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Simultaneous Hα and photometric observations of P Cygni

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Abstract. For the first time an extensive set of (quasi-) simultaneous photometric (UBV) and spectroscopic (Hα line profiles) observations of P Cygni, covering a period from May, 1990 to June, 1994 was analyzed in terms of time variability. It is found that the Hα equivalent width (EW) exhibits two different patterns of variability: a slower one, called Long-Term (LT) variability, with an amplitude of about 30 Å and a characteristic duration of about 600 days and a faster one, called Short-Term (ST) variability, with an amplitude up to 10 Å and duration of 40 to 60 days. Suggestive evidence for EW variation on a longer time scale (about few years) also exists. The variations in the Hα luminosity are not solely due to changes in the underlying continuum but also reflect variations in the physical properties of the wind. We find, in terms of a simplified spherically-symmetric wind model, that the LT variation of the line can be successfully explained in terms of a 26% alteration of the mass-loss rate, possibly accompanied by variations in the velocity field. From the analysis of the photometric behaviour of the star we find evidence for a very slow variation in the stellar brightness with an amplitude of about 0.13 mag and a duration of about 2600 days, i.e. about 7 years. During this variation, i.e. when the star brightens, the effective temperature decreases (by about 10%) and the radius increases (by about 7%). The properties of this Very Long Term (VLT) variation suggest that P Cygni has probably experienced a normal S Dor-type variation with a minimum phase around 1988 and a maximum phase in 1992. Some hints for a positive correlation between mass loss variations and changes in the stellar radius, due to the normal SD variability, do exist implying that the behaviour of P Cygni is more likely similar to that of R71 and S Dor but different from e.g. AG Car, R127 and HD 160529. Superimposed on the VLT component in the photometric variability of P Cygni, we observe ST brightness variations with an amplitude between 0.1 and 0.2 mag which appears to recur on a time scale of three to four months. The colour behaviour of these microvariations, at least of those which appear near the maximum phase of the VLT variation, is redder in $B-V$ and bluer in $U-B$ when the star brightens in V. The properties of this ST photometric variability are similar to the properties of the so-called "100 d-type micro-variations", recognized in other LBVs by van Genderen et al. (1997a,b). Based on time-scale evidences we suggest that the microvariabilities observed are rather due to "relaxation oscillations" (Stothers & Chin 1995) than to strange-mode oscillations in the stellar interior. Evidence for a close relationship between ST variations in Hα and changes in the stellar brightness and temperature is found. From other results about P Cygni's spectral variations (Markova 2000a), we conclude that the ST variability of the wind is most likely connected with processes in the stellar photosphere.

Key words. stars: early type – stars: atmosphere – stars: mass loss – stars: individual: P Cyg

1. Introduction

P Cygni is one of the most luminous stars of the Galaxy and the prototype of S Dor Variables as we know them today. Recently, Langer et al. (1994) have argued that the star is at the end of the hydrogen-shell-burning phase and is evolving to the right on the HR diagram in agreement with results obtained from its photometric history over the last three centuries (Lamers & de Groot 1992). P Cygni had dramatic outbursts in 1600 and 1655 when, on both occasions, it brightened to the 3rd magnitude. Since then the star, although considered to be in a quiescent phase, has shown a wide range of wind activity: line-profile variability at optical (e.g. Markova 1993, 2000; Scuderi et al. 1994; Stahl et al. 1994a) and UV (e.g. Lamers et al. 1985; Israelian et al. 1996) wavelengths, radio-flux variability (van den Oord et al. 1985; Skinner et al. 1997), and

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polarisation variability (Hayes 1985; Taylor et al. 1991). In addition, the star has also shown photometric variability on time-scales ranging from 40 to several hundred days (Percy et al. 1988; de Groot 1990; Percy et al. 1996).

Self-consistent non-LTE calculations made by Pauldrach & Puls (1990) showed that the wind of P Cygni is highly unstable with respect to extremely small changes in the stellar parameters. So, it is reasonable to expect the existence and the observability of some relationship between spectroscopic and photometric variability of the star. Several studies have attempted to establish a connection between the variations for which the star's atmosphere is thought to be responsible and the corresponding variations in the wind but, in general, the results have been contradictory. For example, a relationship between brightness variations and changes in line profiles due to the recurrent appearance of Discrete Absorption Components (DACs) was suggested by Israelian et al. (1996). De Groot (1990) and Percy et al. (1996) suggested the existence of a correlation between the Hα emission-flux variability and variations in the V-band. On the other hand, Stahl et al. (1994a) have monitored P Cygni spectroscopically for almost three years and could not find any clear evidence for the existence of a correlation between line-profile variability, viz. changes in the magnitude of the emission peak and in the position of the maximum absorption depth, and photometric variability over the period covered by their observations. According to Scuderi et al. (1994), the variations of stellar parameters, as deduced from UBV photometry, do correlate with variations in the structure of the wind (i.e. the velocity field or the wind density) but do not produce variations in the global mass-loss rate of the star.

The purpose of our study is to investigate the properties of P Cygni's stellar wind, such as mass-loss rate and velocity field, and the possible connection between their temporal behaviour and the variability in stellar parameters, namely effective temperature and radius. Because the study has been planned as a natural continuation of the work of Scuderi et al. (1994), it was performed using the same methodology. Therefore, an extended – from 1988 to 1994 – self-consistent database, including a number of wind and photospheric parameters of the star, was obtained. In Sect. 2 we briefly describe the observations and data reduction. Section 3 deals with photometric and spectroscopic variability. Section 4 is devoted to the determination of wind properties by fitting the Hα line. In Sect. 5 we discuss the possible correlation between stellar-wind variations and photospheric variations. Finally, in Sect. 6 we discuss the results obtained.

