ASTRONOMY & ASTROPHYSICS
SUPPLEMENT SERIES

Astron. Astrophys. Suppl. Ser. **127**, 243-249 (1998)

Cyclic phenomena in the circumstellar gaseous envelope of the candidate Herbig A0e star HD 163296*

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Received February 26; accepted May 13, 1997

Abstract. We present new results of a spectroscopic and polarimetric investigation of the candidate young Herbig Ae/Be star HD 163296. Twenty two spectra of this object near the Hα, He I 5876 and DNa I lines had been obtained in 1992–1995 at the Astrophysical National Laboratory of Brazil (LNA). In addition, forty seven high-resolution spectra in Hα and Hβ were obtained at the ESO (Chile) in 1991–1992. *VRI*-polarimetry (about forty measurements of the Stokes parameters Q, U, V in each passband) were carried out at the SAAO (South Africa) in July 17–30, 1995.

Striking profile variability has been found in all the lines on time scales from hours to months. Analysis of the profiles revealed manifestations of a remote cool shell which is in active interaction with the variable kinematically stratified stellar wind. Signs of cyclic positional variations of the Hα and Hβ emission peaks were observed during five nights in July, 1991.

Sinusoidal variations of the linear polarization parameters detected in July, 1995 are explained in the framework of a model involving magnetized gaseous condensation, rotating in the envelope with the period of 15 days.

Marginal detection of circular polarization is also reported.

Key words: line: profiles — polarization — stars: circumstellar matter — stars: individual (HD 163296) — stars: mass loss — stars: pre-main sequence

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* Based on observations collected at the Astrophysical National Laboratory (LNA, Brazil), the European Southern Observatory (ESO, La Silla, Chile) and at the South African Astronomical Observatory (SAAO, South Africa).

1. Introduction

The emission line star HD 163296 (B9eV–A2eV, $V = 6\overset{m}{.}8$) was first classified as a young Herbig Ae/Be star by Finkenzeller & Mundt (1984). Later on Thé et al. (1994) also included this object in their enlarged catalogue of Herbig stars, candidates to this group and related objects. The majority of observational properties of HD 163296 is similar to those of the members of the classical catalog by Herbig (1960), although this star is not associated with nebulosity and does not demonstrate remarkable photometric variability.

The first descriptions of the line spectrum of HD 163296 in the visible spectral range were given by Merrill et al. (1925), Merrill (1930) and Merrill & Burwell (1933). They noted that emission Balmer lines with narrow absorption cores and numerous low-ionization metallic shell lines were present in the spectrum. All of them are strongly variable in both intensity and position, and changes of emission and shell components take place independently.

Up to the eighties no detailed investigations of HD 163296 had been carried out. The first high resolution spectroscopy of this star has shown that one of the characteristic features of the Hα variability is the transformation of the profile type from PCyg II to PCyg III (according to Beals 1951), which looks as the appearance of a secondary emission peak on the blue wing of the PCyg absorption component (Finkenzeller & Mundt 1984; Thé et al. 1985). Besides HD 163296, two more classical Herbig Ae stars from the catalogue of Finkenzeller & Mundt (1984) demonstrate the same type of variability (AB Aur and BD+61°154).

The similarity of HD 163296 and the young Herbig Ae/Be stars is also confirmed by results of observations in the ultraviolet (UV) and infrared (IR) spectral domains. A lot of low-ionization lines in the UV and dust IR excess have been discovered in this object (Sitko et al. 1981; Sitko 1981).

Periodicity in changes of the UV Mg II resonance doublet ($P = 50 \pm 8$ h) and the Ca II K line ($P = 35 \pm 5$ h) was reported by Catala et al. (1989). This phenomenon was interpreted by the authors in terms of differential rotation of the circumstellar envelope containing long-lived inhomogeneities.

A detailed investigation of the rapid line profile variability in the photospheric lines of Si II and Mg II, the chromospheric Ca II K and the envelope Hα lines was performed by Baade & Stahl (1989). They have found intensity changes in different parts of line profiles with no evidence of periodicity in these variations.

A detailed spectroscopic study of HD 163296 in the Hα and Hβ emission lines was presented by Pogodin (1994), hereafter Paper I. The main conclusions of the analysis of the line variability were as follows:

- The envelope of HD 163296 contains an active region of the stellar wind near the star, surrounded by a rather stable remote shell.
- Two types of circumstellar inhomogeneities are likely to be formed in the envelope: a) long-lived rotating jets, and b) short-lived local condensations ("bullets").

