ULTRAVIOLET SPECTROSCOPY OF CHEMICALLY PECULIAR STARS

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1. INTRODUCTION

This discussion focuses on high dispersion spectroscopic observations of chemically peculiar (CP) stars of the upper main sequence, classical HgMn, Si and SrCrEu stars, obtained with the IUE. Two subjects will be emphasized - the confirmation of composition anomalies previously identified in ground-based spectra and evidence relating to the validity of the diffusion theory for the production of chemical pecularities.

2. THE GALLIUM AND MERCURY ANOMALIES IN HgMn STARS

The gallium anomaly occurs primarily in the hotter Mn stars (Cowley 1975). Model atmospheres analyses of Mn stars yield overabundances of Ga as large as 2×10^5 relative to the solar value (Heacox 1979). The identification of the Ga peculiarity and estimates of Ga abundances are based upon a few high excitation lines observed in the blue. Figure 1 illustrates the resonance line of GaII, λ1414.44, observed in six Mn stars. The feature is strong and broad in the hotter stars, κ Cnc and μ Lep. It is present but weaker in 46 Dra (A+B). It is absent in the cooler stars ι CrB, χ Lup and HR 4072. The sharp feature seen near λ1414.4 in the latter three stars is probably MnII and is also seen in normal stars. The GaII λ1414.44 line varies in strength from star-to-star in the same manner as the blue GaII lines. The absence of the blue GaII lines in cool Mn stars cannot be an excitation effect, since the resonance line is also absent in these stars. Neither can the presence of the blue GaII lines in hotter Mn stars be due to non-LTE effects, because the resonance line is also abnormally strong in these stars. The IUE observations confirm the Ga peculiarity as a genuine abundance anomaly.

The Hg anomaly in HgMn stars is defined on the basis of one line, HgII λ3984. Corroborative evidence includes the detection of weak HgI lines in two stars and the resolution of the Hg isotope structure in λ3984 (White et al. 1976). Abundance analyses based on λ3984, which account for its isotopic desaturation, yield overabundances as high as 4×10^5 times the solar system value. Unfortuneately, these analyses must

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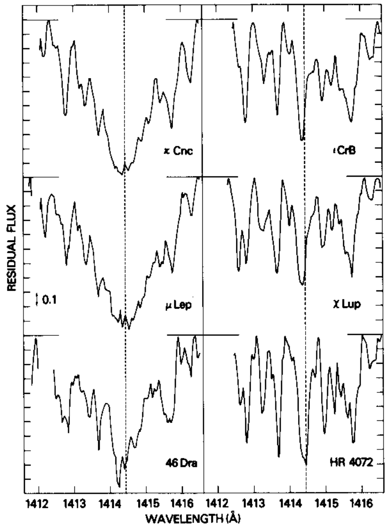


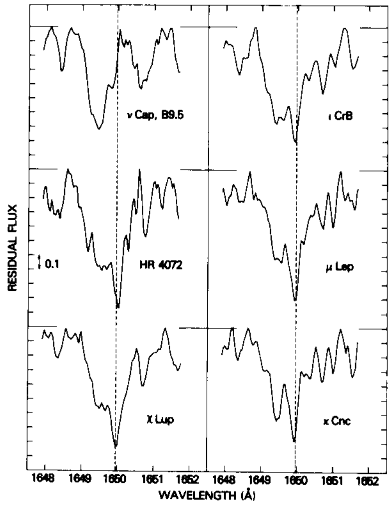


Figure 1 (Left): Spectra of six HgMn stars at the position of the resonance line, GaII λ1414.44.