2. Observations and data reduction

The Hα spectroscopic observations were carried out using the coudé spectrograph of the 2 m RCC telescope at the National Astronomical Observatory (Bulgaria) and an ELECTRON ISD015A CCD with 520 × 580 pixels and a pixel size of 18 × 24 microns as detector. The resolution, $\lambda/\Delta\lambda$, is about 20 000 with a spectral coverage of about 100 Å centred at Hα. Echelle spectra ($\lambda/\Delta\lambda = 12\,000$) published by Stahl et al. (1994b) were also used. The data cover the period JD 2448017 to JD 2449529, which corresponds to May 1990 to June 1994.

Table 1. Photometric observations

Author	N	Accuracy in V, $B-V$	Reference
Zsoldos	10	not reported	private communication
CAMC	124	0.05; –	Carlsberg 1985–1994
APT	220	0.006; 0.010	Genet et al. 1987

The Hα equivalent width (EW) was measured on the normalised spectra. A simple linear interpolation was used to determine the level of the continuum using the average value of the stellar counts in two bands situated on the right (at about 6510 Å) and on the left (at about 6617 Å) of Hα. The EW was estimated by integrating the observed line-flux between λ6510 and λ6617. The accuracy of the determinations is ±1 Å or better. No correction for the contribution of water-vapour lines, the CII doublet or the NII forbidden lines was made. However, we estimate that the total effect of blending did not exceed 1 percent of the Hα EW.

The UBV photometry of P Cygni presented here has been collected from different sources by de Groot et al. (2001), as follows. Observations by Zsoldos at the Konkoly Observatory, Hungary, by the Carlsberg Automatic Meridian Circle (CAMC), La Palma, and by the Automatic Photoelectric Telescope Service (APT) in Phoenix, Arizona, are listed in Table 1 which also lists the number of observations N and the accuracies in V and $B-V$. The data cover the period JD 2446240 to JD 2450252, which corresponds to July 1985 to June 1995. The time coverage is generally excellent, although there are some gaps due to inclement weather in addition to the seasonal gaps.

All in all, we have good overlap between photometric and spectroscopic observations for about 32% of the epochs.

3. Analysis of the observations

3.1. Hα equivalent-width variability

Figure 1 shows the Hα equivalent width as a function of time. The data reveal significant variability on two different time-scales: a LT variation with an amplitude of about 30 Å and a characteristic duration of about 600 days or more, and ST variations with amplitudes between 5 and 10 Å and a characteristic duration of about 40 to 60 days with the latter superimposed on the former. The ST variations show a tendency to repeat after intervals of three to four months, suggesting that some activity of recurrent character is at work. The available data are obviously insufficient and do not enable us to determine with

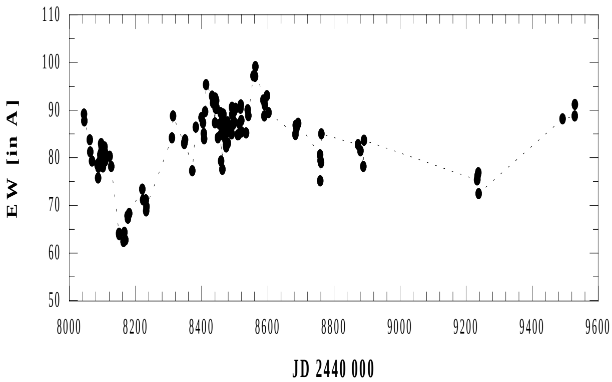

Fig. 1. Hα equivalent-width variability

confidence the character of the LT variability. But it is not excluded, considering the behaviour pattern of the Hα *EW* variations after JD 2448600, that this variability is also a recurrent phenomenon.

3.2. Photometric variability

At the beginning of this section we would like to note explicitly that a detailed analysis of the available photometric data is *beyond* the aim of our study and will be the subject of a forthcoming paper (de Groot et al. 2001, in preparation). In the present work we restrict ourselves to qualitative considerations, emphasizing those aspects of the photometric variability that could have some connection with the observed emission-strength variability of the Hα line.

The light and colour curves of P Cygni are shown in Fig. 2. Data represented by circles have been taken from the work of Scuderi et al. (1994). In each plot the solid line connects points which represent the mean values of V, $B-V$ and $U-B$, respectively, computed over time windows naturally defined by major seasonal gaps in the observations. The observations suggest (top panel of Fig. 2) the presence of a VLT brightness variation with an amplitude of about 0.13 mag and a characteristic duration of about 2600 days. In particular, the rising branch of this variation has a duration of about 1400 days (from JD 2447400 to JD 2448800). According to the $B-V$ colour index (middle panel), the colour was redder when the star brightened and vice versa. At the same time the $U-B$ colour index seemed to exhibit a different pattern of variation (bottom panel): apart from the two events around JD 2447800 and JD 2448550, the $U-B$ values show a gradual decrease by about 0.1 mag, i.e. the star became redder throughout the time interval. This result, however, may well be due to the bad sampling of the relevant data. Irrespective of the small amplitudes of the established VLT colour variations, we are inclined to regard them as real because of their systematic character. The available observations are obviously insufficient to allow us to determine whether the VLT variation is recurrent or not.