A few polarimetric measurements of HD 163296 (see, for example, Gnedin et al. 1992) revealed a complicated behaviour of the multi-component polarization parameters.

All evidence mentioned above illustrates that the true understanding of the structure, kinematics and physical conditions of the circumstellar environment of HD 163296 needs additional spectroscopic and polarimetric observations.

The study presented here was aimed at further investigation of circumstellar peculiarities of HD 163296 with the use of:

1. Spectroscopic data obtained at the ESO (Chile) in 1991–1992 in the region of the Hα and Hβ lines. The analysis of these spectra was published in part in Paper I.
2. New spectroscopic observations performed at LNA (Brazil) in 1992–1995 in the Hα, He I 5876 and DNa I lines.
3. *VRI* polarimetric measurements in July, 1995 at the South African Astronomical Observatory (SAAO, South Africa).

2. Observations

Forty-seven high-resolution spectra (35 in Hα and 12 in Hβ) were obtained in July 16–20, 1991 and in July 25–27, 1992 with the Coudé Echelle Spectrometer (CES) installed at the 1.4 m Coudé Auxiliary Telescope (CAT) of the European Southern Observatory (ESO) at La Silla (Chile). An RCA CCD was used as detector and a spectral resolving power $R = 50\,000$ was ensured for all the spectra. A detailed description of the observational data, their reduction and analysis are given in Paper I.

Besides of that, 16 spectra near Hα and 6 spectra in the region of the He I 5876 and DNa I lines were obtained at the Astrophysical National Laboratory of Brazil in 1992–1995. The observations were carried out using the coudé spectrograph of the 1.6 m telescope equipped with a 770×1152 pixels CCD detector. A spectral resolving power R of 15 000 and S/N ratio of about 200 (near the continuum level) were achieved in each spectrum with the wavelength coverage $\Delta\lambda$ of about 150 Å.

The reduction process follows the standard procedure as described by Wagner (1992), using the IRAF package.

About 50 polarimetric estimates in the VR_cI_c bands were obtained in July 17-31, 1995 at the SAAO with the UCT-polarimeter (Cropper 1985), attached to the 0.75 m telescope. The polarimeter module contains a half-wave and a quarter-wave plate rotating in opposite directions, allowing simultaneous linear and circular polarization measurements. All observations were made with 20$''$ aperture. The polarimeter was calibrated using polarimetric standards of Hsu & Breger (1984). Data reduction was performed in the Keele University using the suite of programs which was created at the SAAO.

3. Results of the spectroscopy in Brazil and the polarimetry in South Africa

Profile variations of the Hα, He I 5876 and DNa I lines for different observing runs are presented in Figs. 1–5. To illustrate a character of the rapid variability on time scales from hours to days, the spectra obtained in neighbouring nights are gathered in separate groups. For comparison the profiles corresponding to the initial dates of each group are given as dotted lines.

3.1. Hα

On the whole, the profile type of the Hα emission line was the same as in the ESO spectra of 1991–1992 (Paper I). However, as is clearly seen in Figs. 1–3, the system of blueshifted absorption components turns out to be more complicated. In different observing nights it contains one component (20 − 21.03.92 and 02.03.93), two components (all the remaining dates except for 31.08.93) or three components (31.08.93). On the latter date a redshifted absorption feature was observed at about 100 km s^{-1}.

The width of Hα profile remains practically constant with positional shift of the profile as a whole from $-410 \div +550$ km s^{-1} (17.04.92) to $-590 \div +430$ km s^{-1} (15.04.95). Residuals from the nightly mean spectrum observed on 20.06.95 (the only date when several spectra were obtained during a night) are presented in Fig. 4. They demonstrate the same character of rapid variability as in 1991–1992

