Spectrophotometric Variability of the Magnetic CP Star α^2 CVn *

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Abstract. The spectrophotometric variability of the classical magnetic CP star α^2 CVn is investigated in the ultraviolet spectral region from 1150 to 3200 Å. This study is based on the archival *International Ultraviolet Explorer* data obtained at different phases of rotational cycle. The brightness of the star in the spectral region from 3015 to 3138 Å is constant over the period of rotation, which means that the so–called "null wavelength region" exists at these wavelengths. Moreover, the minima values of the amplitude of light curves are reached in the spectral region at $\lambda\lambda$ 1660 and 1900 Å. The monochromatic light curves in the "pseudo–continuum" of this star change their shapes with wavelength. All the light curves with $\lambda \leq 2505$ Å have a similar shape, but the monochromatic light curves with $\lambda > 2505$ Å shows the phase displacement of the minimum from 0.0 at λ 2505 Å to 0.3 at λ 2993 Å.

Key words: stars: chemically peculiar – stars: individual: α^2 CVn – stars: variables: other

1 Introduction

The magnetic Chemically Peculiar (mCP) star α^2 CVn (HD 112413, HR 4915) was the first bright star ($m_V = 2.90$) classified as chemically peculiar of the SiHgEuCr type (Leckrone, 1973) and is the prototypical magnetic CP star. This star shows periodic spectrum, magnetic field and brightness variations with a period of 5.46939 days, first established by Farnsworth (1932). In the visual spectral region the light curves for α^2 CVn have been presented by Provin (1953). In addition, twenty–one *UBV* photometric observations of this star were also obtained by Pyper (1969).

Molnar (1973) investigated the ultraviolet photometric observations with the *OAO*–2 satellite for α^2 CVn. He showed that the brightness variations in the wavelength region shorter than $\sim \lambda$ 2960 Å are generally in anti–phase to the brightness variations in the visual region, although the shapes of light curves are different. Moreover, the photometric light curves indicate that there are two important sources of energy blocking in the far–UV region. Strong line blanketing by the rare earths redistributes the flux into the Paschen continuum, causing the major observed photometric variations. In addition, a second source, which may be due to a combination of continuous opacities and blanketing from the iron–peak and rare–earth groups below λ 1600 Å apparently redistributes the flux into the region of the Balmer discontinuity.

Leckrone & Snijders (1979) have been studying the ultraviolet spectrophotometry obtained with the *Copernicus*, *OAO*–2, *TD*–1 and a sounding rocket for α^2 CVn. The authors compared the ultraviolet flux distribution in two phases 0.0 and 0.5 and they pointed out that: (1) at $\lambda < 1190$ Å,

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* Based on INES data from the *IUE* satellite

the flux varies with large amplitude, which appears to result from enhanced continuous opacity sources, (2) variations in the $1190-1365\,\text{Å}$ range are due primarily to the lines of doubly ionised metals and possibly of Si II, and (3) from 1365 to $1800\,\text{Å}$ and from 2700 to $2900\,\text{Å}$ the flux does not vary in any systematic way. One can see that the variations of the ultraviolet fluxes are quite complex and it is necessary to investigate the variations of the ultraviolet fluxes at different phases of rotational cycle for this star.

The brightness variability can be generally explained by the variable abundance of several chemical elements observed in the atmospheres of mCP stars. Enhanced energy blocking decreases the flux in the far–UV region where most of the lines of these elements are present. The blocked flux re–emerges in the visual and the red parts of the spectrum. Such an explanation is supported by the anti-phase relationship of light curves in the far–UV and the visual spectral regions. In addition, this relationship asserts the existence of the "null wavelength region" where the amplitude of brightness variations is zero over the period of rotation (see, for example, Leckrone, 1974; Molnar, 1975; Molnar et al., 1976; Jamar, 1978). Earlier photometric results obtained for some mCP stars reveal the existence of two or more "null wavelength regions" (Jamar, 1977; Muciek et al., 1985). Later, Sokolov (2000, 2006, 2010) has investigated the spectrophotometric variability of two silicon mCP stars CU Vir and 56 Ari in the far–UV spectral region, using the archival *IUE* data. The author showed that in the case of CU Vir the "null wavelength region" is at $\lambda\,2000\,\text{Å}$, but in the case of 56 Ari with more complex light curves the "null wavelength region" is nonexistent. A detailed investigation of several additional stars is necessary to draw a definite conclusion about the mechanism of brightness variations in the spectra of mCP stars. Another mCP star is α^2 CVn for which there are enough *IUE* data in order to investigate the spectrophotometric variability in the ultraviolet spectral region. The *IUE* Newly Extracted Spectra (INES) data from the *IUE* satellite allows to investigate the variability of monochromatic light curves in the far–UV and near–UV spectral regions. The INES archives are available from the INES Principal Center website http://ines.vilspa.esa.es or from the INES National Hosts (Wamsteker, 2000).

