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Correlations Between Line-profile and Photometric Variations in the B 2 IV [*e*] Star HD 45677*

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Summary. The results deduced from two sets of homogeneous simultaneous photometric and spectrographic observations of HD 45677 in 1977 (6 nights of *UBV* data; 38 spectra) and in 1979 (7 nights of *uvby* data; 30 spectra) in a search for correlated variations are described. It appears that photometric data and some spectral features are well correlated (or anticorrelated) at certain epochs, but not at all at others. Because of these conflicting results, no explanation of the behaviour of the extended complex atmosphere surrounding this peculiar object can be proposed.

Key words: emission-line stars – photometry – spectroscopy – correlations

Introduction

In 1976, Feinstein et al. (1976) gave a historical review of the changes in magnitudes of HD 45677 from 1899 to 1972 and presented *UBV* and *uvby* data concerning HD 45677 which were gathered during the years 1973–75: these data show night-to-night variations of some indices that can reach 0.10 mag as well as smaller variations ($\Delta m \leqq 0.02$ mag) during the course of several individual nights.

As far as spectroscopy of HD 45677 is concerned, Swings (1973) described rapid variations which occur essentially in the complex P Cygni profiles of the Balmer lines from night to night and, in some instances, on a time scale of about two hours. A simple-minded physical model was constructed by Swings (1973) in order to interpret the spectrographic data and the existence of the infrared excess studied by Swings and Allen (1971): according to this model HD 45677 would be surrounded by a rotating equatorial ring of gas extending into a patchy dust ring to which we will come back when trying to interpret the more recent data.

As seen from the previous paragraphs, so far either photometric data or spectrographic data were obtained; no simultaneous information was described. Fortunately, we were able to observe HD 45677 during two runs at ESO, simultaneously with a coudé spectrographic telescope and with one of the photometric telescopes. These observations are described in the following chapter.

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Observations

Table 1 gives some information on the telescopes used, photometric filters and, for the spectra, type of emulsion, dispersion, mean exposure time and number of plates obtained.

As an illustration[1], Fig. 1 reproduces a sample of spectrographic data from 1977 in the region from Hδ to Mg II λ 4481.

The lines suffering rapid intensity variations are essentially Mg II, He I, and Ca II absorptions as well as the components of e.g. Hγ and Hδ. The major change between the spectrum of 1977 and that of 1979 concerns the strength of the absorption core of the Balmer lines. It is actually interesting to note that the Balmer-line profiles observed since 1977 are very different from the complex profiles described previously, e.g. P Cygni with several emission and absorption components (see Figs. 4 and 5 and Table 2 of Swings, 1973)

Intensity tracings were performed in order to measure the equivalent widths of a series of emission and/or absorption lines. Figure 2 illustrates, for instance, what components of the Balmer lines were measured in our search for correlations with photometric data. As an illustration[1] the 1977 data (V, $U-B$, $B-V$) are given in Fig. 3 whose hatched areas correspond to the epochs (width = exposure time) when the spectrograms were obtained.

The *UBV* data of 1977 and *uvby* ones of 1979 confirm those published by Feinstein et al. (1976), e.g. night-to-night variations of $\sim$0.1 mag and variations of $\sim$0.03 mag over one night.

Search for Correlations

The following equivalent widths were measured on the intensity tracings of the two samples of spectra:

a) for the 1977 set: absorption lines of Ca II K; He I 4026; He I 4471; Mg II 4481; violet and red emission wings of Hδ and Hγ (called HDV, HDR, HGV, and HGR respectively in Table 2); absorption cores of Hδ and Hγ (HDA and HGA respectively); and

b) for the 1979 set: absorption lines of Ca II K; He I 4026; He I 4388; He I 4471; Mg II 4481; violet and red emission wings of Hγ (HGV and HGR respectively); the absorption core of the Balmer lines was much less visible in 1979 than in 1977 and was, therefore, not measured for this sample.

