Pm II wavelengths each increased by 1 Å, we find 18 coincidences with features in Bidelman's list, a number which is *greater* than the number of coincidences found for the true Pm II wavelengths.

It is clear that Aller and Cowley greatly underestimated the probability of chance coincidences. One reason may be that, when calculating the expected number of coincidences, Aller and Cowley apparently did not allow for the variation of spectral density with wavelength. According to Bidelman's list, the density of lines is significantly greater between λ3898 and λ4200 (3.6 lines $Å^{-1}$) than between λ4400 and λ4530 (2.2 lines $Å^{-1}$). Fifteen of the Pm II lines listed in tables 1 and 2 of Aller and Cowley lie in the interval λλ3898–4200. Using, as did Aller and Cowley, the expression given by Russell and Bowen (1929) with a tolerance of 0.11 Å for an acceptable identification, we find that the expected number of coincidences for a spectral density of 3.6 lines $Å^{-1}$ is 8.2 ± 1.9 (s.d.). The actual number found was 12. One of the remaining three lines is absent; the other two were identified from microphotometer tracings and would not have been identified from the line list alone. Two of the lines longward of λ4200 are masked by Hγ, and nine lie beyond λ4400. Using a spectral density of 2.2 lines $Å^{-1}$, we find that the expected number of chance coincidences for nine lines is 3.5 ± 1.5. The number found is four. The remaining lines were identified from microphotometer tracings. From these calculations we conclude that, if the variation in spectral density with wavelength is taken into account and if identifications are based solely on the list of features used to determine the spectral density, then the number of coincidences does not significantly exceed the number to be expected on a purely random basis.

In making line identifications, one usually requires not only that a feature be present, but also that there be reasonable agreement between stellar and laboratory intensities and wavelengths. In the present instance, we note that there is no correlation between the laboratory intensities of the Pm II lines and the strengths of the corresponding stellar features. To be sure, any correlation would be reduced by unrecognized blending in HR 465 and by differences in thermodynamic properties, and in particular in temperature, between the stellar atmosphere and the laboratory source. Generally, however, the other rare-earth lines in the ultraviolet spectrum of HR 465 arise from levels with excitation potential less than 1.5 eV, and, if the same is true for Pm, the effect of a change in temperature should be small. It is true that features are apparently present at the wavelengths of all eleven of the strongest lines of Pm. However, as we have pointed out, the spectral density in HR 465 is so high that there is a reasonable possibility that the apparent coincidences are due to chance. The fact that there is no closer correlation between laboratory and stellar intensities means that no additional support for the identification of Pm can be obtained from a consideration of line intensities.

An examination of the agreement between the wavelengths of the Pm II lines and the associated stellar features indicates that this criterion also fails to strengthen the case in favor of the proposed identification. Using the formulation of Russell and Bowen (1929) with a wavelength tolerance of 0.11 Å and a spectral density of 3.6 lines $Å^{-1}$, we find that the average difference between the stellar and laboratory wavelengths that is to be expected in the case of random coincidence is 0.048 Å. For a spectral density of 2.2 lines $Å^{-1}$, the expected average residual is 0.051 Å. The actual value derived from the identifications given by Aller and Cowley is 0.050 Å. We note further that there is no predominance of small residuals. In contrast, 60 percent of the lines in HR 465 that were identified by Bidelman lie within 0.02 Å of the laboratory wavelengths, and just 10 percent disagree by more than 0.04 Å. It would be reasonable to expect similarly good agreement for Pm, since neither the laboratory (Meggers, Scribner, and Bozman 1951) nor the stellar wavelengths are likely to be in error by more than 0.02 Å. Promethium does show hyperfine structure, but this fact probably does not explain the poor wavelength agreement. First, since the hyperfine structure was unresolved on the spectrograms of Meggers *et al.* (1951), both the laboratory wavelengths and the stellar ones are averaged over the hyperfine components. Second, the sign of the wavelength difference, $\lambda_{lab} - \lambda_{star}$, is in no way correlated with whether the flag pattern produced by the hyperfine splitting is shaded to longer or shorter wavelengths (Reader and Davis, private communication). It is true that all of the laboratory measurements were of ^{147}Pm. If the isotopic composition of Pm is different in HR 465, then one might not expect correlation between the laboratory and stellar hyperfine patterns. In any case, the agreement of stellar and laboratory wavelengths is no better than one would expect for random coincidences and so cannot strengthen the identification.

All of the arguments concerning number of coincidences, wavelengths, and intensities apply with equal force to the discussion presented by Aller (1971) of additional and even weaker lines of Pm.

The identification of Pm would receive some support if Tc were also present in the atmosphere of HR 465. (This suggestion was made by W. A. Fowler and reported to us by G. W. Preston.) One isotope of each element can be formed through the *s*-process, and if this process were the one responsible for the production of Pm, then one would expect ^{99}Tc, with a half-life of 2.1×10^5 years, to be present in substantially greater abundance than ^{147}Pm, which has a half-life of only 2.5 years. Bidelman (private communication) has searched for Tc II lines in the ultraviolet spectrum of HR 465 and finds that they are not present. It should be noted, however, that the longest-lived isotope, ^{145}Pm, with a half-life of 17.7 years, does not lie on the *s*-process path (Seeger, Fowler, and Clayton 1965). Other processes for the production of Pm have been proposed (e.g., Kuchowicz 1971); if one of these were operative the lack of Tc would not be significant.

In conclusion, we suggest that since, in the spectra from 1960–1961, the number of coincidences between lines of Pm and features in HR 465 does not significantly exceed the number to be expected on the basis of chance, and since consideration of the agreement between the laboratory and stellar wavelengths in no way serves to strengthen the case in favor of the proposed identification, there still is reasonable doubt that Pm was ever present in the atmosphere of HR 465. The entire problem should be reexamined in more detail, with observations at longer wavelengths where blending is much less severe, when the star returns to rare earth maximum.

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