In this paper, the low–dispersion spectra of the mCP star α^2 CVn are analysed in detail for the variability of the monochromatic light curves in the far–UV and near–UV spectral regions, using the INES data from the *IUE* satellite.

2   Observational Data

2.1   *IUE* Spectra

The following list of a series of two observations of α^2 CVn obtained with the Short Wavelength Prime (SWP), Long Wavelength Redundant (LWR) and Long Wavelength Prime (LWP) cameras was obtained from the INES archive.

1. The first one contains 10 SWP spectra and 8 LWR spectra obtained in December 1981.

2. The second one contains 11 SWP and 7 LWP spectra obtained in March 1984.

Additionally, four spectra (SWP 04812, SWP 04813, LWR 02674, LWR 04153) obtained in October 1978 and March 1979 were taken from the INES archive as well. In all cases, the spectra were obtained through a large aperture ($9.5'' \times 22''$).

In the INES archive, each high–dispersion image has an associated "rebinned" spectrum, which is obtained by rebinning the "concatenated" spectrum at the same wavelength step size ($1.676\,\text{Å/pixel}$ for the SWP camera and $2.669\,\text{Å/pixel}$ for LWR and LWP cameras) as low–resolution data (González–Riestra et al., 2000). This data set represents an important complement to the low–resolution archive, and it is especially useful for the time–variability studies. The ultraviolet spectra
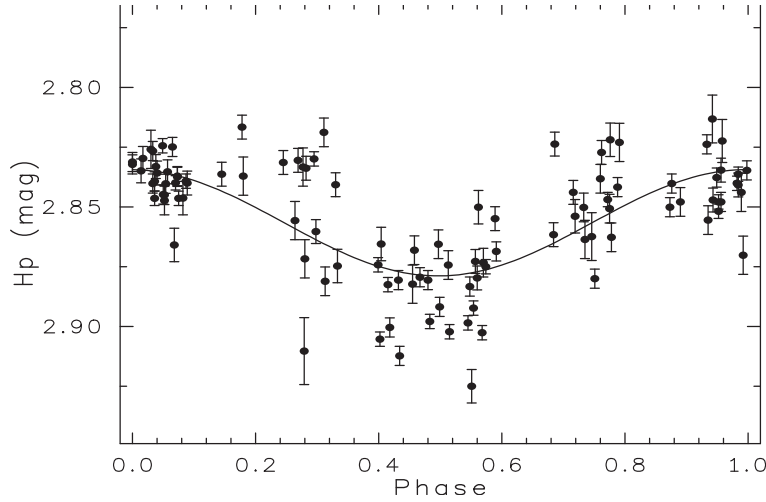
Figure 1: The Hipparcos photometry variations of α^2 CVn. Solid lines denote the fit according to equation (2).

used in this study are low–resolution echelle spectra obtained with a resolution of about 6 Å. We additionally used the "rebinned" spectra from high–dispersion images of α^2 CVn as well.

The inspection of the spectra of α^2 CVn showed that the fluxes of the SWP 27838 spectrum are systematically lower and hence unsuitable for our purposes. Additionally, the high–dispersion spectrum LWP 07741 was excluded because the exposure time is only 2.184 sec. Finally, we analyzed 22 SWP, 10 LWR and 6 LWP spectra, distributed quite smoothly over the period of rotation.