We then searched for correlations between spectroscopic and photometric data obtained really simultaneously: the first set

1 Four figures reproducing the 1977 and 1979 spectra as well as all the *UBV* or *uvby* data are available upon request.

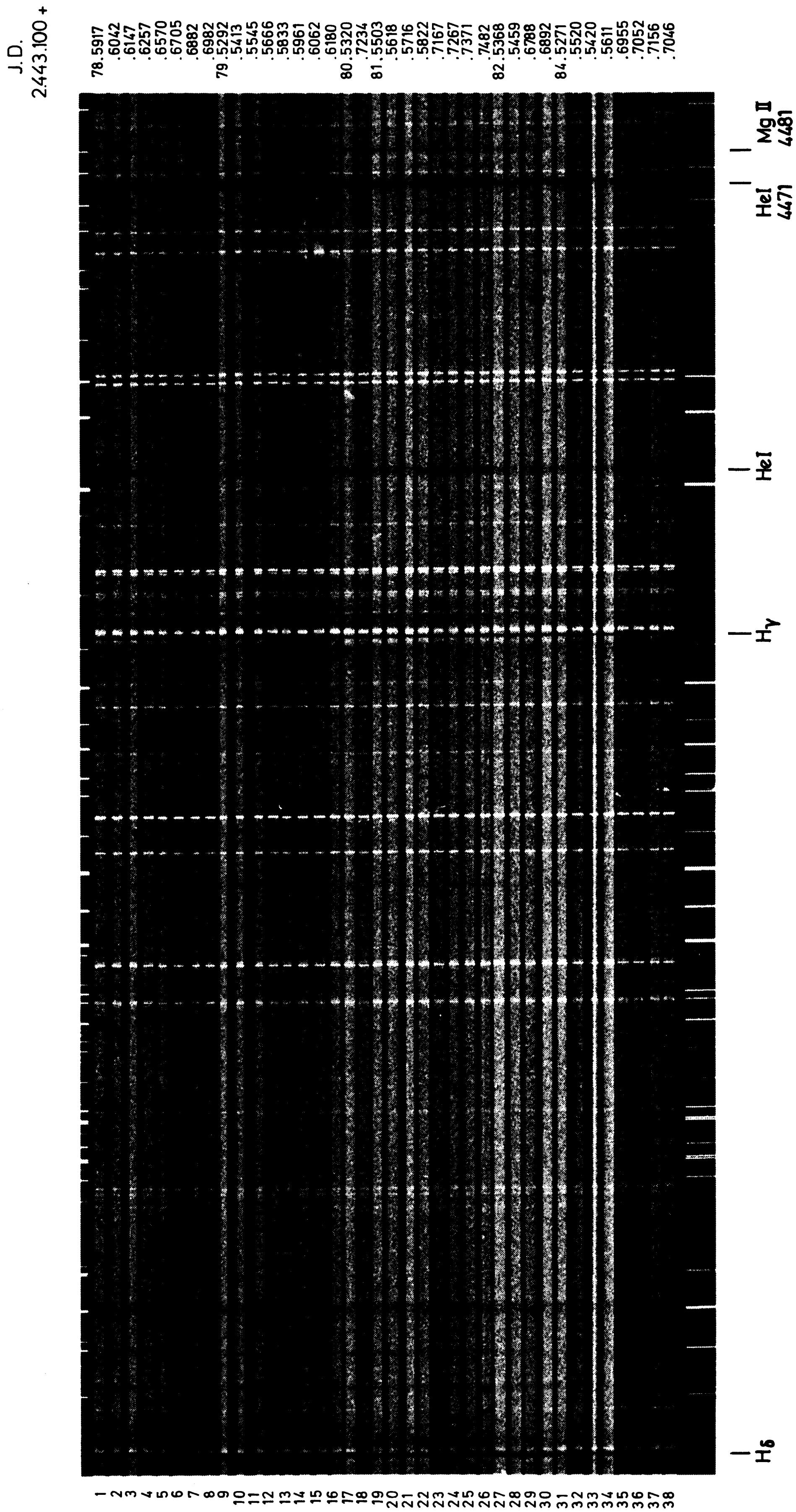
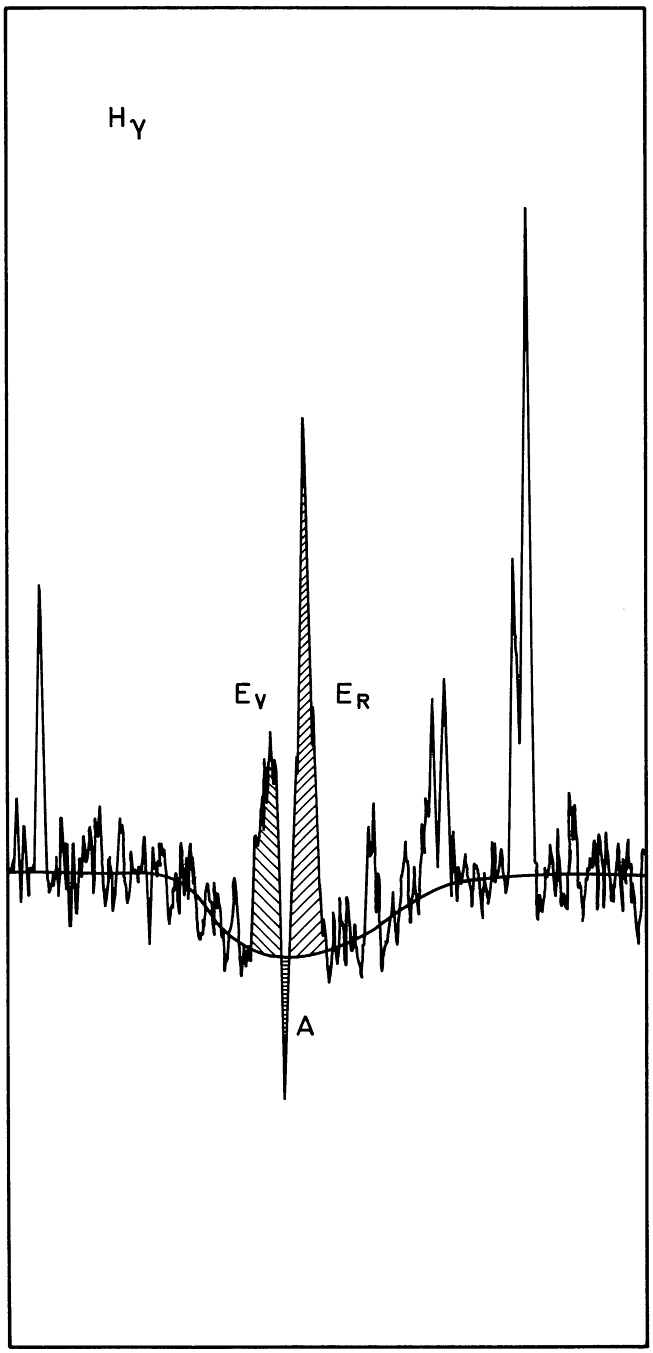