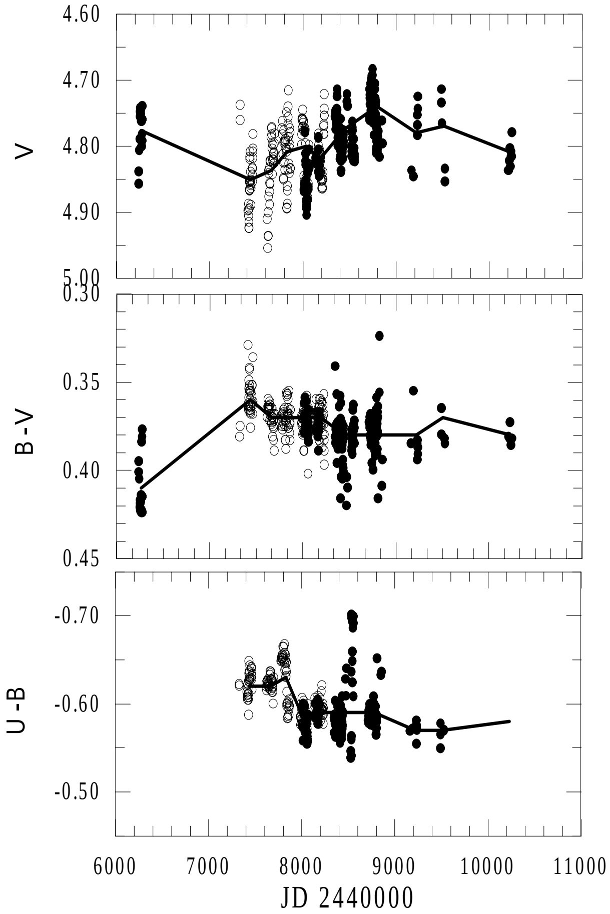

Fig. 2. Extended light and colour curves of P Cygni. The data set from Scuderi et al. (1994) is represented by circles, those from de Groot et al. (2001) – by dots. The solid lines connect the mean values of V, $B-V$ and $U-B$ computed over temporal windows defined by major seasonal gaps in the observations

In addition, the observations reveal the existence of short-term (ST) brightness variations with amplitudes between 0.1 to 0.2 mag superimposed on the VLT variability. Incorporating V data published by Percy et al. (1996), we estimate a peak-to-peak time-scale of three to four months for this ST variability. Figure 3 displays a subset of V-band data covering a two-year time-interval: circles denote data published by Percy et al. while dots represent data of de Groot et al. (2001). The figure emphasizes the apparent cyclicity of the phenomenon. Unfortunately, due to the very limited number of B and U observations, the colour behaviour of the ST variations could not be determined with confidence. The available data do suggest, however, (at least for ST variations that appear near visual maximum) that, when the star brightens in V, it becomes redder in $B-V$ and bluer in $U-B$. Examples of observed brightness-colour correlation are shown in Fig. 4. Irrespective of the small amplitudes of the ST colour variations – in most cases they are comparable to the error of the measurements – we regard them as real since they usually follow the same behaviour pattern.

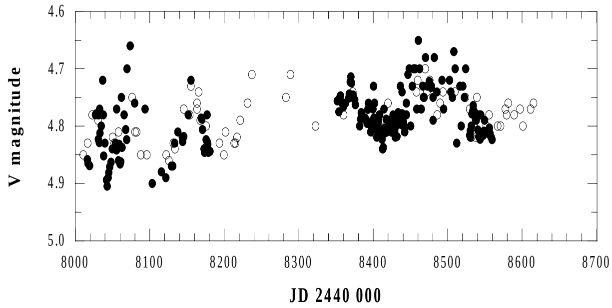

Fig. 3. Example of short-term brightness variations in P Cygni. The dataset from Percy et al. (1996) is represented by circles, those of de Groot et al. (2001) – by dots. Note the apparent cyclicity of the observed phenomenon

Finally, we would like to draw attention to the behaviour of the star around JD 2448550 (last panel in Fig. 2). At that time we observed a rapid and very strong variation in $U-B$ that was not accompanied by any special event in either the $B-V$ or the V-band. We argue that this event is entirely due to U-band variations: in less than 50 days the brightness in U has increased by about 0.2 mag, suggesting the occurrence of some sort of outburst. It appears that a similar event, although not so prominent, has appeared 700 days earlier, i.e. around JD 2447800.

3.3. Possible relationships between spectral and photometric variability

The establishment of relationships between different sorts of line-profile variations, on the one hand, and photometric variability, on the other, is crucial for the study of stellar-wind variability since it may give important information about the origin of variations in the wind and their relation to processes going on in the stellar photosphere.

A direct comparison of the available spectral and photometric data revealed the existence of a close relationship between the ST variability of the Hα EW and the ST variability in V, $B-V$ and $U-B$, in the sense that when the Hα EW decreases the star becomes brighter in V, redder in $B-V$ and bluer in $U-B$. The establishment of a clear anti-correlation between variations in the Hα luminosity and changes in the stellar brightness (Fig. 5) implies that the observed line-strength variability may be due to the changing continuum rather than to variations in the number density of the wind (however see also Sect. 4.3). This result indicates that the effect of the changing continuum must be taken into account when studying the properties of the wind and, especially, the mass-loss rate.

No clear evidence for a direct coupling between the LT spectral variability and the VLT photometric variability was found. The time-scales of the two phenomena differ too much to suggest that they may be physically linked. On the other hand, the maximum of the LT variation in Hα occurs very close to the maximum of the VLT photometric curve and, also, practically coincides with the strong and rapid increase of the brightness in the U-band. It is not clear at present whether these events are causally or physically linked.

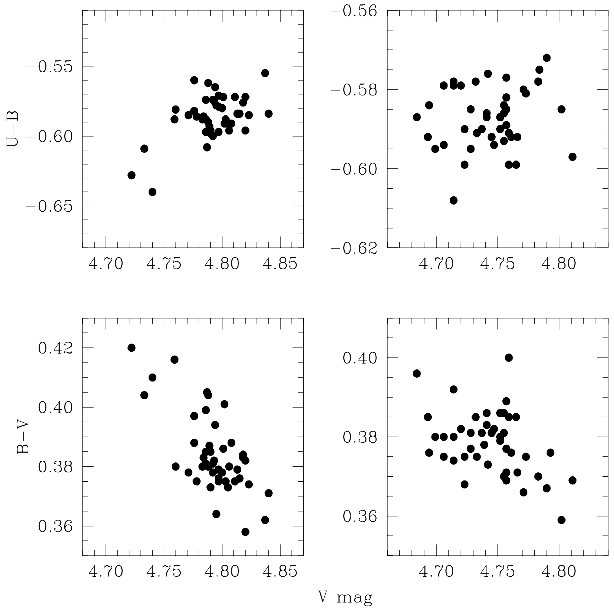

Fig. 4. Brightness-colour correlations observed within two time-intervals showing ST brightness variations: JD 2448 380-422 (panel on the left) and JD 2448 720-800 (panels on the right

