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THE CHROMOSPHERES OF CLASSICAL CEPHEIDS. III. A SEARCH FOR TRANSITION REGION EMISSION LINES

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ABSTRACT

In previous studies of Cepheid chromospheres with the *IUE*, we found that the chromospheric emission is strongly dependent on the period of the star and varies substantially through the cycle. For the shortest period star in our sample, δ Cep, we were able to detect little significant chromospheric emission in the short wavelength region, and we were only able to detect transition region emission in the longest period star, *l* Car. However, the upper limits on these emissions were slightly above expected flux levels for nonvariable stars. To detect them or place lower and physically more interesting limits on the fluxes we have obtained longer exposures at several critical phases for three of the stars. We have succeeded in detecting O I λ 1305 in δ Cep, but it is substantially weaker than in the other Cepheids. We have also succeeded in detecting transition region lines at one phase of β Dor and one phase of ζ Gem and in placing much lower limits on the emission at other phases. The strength when detected is similar to nonvariables, but at other phases the upper limits indicate smaller fluxes than observed in nonvariable stars.

Subject headings: stars: Cepheids — stars: chromospheres — ultraviolet: spectra

I. INTRODUCTION

For reasons which were discussed in Papers I and II of this series (Schmidt and Parsons 1982; Schmidt and Parsons 1984) we obtained ultraviolet spectra of five bright Cepheids with the *IUE* satellite. These spectra extended what had already been known from ground-based spectroscopy; the chromospheres of Cepheids vary greatly with period and with the phase of the star. The longer period stars have stronger chromospheric emission, and it is detectable over a larger part of the cycle. It appears that the chromosphere is excited at a particular point during rising light, and the emission declines more or less steadily until the next cycle again excites it. At the phase of strongest emission, the flux is comparable to nonvariable stars of similar luminosity and temperature, but at other phases and averaged over the cycle the chromospheric activity is significantly less than in the nonvariable stars. The size of this effect differs for various of the ultraviolet emission lines we have observed.

The profiles of the Mg II lines at 2800 Å were found to show a variety of forms in different stars and at different times in the same star. This was interpreted as being due to the presence of both an emission component of varying velocity and flux and a number of overlying absorption components. The strongest absorption component has a velocity which is nearly constant and is probably dominated by interstellar absorption. The weaker components show velocities which are as large as 200 km s⁻¹ relative to the star and contain both rising and falling elements. From the velocities of these components we

argued that the regions in which they originate have a minimum extent which ranges from several tenths of a stellar radius to several stellar radii in various stars. This is much larger than the solar chromosphere, but not as extended as the chromospheres of late-type giants.

In Paper I we presented the strengths of lines in the far-ultraviolet region. The intention was to make an initial survey of chromospheric activity in Cepheids with as extensive phase coverage as possible. Thus, the exposures were all relatively short (< 1 hr). While emission was seen in most of the stars, in the shortest period star, δ Cep, little significant emission was found. The upper limits we were able to place on the fluxes were, however, larger than the expected values based on the other Cepheids and on nonvariables. In order to determine whether the chromosphere of this star is similar to those of longer period stars, it is necessary to obtain deeper exposures. A further deficiency in the previous material is that only in the longest period star of our sample, *l* Car, was emission from hot material (temperature > 10,000 K), indicative of a transition region observed. Again, the upper limits we were able to obtain for the other stars were larger than the expected emission strength.

Since the Mg II data suggested an extended chromosphere, it is of interest to determine whether these stars possess coronae. Böhm-Vitense and Parsons (1983) reported an attempt to study this question directly by searching for X-ray emission from coronal gas. In ζ Gem they possibly detected X-rays, and they were able to place upper limits on the emission in δ Cep and β Dor. These data imply that coronal activity in Cepheids is no stronger than in nonvariable supergiants of similar temperature and is consequently one or two orders of magnitude weaker than in dwarfs. In the present study we will approach

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TABLE 1
EMISSION-LINE FLUXES

