The ultraviolet variability of CU Virginis [1]

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Abstract. The spectrophotometric variability of the magnetic CP star CU Vir in the spectral region from 1150 Å to 3509 Å is investigated. This study is based on the archival ***IUE*** data obtained at different phases of the rotational cycle. The light variations in the wavelength region longer than λ 2000Å are generally in antiphase to the variations in the shorter wavelength region, although the shapes of light curves are different. The existence of the "null wavelength region" at λ2000 Å, where the amplitude of light variations is practically zero over the period of rotation, is confirmed. Moreover, the amplitudes of light variations reach minimum values in the core of the L_α line. The comparison of the monochromatic light curves with variations of the Si II features shows that the light variations in the far-UV are influenced by the non-uniformity of the silicon distribution over the stellar surface.

Key **words:** stars: chemically peculiar - stars: variable - stars: individual: HD 124224

1. Introduction

The light variability of magnetic chemically peculiar (henceforth CP2 stars, following Preston, 1974) stars can be generally explained by the variable overabundance of several heavy elements observed in the atmospheres of these stars. This mechanism arises from non-uniform distribution of elements over the surface of the star. Enhanced energy blocking decreases the flux in the far-UV region where most of the lines of these elements are present. The blocked flux appears in the visual and red parts of the spectrum. Such an explanation is supported by the antiphase relationship of light curves in the visual and far-UV spectral regions.

Stepien & Czechowski (1993) investigated the spectrophotometric behaviour of the rapidly rotating CP2 star 56 Ari, using the archival *International Ultraviolet Explorer (IUE)* data and the published visual spectrophotometric data. They showed that the variations in the visual are in antiphase to the UV variations but there exists no "null wavelength" region where the amplitude of light variations is zero over the period of rotation. Instead, the light curve changes continuously its shape. Detailed investigation of several additional stars is necessary to draw a definite conclusion about the mechanism of light variations in CP2 stars. Another rapidly rotating CP2 star with a wealth of photometric and spectrophotometric data is CU Virginis (HR 5313, HD 124224). The star displays well-defined periodic variations of hydrogen, helium and silicon lines. Good photometric, magnetic field and radial velocity observations are available in the literature. Molnar & Wu (1978) reported the photometric observations of CU Vir with the five-channel photometer aboard ANS satellite. By interpolating the photometric amplitude as a function of wavelength, they established a possible "null wavelength" region at λ2000 Å ($\pm$100 Å).

In this paper we will discuss the spectrophotometric behaviour of CU Vir in the spectral region from 1150 Å to 3509 Å. This study is based on the archival ***IUE*** data and on the spectrophotometric scans in the near-UV from the catalogue of stellar spectrophotometry by Adelman et al. (1989) obtained at different phases of the rotational cycle, as described in Sect. 2. The principle results and discussion are presented in Sect. 3.

2. Observational data

2.1. The period variations

The rotational period of CU Vir has been studied by Deutsch (1952), Hardie (1958), Peterson (1966), Blanco & Catalano (1971) and Winzer (1974). It appears that a period of 0.520675±0.000005 days is consistent with all the observations. On the other hand, Adelman et al. (1992) refined the period of CU Vir, using the ***UBV*** data consisting of 357 values obtained over a span of some 26 months. They found a period of 0.5206800±0.0000005 days. Recently, Pyper et al. (1998) have studied all possible variations for

[1] Based on INES data from the IUE satellite

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this star from 1956 to 1997. They found that all observational data might be fitted using two periods. For observational data with JD < 2446000 they adopted the following ephemeris:

$$JD(U, B\ min) = 2435178^{d}.6417 + 0^{d}.5206778E, \quad (1)$$

and for observational data with JD > 2446000 they found a slightly longer period using the same zero epoch:

$$JD(U, B\ min) = 2435178^{d}.6417 + 0^{d}.52070308E. \quad (2)$$

Moreover, the authors noted that there was an indication of a continually changing period.

As one can see, the situation in the determination of the period variations for CU Vir is sufficiently puzzling. Nevertheless in our investigation the phases were computed by using Eq. (1), because the *IUE* observations were made with JD < 2446000.