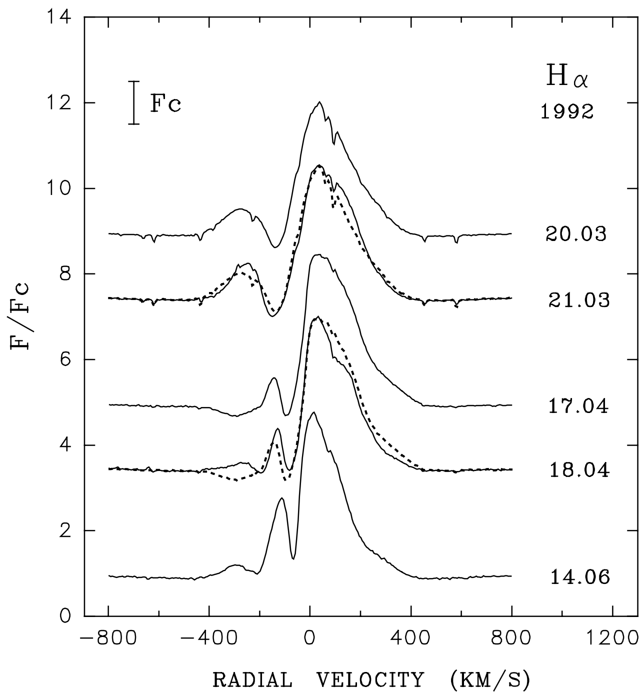

Fig. 1. Line profiles of Hα observed in the spectrum of HD 163296 in 1992 at the LNA. For the sake of comparison, the profiles obtained on 20.03 and 17.04 are also superimposed as dotted lines on the profiles of the respective next observing nights

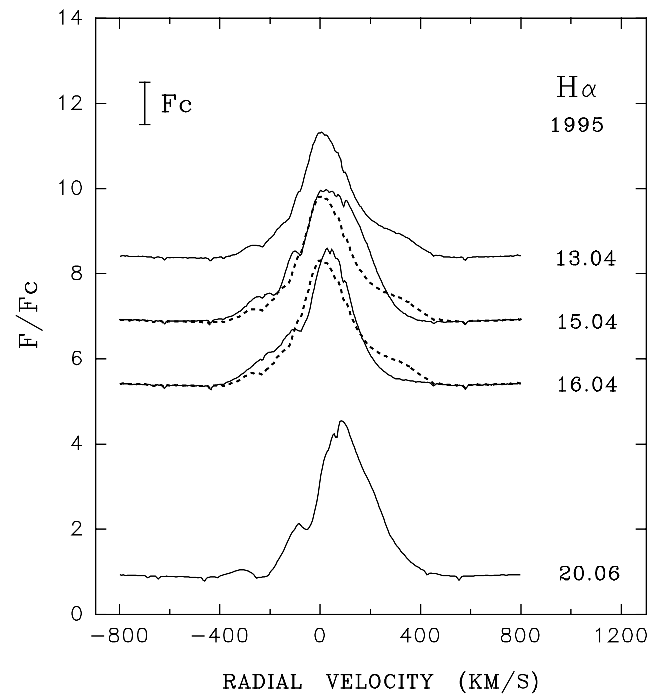

Fig. 3. The same as Fig. 1 but for 1995. The dotted line shows the profile obtained on 13.04. The nightly mean profile for 20.06 is presented at the bottom

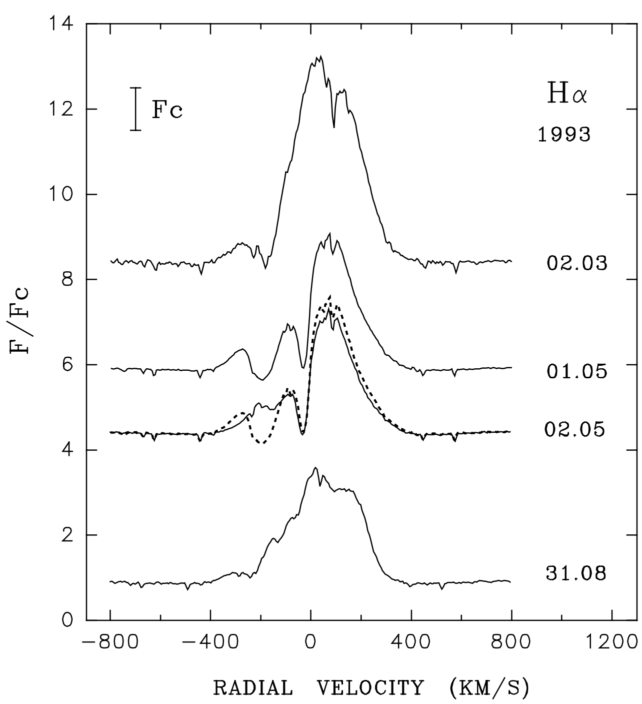

Fig. 2. The same as Fig. 1 but for 1993. The dotted line shows the profile obtained on 01.05