Fig. 1. The 1977 spectra of HD 45677 between Hδ and Mg II λ 4481 Å (original dispersion: 20 Å mm^{-1}; ESO. 1.5-m coudé spectrograph)

Table 1. Summary of the observational material

Dates	Photometry		Spectroscopy				
	Instrument	Filters	Instrument	Plate	Dispersion	Mean exposure Time	Number of spectra
February 3–9, 1977	Bochum 61-cm	*UBV*	1.52-m coudé	baked IIa-O	20 Å mm^{-1}	13 min	38
January 12–20, 1979	Danish 50-cm	*uvby*					30



thus comprises 23 pair-clusters of data whilst the second contains 24 pair-clusters.

Since the possible relations between the equivalent widths and the magnitudes or colours could be non-linear, we tried a rank correlation method (Kendall, 1948) which only requires the weak hypothesis of monotonicity of the relation. We thus computed Kendall's τ coefficient for all the pairs of data: the results (τ values) are given in Tables 2 and 3 for the 1977 and 1979 sets respectively. For 46 or 48 random observations clustered in 23 and 24 pairs the probability that the absolute value of τ be larger than 0.3, 0.4, or 0.5 is respectively 0.95, 0.99, and 0.999. Hereafter we first discuss the reality of the observed variations and subsequently describe the meaningful correlations between spectroscopic data and between spectroscopic and photometric data. We will not consider the correlations between pairs of photometric data.

Reality of the Observed Variations

Before considering the variations let us first estimate the accuracy of the measurements. The relative error in calculating the equivalent widths of a strong emission or absorption line is found to be of the order of 10% and is around 50% for the very weak or shallow lines. However, the position chosen for the level of the continuum has always been taken in a similar way, so that the relative error on the variations is respectively reduced to 5 and 30% of the equivalent widths. It is, of course, to be kept in mind that the search for correlations between two values suffering large uncertainties will lead to much weaker results than, e.g., between one accurately-measured value and one inaccurate value (see, e.g., two He I lines in Table 2 correlated with HGA but not among themselves).