2.2. IUE scans

Eleven low-dispersion spectra of CU Vir have been recorded with *IUE* in the spectral range 2000-3200 Å with the large aperture (camera LWR) and twelve in the domain 1150-2000 Å (camera SWP) with the large aperture as well. All images of CU Vir were obtained on January 10, 1979 and March 17, 1979 and are listed in Table 1 with camera, image number, the date of the observation and phase of each spectrum. The values of phases were computed from Eq. (1). The spectra were received from the *IUE* database and were calibrated using standard reduction techniques described in Garhart et al. (1997). The spectra have a limiting resolution in the range 6-7 Å. Unfortunately, the *IUE* data in the spectral range between 3080 Å and 3200 Å were not included in our investigation, because of the large uncertainty of the flux. Instead, the spectrophotometric scans in the near-UV ($\lambda\lambda$ 3300-3700 Å) were taken from the catalogue by Adelman et al. (1989). The scans were reduced to absolute units with a standard procedure, using the absolute calibration of *uvby* filters of Strömgren photometry obtained by Straižys & Kuriliene (1975). They established that the flux from the star (Sp: AO V, V = $0.^{m}0$) is equal to 3.7 x 10^{-9} erg s^{-1} cm^{-2} $Å^{-1}$ in the *y* filter of Strömgren system.

3. Data analysis

To analyse the ultraviolet spectra of CU Vir we used a linearized least squares method. An attempt was made to describe the light curves in a quantitative way by adjusting a Fourier series. This method is described by North (1987) and assumes that the curve

Table 1: *List of the spectral IUE observations of CU Vir*

IUE	Images	Julian date 2,440,000+	Phase
LWR	3443	3883.90609	0.100
LWR	3445	3883.94638	0.178
LWR	3446	3883.98738	0.256
LWR	3447	3884.03271	0.343
LWR	3448	3884.07599	0.427
LWR	3449	3884.11679	0.505
SWP	3863	3883.88328	0.056
SWP	3864	3883.91221	0.112
SWP	3865	3883.95255	0.189
SWP	3866	3883.99435	0.270
SWP	3867	3884.03750	0.353
SWP	3868	3884.08043	0.435
SWP	3869	3884.12172	0.514
LWR	4044	3949.79617	0.647
LWR	4045	3949.83722	0.726
LWR	4046	3949.87819	0.804
LWR	4047	3949.91787	0.881
LWR	4048	3949.95900	0.960
SWP	4670	3949.80036	0.655
SWP	4671	3949.84244	0.736
SWP	4672	3949.88249	0.813
SWP	4673	3949.92211	0.889
SWP	4674	3949.96452	0.970

has the form:

$$F(\lambda, t) = A_0(\lambda) + \sum_{i=1}^{n} A_i(\lambda)\cos(\omega i(t - t_0) + \phi_i(\lambda)), \quad (3)$$

where $\omega = 2\pi/P$ and P is the period. The coefficients $A_0(\lambda)$ of the fitted curves give the mean flux distribution over the cycle of the variability. From several scans distributed over the period one can produce light curves at different wavelengths. Experience showed that in all cases the data could be fitted by Fourier series limited to $n=2$, i.e. by the fundamental frequency and its first harmonic. A least squares fit was applied to all the short-wave and long-wave *IUE* monochromatic light curves. For the analysis of the spectrophotometric scans in the near-UV ($\lambda\lambda$ 3300-3700 Å) of CU Vir the same procedure was used.

3.1. The average flux distribution

The average flux distributions of short-wave and long-wave scans are plotted as the solid line in the upper and lower parts of Fig. 1, respectively. The error bars in Fig. 1 indicate the amplitude variations of the fun-