4. Wind properties

The properties of the stellar wind were determined by fitting the observed Hα profiles with model calculations. The theoretical profiles were calculated as described by Scuderi et al. (1994), assuming a stationary, spherically-symmetric, fully-ionized, isothermal wind. The velocity field was assumed to have a truncated power-law dependence upon the stellar radius, as follows:

$$v(r) = v_\circ \left(\frac{r}{R_\circ}\right)^\gamma \qquad \frac{r}{R_\circ} \leq \left(\frac{200}{v_\circ}\right)^{\frac{1}{\gamma}} \qquad (1)$$

$$v(r) = 200 \qquad \frac{r}{R_\circ} > \left(\frac{200}{v_\circ}\right)^{\frac{1}{\gamma}}$$

where v is in $\mathrm{km\,s^{-1}}$. $R_\circ$ is the lower boundary of the Hα emitting region, which is assumed to be equal to the photospheric radius, $R_\star$. (Scuderi et al. 1994 showed that $R_\circ$ could only be marginally larger than $R_\star$.) The velocity law starts with $v(R_\circ) = v_\circ$ (hereafter called "initial velocity") and reaches a maximum of 200 km s^{-1}.

The line-radiation transfer was treated adopting the Sobolev approximation. The line profiles were assumed to be the result of the combination of photospheric absorption with emission and resonant scattering by hydrogen atoms in the wind. The photospheric profile was deduced from the grid of model atmospheres computed by Mihalas (1972) and rotationally broadened by $v \sin i = 75$ km s^{-1} (Hoffleit & Jaschek 1982). The effect on the Hα profile

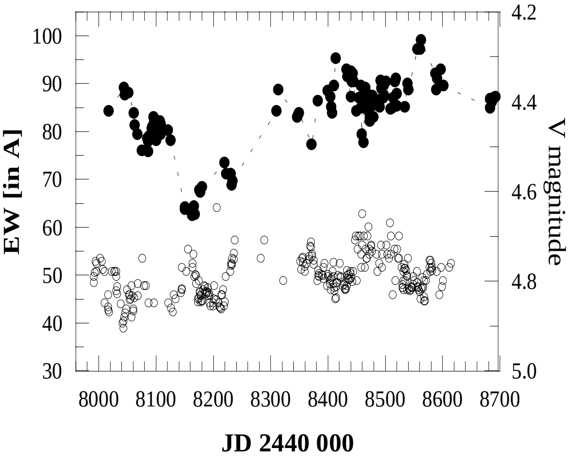

Fig. 5. Comparison between ST variations in the Hα equivalent width and in the V-magnitude. Note the apparent anti-correlation between the two sets of data

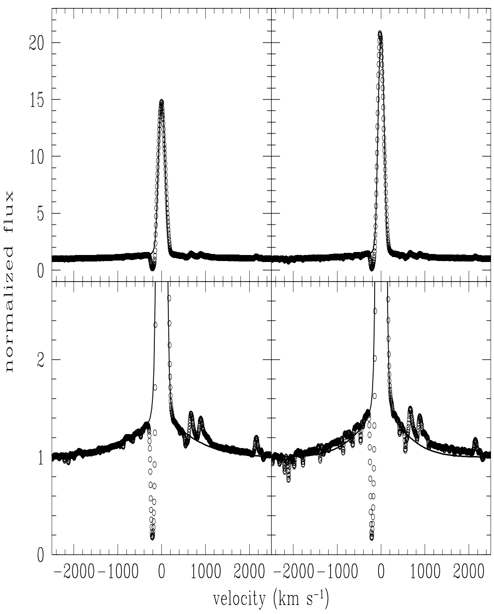

Fig. 6. Examples of a good and a bad fit to the observed Hα line profiles

of Thomson scattering by free electrons present in the wind was also taken into account. The detailed procedure of the fit can be found in Scuderi et al. (1992, 1994). Representative cases of a good and a bad fit are shown in Fig. 6. The fact that the computed profile does not reproduce the blue-shifted absorption of Hα does not really affect the mass-loss rate determinations since the relative contribution of absorption to the total EW of the line is about two orders of magnitude smaller than that of the emission component, which, in turn, is well matched by the fit.

From the fitting procedure we derive:
i) $v_\circ$ and γ, which characterize the velocity field of the wind;
ii) the optical depth in Hα, $\tau_\circ$, which gives the stellar mass-loss rate;
iii) the electron temperature in the wind, $T_{\rm e}$, and the Thomson scattering optical depth, $\tau_{\rm e}$.

4.1. Velocity field

In agreement with Scuderi et al. (1994), we find that a value of 0.5 for the exponent of the velocity power law, γ, gives a satisfactory fit of all observed Hα profiles. In addition, we find that $v_\circ$ assumes values 2 to 3 times higher than the sound speed of $\sim$19 km s^{-1} ($T_{\rm eff}$(P Cyg) = 19 300 K) suggesting that the lower boundary of the Hα emitting region was situated close to the base of the supersonic wind.

Figure 7 shows the temporal behaviour of $v_\circ$ over an interval of about 6 years. Data represented by circles are taken from the work of Scuderi et al. (1994). Dots denote data obtained in the present study. The error bars (usually of the order of ± 5 km s^{-1}) are also shown. A casual inspection shows that most of the observed variations have an amplitude smaller than the accuracy of the individual determinations and might, therefore, not be real but due to random errors. On the other hand, the presented data suggest evidence for the real presence of a slow (characteristic duration of at least 200 days) systematic variation in $v_\circ$ with an amplitude comparable to or larger than the relevant uncertainty.

Our analysis also shows that the variations in $v_\circ$ are anti-correlated with changes in the Hα optical depth, $\tau_\circ$, in the sense that an increase in $\tau_\circ$ is accompanied by a decrease in $v_\circ$. This is fully explained by the fact that a lower velocity implies a higher density and, therefore, a larger optical depth. Summarizing, we conclude that the velocity field of P Cygni's wind seems to be variable.