When observing the photoelectric lightcurves of HD 45677 we measured regularly two comparison stars chosen close to the target star and of similar colours and magnitudes. This allowed to remove easily the small extinction effects from the lightcurves of HD 45677, as well as to judge the quality of the nights – rather good during both observing runs. The general observing routine included repeated observations of HD 45677, sky, comparison stars and some standard stars in the *UBV* or *uvby* systems to determine the magnitudes of HD 45677 and of the comparison stars.

Fig. 2. Profile of Hγ in 1977 showing two emission wings (V and R) and an absorption core (A). The equivalent widths of these three components were measured for our search for correlations (see text)

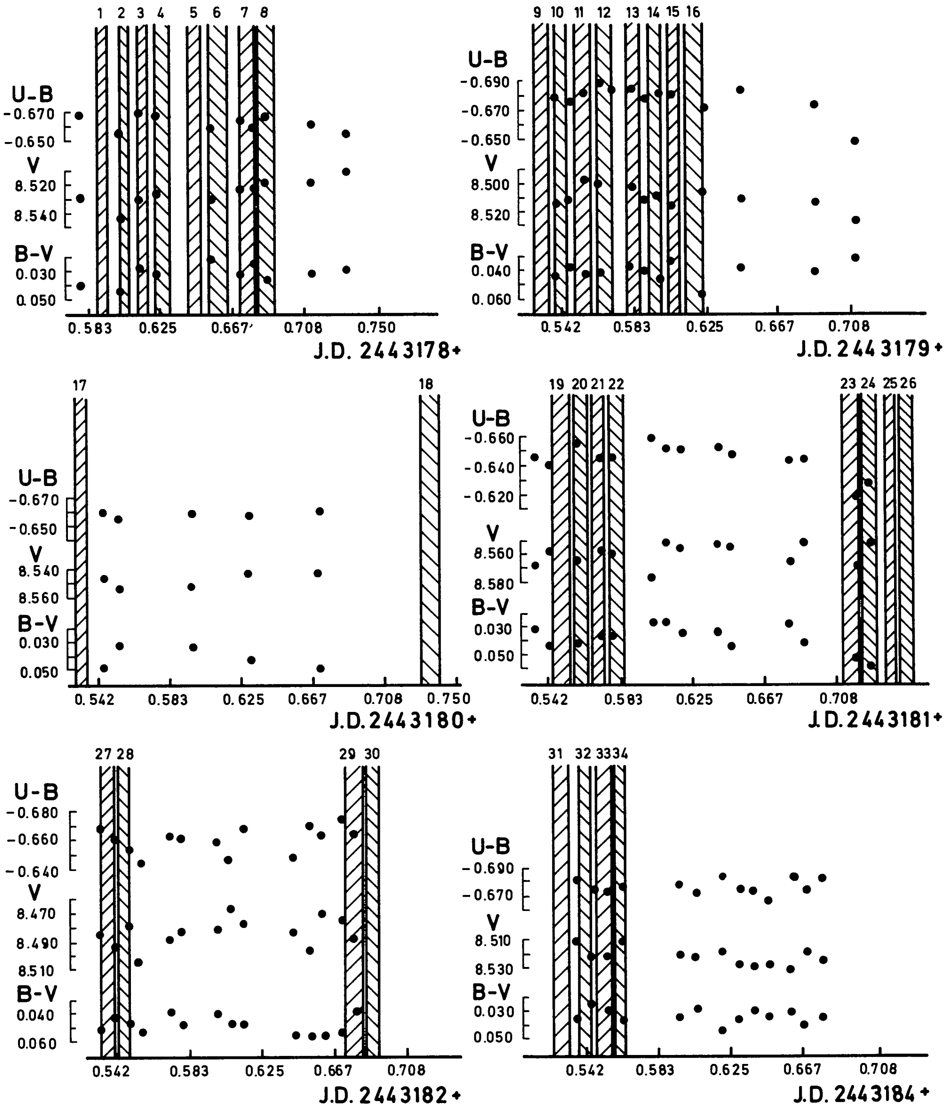


Fig. 3. Simultaneity between the *UBV* data and the spectroscopic data: the widths of the hatched areas correspond to the exposure times of the spectrograms. Only the perfectly simultaneous pairs of photometry and spectroscopy were used

The estimated accuracy of the photometric measurements is thus as follows: $\Delta V \simeq 0.004$; $\Delta(B-V) \simeq 0.006$; $\Delta(U-B) \simeq 0.008$; $\Delta(y) \simeq 0.005$; $\Delta(b-y) \simeq 0.004$; $\Delta(v-b) \simeq 0.003$; $\Delta(u-v) \simeq 0.006$.