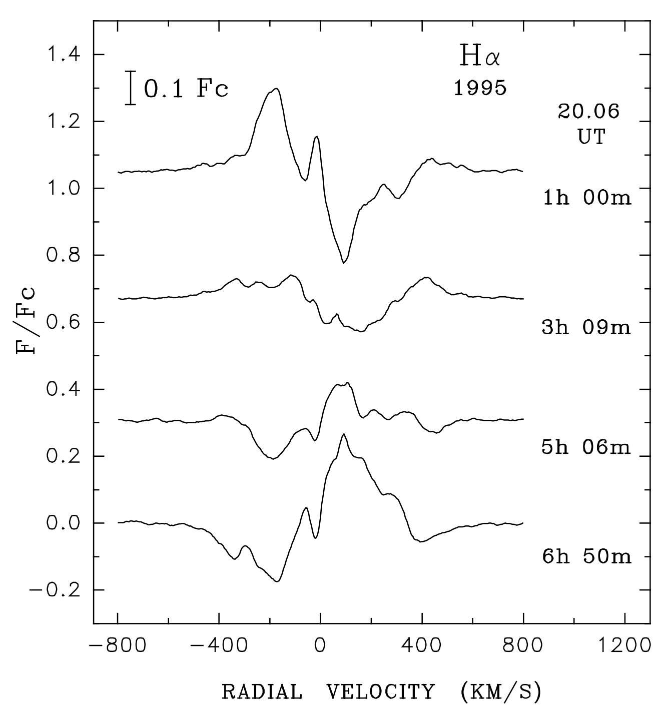

Fig. 4. Residuals with respect to the nightly mean Hα profile observed on 20.06.95

(Paper I). It looks like monotonous changes of intensity within the narrow intervals of radial velocities without positional shifts (so called “standing waves” in the residuals).

3.2. He I 5876

The He I 5876 line profile exhibits a somewhat smaller width in comparison with Hα (Fig. 5) and a positional shift from $-350 \div +350\,\mathrm{km\,s^{-1}}$ (April, 1995) to $-440 \div +310\,\mathrm{km\,s^{-1}}$ (20.03.92). The majority of line profiles are blueshifted and double-peaked, with the blue emission peak being stronger and the central absorption being slightly redshifted. Occasionally, it acquires a reverse P Cyg-type (16.04.95 and 20.06.95, (b)-profile), while the (a)-profile of 20.06.95 exhibits an intense additional emission peak near zero velocity.

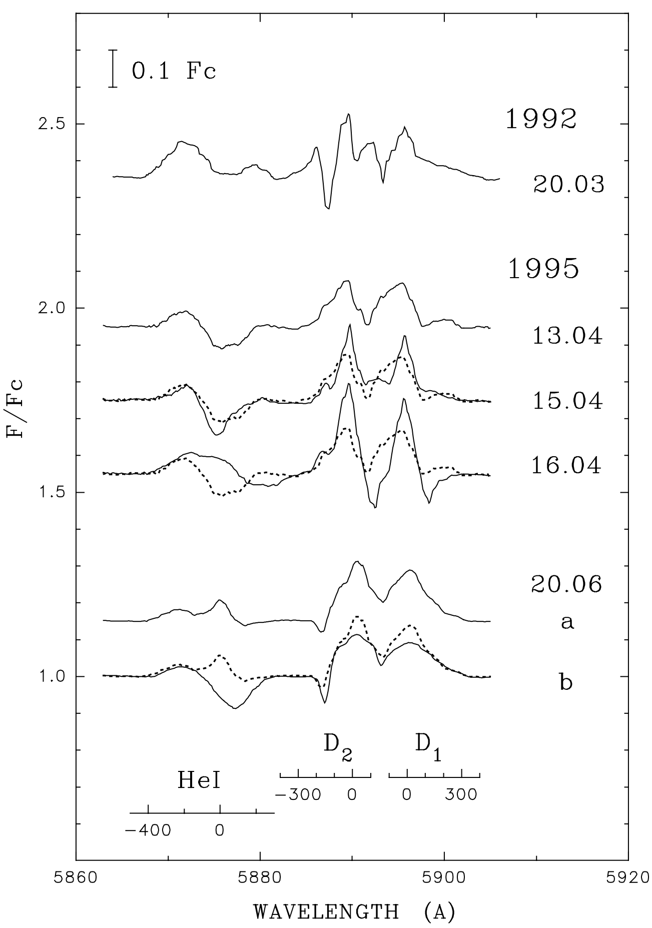

Fig. 5. The same as Fig. 1 but for the He I 5876 and DNa I lines. The profiles obtained on 13.04.95 and 20.06.95 **a)** are also superimposed as dotted lines on the respective subsequent observations. The radial velocity scales for He I 5876 , and the D_2 and D_1 lines are given in $\mathrm{km\,s^{-1}}$ at the bottom. Spectrum **a)** was taken at UT= $1^{\mathrm{h}}14^{\mathrm{m}}$, **b)** at UT = $5^{\mathrm{h}}57^{\mathrm{m}}$