2.2   The Period Variations of α^2 CVn

Since the beginning of the 20th century till now (e.g., Romanyuk et al., 2007) the investigators use the ephemeris obtained by Farnsworth (1932), which refers to the phase of the maximum intensity of Eu II spectral lines. On the other hand, some mCP stars displayed an increase in their rotational periods (Mikulasek et al., 2008). Unfortunately, in literature there are no photometric data, except for the *UBV* photometric observations obtained by Pyper (1969). Other publications concerning the photometric observations of α^2 CVn are not available as they are published only as plots. In order to check the trustworthiness of the ephemeris obtained by Farnsworth (1932) we used the photometric data from the Hipparcos (ESA, 1997). The Hipparcos Epoch Photometry contains 107 measurements of α^2 CVn obtained between the Julian dates 2447896 – 2449018. The Hipparcos photometry (H_p) are plotted in Fig. 1 versus the phase computed by means of Farnsworth (1932) ephemeris:

$$JD = 2419869.720 + 5^{\mathrm{d}}.46939\,E \tag{1}$$

We find a cosinusoidal variation of H_p with an amplitude of the order of 0.06 mag, although the scattering of H_p measurements around the fitted curve is significant. The mean standard deviations of the residual scatter around the fitted curve (σ_{res}) is equal to 0.018 mag. Probably, such scattering of the H_p measurements can be explained by the influence of α^1 CVn on the H_p data of α^2 CVn at the passband of the Hipparcos photometry. The pair α^2 CVn and α^1 CVn is a visual binary with a separation of $20''$. The secondary has the spectral class F0 V and $m_V = 5.60$. In any case, the maximum and the minimum of the fitted H_p light curve correspond to the phases 0.0 and 0.5, respectively. It is in good agreement with the V light curve (see Fig. 1 of Pyper, 1969).

3   Data Analysis

To analyse the *IUE* spectra of α^2 CVn we used the linearized least–squares method. An attempt was made to describe the light curves in a quantitative way by adjusting the Fourier series. The method has already been applied to the *IUE* data of two silicon mCP stars CU Vir and 56 Ari and has shown very good descriptions of the monochromatic light curves (Sokolov, 2000, 2006, 2010). In the case of α^2 CVn the observations were fitted by a simple cosine wave:

$$F(\lambda, T') = A_0(\lambda) + A_1(\lambda) \cos(\omega T' + \phi_i(\lambda)), \tag{2}$$

where $F(\lambda, T')$ is a flux for the given λ, $T' = T - T_0$ and $\omega = 2\pi/P$. The T_0 and P are zero epoch and rotational period of the ephemeris, respectively. The coefficients $A_0(\lambda)$ of the fitted curves define the average distribution of energy over the cycle of variability while the coefficients $A_1(\lambda)$ define the semi–amplitude of the flux variations for the given λ. From several scans distributed over the period one can produce light curves at different wavelengths. This procedure can be partially accounted for by considering that within the accuracy of measurements a cosine wave appears to be generally adequate to describe the monochromatic light curves in the ultraviolet spectral region.

The least–squares fit was applied to separate *IUE* monochromatic light curves. An error analysis has shown that the uncertainties in the coefficients $A_0(\lambda)$ and $A_1(\lambda)$ of the fitted curves are no more than 0.05 and 0.07, respectively. However, standard deviations of the residual scatter around the fitted curves (σ_{res}) vary from 0.03 to 0.18 in the investigated wavelengths. The maximal errors of the coefficients $A_0(\lambda)$ and $A_1(\lambda)$ as well as in σ_{res} are in the blue and red parts of *IUE* spectra. Probably it is connected with uncertainties of fluxes in both ends of the spectra, as presented in the INES database. Thus, we limited our investigation to the wavelength region from 1150 to 1950 Å and from 1950 to 3200 Å for the far–UV and near–UV spectral regions, respectively. In order to minimise the uncertainties in the coefficients of the fitted curves, the light curves were determined by averaging three nearest fluxes for a given λ:

$$F(\lambda) = \frac{F(\lambda - \lambda_{\mathrm{step}}) + F(\lambda) + F(\lambda + \lambda_{\mathrm{step}})}{3}, \tag{3}$$

where λ_{step} is equal to 1.676 Å for the SWP camera, and to 2.669 Å for LWR and LWP cameras. As far as the errors in $F(\lambda)$ are concerned, we computed them by taking into account the errors in the fluxes as presented in the INES *Catalog*, according to the standard propagation theory of errors.