4.2. Electron temperature

Scuderi et al. (1994) have noted that their fitting procedure turned out to be not very sensitive to variations in the electron temperature of the wind: while the accuracy of an individual determination of $T_{\rm e}$ was about 30% the rms deviation of the mean, which was estimated to be of 13 000 K, was ±14%, i.e. of the order of the expected error. This simply means that the procedure used does not give a direct means to measure the variations of $T_{\rm e}$ and consequently of $\dot{M}$ (via Eq. (2)). To avoid this problem we adopted, following Scuderi et al. (1994), a mean value of $T_{\rm e} = 13\,000$ K and assumed that the electron temperature of the wind is proportional to the effective temperature of the star. As we shall show later this assumption is not only reasonable but also essential for our study since it will enable us to use the *relative* variations of $T_{\rm eff}$, determined from the available UBV photometry, as a measure of the *relative* variations of $T_{\rm e}$ (for more information see Sect. 4.3).

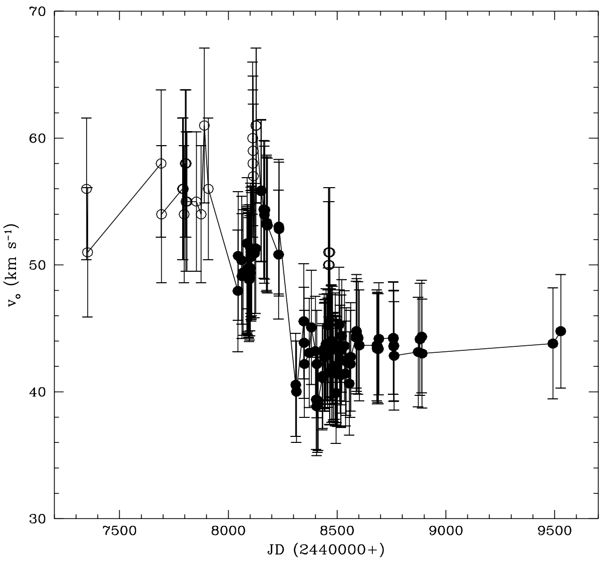

Fig. 7. Variability of the initial velocity of P Cygni's wind. The data set represented by circles is taken from Scuderi et al. (1994) while those represented by dots refer to our study

4.3. Mass-loss rate

As demonstrated by Scuderi et al. (1994), the mass-loss rate can be evaluated from the fitting parameters in two independent ways: either by using the Hα optical depth, the so-called $\tau_\circ$-method, or by using the electron-scattering optical depth, the $\tau_{\rm e}$-method. Scuderi et al. have shown that the two methods give consistent results with the former being intrinsically more precise than the latter. For this reason we decided to use the $\tau_\circ$-method for determining the mass-loss rate of the star. In terms of this method the relationship between the mass-loss rate, $\dot{M}$ and the stellar and wind parameters is given by the following expression:

$$\dot{M} = 0.203\mu_{\rm e}\left(1+\frac{n({\rm He}^+)}{n({\rm H}^+)}\right)^{1/2}\left(\frac{\tau_\circ}{b_2}\right)^{1/2}\left[\frac{T_{\rm e}}{10^4\ {\rm K}}\right]^{3/4} \times\left[\frac{R_\circ}{10\ R_\odot}\right]^{3/2}\left[\frac{v_\circ}{100\ {\rm km\ s}^{-1}}\right]^{3/2} \times\left[{\rm e}^{E_2/kT}-{\rm e}^{E_3/kT}\right]^{-1/2}\quad 10^{-6}\ M_\odot\ {\rm yr}^{-1} \qquad (2)$$

where $\mu_{\rm e}$ is the mean atomic weight per electron, given by

$$\mu_{\rm e} = \frac{\sum_i X_i m_i}{\sum Z_i M_i}, \qquad (3)$$

X_i, m_i, and Z_i are the abundance by number, the mass and the charge of the ith ion, respectively; E_2 and E_3 are the ionization energies from the second and the third level of hydrogen; b_2 is the ratio of the population of the second level to that in LTE. Other symbols have their usual meaning. We adopted a helium to hydrogen abundance of $n({\rm He}^+)/n({\rm H}^+) = 0.5$ (Barlow 1990) with $\mu_{\rm e} = 2.0$ since the gas was assumed to be composed of ionized hydrogen and singly-ionized helium only. Finally, for the population of the $n = 2$ and $n = 3$ levels of hydrogen we adopted $b_2 = b_3 = 1.3$ as suggested by the non-LTE calculations of O-star winds (Klein & Castor 1978). Scuderi et al. (1994) have shown that the adopted constant (instead of variable) values of b_2 and b_3 may introduce errors of not more than a factor 2.

As we have shown in Sect. 3.3, ST variations in the Hα *EW* were anti-correlated with changes in the stellar brightness. This result implies that the observed line-strength variability may not be due to real variations in the number density of the wind but, rather, may reflect changes in the stellar continuum. The procedure used for determining the mass-loss rate allows the effect of the changing continuum to be taken into account if variations in the stellar radius, $R_\star$, and effective temperature, $T_{\rm eff}$, are known. The latter can be determined from photometric data in the following way: correcting the observed $B-V$ colour index for interstellar extinction with $E(B-V) = 0.63$ and using the empirical relations between the intrinsic colour $(B-V)_0$ and $T_{\rm eff}$ for normal supergiants given by Schmidt-Kaler (1982), we estimated the temperature of the star at any time from the available photometric data. Then, from these temperature values and the corresponding V magnitude we derived – again using the empirical relations of Schmidt-Kaler (1982) – the stellar radius. More information about the procedure used can be found in Scuderi et al. (1994). Here we shall only note that, since the *absolute* values of $T_{\rm eff}$ and $R_\star$ obtained in this way are expected to be rather uncertain, only the *relative* variations of the two quantities, $\Delta T_{\rm eff}/T_{\rm eff}$ and $\Delta R_\star/R_\star$, were considered. The accuracy of the results is 2% for $T_{\rm eff}$ and 4% for $R_\star$.