3.3. DNa I lines

The DNa I lines are anomalously wide compared to classical Herbig Ae/Be stars (Fig. 5): from $-230 \div 360\,\mathrm{km\,s^{-1}}$ (20.06.95) to $-380 \div +450\,\mathrm{km\,s^{-1}}$ (March, 1992). As a rule, the DNa I line profiles are of the same type as Hα, but the set of absorption components is more diverse. Sometimes narrow redshifted features can be met in the DNa I profile, such as that seen at $+130\,\mathrm{km\,s^{-1}}$ in the profile of 16.04.95.

3.4. Polarization parameters

VRI polarimetric observations of HD 163296 in July 17–31, 1995 give evidence of the presence of at least two

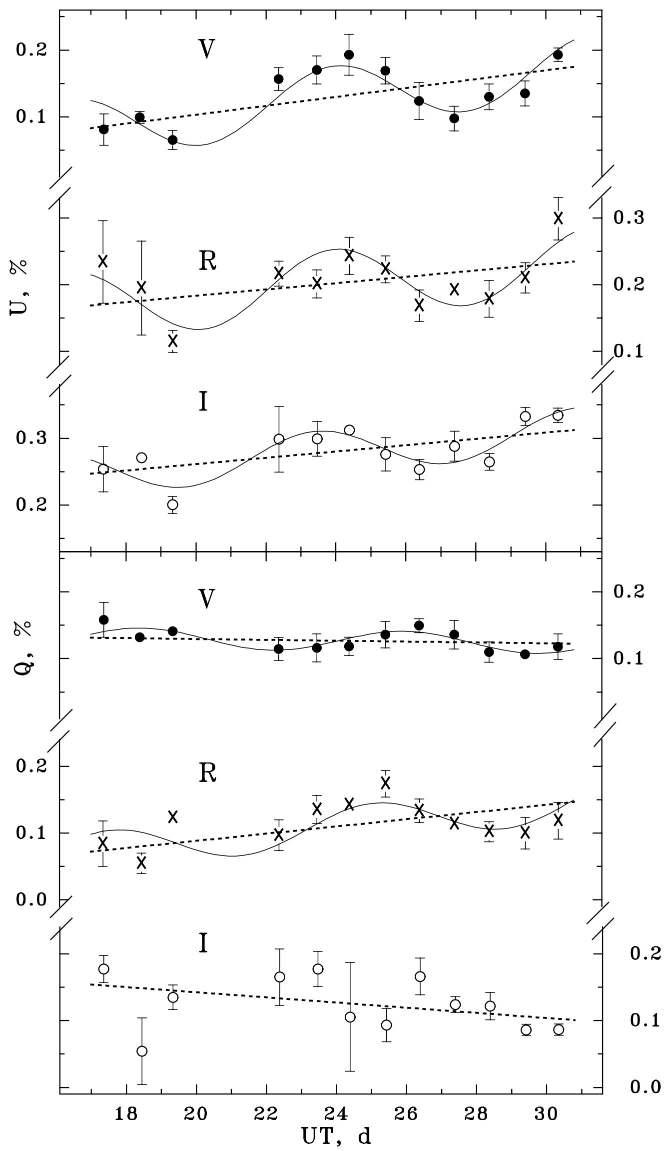

Fig. 6. Illustration of the cyclic variability of the nightly mean Q, U polarization parameters of HD 163296 in July, 1995