4   Monochromatic Brightness Variations in the Pseudo–Continuum

Figure 2 displays the average energy distribution $A_0(\lambda)$ of α^2 CVn over the cycle of variability in the spectral region from 1150 to 3200 Å. First of all, it is necessary to fix the continuum in the low–dispersion *IUE* data. This is very difficult in the UV due to the line crowding. Nevertheless, one can find some high flux points located at the same wavelength in several spectra of α^2 CVn. It should be noted that such a choice of the continuum might be a "pseudo–continuum". However, there is no chance to reach the true continuum if it occurs at high flux points. From several scans distributed over the period of rotation one can produce light curves in different wavelengths. The light curves discussed below will be called "monochromatic", although they were determined by averaging three nearest fluxes for a given λ according to equation 3. Several monochromatic light curves in the "pseudo-continuum" at different wavelengths were formed. The examples of light curves together with the fitted cosine curves are shown in Fig. 3. Note that the vertical scales differ for each part of the figure. In order to exclude overlapping of some curves, the vertical shift on the constant value was used. In this way, the curves at $\lambda\lambda$ 2649, 2993 and 3015 Å were shifted down to the values of
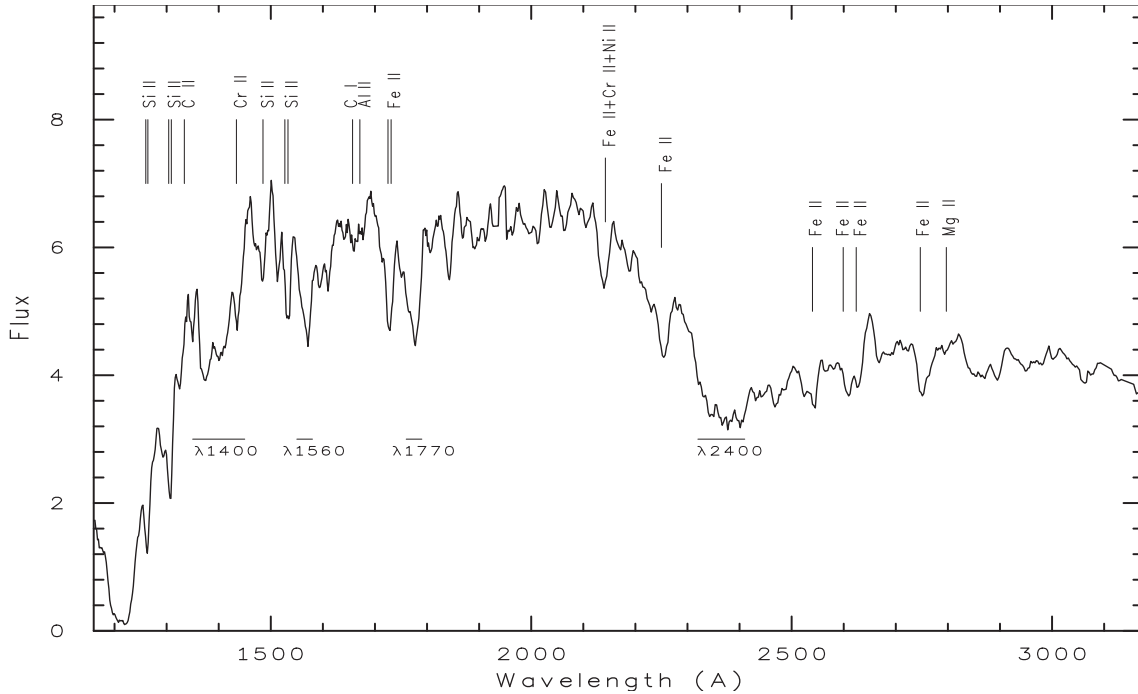
Figure 2: The average distribution of energy in $10^{-10}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,\mathring{A}^{-1}}$ for α^2 CVn. Prominent spectral lines and features are shown by vertical and horizontal lines, respectively.

