Abstract

We report the detection of rapid wavelength and intensity variations of narrow components in absorption line profiles of the hot galactic supergiant P Cygni. During most of the time, in one week of observations, there were two such components present. Although the period of observation is too short for firm conclusions, the velocity curves do not contradict the photometric period of 17.3 d. These curves may be interpreted as a double wave, ‘swinging in counterphase’. This observation would suggest the presence of one long wave over the stellar surface. The waves are possibly gravity waves with wavelengths of the order of half the stellar radius.

Key words: stars: atmospheres; supergiants; LBVs; mass-loss

1 Introduction; Long-Period DACs

P Cyg is a blue hypergiant (de Jager 1998) or a Luminous Blue Variable (LBV, Humphreys & Davidson 1994) whose observed characteristics make the star among the most peculiar ones in the Galaxy. The properties of P Cyg and its wind have been reviewed by Israelian and de Groot (1999).

Narrow absorption line components called DACs were discovered in Balmer line profiles of P Cyg by de Groot (1969). He also found them in lines of He, Fe and many other elements. Identifications of other lines were published by others. Cassatella et al. (1979) and Luud and Sapar (1980) detected DACs in...
UV lines of various ions, such as Cr\textsuperscript{II}, Ni\textsuperscript{II}, and others. Lamers et al. (1985) found them in Fe\textsuperscript{II} lines.

In his Balmer line observations de Groot found velocities of \(-215\), \(-160\) and \(-95\) km\ s\(^{-1}\). The first component showed periodic \(v_R\)-variations of \(P = 114\) days, while the others did not present temporal variations. The observations by Luud et al. (1975) however, give contrasting results. They found that the first component was not variable, while the second was, with a period of 57 d. Since, many characteristic times of variability (we prefer this term above the too suggestive 'period') have been mentioned: 200 d (Markova, 1986), \(60 - 75\) d (van Gent and Lamers, 1986), 4 to 5 months (Markova, 1993) and 200 d (Israelian et al., 1996). The apparent diversity in the communicated 'periods' may partly be related to insufficient lengths of periods of observations; moreover, it may be a real phenomenon.

As to the interpretation of these motions, current thinking converges on a model according to which shells are periodically ejected from the star, while increasing their velocity on the way outward through the stellar wind. This hypothesis of expanding shells was proposed first by Kolk (1983), Markova and Kolk (1984) and Markova (1986). They were supported by van Gent and Lamers (1986), and are also shown in a diagram published by Israeli et al. (1996), where three or four shells appear, of which the velocity increases steadily from about 80 to 190 km\ s\(^{-1}\) over a period of about 1000 days.

Most of the above mentioned variations have characteristic times of the order of 2 to 7 months. There is another component, though, the period of which is not related to such presumed outgoing shells. De Groot et al. (2001) published the results of a fairly complete survey of P Cyg photometry in which they demonstrate that at each time there are two periods in the light variation. The shorter one, of 17.3 d, occurred persistently, at least during the last 20 years albeit with variable amplitude. The longer period ranges between about 60 and 130 d, with a clear maximum near 100 d. It does not seem impossible that this latter variability is associated with the outgoing shells described above. But what to say about the shorter period? The question arises if there is any wavelike phenomenon in the wind that could be associated with the shorter (17.3 d) light variation. Its study is the main content of this paper.

2 The detection of short-period absorption components

Observations of P Cyg were carried out during the week 1999, May 28–June 4, using the SOFIN Echelle Spectrograph of the 2.6-m Nordic Optical Telescope (NOT) at the ORM (La Palma). A resolving power of \(R = \lambda/\Delta\lambda \sim 80000\) has been achieved with the second camera. The CCD used in this run was a 1152 × 770 pixel\(^2\) EEV. We obtained echelle spectra with a slit width of 0.8
Table 1: Wavelengths of absorption components measured in the profiles of H$\alpha_{12}$ and H$\alpha_{17}$. The wavelengths $\nu$ are expressed in km s$^{-1}$. For details see the text.

| Date    | $\nu_1$ | $\nu_2$ |
|---------|---------|---------|
| 28-05-99| 87      | 49      |
| 30-05-99| 87      | 52      |
| 02-06-99| 75      | 72      |
| 03-06-99| 84      | 69      |
| 04-06-99| 80      | 66      |

arcsec. They cover the wavelength range between 3600 and 4200 Å in 18 orders. All spectra were flat-fielded, background and scattered light subtracted. The wavelength calibration was performed with a Th–Ar lamp. The ultimate signal-to-noise of our spectra at 4000 Å is about 200.

Apparently, one week is too short for observing recurrent variability or for checking a periodicity of 17.3 d. In that respect our results have a preliminary character. The positive aspect is, though, that our observations (Fig. 1) do show the presence of rapidly changing absorption components in profiles of the higher members of the Balmer series.

The lines showed split absorption cores. These are best visible in the profiles of 28/05/99 (solid lines in Fig. 1), which have two distinct cores. Closer examination shows that these cores existed also in later spectra. The cores approached each other during the next few days and nearly merged around 02/06/99. Thereafter they reappeared. We measured the wavelength variation of these absorption cores by two methods: directly by determining the central wavelengths of the absorption component, and also by fitting the profiles by two Gaussians. This was done in the two lines, so we got 4 data points for each component at each day. The measurements agree reasonably well; the mean scatter of the individual velocity measurements is 3 km s$^{-1}$. Table 1 gives the average velocities measured in the two line components.