Figure 8 shows the temporal behaviour of $T_{\rm eff}$ and $R_\star$ over an interval of about 6 years. Circles denote data derived by Scuderi et al. (1994), dots are our determinations. The solid line connects points that represent the mean values of variations in $T_{\rm eff}$ and $R_\star$, i.e. averages within time windows naturally defined by seasonal gaps in the observations. We call these values "fractional mean" values. The results reveal the existence of a slow variation in both $T_{\rm eff}$ and $R_\star$ which appears in concert with the VLT variation in the V-band: when the brightness increases the radius also increases while the temperature decreases. The amplitude of the variation, about 10% in $T_{\rm eff}$ and about 7% in $R_\star$, exceeds the accuracy of the individual determinations and must be considered real. The anti-correlation between the $T_{\rm eff}$ and $R_\star$ variations suggests that the luminosity of the star remains constant during the VLT photometric variability. It appears from a casual inspection of Fig. 8 that the scatter of the data around the solid lines exceeds the accuracy of the relevant determinations, indicating the presence of variations on a shorter time-scale. These variations are most likely connected with the ST variability of the stellar photosphere.

Once the variations in the stellar radius and temperature are known, one may use Eq. (2) to determine the behaviour of the mass-loss rate corrected for the effect of the changing continuum under the additional assumption that the electron temperature of the wind is proportional

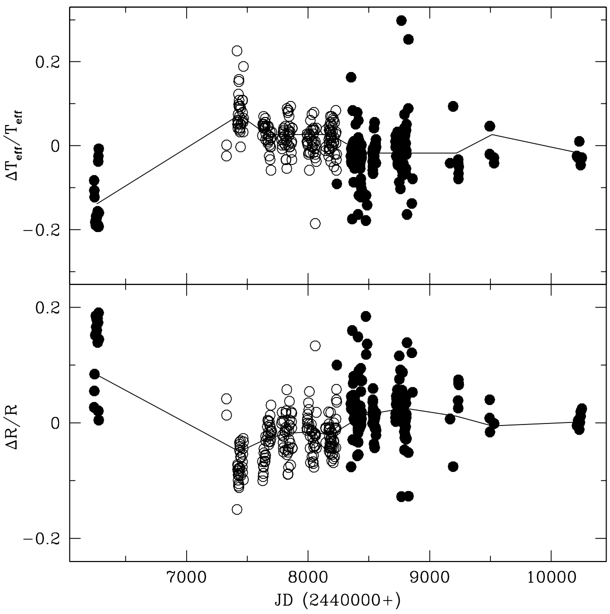

Fig. 8. Relative variations in the stellar temperature and radius of P Cygni as derived from $B-V$ data. Circles represent the data from Scuderi et al. (1994); dots are results obtained in the present study. Solid lines connect points that represent mean values of variations in $T_{\rm eff}$ and $R_\star$, calculated over time windows naturally defined by seasonal gaps in the observations

to the effective temperature of the star (Sect. 4.2). This assumption, together with the one mentioned in the beginning of this section, i.e. $R_\circ = R_\star$, allows the *relative* variations of $T_{\rm eff}$ and $R_\star$ to be used as a measure of the *relative* variations in $R_\circ$ and $T_{\rm e}$. Unfortunately, the available spectroscopic and photometric observations were not always simultaneous and, thus, leave us with the problem of the treatment of non-simultaneous data. One way to resolve the problem is to interpolate between the available photometric data. This approach has the disadvantage of introducing artificial values for the temporal behaviour of the mass-loss rate. Another possibility is to use the corresponding "fractional mean" values for $\Delta T_{\rm eff}/T_{\rm eff}$ and $\Delta R_\star/R_\star$ on those dates when simultaneous observations are not available.

Figure 9 illustrates the temporal behaviour of the mass-loss rate of P Cygni over the period studied. The upper panel shows mass-loss rate estimates obtained by keeping $T_{\rm e}$ and $R_\circ$ constant: $T_{\rm e} = 0.7T_{\rm eff} = 13\,000$ K and $R_\circ = R_\star = 76$ $R_\odot$ (hereafter these values will be called "reference" values). Triangles refer to the epoch studied by Scuderi et al. while crosses denote data from the present study. Mass-loss rate determinations *corrected* for the effect of the changing continuum are displayed in the lower panel. Here, $T_{\rm e}$ and $R_\circ$ values derived as a sum of the "reference" values and the values of $\Delta T_{\rm eff}/T_{\rm eff}$ and $\Delta R_\star/R_\star$ obtained from the photometric data and subsequently expressed in units of the "reference" value, are used to calculate $\dot{M}$. Estimates based on simultaneous photometric and spectroscopic observations are represented by open triangles and circles. Dots denote data obtained in terms of the "fractional mean" values for variations in $T_{\rm eff}$ and $R_\star$. The error bar for individual determinations is also given.

These plots show that the pattern of variability of $\dot{M}$ does not change significantly when the effect of the changing continuum is taken into account. The rms deviation in $\dot{M}$ amounts to 6% of its mean value (1.8 ± 0.1 10^{-5} $M_\odot$ yr^{-1}), i.e. it is of the order of the estimated uncertainty in $\dot{M}$ determinations (±10%) thus implying that most of the fluctuations (especially those on a shorter time-scale) may not be real, but due to random errors. On the other hand, the results obtained suggest the presence of a slow systematic variation in $\dot{M}$ whose amplitude (of about 26%) exceeds the uncertainty in the individual determination by more than a factor two and could, thus, be considered real. This variation closely follows the LT component in the Hα variability (see Fig. 1) indicating that the relevant intensity variation can not be assigned uniquely to the variation in the underlying continuum but also reflects real variations in $\dot{M}$, i.e. in the number density of the wind. This conclusion seems to be supported by results obtained for possible variations in the velocity field: a comparison of the data presented in Figs. 7 and 9 (lower panel) shows that an increase in $\dot{M}$ is accompanied (as can be expected) by a decrease in the velocity of the outflowing matter and vice versa. Unfortunately, the accuracy of our mass-loss determinations is rather low and does not allow us to examine the behaviour of $\dot{M}$ in terms of possible short-term low-amplitude variations relevant to the ST variability in the Hα luminosity. It is, therefore, not clear at present whether the ST variability of Hα can be assigned completely to variations in the underlying continuum, or whether it also reflects variations in the physical properties of the wind. Neither does it seem possible, due to small overlap between spectral and photometric data, to determine whether the VLT photometric variation is accompanied by a similar variation in $\dot{M}$ or not.