STAR (1)	IUE IMAGE NUMBER SWP (2)	EXPOSURE (min) (3)	J.D. -2,445,220 (4)	PHASE (5)	EMISSION-LINE FLUXES (10^{-13} ergs $\text{cm}^{-2} \text{s}^{-1}$)											σ (14)	NORMALIZED LINE FLUXES $f_{\text{line},0}/\langle f_{\text{H}\beta,0} \rangle \times 10^7$															
					Si I $\lambda 1296$ (6)	O I $\lambda 1305$ (7)	C II $\lambda 1336$ (8)	O I $\lambda 1335$ (9)	Si IV $\lambda 1400$ (10)	? $\lambda 1470$ (11)	C IV $\lambda 1550$ (12)	C I $\lambda 1657$ (13)	Si I $\lambda 1296$ (15)	O I $\lambda 1305$ (16)	C II $\lambda 1336$ (17)		O I $\lambda 1355$ (18)	Si IV $\lambda 1400$ (14)	Si IV $\lambda 1550$ (21)	C I $\lambda 1657$ (22)	$f_{\text{Fe II}}$ (23)											
δ Cep	17296	150	4.55	0.926	...	1.4	...	...	0.6	...	...	...	...	...	...	...	...	0.7	1.8	3.5	1.7	1.4	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	1.6	0.1
β Dor	17914	210	3.56	0.733	1.0	9.1	0.4	1.4	1.0	0.5	1.0	1.0	1.0	1.0	0.3	2.0	18.3	0.8	2.7	1.9	0.9	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	0.02
ζ Gem	17915	130	3.73	0.675	...	2.8	...	...	...	...	...	...	...	...	1.1	2.2	13.5	2.2	2.1	2.1	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	2.0	0.05
	17927	147	4.72	0.772	1.6	6.7	0.9	1.2	...	...	...	...	...	...	0.6	1.0	4.5	0.9	...	...	...	...	...	...	...	...	...	...	...	...	...	0.02
	17939	180	5.58	0.857	1.4	5.5	...	0.6	...	0.3	...	...	...	...	0.7	2.6	10.7	1.4	1.9	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	1.1	0.01-0.026
															0.3	2.2	8.8	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.02

^a Radiation spot obscures any emission.

this question by attempting to detect transition region emission.

II. THE OBSERVATIONS

Six spectra were obtained with the short wavelength spectrograph on *IUE* during low radiation shifts. These spectra are listed in Table 1. The exposures are generally several times longer than those used previously, and the times of observation were chosen as nearly as possible to correspond to phases when we expect strong emission. The phases were calculated using the same ephemerides as in Paper I. Table 1 also lists the fluxes of the emission lines identified on these spectra.

Since we are interested in detecting weak emission, care was taken to ensure that tabulated features are real and that no significant feature escaped notice. The photowrites were examined carefully and compared with tracings of the spectra. A number of features were rejected as likely radiation hits. In two cases these coincided with locations of possible emission lines, as indicated in the table. As a further guide to the reality of features an estimate was made of the noise level for each spectrum. This was done by choosing six regions of the spectrum which should be relatively line-free. The strength of a supposed emission in each region was then extracted, and the scatter in these values was taken as an indication of the accuracy of the line fluxes. This is given in column (14) of the table (" σ "). This value is intentionally a somewhat high estimate of the errors (due to faint unrecognized lines and possible radiation hits). Thus, in a number of cases line strengths are listed which are less than the standard error. Although a detection at less than the 1σ level is generally considered to be insignificant, in the present case this is not true. The presence of a line is only indicated when it is visible on the photowrite and has the appearance of a real feature on both the photowrite and the tracing. That is, more information than just the standard error has been used in deciding on the reality of a feature. Those strengths which are near or less than the indicated errors should thus be regarded as likely detections, but the fluxes are very uncertain. When no line could be detected, we have taken the error from the last column to be a conservative estimate of an upper limit of the strength.

In columns (15)–(22) of Table 1 the normalized fluxes (or their upper limits) are listed. These have been corrected for the effects of interstellar absorption and normalized by the bolometric flux of the star averaged over the cycle. The bolometric fluxes were taken from Paper I, as were the color excesses. The mean reddening curve of Savage and Mathis (1979) was used to obtain the absorption corrections from the color excesses. In the final column of the table we give the sum of the normalized flux of the three high temperature lines, C II $\lambda 1336$, Si IV $\lambda 1400$, and C IV $\lambda 1550$, divided by the normalized flux of the Mg II h and k emission lines at the same phase. The Mg II data are from Paper II and have been interpolated to the correct phase when necessary.