-1.5, -0.5 and $-1.0 \cdot 10^{-10}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,\mathring{A}^{-1}}$, respectively. On the other hand, the curves at $\lambda\lambda\,2097$ and $2505\,\mathring{A}$ were shifted up to the values of $+0.5$ and $+1.0 \cdot 10^{-10}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,\mathring{A}^{-1}}$, respectively.

The monochromatic light curves in the "pseudo–continuum" of α^2 CVn change their shapes with wavelength. All light curves with $\lambda \leq 2505\,\mathring{A}$ have a similar shape: a minimum of the flux at phase 0.0 and a maximum of the flux at phase 0.5. On the other hand, the monochromatic light curves with $\lambda > 2505\,\mathring{A}$ show the phase displacement of the minimum from 0.0 at $\lambda\,2505\,\mathring{A}$ to 0.3 at $\lambda\,2993\,\mathring{A}$. The maximum also moves from the phase 0.5 at $\lambda\,2505\,\mathring{A}$ to the phase 0.8 at $\lambda\,2993\,\mathring{A}$. Moreover, the amplitude of brightness variations decreases with increasing wavelength and, as a result, at $\lambda > 2993\,\mathring{A}$ there is the "null wavelength region", where the amplitude of brightness variations is zero over the period of rotation. Our result is in an agreement with the previous investigation of Molnar (1973) obtained from the ultraviolet photometric observations with the OAO–2 satellite for α^2 CVn. It is necessary to note that the amplitude of brightness variations can also change in the spectral region with $\lambda \leq 2505\,\mathring{A}$, as illustrated by Fig. 3.

5 The Null Wavelength Regions

The situation with the position of the "null wavelength region" in the spectrum of α^2 CVn is mysterious enough. Thus, Molnar (1973) has determined the position of the "null wavelength region" at $\sim\lambda\,2960\,\mathring{A}$. On the other hand, Leckrone & Snijders (1979) find that the "null wavelength region" extends over the short wavelength region to about $2700\,\mathring{A}$. Moreover, they have noted that from 1365 to at least $1800\,\mathring{A}$ and from 2700 to at least $2900\,\mathring{A}$, α^2 CVn does not vary in any systematic way.

The INES data from the *IUE* satellite allows to estimate more accurately the position of the "null wavelength region" in the spectrum of this star. In order to investigate the behaviour of the monochromatic light curves in the "pseudo–continuum" of α^2 CVn we used the coefficients $A_1(\lambda)$ (semi–amplitude of the flux variations). Figure 4 presents the dependence of the amplitude of light