5. Discussion

Our spectroscopic survey reveals the presence of significant variations in the Hα emission-line strength, i.e. its equivalent width, on at least two different time-scales: a LT variation with an amplitude of more than 30 Å and a characteristic duration of about 600 days, and ST variations with amplitudes between 5 and 10 Å and a characteristic duration of 40 to 60 days with the latter superimposed on the former. The ST variability is more likely a recurrent phenomenon: the variations show a tendency to repeat after intervals of three to four months. The available data are clearly insufficient and do not allow us to determine the character of the LT variability with confidence. Additional observations collected through another study (Markova et al. 1999, 2000), however, show that this variability is also a recurrent phenomenon.

The simultaneous analysis of the spectroscopic and photometric data shows that the variability of Hα is not solely due to variations in the underlying continuum, but

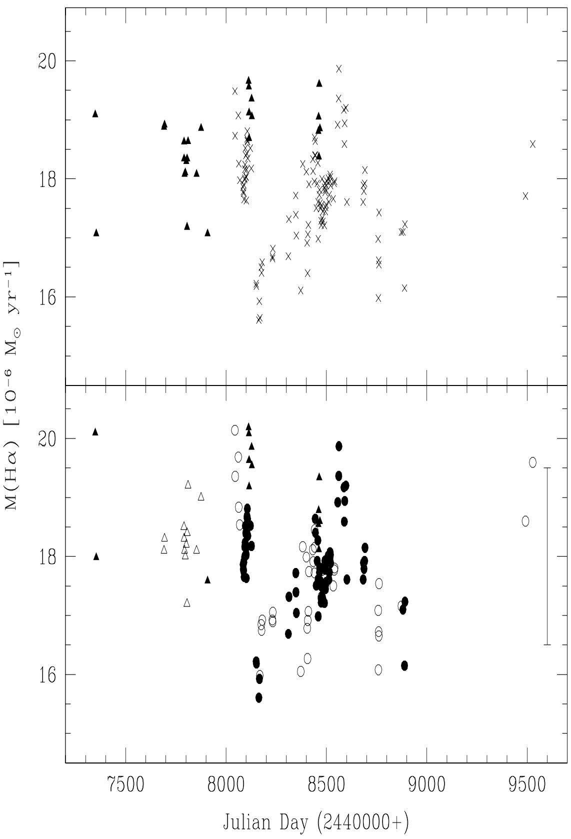

Fig. 9. Mass-loss rate estimates as a function of date. Upper panel: mass-loss rate obtained by keeping $T_{\rm e}$ and $R_\circ$ constant: $T_{\rm e} = 0.7\ T_{\rm eff} = 13\,000$ K and $R_\circ = R_\star = 76\ R_\odot$. Triangles refer to the epoch studied by Scuderi et al. (1994) while crosses denote data from the present study. Lower panel: mass-loss rate corrected for the effect of the changing continuum. Data marked with open circles represent cases when simultaneous photometric and spectral observations were available, while dots denote data obtained using the so-called "fractional mean" values for variations in $T_{\rm eff}$ and $R_\star$ (for more information see the text)

also reflects variations in the physical properties of the wind. In particular, we showed, in terms of a much simplified spherically-symmetric wind model, that the LT variation of the Hα line can be successfully explained in terms of a 26% change of the mass-loss rate accompanied by possible variations in the velocity field. The accuracy of our mass-loss determinations is found to be rather too low to reveal variations in $\dot{M}$ relevant to the ST variability of Hα.

As a result of our photometric analysis we found that P Cygni exhibits a VLT brightness variation with an amplitude of about 0.13 mag and a duration of about 2600 days: when the star brightens, the temperature decreases and the radius increases leaving the luminosity almost constant. Such behaviour is typical for LBVs in a normal S Dor (SD) phase, although the amplitude of the variation (in V, $T_{\rm eff}$ and $R_\star$) observed in P Cygni is much smaller than those measured in other LBVs (van Genderen et al. 1997a, 1997b). Thus, we conclude that over the time-period studied P Cygni has probably passed from a minimum (around 1988) to a maximum (around 1992) of a normal or SD-phase.

The S Dor phenomenon is usually associated with variations in mass-loss rate. The observations, however, indicate that the relationship between the brightness variation due to the S Dor-phases and the mass loss rate is not unique: the mass loss rate can increase with increasing $R_\star$ (as in the case of R71 and S Dor); can remain about constant (as in the case of HD 160529) or can vary irregularly with increasing $R_\star$ (as in the case of AG Car and R127). Lamers (1997) argued that the behaviour of $\dot{M}$ during a typical LBV variation (i.e. S Dor-phase) depends on three competing effects: a) the proximity to the Atmospheric Edington Limit (AEL); b) the crossing of a bistability limit; c) variations in $L_\star$. In particular, if a star is close to the AEL and its luminosity remains about constant during a S Dor-type variation – what appears to be the case of P Cygni – than an increase in $R_\star$ and a decrease in $T_{\rm eff}$ will result in an increase in $\dot{M}$ and a decrease in $V_{\rm inf}$. Although some hints for a positive correlation between variations in $\dot{M}$ and changes in $R_\star$ of P Cygni appears to exist (see e.g. Figs. 8 and 9) it seems impossible to ascertain confidently, from the data here presented, whether the behaviour of the star really agrees with the noted predictions or not. Preliminary results, based on a more extensive study of the long-term (over a period of about 10 years) behaviour of the star, however, show that the mass loss rate has indeed increased with increasing $R_\star$ (Markova 2000b; Markova et al. 2000).