Some of the spectrographic or photometric variations are readily visible on the spectrograms. However, in order to see by what amount several quantities were indeed varying, we computed their mean values, r.m.s., and σ_x/x in %, that are listed in Table 4. The latter clearly indicates that most of the measured quantities do indeed suffer real variation during both observing periods.

Correlations in 1977

Table 5 summarises the correlations for the 1977 data at the 99.9, 99, and 95% significance levels. As we reported earlier (Klutz et al., 1977; Barbier et al., 1979), some of the results of the observations given in Table 4 can probably be understood in terms of the patchy dust shell (or ring) model: indeed, if the light variations observed for HD 45677 are interpreted in terms of obscuration by circumstellar dust clouds, located between the star and the observer, it is likely that part of the stellar UV and visible radiation will be backscattered inside the extended atmosphere surrounding the star. The excitation of all atoms present in the envelope will be affected by such a process: subsequent variations of the line emissions and absorptions are bound to occur. It is expected, however, that this backscattered radiation will have a stronger influence on the excitation of atoms moving towards the observer than on that of those escaping behind the star in an opposite direction. Such a mechanism would, therefore, lead to a selective increase of the intensity of the blue emission wings of the Balmer lines relative to the red wings: at the same time, the stellar flux observed from the Earth would be fading. Such a mechanism could explain the correlations between HDV, HGV, and U, B, V, $(U-B)$. The induced backwarming effect would also enhance the absorption lines of He I. It is then hard to understand why the Mg II lines become stronger at the same moment: indeed, if they are assumed to be found at the same photospheric level, they should be affected in an opposite direction by a change in temperature.

When the effect of the dust patches is slightly reduced [$(U-B)$, $(B-V)$, and V decreased], the red emission wings of Hδ and Hγ

Table 2. Spectroscopy vs *UBV* photometry in 1977. Search for correlations

	CaII K	HeI 4026	HeI 4471	MgII 4481	$\frac{\text{MgII}}{\text{HeI}}\left(\frac{4481}{4471}\right)$	HDV	HDA	HDR	HGV	HGA	HGR	U	B	V	U-B	B-V	
CaII K	–	-.08	.21	-.08	-.17	.14	-.05	-.19	.28	-.27	-.23	.15	.18	.14	.25	.06	CaII K
HeI 4026		–	.16	.29	.17	.10	-.37	.04	.25	-.42	.00	.30	.23	.21	.20	.01	HeI 4026
HeI 4471			–	.29	.04	.04	-.19	-.22	.23	-.38	-.12	.20	.17	.17	.33	.12	HeI 4471
MgII 4481				–	.68	.19	-.20	-.23	.44	-.33	-.12	.44	.38	.36	.34	.16	MgII 4481
$\frac{\text{MgII}}{\text{HeI}}\left(\frac{4481}{4471}\right)$					–	.22	-.14	-.21	.33	-.17	-.05	.29	.25	.27	.16	.01	$\frac{\text{MgII}}{\text{HeI}}\left(\frac{4481}{4471}\right)$
HDV						–	-.28	-.23	.56	-.34	-.23	.50	.45	.60	.42	-.03	HDV
HDA							–	.16	-.33	.44	.17	-.31	-.33	-.45	-.36	.16	HDA
HDR								–	-.23	.12	.30	-.21	-.20	-.14	-.40	-.38	HDR
HGV									–	-.57	-.18	.57	.52	.56	.51	.04	HGV
HGA										–	.29	-.39	-.38	-.44	-.50	.11	HGA
HGR											–	-.23	-.15	-.30	-.35	-.08	HGR
U												–	.79	.67	.70	.20	U
B													–	.73	.49	.15	B
V														–	.49	-.12	V
U-B															–	.19	U-B
B-V																–	B-V