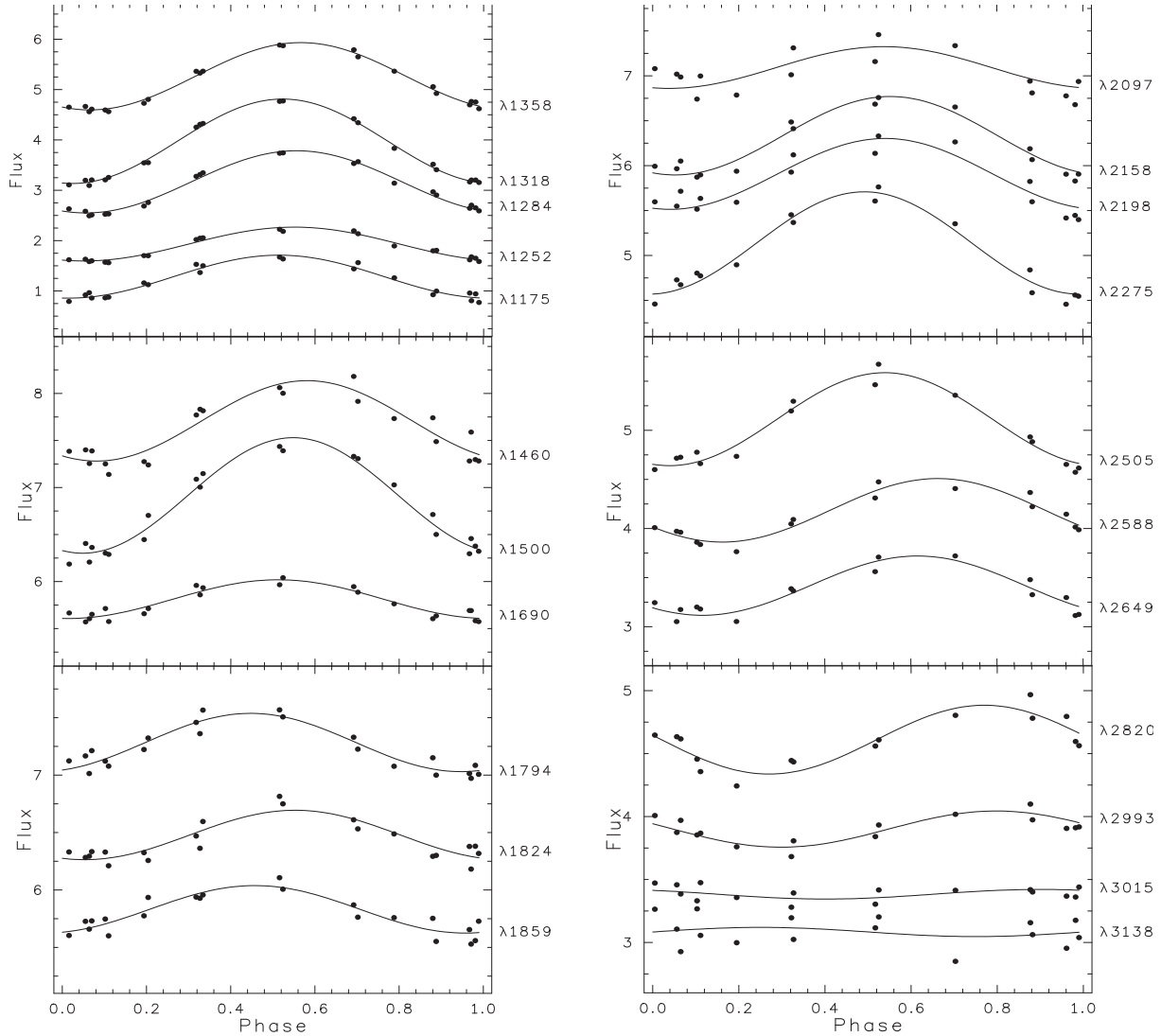Figure 3: Phase diagrams of the monochromatic light curves in $10^{-10}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,\mathring{A}^{-1}}$ for α^2 CVn. To avoid overlapping the vertical shift on the constant value of some curves was used (see text). Solid lines denote the fit according to equation (2).

curves from wavelength. One can see from Fig. 4 that the variations of the light curve amplitudes are quite complex. The maximal values of the amplitudes are reached in the spectral regions $\lambda\lambda\,1281-1294$, $1314-1360$, 1500, 2048, 2219, 2275, 2420 and $2505\,\mathring{A}$. On the other hand, the minimal values of the amplitudes are in the spectral region from 1660 to 1900 $\mathring{A}$ as well as in the region with $\lambda > 2993\,\mathring{A}$. Also, the minimal values of the amplitude are reached at the cores of large features at $\lambda\lambda\,1560$ and $1770\,\mathring{A}$ and at the cores of the strong Si II resonance lines at $\lambda\lambda\,1260-64$, $1304-09$ and $1485\,\mathring{A}$. Moreover, the minimal values of the amplitude are at the cores of the Fe II depression at $\lambda\lambda\,1725-31$ and $2250\,\mathring{A}$.