Figure 2 (Right): Spectra of five HgMn stars and ν Cap, B9.5IV, at the position of the resonance line, HgII λ1649.94.

utilize an "astrophysical" f-value for λ3984. Figure 2 illustrates observations of five HgMn stars and one normal star, ν Cap, at the wavelength of the HgII resonance line, λ1650. The strong feature seen in the five HgMn stars, and not observed in ν Cap, is the HgII line. Its average central position is 1649.948Å ± 0.015Å, closely corresponding to the laboratory wavelength 1649.939Å, measured by Wilkinson and Andrew (1963). I also have observations of ι CrB, HR 4072, χ Lup, κ Cnc and ν Cap at the wavelength of HgII λ1942. A strong feature is observed in the CP stars, but not in ν Cap, at an average wavelength 1942.265Å ± 0.010Å, again closely matching Wilkinson and Andrew's laboratory value, 1942.275Å, for HgII. Figure 3 illustrates λ1942 observed in ι CrB. Also shown is an exploratory theoretical spectrum synthesis calculation. Fortuneately excellent laboratory f-value measurements exist for this line. Although 59 blending lines, taken from Kurucz and Peytremann (1975), have been included in the computation, the match to the observed blending features is poor. This is a common problem at vacuum ultraviolet wavelengths for both normal and peculiar stars. It is probably due to large systematic errors in the log gf-values of several important iron-peak ions in the list of Kurucz and Peytremann. The core of the HgII line is well matched for an abundance ratio, N(Hg)/N(H), $\simeq 1.2\times10^{-6}$, in excellent agreement with the value derived by White et al. from λ3984. The IUE data confirm the reality of the Hg anomaly and corroborate the accuracy of Hg abundances derived from λ3984.

3. OBSERVATIONAL TESTS OF THE DIFFUSION THEORY

3.1 Boron

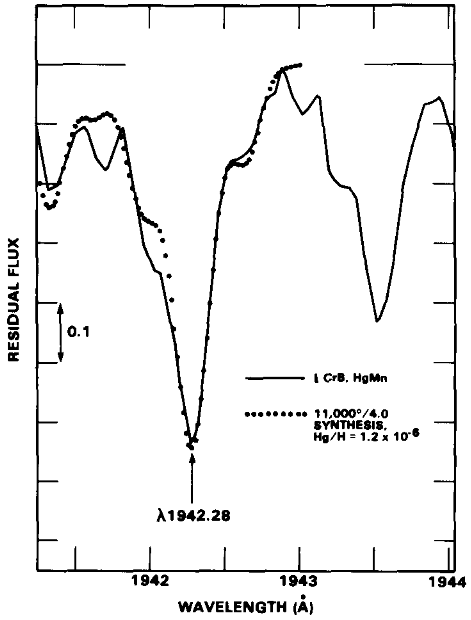
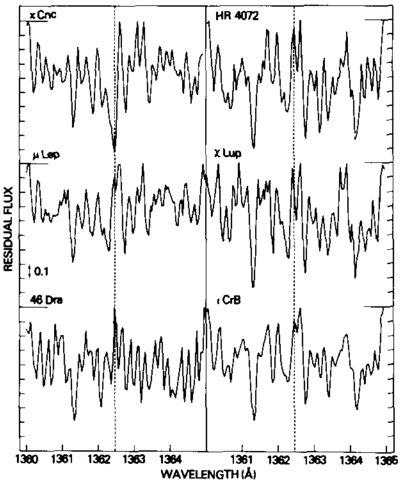


Figure 3: Spectrum of ι CrB, compared to theoretical profile of the resonance line, HgII λ1942.28.