From the data in Table 1 it can be seen that we succeeded in detecting chromospheric emission from δ Cep and were able to detect emission from hot plasma in β Dor at one phase and probably from ζ Gem at one phase. Furthermore, a comparison of the upper limits for the strengths in Table 1 with those from Paper I shows that the present values are much lower. These data are adequate to discuss the points raised above.

III. DISCUSSION

In Paper I we found that the upper limit we were able to place on the strength of the O I emission from δ Cep was near the flux level for nonvariable stars. The present detection was made at a phase when the Mg II emission in this star is near its peak, so we should expect that the O I is probably also near peak emission. In Figure 1 we have replotted Figure 7a from Paper I with the addition of the present point for δ Cep. It can be seen that this point is well below the flux of the nonvariable stars at the same color. This contrasts with the situation in the other Cepheids in which the flux at maximum strength is comparable with the nonvariable stars. Also, assuming that this is actually a phase of strong emission for this star, the mean must be even lower than our previous upper limit, and we conclude that the O I emission from δ Cep is significantly lower than expected from the other Cepheids and from the nonvariable stars. This was also the case for the Mg II emission from this star (Paper II) but is more extreme for O I.

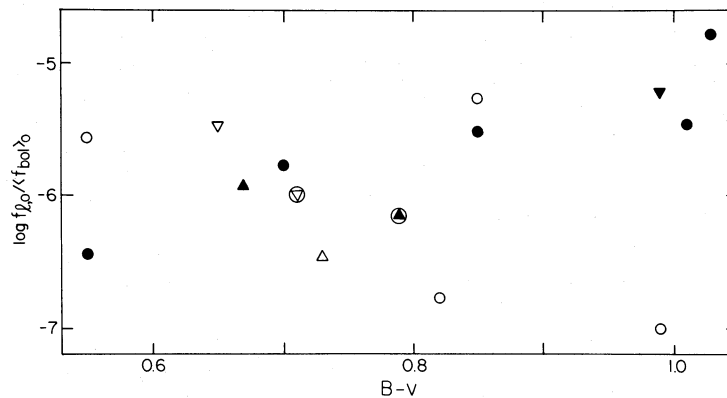


FIG. 1.—Normalized flux of O I $\lambda 1305$ plotted against the intrinsic color. Nonvariable stars of luminosity class I are plotted as filled circles, nonvariables of class II as open circles. Open triangle with vertex up represents the flux for δ Cep from Table 1 and the color at the same phase. Other triangles represent data for other Cepheids from Paper I as follows: open triangle with vertex down, β Dor; filled triangle with vertex up, ζ Gem; filled triangle with vertex down, I Car. Circled symbols denote averages over the cycles, while uncircled symbols are for the phase of peak O I emission.

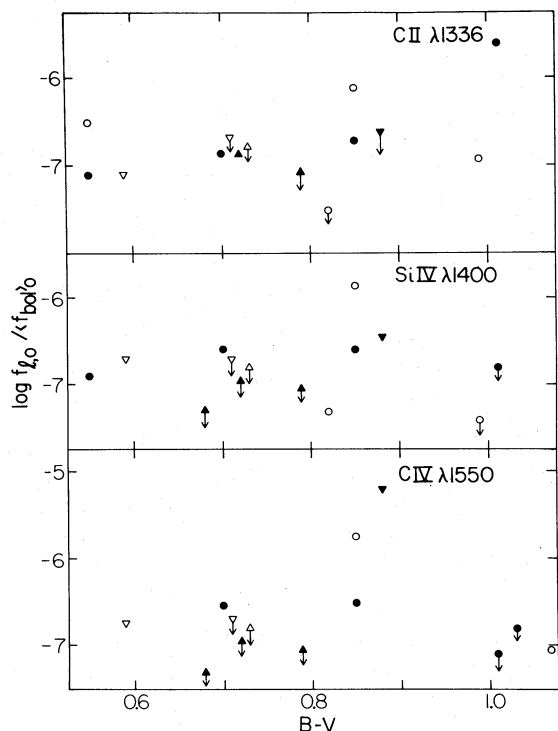


FIG. 2.—Normalized fluxes of the high-temperature emission lines plotted against the intrinsic colors. The various stars are represented with the same symbols as in Table 1. For I Car we have plotted the point from phase 0.95. Of the phases observed for that star, this one exhibited the strongest high-temperature lines. Arrows indicate upper limits. For the Cepheids the color plotted is for the same phase as the flux was measured.