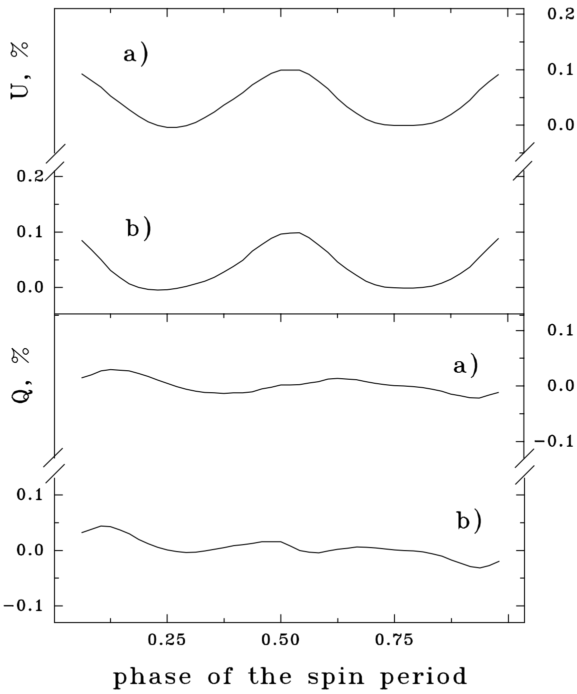

Fig. 7. Theoretical changes of the Q, U polarization parameters calculated for a model of a rotating magnetized gaseous condensation ($i = 78^\circ$, $B = 120\,\mathrm{G}$, $N_0 = 6\ 10^{11}\ \mathrm{cm}^{-3}$) a) for the V band, and b) the I band

variable linear polarization components. A detailed periodogram analysis of the Stokes parameters Q and U has been carried out by means of the Laefler-Kinman (1965) method implemented in a computer code by Pelt (1980). We have found the nightly mean values of the U-parameter to be satisfactorily approximated by a sinusoidal curve with a period $P = 7.5 \pm 0.3$ days, superimposed on a linear trend with the same slope in all three bands and the mean value increasing towards longer wavelengths (Fig. 6). Variations of the Q-parameter are of essentially lower amplitude. The noticeable difference of the trend component for the Q-parameter in the R passband can be caused by the distorting influence of the variable lowly-polarized emission in the Hα line. After subtraction of the trend, the variations of the Q parameter in the VR-bands can be fitted by a sinusoidal curve with the same period (7.5 days) and $\pi/4$ phase shift relative to the corresponding U-curves, while in the I-band the sinusoidal variations disappear.

Measurements of circular polarization performed within the same observing set allowed to derive weighted mean values in excess of the 3σ noise level in all passbands, displaying an increase towards longer wavelengths ($0.012 \pm 0.003\%$ in the V band, $0.020 \pm 0.005\%$ in the R band, and $0.025 \pm 0.005\%$ in the I band). Variations of the nightly mean values are weekly correlated with those of the linear polarization degree. These results imply the presence of aligned particles in the dusty envelope of this object.

4. Discussion

4.1. Azimuthal inhomogeneity of the envelope

The behaviour of the Hα and Hβ emission line profiles observed at the ESO in 1991 and 1992 was analysed in Paper I. These results allowed to suggest the model of a gaseous circumstellar envelope around HD 163296 containing the region of a non-stationary stellar wind and a more stable remote shell. However, new observations performed at the LNA in 1992–1995 have shown that this model is too simplified. Episodic appearance of the variable blue absorptions travelling towards zero velocity (Figs. 1–3) gives evidence of a boundary layer, arising from the interaction between an active wind and an outer shell.

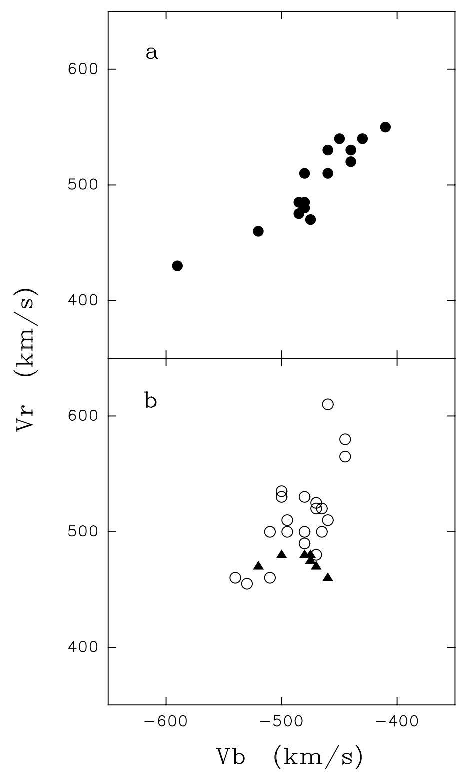

Fig. 8. a) Correlation between the radial velocities of the blue (V_b) and red (V_r) limits of the Hα emission. Only mean data for 1991 and 1992 seasons are given for spectra obtained at the ESO. **b)** The same as **a)**, but for the individual spectra obtained at the ESO in 1991 (filled triangles) and in 1992 (open circles)

"Standing waves" on the residual Hα profiles observed within one night (Fig. 4) are likely to be a common type of the rapid variability in the Herbig Ae/Be stars. Beskrovnaya et al. (1995) proposed an interpretation of this phenomenon on the basis of numerical modeling of