Table 3. Spectroscopy vs *uvby* photometry in 1979. Search for correlations

	CaII K	HeI 4026	HeI 4388	HeI 4471	MgII 4481	$\frac{\text{MgII}}{\text{HeI}}\left(\frac{4481}{4471}\right)$	$\frac{\text{HeI}}{\text{HeI}}\left(\frac{4026}{4471}\right)$	HGV	HGR	u	y	b-y	v-b	u-v	$[m_1]$	$[c_1]$	
CaII K	–	.45	.12	.11	.46	.52	.43	.16	.02	.58	.60	-.28	-.17	.51	.04	.58	CaII K
HeI 4026		–	.11	.10	.29	.39	.63	.20	.04	.28	.26	-.04	-.14	.23	-.13	.24	HeI 4026
HeI 4388			–	-.09	.20	.27	.14	-.20	-.05	.03	.02	-.02	.02	-.03	.06	-.03	HeI 4388
HeI 4471				–	.13	-.05	-.25	-.13	-.09	.28	.26	-.04	-.12	.15	-.10	.26	HeI 4471
MgII 4481					–	.82	.30	.00	-.02	.64	.59	-.26	-.26	.46	.00	.53	MgII 4481
$\frac{\text{MgII}}{\text{HeI}}\left(\frac{4481}{4471}\right)$						–	.42	.09	.01	.52	.51	-.33	-.23	.39	.06	.44	$\frac{\text{MgII}}{\text{HeI}}\left(\frac{4481}{4471}\right)$
$\frac{\text{HeI}}{\text{HeI}}\left(\frac{4026}{4471}\right)$							–	.21	.04	.12	.14	-.07	-.10	.13	-.06	.14	$\frac{\text{HeI}}{\text{HeI}}\left(\frac{4026}{4471}\right)$
HGV								–	.36	.07	.04	.02	-.07	-.07	-.10	.04	HGV
HGR									–	.13	.12	.07	.20	.06	.26	.06	HGR
u										–	.88	-.23	-.16	.72	.04	.80	u
y											–	-.31	-.20	.68	.06	.79	y
b-y												–	.46	-.24	.03	-.25	b-y
v-b													–	-.16	.53	-.30	v-b
u-v														–	.08	.86	u-v
$[m_1]$															–	.01	$[m_1]$
$[c_1]$																–	$[c_1]$

Table 4. Reality of the observed variations
Variations in 1977

x	$\overline{x}$	σ_x	$\frac{\sigma_x}{\lvert x \rvert}$(%)
Ca II K	0.25 Å	0.07 Å	28
He I 4026	0.95 Å	0.19 Å	20
He I 4471	0.84 Å	0.24 Å	29
Mg II 4481	0.17 Å	0.12 Å	71
HDV	0.15 Å	0.12 Å	80
HDA	0.39 Å	0.09 Å	23
HDR	0.47 Å	0.15 Å	32
HGV	0.40 Å	0.14 Å	35
HGA	0.18 Å	0.05 Å	28
HGR	1.4 Å	0.27 Å	19
U	7.90	0.04	
B	8.56	0.03	
V	8.53	0.03	
U–B	−0.66	0.04	
B–V	0.02	0.01	

Variations in 1979

x	$\overline{x}$	σ_x	$\frac{\sigma_x}{\lvert x \rvert}$(%)
Ca II K	0.16 Å	0.08 Å	50
He I 4026	0.71 Å	0.20 Å	28
He I 4388	0.47 Å	0.13 Å	28
He I 4471	0.66 Å	0.10 Å	15
Mg II 4481	0.18 Å	0.08 Å	44
HGV	0.52 Å	0.09 Å	17
HGR	1.67 Å	0.25 Å	15
u	9.08	0.08	
y	8.62	0.05	
b–y	0.11	0.01	
v–b	0.13	0.01	
u–v	0.23	0.04	

become stronger in comparison to the violet wings. As far as the observed anticorrelation between HDV, HGV, and HDA, HGA is concerned, it could be due to filling-in of the absorption cores by greater violet emission wings.

If interpreted in terms of motion (rotation) of the extended atmosphere (elliptical ring such as suggested by Huang, 1973), the V/R variations would imply motions of the ring which appear to be far too rapid. If the fact that V/R is smaller than unity is due to an expansion of the envelope, then the V/R variations would imply rapid changes in the velocity gradient in that envelope. Here, again, the time-scale seems too short.

It is also likely that the backscattering of the radiation occurring from dust clouds not located between the star and the observer could induce variations of spectral features without causing any observable changes of the continuum (U, B, V; or u, v, b, y) of the star.