In Paper II we speculated that the behavior of Cepheid chromospheres could be understood if the pulsation disrupted the mechanisms of chromospheric heating which operate in nonvariables. The chromospheres of these stars are then generated by mechanical energy associated with the pulsation. In δ Cep we did not see bumps on the far-ultraviolet light curves which appeared to be associated with the excitation of the chromosphere in the longer period stars. Ultraviolet light curves of other short period Cepheids also seem to lack such features (Hutchinson 1975). Thus, it appears that the pulsation in the shorter period stars is unable to excite the type of chromosphere seen in the longer period stars while still being able to disrupt the mechanisms operating in the nonvariables.

The most important fact concerning the two 10 day Cepheids, β Dor and ζ Gem, is that we were able to detect three transition region lines in one spectrum of β Dor (C II λ 1336, Si IV λ 1400, and C IV λ 1550) and one such line in one spectrum of ζ Gem (C II λ 1336). Thus, there is high temperature plasma in the chromospheres of these stars at least at times.

In Figure 2 we compare the fluxes or upper limits to the fluxes of these lines with the fluxes in nonvariable giants and supergiants. The data for the nonvariables were taken from Ayres, Marstad, and Linsky (1981) and Simon, Linsky, and Stencel (1982). Corrections have been applied for interstellar absorption in the same way as for the Cepheids. Unfortunately, there are few stars with which to compare our observations. Only three nonvariable class I stars fall near the Cepheids in

the diagram, α Aqr (G2 Ib), β Aqr (G0 Ib), and δ CMA (F8 Ia). The upper limits for the Cepheids are mostly smaller than the emission from the nonvariables. On the other hand, when the lines were detected, the strength are in reasonable agreement with the nonvariables. These results are similar to the situation for the low-temperature lines discussed in Papers I and II; at peak strength the emission fluxes are similar to nonvariable stars, but they are lower at other times.

It should be noted that there are potentially serious uncertainties in the discussion of the emission-line fluxes and the comparison with other stars. It is likely that among the nonvariables of a given luminosity and temperature there is a range of chromospheric activity present. With the small sample of such comparison stars available, we are unable to determine how this might affect our conclusions. A second caveat concerns the reddening corrections. Clearly, even for relatively lightly reddened supergiants a correction must be applied. However, the absorption curve in the ultraviolet has been found to vary significantly from star to star, and we have used a mean curve. Looking at the curves shown by Savage and Mathis (1979) we can estimate how large an uncertainty might be involved. At 1550 Å the various extinction curves (excluding the anomalous case of σ Sco) have a range of ~ 0.7 mag for a color excess of $E(B-V) = 1.0$. This, in turn, indicates a range in the extinction correction of $\sim 10\%$ for the most heavily reddened star we are considering here ($E[B-V] = 0.13$ for the nonvariable supergiants). If we were unfortunate enough to see some of our sample through dust similar to that in front of σ Sco, the error would be $\sim 30\%$. Thus, errors from this source should be no larger than $\sim 30\%$ or 0.1 in $\log f_{\lambda,0} / \langle f_{bol} \rangle_0$, and this will have no significant effect on Figure 2.

Another useful comparison between the Cepheids and the nonvariables can be made by considering the ratio of transition region flux to flux from the low chromosphere (as represented by Mg II h and k). The three stars in the list of Ayres, Marstad, and Linsky which are the most similar in color, luminosity, and chromospheric flux to the Cepheids are δ CMA, α Aqr, and β Aqr. For these three stars the ratio of the total flux of C II λ 1336, Si IV λ 1440, and C IV λ 1550 to the Mg II flux (all corrected for interstellar absorption) is 0.022, 0.018, and 0.009, respectively. The corresponding quantities for the Cepheids are listed in the last column of Table 1. For the two cases in which we have detected transition region material, there is good agreement with the nonvariables, while none of the upper limits indicate any serious discrepancy. This then implies that the transition regions above the Cepheid chromospheres are similar to those above corresponding nonvariable star chromospheres.

The results of Paper II indicated a chromosphere which is very heterogeneous over the surface of the star. The existence of a transition region in spite of the depth we inferred for the chromosphere from the absorption lines (at least several tenths of a stellar radius) and the lack of a corona as indicated by the X-ray observations (Böhm-Vitense and Parsons 1983) would seem to strengthen the impression of a great deal of heterogeneity over the stellar surface.

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