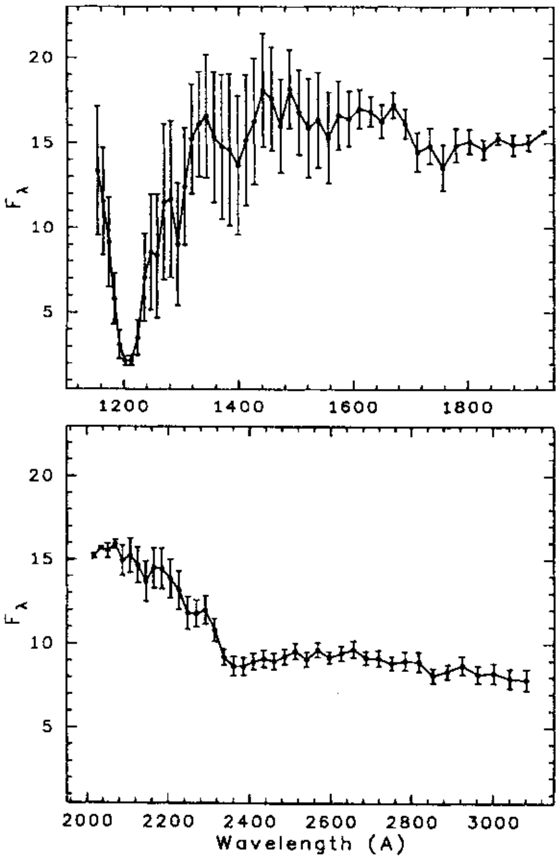

Figure 1: *The average flux distribution in $10^{-11} ergs^{-1} cm^{-2}$ Å^{-1} for CU Vir. The top and bottom panels show the short-wave and long-wave scans from the IUE archive, respectively.*

damental frequency. As one can see from Fig. 1, the largest changes of the flux for CU Vir are in the short-wavelength range of *IUE* spectra. The variability of the flux in the long-wavelength range of *IUE* spectra is up to 10 times smaller. On the other hand, there are no significant changes of the flux at λ2000 Å. The amplitude of the light variations reaches a minimum value of 0.4%. This is in good agreement with estimates obtained by Molnar & Wu (1978). They established a possible "null wavelength region" near 2000 Å ($\pm$100 Å) where the amplitude of light variations is zero over the period of rotation. It should be noted that the flux in the core of the L_α line varies with a small amplitude of 9% at λ1213 Å. However the wings of this line vary significantly.

3.2. The monochromatic light variations

The monochromatic light curves of CU Vir change their shape with wavelength. Examples of light curves of the short-wave and long-wave scans together with the fitted two-frequency cosine curves are shown in Figs. 2 and 3, respectively. All curves in the spectral region with λ<1556 Å have a similar shape: a deep minimum at phase 0.3-0.4 and another one at phase 0.6-0.7, except for the core of the L_a line. The light curve at λ1397 Å, where the minimum of the broad feature is at λ1400 Å, conforms to this general trend. The amplitude of the first minimum decreases with increasing wavelength. At λ1556 Å both minima become equally deep, but at λ1611 Å and beyond, the amplitude of the first minimum at phase 0.3-0.4 is quickly replaced by a maximum. This maximum is seen up to λ2000 Å. The amplitude of the second minimum at phase 0.6-0.7 decreases with increasing wavelength and disappears at λ1962 Å. At λ1933 Å the amplitude of the two features is the same and, as a result, a double wave is seen at this wavelength.

As one can see from Fig. 3, at λ2000 Å there is a "null wavelength region", where the amplitude of light variations is zero over the period of rotation. After the "null wavelength region" the double wave suddenly appears again. The maximum of amplitude variations of this double wave is at λ2069 Å, but the maximum at phase 0.8 quickly disappears (see λ2106 and beyond). As a result, the monochromatic light curves show one maximum in the spectral range of $\lambda\lambda$2106-3509 Å. In other words, the variations of the flux in this spectral region are in antiphase to the first minimum in the shortest wavelength region. Moreover, the maximum of the light curves moves with increasing wavelength, except for the λ2486 Å curve, which is essentially identical to the λ4200 Å curve (the core of the strong Si II doublet at $\lambda\lambda$4128-30 ÅÅ). The maximum of light curves at λ2106 Å and at λ3509 Å is at phases 0.4 and 0.6, respectively. The general appearance of the Strömgren photometry published by Pyper et al. (1998) is similar to that in the spectral range $\lambda\lambda$2106-3509 Å.

3.3. Variations of the UV features

The spectrum in the far-UV (λ<2000 Å) of silicon-rich B and early A-type stars is dominated by Si II features (Artru et al., 1981). Recently, Lanz et al. (1996) have shown that the effect of Si^+ becomes dramatic: the Si II continuum opacity is comparable to the H I opacity at many frequencies and allows reproducing the most characteristic UV features of these stars. They established that the broad features at 1300 Å, 1400 Å, 1560 Å and 1780 Å in the spectra of CP2 stars are mainly due to Si II autoioniza-