Correlations in 1979

In contrast to what resulted from the 1977 set of data, only very few correlations appear in 1979. More worrying are the existence of a positive correlation between the intensities of the red and violet emission wings of Hγ (that were anticorrelated in 1977) and the fact that the two lines of the He I originating from triplet levels (λ 4026 and λ 4471 Å) do not show at all the same behaviour. It is not easy either to understand the reason why Ca II K is correlated only with the He I λ 4026 and not with the other He I lines $\lambda\lambda$ 4388 and 4471, the latter two being no longer correlated with some of the photometric data as they were in 1977; no conclusion can, of course, be drawn from such weak lines for the reason mentioned in a previous paragraph.

The strengths of the Ca II and Mg II absorption lines are correlated among themselves, and also with u, y, u–v, [c_1] and the ratio Mg II/He I (4481/4471). No such correlations appeared in 1977. The fact that lines of ionised calcium and magnesium exhibit a similar behaviour is probably understandable on the grounds that these lines vary accordingly to a chromospheric activity that is suspected to exist around HD 45677 (Swings, 1973). It was actually more surprising that Ca II K did not seem

Table 5. Correlations and anticorrelations (−) in 1977 (τ values are in parentheses)

	Significance level: 99.9%	99%	95%
He I 4026		HGA(−0.42)	HDA(−0.37) U(0.30)
He I 4471			HGA(−0.38) U–B(0.33)
Mg II 4481	$\frac{4481}{4471}$ (0.68)	HGV(0.44) U(0.44)	HGA(−0.33) B(0.38) V(0.35) $U-B$(0.34)
HDV (H$_\delta$)	HGV(0.56)(U(0.50) V(0.60)	B(0.45) U–B(0.42)	HGA(−0.34) $\frac{4481}{4471}$ (0.32)
HDA (H$_\delta$)		HGA(0.44) V(−0.45)	HGV(−0.33) U(−0.31) B(−0.33) U–B(−0.34)
HDR (H$_\delta$)		U–B(−0.40)	HGR(0.30) B–V(−0.38)
HGV (H$_\gamma$)	HGA(−0.57) U(0.57) B(0.51) V(0.56) U–B(0.51)		$\frac{4481}{4471}$ (0.31)
HGA (H$_\gamma$)	U–B(−0.50)	V(−0.44)	U(−0.39) B(−0.38)
HGR (H$_\gamma$)			V(−0.30) U–B(−0.35)

to be correlated to, e.g. the absorption cores of Hγ and Hδ in the 1977 data or in those described by Swings (1973) since these lines probably originate in the same circumstellar material.

Discussion and Summary

It is unlikely that the different correlations and/or lack of correlations existing in and/or between the two sets of data are caused by the use of a different photometric system. We indeed checked on the location and widths of the various bands with respect to the positions of the emission and/or absorption lines and infer no reason for the different behaviours that result from the present investigation. In any case the use of two different photometric systems would have no effect on the correlations or anticorrelations existing between line intensities.

The search for correlations described in this paper, therefore, leads us to conflicting results from the sets of simultaneous photometry and spectroscopy of HD 45677.

From the first set (1977: six nights of *UBV* data; 38 spectra) positive correlations are found between the equivalent widths of the violet emission wings of Hγ and Hδ and *U*, *B*, *V*, *U–B*, and the Mg II/He I (4481/4471) ratio; between the strength of photospheric absorptions and some photometric data (*U*, *U–B*); between the intensities of the absorption cores of Hγ and Hδ; while anticorrelations exist between the strengths of the violet and red emission wings of Hγ and Hδ, and between their absorption cores and *U*, *B*, *V*, *U–B*.

From the second set (1979: seven nights of *uvby* data; 30 spectra) the only positive correlations are between the intensities of the violet and red wings of Hγ and between the strengths of Ca II K and of Mg II λ 4481 and *u*, *y*, *u–v*, and [c_1].

The backscattering model proposed on the basis of most of the 1977 data cannot explain the 1979 data; no simple explanation of the behaviour of the variations occurring in the extended atmosphere + ring + shell + dust patches surrounding HD 45677 can therefore be proposed.

It would be of great interest to investigate simultaneously variations of spectral features and photometric data from other known variable objects (e.g. Be and B[e] stars) in order to state whether the mechanism responsible for the observed variations leads to correlations similar to those observed for HD 45677 and whether such correlations are representative of one or different types of mechanisms.

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