We wanted to check if these velocities are related in some way to the photometric period of 17.3 d, reported in Section 1. To that end we replotted the data in the same diagram for a period, 17.3 days later (Fig. 2). The diagram shows that it is not impossible that the observations have a repetition period of 17.3 d, and it appears moreover that there are possibly two waves that are 'swinging in counterphase', cf. the dotted lines in Fig. 2. If this interpretation would be verified by measurements taken over a period of a month or longer, then they could be interpreted in terms of a long wave in the wind over the stellar surface having a wavelength of the order of the star’s diameter. This hypothesis will be examined in the next section.

An interesting aspect of the observations is the high acceleration that is inferred from the wavelength variation of the absorption components. It is about 10 km s$^{-1}$ d$^{-1}$. This value stands in contrast to the acceleration of the long-

Figure 1: High-resolution profiles of the Balmer lines H$_{17}$ and H$_{12}$ obtained with the NOT/SOFIN telescope combination at the ORM (La Palma). During seven days of observations the profiles changed considerably.
Figure 2: Measured wavelengths for the two line components in the lines H_{12} and H_{17}. The data have been plotted for the dates of observation and again for a period of time, 17.3 d later. Assuming that the high-velocity component becomes the low-velocity one and vice-versa after a 'switch-over', the data may be interpreted as a periodic variation of two waves in counterphase; cf. the dotted lines.
period DACs, which is about 100 times smaller, of the order of 0.1 km s\(^{-1}\) d\(^{-1}\).

3 A Possible Interpretation

In this section we examine the following question: if a periodic motion with \(P = 17.3\) d occurred in the wind of P Cyg, what would be the physical character and the wavelength of that motion?

We base our answer on the dispersion equation for perturbations in line driven winds as developed by Abbott (1980, in his eq. (45)). That equation reads

\[
\omega^3 + \omega^2 k^2 F_2 - \omega (a^2 k_x^2 + a^2 k_z^2) - a^2 k_x^2 k_z F_2 = 0 \tag{1}
\]

with

\[
F_2 = \delta g_{\text{rad}} / (\delta (\delta w / \delta r)) \tag{2}
\]

where \(w\) is the wind velocity, \(a\) that of sound, \(k = 2\pi / L\); \(L\) is the wavelength, \(\omega = 2\pi / P\), where \(P\) is the period of the disturbance and \(g_{\text{rad}}\) is the radiative acceleration. For purely horizontal or vertical waves \(k_z = 0\) or \(k_x = 0\) respectively.

For the calculation of the diagram we used the model of the wind of P Cyg given by Najarro et al. (1997), which has the main parameters \(T_{\text{eff}} = 18200\) K, \(\log L / L_{\odot} = 5.75\) and \(n_{\text{He}} / n_H = 0.3\). The physical conditions at the level where the short-period absorption components are formed were derived by using the observation (cf. Fig. 1) that these absorption components are formed at the level where the stellar wind velocity is between 30 and 100 km s\(^{-1}\). We took an average value of 60 km s\(^{-1}\). From Najarro et al.’s velocity law we then find that this level corresponds with \(r = 2.1 R_*\). The density and pressure at that level follow from Najarro et al.’s rate of mass loss. We assumed for that level a temperature of 12,000 K, an assumption that appeared not to be critical. That yields the continuous absorption coefficient. The value of \(\Gamma_1\) was computed using a non-LTE approach involving the 16 most abundant elements, developed by Lobel (in prep).

At that level \(R_* = 5.24 \times 10^{12}\) cm, \(g_{\text{rad}} = -22.49\) cm s\(^{-2}\) (cf. Lamers and Cassinelli, 1999) and \(\delta (\delta w / \delta r) = -3.626 \times 10^{-20}\) s\(^{-1}\). Hence \(F_2 = -2.15210^8\) cm s\(^{-1}\).

The two asymptotic cases are easiest to handle. With \(k_z = 0\), hence assuming strictly horizontal waves, and taking \(P = 17.3\) d we obtain for the horizontal wavelength \(L_x = 1.982 \times 10^{12}\) cm or 0.38\(R_*\). For purely vertical waves \((k_x = 0)\) we get \(L_z = 1.22 \times 10^{10}\) cm or 0.0023\(R_*\).

The waves are gravity waves since for \(P = 17.3\) d the corresponding value of \(\omega\) falls below the Brunt-Väisälä frequency (de Jager, 2001). Since gravity waves mostly travel horizontally we tend to prefer the first solution, that for horizontal waves. An additional argument for choosing that option is that the
wavelength (0.38R\_\ast) is close to the wavelength suggested by the observations, for which we concluded in Section 2 that the waves should have lengths of the order of the stellar radius.

The conclusion of this Section is that if the short-period absorption components would have a period of 17.3 d, then they could be interpreted as horizontally propagating gravity waves with wavelengths of the order of 0.4 times the stellar radius.

4 Conclusions

The high S/N and high-resolution observations reported here show for the first time the existence of short-period narrow absorption components in the cores of high Balmer lines and their rapid variations. If their period was 17.3 d, which is the only known short period observed in the light of P Cyg, they should be interpreted as gravity waves with wavelengths of the order of 0.4 times the stellar radius, a conclusion that is also suggested by the observed behaviour of the absorption components, which seem to consist of two waves in counterphase. A period differing by a factor 2 or so would not change these conclusions. But, evidently, more observations are needed to check this statement and we urge observers to monitor these features.

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