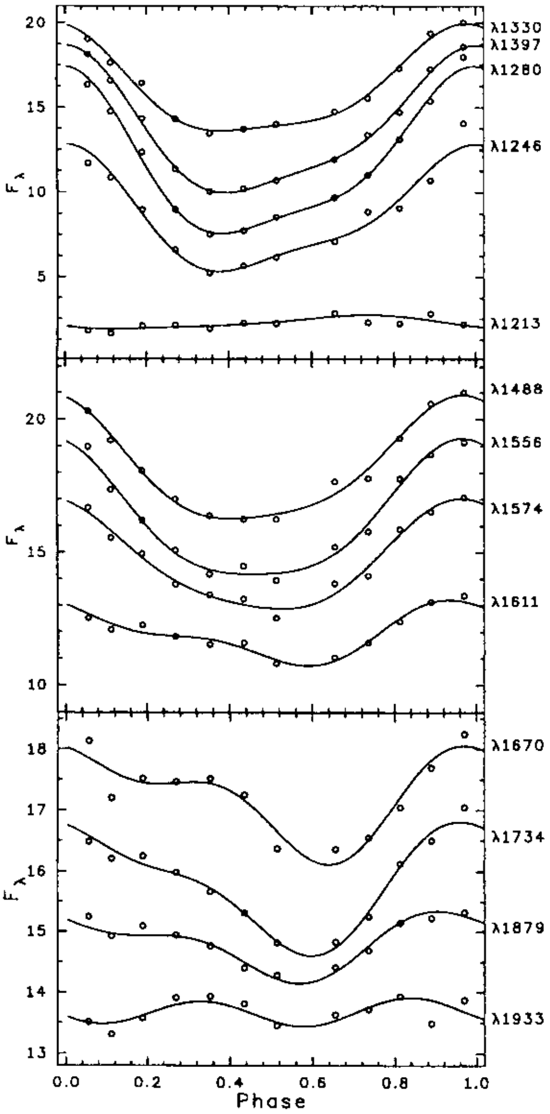

Figure 2: *Phase diagrams of the monochromatic light curves of the short-wave scans for CU Vir. Note different vertical scales for each part of the figure. To exclude the overlap, the vertical shift on the constant value was used. The solid lines are the least squares fits.*

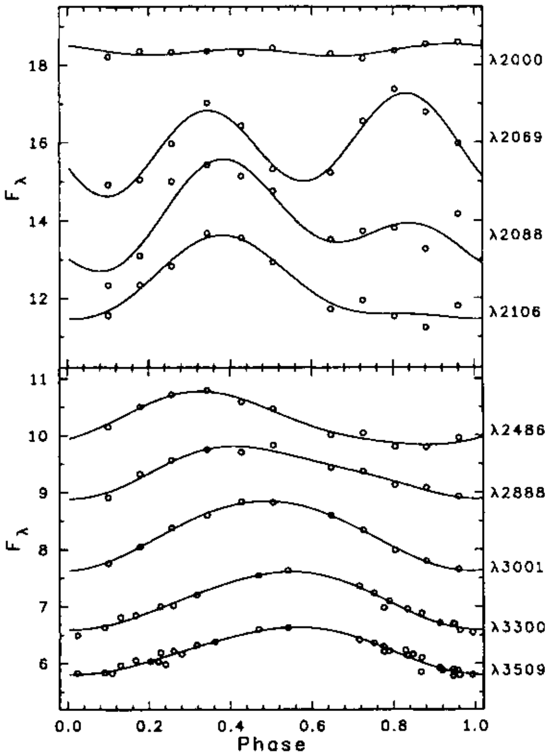

Figure 3: *Same as Fig. 2 for the long-wave scans.*

tion transitions. The characteristic flux deficiency at λ1400 Å is well seen in the spectrum of CU Vir. Moreover, the average flux distribution, especially between 1250 and 1850 Å, most of the important features and another more diffuse depression around λ2400 Å are reproduced (see Fig. 1).