In order to establish the position of the "null wavelength region" in the spectral region with $\lambda > 2993\,\mathring{A}$ the amplitudes of the brightness variations in the "pseudo–continuum" have been used. The inspection of the values of amplitudes in this spectral region shows that within the errors of measurements the fluxes do not vary in the spectral region from 3015 to 3138 $\mathring{A}$, as illustrated by Fig. 5. In other words, the brightness of the star at this spectral region is constant over the period of rotation, which means that the so–called "null wavelength region" exists on these wavelengths.
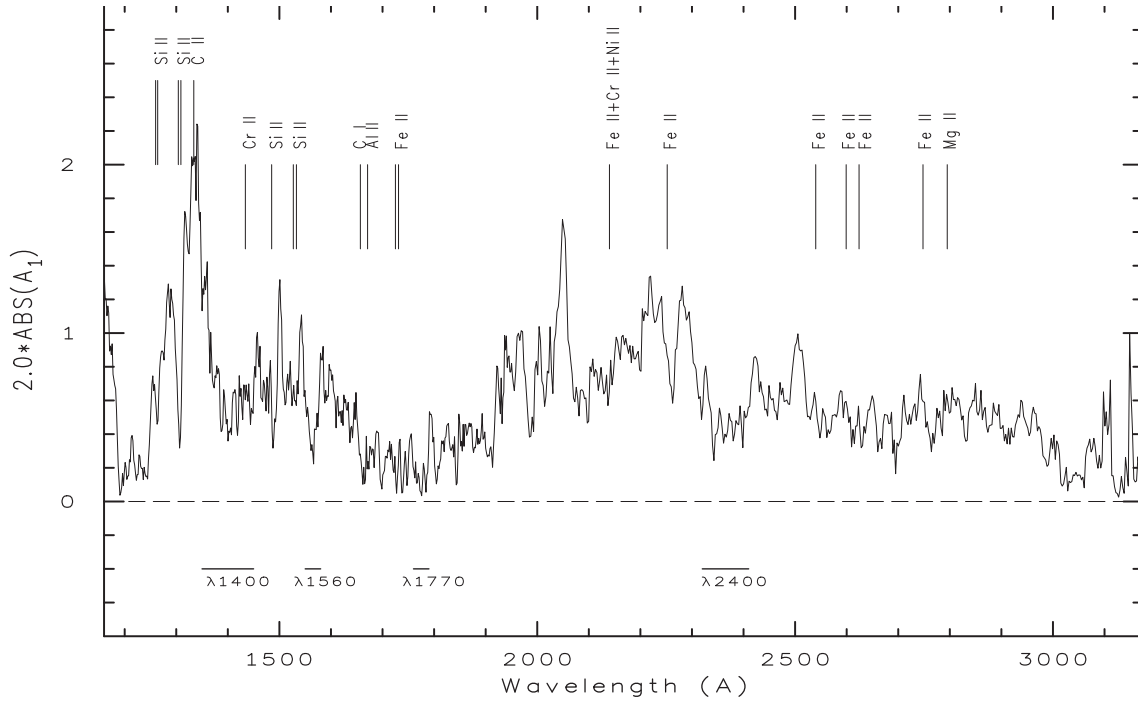
Figure 4: The amplitudes of the monochromatic light curves in $10^{-10}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,\mathring{A}^{-1}}$ for $\alpha^2\,\mathrm{CVn}$. Prominent spectral lines and features are shown by vertical and horizontal lines, respectively.

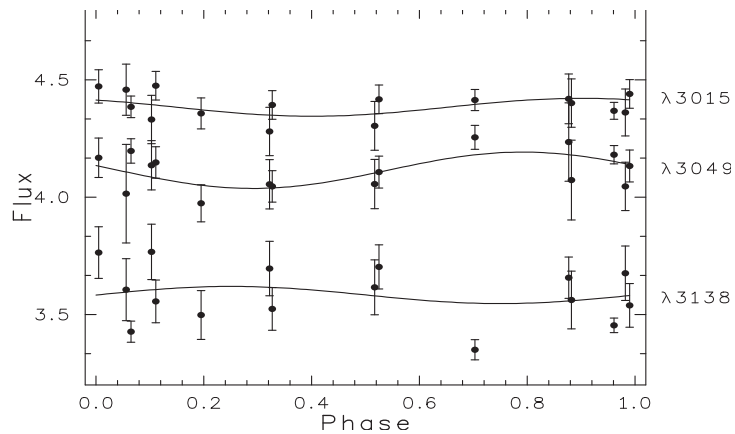Figure 5: Phase diagrams of the monochromatic light curves in $10^{-10}\,\mathrm{erg\,s^{-1}\,cm^{-2}\,\mathring{A}^{-1}}$ in the near–UV spectral region for $\alpha^2\,\mathrm{CVn}$. Solid lines denote the fit according to equation (2).