Superimposed on the VLT brightness variation we find ST variations with amplitudes between 0.1 and 0.2 mag and a peak-to-peak time-scale of three to four months. The colour behaviour of the variations (at least of those that appear near visual maximum) is such that $B-V$ becomes redder and $U-B$ bluer when the star brightens in V. The properties of the ST photometric variations are similar to the properties of the so-called "100 d-type microvariations" recognized in other LBVs (van Genderen et al. 1997a, 1997b). The origin of these variations is discussed below.

In recent years many efforts have been devoted to finding observational evidence for a possible relation between photospheric and wind variability (the so-called "photospheric connection") in hot luminous stars. At present, the O4I(n)f star ζ Pup appears to be the best candidate to demonstrate such a connection (Reid & Howarth 1996) though this has been disputed by Kaper et al. (1997). In the present study we have found evidence for a close relationship between ST variations in Hα and changes in the stellar brightness and temperature. The available data do not, however, allow us to ascertain whether the observed line-strength variations are solely due to the impact of the changing continuum or whether they also reflect variations in the properties of the wind. An indirect way to check this point is by studing the variability of lines with P Cygni-type profiles. Note that a variation in the continuum will act in a direction opposite to the measured emission and absorption equivalent width. Motivated by this possibility, Markova (2000a) has recently performed an extensive study of line-profile variability in P Cygni's optical spectrum including more than 60 lines formed in different layers of the stellar wind. The results obtained show that line-strength variations (both in absorption and emission), similar to and in phase with the ST variability traced by Hα, do in fact occur in almost all lines in the optical, including the strongest lines of SiIV, which presumably form near or at the base of the supersonic wind. This finding allows us to suggest that the ST variability of the Hα luminosity is caused by real variations in the stellar wind and that these variations are connected with processes in the stellar photosphere. Thus we see that, although the hypothesis of a "photospheric connection" has not yet been discussed in relation to the wind variability of LBVs in general, it may be quite relevant in the case of P Cygni. In this connection it is worth noting that van Genderen et al. (1995) reported oscillation in the Hβ colour index of the Strőmgren system in antiphase with the $58\overset{\mathrm{d}}{.}56$ light curve variations of η Carinae. The phenomenon was first interpreted as due to the presence of an extended HII region in the core of the nebula but later was attributed to the S Dor variable itself (van Genderen 2000).

The possibility that the ST variability of P Cygni's wind is triggered by photospheric processes does not yet answer the question of the origin of this variability, i.e. what is the physical mechanism that causes this phenomenon? The position of P Cygni on the HR-diagram agrees with the predicted instability strip for strange-mode oscillations (Kiriakidis et al. 1993) suggesting that non-radial pulsations (NRP) of strange-mode oscillations might be the cause for the ST photometric variability of the star. Kiriakidis et al. published the results they obtained for a star with an initial mass of 60 $M_\odot$ and a metalicity of $Z = 0.02$. Using these results we found that for the temperature range relevant to P Cygni ($T_{\rm eff} = 19\,300$ K) the predictions show two unstable modes with a period of $P = 2\pi\sigma^{-1}\sqrt{R^3_{\rm star}/3GM_{\rm star}}$ with $\sigma = 1.35$ and 2.7, which correspond to a period of 6 and 3 days, respectively. These values are a factor of 17 to 30 smaller that the observed timescales for the ST variability indicating that strange mode oscillations are not likely a cause of the established phenomenon. Lamers et al. (1998) have recently argued that the microvariability of LBVs ($\Delta V \simeq 0.2$ mag) appears to be very similar to the variability of the normal B-supergiants and of the slowly-pulsating B stars both of which are due to gravitational-mode pulsations. These authors further suggested, based on a simple linear pulsation model by means of the multicolour Strőmgren data, that the microvariability of LBVs could be explained by means of NRPs of gravity-modes of low l. However, the majority of the microvariations studied by Lamers et al. are situated near the light minima and the bottom part of the rising branches of the light curves, i.e. they should be of the so-called "α-Cygni type microvariations", which are quite different (in their properties) from the "100d microvariations" (van Genderen et al. 1997b). Hence, although the hypothesis of g-mode oscillations seems quite probable in respect of the "α-Cygni type microvariability" of LBVs, it must be still proved that it works for the "100d microvariability" as well. An interesting idea has been recently announced by van Genderen (van Genderen 2000) and concerns the so-called "relaxation oscillations" found by Stothers & Chin (1995). These oscillations are caused by the same opacity (κ) mechanism but their periods are in the order of months that makes their nomination as a possible cause of the "100d microvariability" quite probable.

Finally, we want to point out that, contrary to our own expectations, the method used for determining the *relative* variations in the mass-loss rate turns out to be quite relevant for determining the *absolute* values as well. In particular, our estimate of $\dot{M}$, obtained as an overall data average, equals $(1.8 \pm 0.1)\ 10^{-5}\ M_\odot\ {\rm yr}^{-1}$. This estimate is in excellent agreement with values obtained from IR and radio observations, $\dot{M}_{\rm IR} = (2.2 \pm 0.7)\ 10^{-5}\ M_\odot\ {\rm yr}^{-1}$ (Felli et al. 1985) and $\dot{M}_{\rm radio} = (2.1 \pm 0.4)\ 10^{-5}\ M_\odot\ {\rm yr}^{-1}$ (Scuderi et al. 1998).

Note added in proof: Our conclusion about strange mode oscillation as a possible cause of the ST variability is based on results originating from a linear stability analysis (Kiriakidis et al. 1993). However, the nonlinear analysis indicates that the typical time scales in the nonlinear regime are much longer – up to a factor 20 longer than in the linear regime (Glatzel, private communication) – that means strange mode oscillations might still be a cause of the ST variability of P Cygni.

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