To measure the broad features at λ1400 Å, Jamar et al. (1978) have introduced a photometric index $\delta 400$, using TD-1 low resolution spectra. The *IUE* spectra with the high and low dispersion modes were used by Maitzen (1980, 1984) and by Shore & Brown (1987) to form the photometric indices Δa and a_{1400}) respectively. In order to derive the total absorption in the broad features at 1300 Å, 1400 Å and 1560 Å, we introduce the photometric indices a_{1300}, a_{1400} and a_{1560}. These indices are analogous to the a_{1400} index of Shore &; Brown (1987), and are given by:

$$
\begin{aligned}
a_{1300} &= \frac{1}{2}(m_{1280} + m_{1304}) - m_{1292}, \\
a_{1400} &= \frac{1}{2}(m_{1342} + m_{1441}) - m_{1397}, \qquad (4) \\
a_{1560} &= \frac{1}{2}(m_{1488} + m_{1610}) - m_{1555}.
\end{aligned}
$$

The depressions at 1780 Å and 2400 Å were excluded from our investigation, since these depressions are very wide in the spectra of CU Vir.

Fig. 4 exhibits the variations of the measured total absorption for the three broad features versus the rotational phase. The solid lines represent least-squares fits by two-frequency cosine functions. It can be seen on the graphs of Fig. 4 that all photometric indices have minimum values at phase 0.0 and maximum values at phases 0.4 and 0.7, although the shapes of the

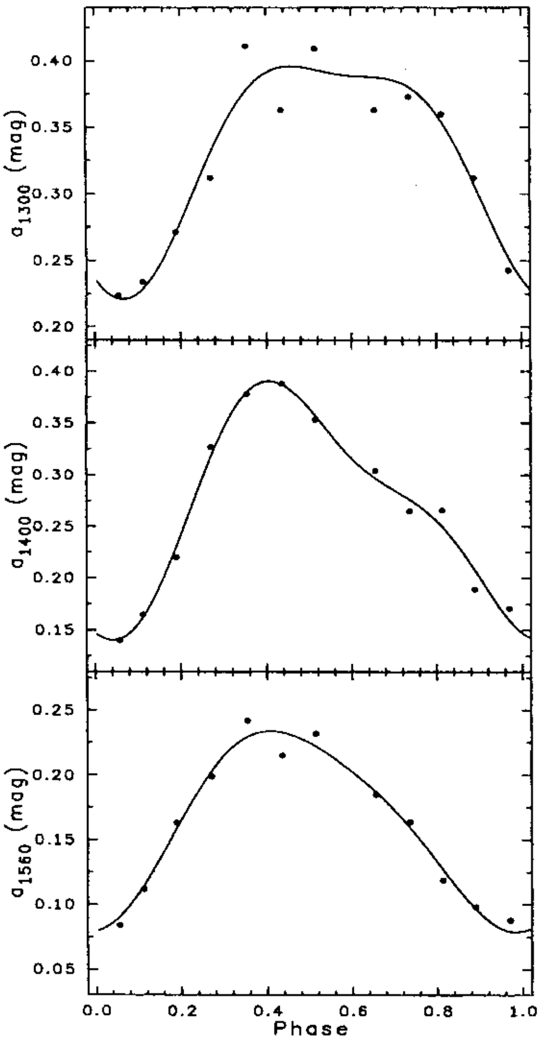

Figure 4: *The phase diagrams of the broad features in the far-UV spectral region of CU Vir. The solid lines are the least squares fits.*

fitted curves, especially after the first maximum, are different. A comparison of the light variations in the spectral region with $\lambda < 1500$ Å and the variations for silicon features shows that they vary in antiphase. This agrees with the anticorrelation which has been supported by the energy blocking mechanism in the far-UV for CP2 stars.

4. Conclusions

The archival *IUE* data have permitted analysis of the light variations of CU Vir in the UV spectral region. First of all, the monochromatic light curve changes continuously its shape depending on the wavelength. The light variations in the wavelength region longer than $\lambda 2000$ Å are generally in antiphase to the light variations in the shorter wavelength region.

However the second minimum at phases 0.6-0.7 of the monochromatic light curves with $\lambda < 2000$ Å is not compensated by the maximum in the longer wavelength region. The brightness of the star at $\lambda 2000$ Å is constant over the period of variations which means that the so-called "null wavelength region" exists for CU Vir. Moreover, the amplitudes of light variations reach minimum values in the core of the L_α line (see Fig. 1), where the flux forms in the outer layers of the stellar atmosphere.

The variable broad features in the far-UV connected with the non-uniform distribution of silicon over the surface of CU Vir influence substantially the light variations in the UV. The anticorrelation between the light variations in the far-UV and the silicon features intensity variations are caused by extra blocking of the flux in the far-UV and its redistribution at the longer wavelengths.

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