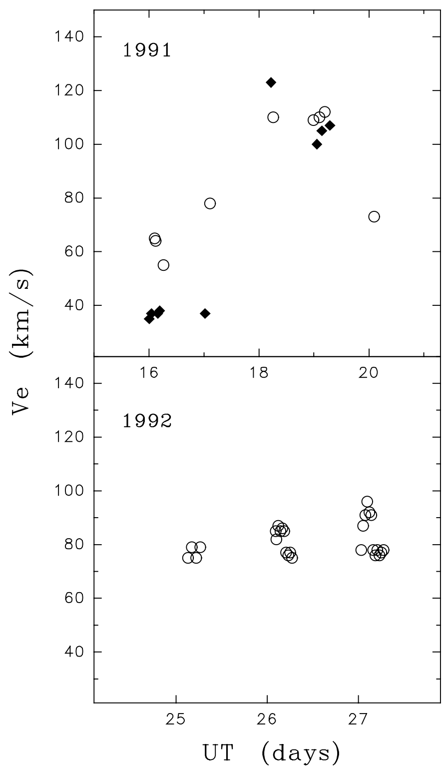

Fig. 9. Positions of emission peaks of Hα (open circles) and Hβ (filled diamonds) for the data obtained at the ESO in July, 1991 and July, 1992

an envelope containing a jet-like inhomogeneity (Pogodin 1990). It has been found that the rotation of a long-lived jet around the star results in the local intensity changes in the line profile without noticeable positional shift on the timescale of a few hours. This is connected with the fact that near the line of sight the jet is moving along the surfaces of equal radial velocities.

If the lifetime of a gaseous jet exceeds its spin period, the following peculiarities in the line profile behaviour are expected:

– changes of the blue and red emission wings in counter phase;
– cyclic variations of the emission peak position;
– periodic variations of different profile parameters with the period of the envelope rotation in the region of the jet formation (as a rule, of the order of a few days).

Observational data available allow to perform the diagnostics of circumstellar inhomogeneities on the basis of the first two criteria. The changes of the red and blue Hα emission wings in counter phase were detected in two data sets: April, 1992 and April, 1995 (Figs. 1 and 3). Figure 8a presents the dependence of the red ($V_{\rm r}$) and blue ($V_{\rm b}$) edges of the Hα emission line for all observing seasons. The anti-correlation character of these variations is clearly seen. It is remarkable, that during 3 nights in July, 1992, this anti-correlation is also noticeable, but with steeper slope, while in July, 1991 (5 nights) it was not observed at all (Fig. 8b). At the same time, the position of the central peak ($V_{\rm e}$) of the Hα and Hβ emission lines detected in July, 1991 is very variable (Fig. 9). The observing series not being sufficiently long, it is difficult to determine clearly the character of the variability. It could be a single episode but cyclic sinusoidal-like variations with a period of about 4–5 days cannot be discarded either. In July, 1992 such a phenomenon was not observed.

All these results make it possible to assume an episodic appearance of azimuthal inhomogeneities in the gaseous envelope of HD 163296.

The existence of inhomogeneities in the outer envelope of HD 163296 is confirmed by the results of polarimetric observations in July 1995. Sinusoidal component of variability of the Q, U Stokes parameters in V and R passbands can be caused by the orbital motion of a dust or gas condensation scattering non-selectively the stellar light. Similar dusty inhomogeneities in the form of planetesimals were considered by Grinin et al. (1994). If the trajectory of such a feature at the time of the observations passed in the immediate vicinity of the star then the observed pattern of the Stokes parameter variations could arise in the form of a sinusoid.

However, the model involving a dust condensation cannot explain the non-sinusoidal character of the Q parameter variations in the I passband. Nevertheless, the observed phenomenon can be interpreted assuming that a rotating inhomogeneity arises in the gaseous media in the presence of magnetic field. In particular, such a feature might originate from the interaction of an inhomogeneous stellar wind with an outer shell.

Magnetic fields in the circumstellar environment of young stars are presently one of the most popular hypotheses for the explanation of kinematical peculiarities in their gaseous envelopes (Appenzeller 1994).

In order to test the influence of circumstellar magnetic fields of different configurations on the parameters of linear polarization observed from a star with azimuthally inhomogeneous envelope, Beskrovnaya & Pogodin (1997) calculated the Stokes parameters Q and U within a model of a rotating magnetized gaseous condensation for different values of the orbit inclination (i) and the magnetic field strength (B). The calculations were performed with allowance for the single electron scattering and the Faraday rotation of the polarization plane in the presence of magnetic field (Gnedin & Silant'ev 1984).