Borsenberger et al. (1979) have made sophisticated, non-LTE radiation force computations for B ions in model atmospheres applicable to CP stars. They were motivated in part by two earlier observations - 1. Boesgaard and Heacox's (1973) observation of a weak line at 3451.29Å in the HgMn star κ Cnc, which they ascribed to a high excitation line of BII and from which they derived $N(B)/N(H) \simeq 2x10^{-7}$, about 10^3 times the cosmic value, and 2. the discovery by Praderie et al. (1977) from Copernicus data that the BII λ1362.46 resonance line is absent in the HgMn star μ Lep, implying a boron abundance well below the cosmic value. Borsenberger et al. conclude that in a non-magnetic, stable atmosphere of the kind HgMn stars presumeably possess, boron should not be observed - i.e. radiation pressure "blows" it out of the atmosphere. Horizontal magnetic field lines would retard this process, perhaps allowing boron to build up to large photospheric overabundances, depending on the magnetic field configuration. An overabundance in κ Cnc might result if it, unlike most HgMn stars, were magnetic. Figure 4 illustrates the region near λ1362 in six HgMn stars. I attribute the strong line at 1362.46Å in κ Cnc's spectrum to BII. The feature is absent in the other spectra shown. The feature is present, though less well resolved, in IUE spectra of the normal stars ν Cap and α Lyr, with the strength expected for a normal abundance, $N(B)/N(H) \simeq 2x10^{-10}$. Preliminary calculations yield $N(B)/N(H) \simeq 3x10^{-8}$ for κ Cnc, a factor of seven lower than Boesgaard and Heacox's value, but still overabundant by 150X. Figure 5 shows the same spectral region in four stars which are unequivocally magnetic. In 21 Per, α^2CVn and 17 Com the BII line is not clearly resolved. Its strength is probably no greater than that expected for a



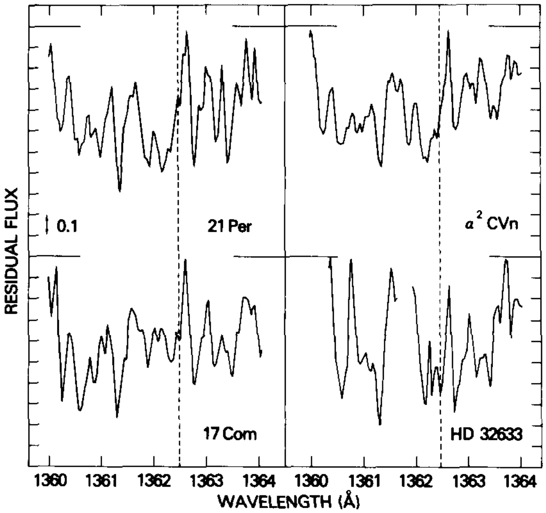


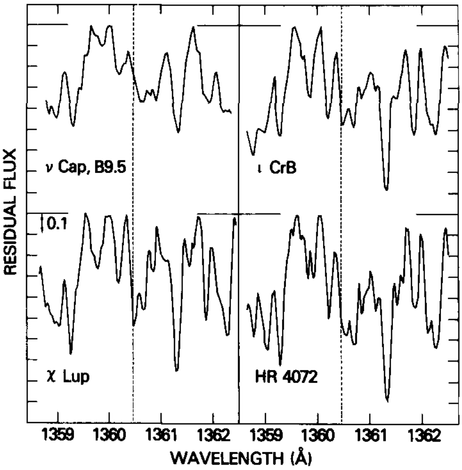
Figure 4 (Left): Spectra of six HgMn stars at the position of the resonance line, BII λ1362.46.

Figure 5 (Right): Spectra of four magnetic Ap stars at the position of BII λ1362.46.

normal boron abundance. In the strongly magnetic Si star, HD32633, the BII line appears to be resolved and rather strong (although spectrum synthesis will be required to clarify the blending). In none of these stars is BII λ1362 as strong as it is in κ Cnc. Except for κ Cnc, the observations are generally consistent with the diffusion model, although the fact that the BII line is not stronger in the magnetic stars is surprising. However, if future photo-polarimetric observations should show that κ Cnc is no more magnetic than other HgMn stars, it would render the predictions of the diffusion theory inconsistent with the observational facts--a serious, if not fatal blow to the theory.