6   Discussion

For the first time, Molnar (1973) investigated the photometric variability of α^2 CVn in the far–UV spectral region using the photometric data obtained with *OAO*–2 satellite. Unfortunately, it is very difficult to compare the phase diagrams obtained from the photometric data with our phase diagrams, because the *OAO*–2 photometric filters had FWHM $\gtrsim 200$ Å (Code et al., 1970). On the other hand, the *IUE* satellite performed UV spectrophotometry in the low–resolution mode with the spectral resolution ~ 6 Å. However, there is some evidence for the phase displacement of the flux minimum at $\lambda\lambda$ 1332, 1430 and 1554 Å obtained from the photometric data in the far–UV spectral region. These have a very strong minimum of the flux in phase 0.1 and a secondary minimum in phase 0.5. However, this latter feature is not very evident at λ 1554 Å. Perhaps the minimum of the flux in phase 0.1 is related to the maximum of the light curves in phase 0.1 for the light curve at λ 3317 Å and the light curves in the *U* and *B* filters (see Fig. 1 and 2 of Molnar, 1973). Molnar (1973) has indicated that there are two important sources in the blocking of the emergent flux in the far–UV spectral region. A strong blanketing by the rare–earths elements (REE) redistributes flux into the visual spectral region. In addition, the second source, which may be due to a combination of continuous opacities and line blanketing from the iron–peak and rare–earth groups below λ 1600 Å. Leckrone & Snijders (1979) noted that the complex shapes of Molnar's far–UV light curves can be understood in terms of the competition between the Cr, Fe and Si lines, which vary out of phase with the REE lines, and Ti, Mn and V, which vary approximately in phase with the REE lines.

Probably, uneven surface distribution of chromium, silicon and iron mainly influences the flux redistribution from the far–UV to the visual spectral regions in the spectrum of α^2 CVn, although additional sources of opacity can be involved. It is not new that chromium, silicon and iron affect the flux redistribution in the spectra of mCP stars. Khan & Shulyak (2007) have studied the effects of individual abundance patterns on the model atmospheres of mCP stars. They have shown that the group of elements which produce large changes in the model atmosphere structure and energy distribution mainly consists of silicon, iron and chromium. It should be noted that the lines of these elements are widely presented in the spectra of mCP stars in the far–UV spectral region. Recently, Krticka et al. (2009) have simulated the brightness variability of the star HR 7224 using the observed surface distribution of silicon and iron. They have concluded that a promising explanation for the brightness variations in mCP stars is the flux redistribution through the line and bound–free transitions combined with inhomogeneous surface distribution of various elements.

Our investigation indicates that the variations of the monochromatic light curves in the "pseudo–continuum" of α^2 CVn are more complex. For example, the monochromatic light curves with $\lambda > 2505$ Å show the phase displacement of the minimum. Moreover, the minimal values of the amplitude are reached at the cores of large features at $\lambda\lambda$ 1560 and 1770 Å and at the cores of the strong Si II resonance lines at $\lambda\lambda$ 1260 − 64, 1304 − 09 and 1485 Å. Also, the minimal values of the amplitude are at the cores of the Fe II depressions at $\lambda\lambda$ 1725 − 31 and 2250 Å. Possibly, an additional investigation of the flux variations at the cores of large features and spectral lines will help to understand such behaviour of light curves in the spectrum of α^2 CVn. It is laid out in our second paper (Sokolov, 2011, this issue).

7   Conclusions

The archival *IUE* spectrophotometric observations of α^2 CVn allowed us to analyse the light variations in the spectral region from 1150 Å to 3200 Å at various wavelengths. The monochromatic light curves in the "pseudo–continuum" of α^2 CVn change their shapes with wavelength. All light curves with $\lambda \leq 2505$ Å have a similar shape: a minimum of the flux at phase 0.0 and a maximum of the flux at phase 0.5. On the other hand, the monochromatic light curves with $\lambda > 2505$ Å show the

phase displacement of the minimum from 0.0 at $\lambda\,2505\,\text{Å}$ to 0.3 at $\lambda\,2993\,\text{Å}$. The brightness of the star in the spectral region from 3015 to $3138\,\text{Å}$ is constant over the period of rotation which means that the so called "null wavelength region" exists at these wavelengths.

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