Figure 7 presents the results of calculations for the following model parameters: the orbital period $P = 15^{\rm d}$, $i = 78^{\circ}$, and $B = 120\,{\rm G}$ with the lines of force along the radius-vector. Comparison of the theoretical curves with observed variations (Fig. 6) demonstrate that this model can explain phase shifts on the Q, U-curves as well as the disappearance of the second harmonic of the Q-parameter variations in the I-band, where the influence of magnetic field is stronger.

4.2. Kinematical stratification of the envelope

The positional shifts of the blue absorption features observed in the Hα profiles during consecutive nights make it possible to reconstruct the dependence of these variations on the wind velocity V (Fig. 10). This figure also presents theoretical tracks of the Keplerian wind deceleration, calculated with the use of the following expression:

$$\frac{\mathrm{d}V}{\mathrm{d}t} = -\frac{(V^2 - a)^4}{4GM_\star},$$

where G is the gravitational constant, $M_\star$ is the stellar mass, $a = V_\infty^2$ for hyperbolic motion (V_∞ is the terminal velocity), and $a = -2GM_\star/r_\mathrm{m}$ for elliptical motion (r_m is the apoastron distance).

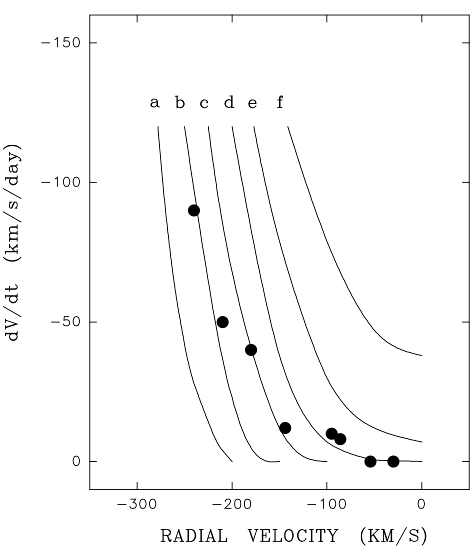

Fig. 10. Observational deceleration of moving blueshifted absorption features on Hα -profile in comparison with theoretical tracks of Keplerian deceleration for the following parameters: **a)** $\sqrt{a} = 200\,\mathrm{km\,s^{-1}}$, **b)** $\sqrt{a} = 150\,\mathrm{km\,s^{-1}}$, **c)** $\sqrt{a} = 100\,\mathrm{km\,s^{-1}}$, **d)** $a = 0$, **e)** $\sqrt{-a} = 100\,\mathrm{km\,s^{-1}}$, and **f)** $\sqrt{-a} = 150\,\mathrm{km\,s^{-1}}$

As can be seen in Fig. 10, the observed values of $\frac{\mathrm{d}V}{\mathrm{d}t}$ follow a line which is less steep than the theoretical tracks. This might be connected with:

- sufficiently high efficiency of wind acceleration at large distances from the star, leading to non-Keplerian motion of the gas at the periphery, or
- Keplerian motion of the gas in the outer envelope with variable terminal velocity, V_∞, ranging from 0 up to $150\,\mathrm{km\,s^{-1}}$.

Taking into account that the width of the DNa I emission line was about $\pm 400\,\mathrm{km\,s^{-1}}$ during all observing seasons, we can suspect a kinematical stratification of the stellar wind near HD 163296. It seems probable that there exists a region of the wind with low initial velocity which cannot leave the system and is likely to support the outer shell. Interaction of such a shell with the faster wind can result in spatial inhomogeneities of the envelope, as well as in the loss of angular momentum by some portion of the circumstellar gas rotating around the star, leading to its subsequent infall onto the stellar surface. This hypothesis can explain the appearance of local features with positive radial velocities in the Hα, He I 5876 and DNa I line profiles.

Reconstructing a complete picture of the cyclic phenomena in the circumstellar envelope of HD 163296 requires long continuous series of spectral and polarimetric observations, which are planned for our forthcoming investigation.

Acknowledgements. The research described in this paper was made possible in part by the ESO C&EE grant A–05–21 for the acquisition of the necessary computer equipment. The work of the Russian authors was sponsored by the INTAS under grant 93-2478-Ext. The Brazilian authors acknowledge CNPq and FAPEMIG for financial support.

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