3.2 Mercury

White et al. (1976) found that the blend of Hg isotopes in the hotter Hg stars corresponds closely to the terrestrial isotope mix. In cool Hg stars, such as ι CrB, HR 4072 and especially χ Lup, there is a relative underabundance of the light Hg isotopes. Michaud et al. (1974) have attempted to explain this apparent mass fractionation with a diffusion model in which, in a delicate equilibrium between radiation pressure and gravity high in the photosphere, the light Hg isotopes become predominately HgIII, while the heavier isotopes congregate at slightly greater depths and are predominately HgII. Thus the "missing" light Hg isotopes in cool Hg stars might be found in the form of anomalously strong ultraviolet lines of HgIII. I have conducted an exhaustive search for these lines. One example is shown in Figure 6. Here a feature of moderate strength, but blended with other lines, is resolved near the laboratory wavelength of HgIII λ1360.46 in three cool HgMn stars, but is not seen as a distinct line in the normal star ν Cap. Several other HgIII lines have also been found, although they are weaker than λ1360.46 or are more seriously complicated by blends. Still others cannot be precluded but are hopelessly blended. The f-values for these HgIII lines are unknown. If they are reasonably large (eg. log gf ≃ 0.0 to -1.0), then the observed line strengths are what one would expect from ordinary ionization equilibrium in a chemically homogeneous atmosphere, even at these relatively cool effective temperatures, given N(Hg)/N(H) ratios ∿ 10^{-6} or 10^{-5}. If their log gf-values prove to be much less than -1.0, then the very detection of the HgIII lines in cool HgMn stars would be anomalous, given the observed HgII line strengths and would support the diffusion model. We must await the laboratory f-value measurements for the HgIII lines before conclusions may be drawn.



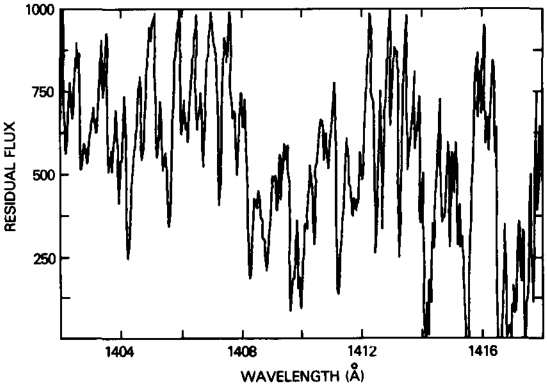


Figure 6 (Left): Spectra of three cool HgMn stars and ν Cap at the position of HgIII λ1360.46.

Figure 7 (Right): Unidentified broad features in the spectrum of the Si star 21 Per.

3.3 Silicon

In his epochal paper, Michaud (1970) had difficulty explaining the abnormal richness of silicon in the Si stars in terms of radiatively driven diffusion, because of the strong saturation of the ultraviolet lines of Si ions. He postulated that previously unobserved Si autoionization lines might provide the necessary medium for the transfer of radiation pressure to Si. Jamar et al. (1978) discovered a strong, broad absorption near 1400Å in low-resolution spectrophotometry of Si stars obtained with TD-1. They attributed this feature to numerous Si II autoionization lines whose positions they predicted from energy levels observed in the laboratory. I have searched for these broad features at each wavelength tabulated by Jamar et al. in spectra of the Si star 21 Per, and I have not found them. I have found three broad absorption features near 1410, 1415 and 1417Å, shown in Figure 7, which might have produced the 1400Å dip they observed. These three features are not yet identified and in that sense are analogous to the unidentified broad absorptions observed in blue-visible spectrophotometry of Si stars. Thus, the preliminary evidence is that the predicted SiII autoionization lines are not a significant factor in the formation of Si anomalies through radiative diffusion.

On the other hand the sophisticated, non-LTE diffusion calculations of Vauclair _et al._ (1979) show that SiI atoms may be the critical agent in carrying the upward momentum of silicon. The numerous ultraviolet SiI lines included in their calculations are clearly present in 21 Per. The UV 30 multiplet of SiI is shown, as an example, in Figure 8. This lends observational support to their diffusion model for the formation of Si anomalies.

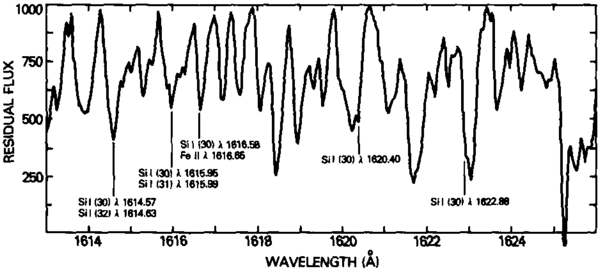


Figure 8: The multiplet SiI (UV30) observed in 21 Per.

Serious questions about the validity of the diffusion theory have been raised by some of the present observations. These can only be resolved by means of the additional data specified and possibly by the incorporation of more realistic physical assumptions in the diffusion models. However, the continued exploration of other mechanisms for the production of chemical anomalies is still very much in order.

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DISCUSSION:

F. Praderie: The observations of B II shown in Si Ap stars are not in conflict with the predictions of Borsenberger et al. (1979). Boron does not leave the atmosphere, and concentrates where the B lines of force are parallel to the star's surface. Therefore the strength of B II depends on the aspect of the star. Time variable observations ought to be performed, in these magnetic variable stars.

D. Leckrone: I have time-resolved observations of several of the magnetic stars which will be analysed in the near future. However, the crucial test of diffusion theory with respect to Boron is to determine with high accuracy the magnetic field strength of κ Cnc. I have suggested this observation to Borra and Landstreet. If κ Cnc turns out to have a negligible magnetic field, as do other HgMn stars, then the great strength of its B II λ1362.46 line would refute the prediction of diffusion theory.

F. Praderie: The atomic structure of Si II has been computed by Petrini. The width of the autoionization features around 1400Å is several tens of Å; they have to be searched as broad dips in the continuum; too good a spatial resolution is not useful! New computations of these lines will be published (Artru, Jamar, Petrini, and Praderie).

D. Leckrone: I searched for all the predicted Si II autoionization lines in 21 Per and in the normal comparison star ν Cap, over approximately 20-Å intervals. If the lines are much broader than this, I would not have seen them. Probably low dispersion IUE spectra would be better suited to the search for very broad depressions. However, this does not reduce my suspicion that the feature Jamar et al. saw as a broad dip in S2/68 spectrophotometry of Si stars at 1400-1420 Å is due to the three broad absorption features I've shown.

A.W. Irwin: Are there problems with the Kurucz-Peytremann line list for normal stars? My understanding is this line list is taken from the literature for atomic number >28. Therefore it is incomplete for the rare earths, for example, and you would expect problems for Ap stars but not necessarily for normal stars.

D. Leckrone: I first encountered the problem in attempting to synthesize the spectrum of the normal star, ν Cap (B9.5 IV), which I use as a comparison standard, near the B II line at 1362.46 Å and also near the Hg II line at 1942. 32 Å. So the problem is apparently not one of chemical peculiarity, but rather one of gf-values which are systematically too low. My short-term approach to solving the problem is to increase the assumed log gf's to values sufficiently large to force the calculations to fit the normal star data and then to use these "astrophysical" log gf values to simulate the blending within the line of primary interest. This is not a good substitute for atomic data accurately measured in the laboratory, however.

C. Megessier: I have a doubt concerning the identification of λ1942. 317 Hg II line. We got spectra of μ Cep and χ Lup with Copernicus satellite which has a wider dispersion than IUE. It appears that there is a strong feature at λ1942. 1, and Hg II λ1942. 317 would be a much smaller line near the strong one.

D. Leckrone: My IUE wavelength scale has been derived from the observed positions of numerous strong Fe II and other lines distributed throughout the image. Combined wavelength errors should be less than 0.05 Å. The observed wavelength of the feature I ascribe to Hg II λ1942 is in excellent agreement with the best laboratory measurement (though not in as good agreement with the UMT value). The feature's strength is as expected, given the observed strength of Hg II λ1650, since the log gf values for these two lines differ by only 0.36. I have no doubt about the identification of the feature as Hg II.