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Circumstellar peculiarities in the unusual Be star HD 50138*

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Abstract. Ninety-two high-resolution spectra of the peculiar Be star HD 50138 have been obtained in two spectral regions encompassing the lines He I 5876 , DNa I and Hα . The profiles of the Hα and DNa I lines display a number of blue-shifted shell components overlapping the intense emission. Rapid variability of these lines favours a discrete structure of the remote stellar wind and an extensive shell containing local condensations. In the He I 5876 line, which is probably formed in the chromosphere near the stellar surface, the type of profile is more complex and variable. The analysis of its variability has shown that circumstellar gas in the vicinity of the star contains both outflows and accretion zones. The DNa I emission components are very asymmetric with line-centre positions being displaced to about $-50\,\mathrm{km\,s^{-1}}$. This is probably connected with an opaque circumstellar disk in the remote envelope. Obvious similarity of circumstellar peculiarities in HD 50138 and some young Herbig stars is noted.

Key words: line: profiles – stars: circumstellar matter – stars: individual: (HD 50138) – stars: mass loss – stars

1. Introduction

This investigation was performed within the frame of a complex programme on the study of structural and kinematical peculiarities in the gaseous circumstellar envelopes around the young Herbig Ae/Be (HAEBE) stars and related objects. The method involved is based on a search for rapid line-profile variability of lines originating in different circumstellar regions. Analysis of these variations opens the way for reconstructing the density and velocity distributions throughout the envelope.

The previous results of the programme were published by Pogodin (1992, 1994,1995) and by Beskrovnaya et al. (1994,1995). They can be summarized as follows:

1. The envelopes of many wellknown HAEBE stars (AB Aur, HD 163296, HD 200775) are apparently concentrated towards the equatorial plane with the variable latitudinal density distribution of circumstellar gas.
2. Some objects such as HD 163296, HD 200775 and HD 100546 display the manifestations of a remote cool shell, which is more stable and less flattened in comparison with the internal active circumstellar region.
3. A common property of circumstellar matter near the HAEBE stars is its inhomogeneous spatial structure. Long-lived rotating streams are observed in all these objects, and short-lived moving local condensations (“blobs”) were discovered in the envelope of HD 163296.
4. Analysis of circumstellar kinematics shows that the envelopes of the HAEBE stars are presumably forming by stellar wind, although signs of accretion onto the star are also observed in HD 200775 and HD 100546.

The bright Be star HD 50138 (m_V = 6$^\mathrm{m}_{.}$7) was first mentioned as an emission-line object by Humason & Merrill (1921). Afterwards it became a subject of detailed study. HD 50138 demonstrates the properties of both an evolved Bep star and a young early-type object. The main peculiarities distinguishing it from the classical Be stars are: a) bright emission of [O I], Ca II , Fe II and [Fe II] lines (Merrill 1931,1952; Struve & Swings 1940; Houziaux 1960; Doazan 1965; Houziaux & Andrillat 1976), and b) an excess in the middle IR (1–20 μ) which is evidently connected with the circumstellar dust (Allen 1973, Sitko 1981). These observational characteristics allowed Allen & Swings (1976) to classify HD 50138 as a peculiar Bep star of Group 1.

In spite of the fact that the object is not associated with nebulosities and is situated far from star formation regions, it exhibits some features typical for the HAEBE stars. Grady et al. (1994) reported significant asymmetry of the red wings of the UV C IV and Fe III lines and concluded that this is a result of accretion onto the star, and HD 50138 may belong to the group of HAEBE stars.

The main goal of this paper is: a) to present the analysis of structural peculiarities and processes in the circumstellar gas near HD 50138 based on new spectral data, and b) to compare

* Based on observations collected at the European Southern Observatory, La Silla, Chile

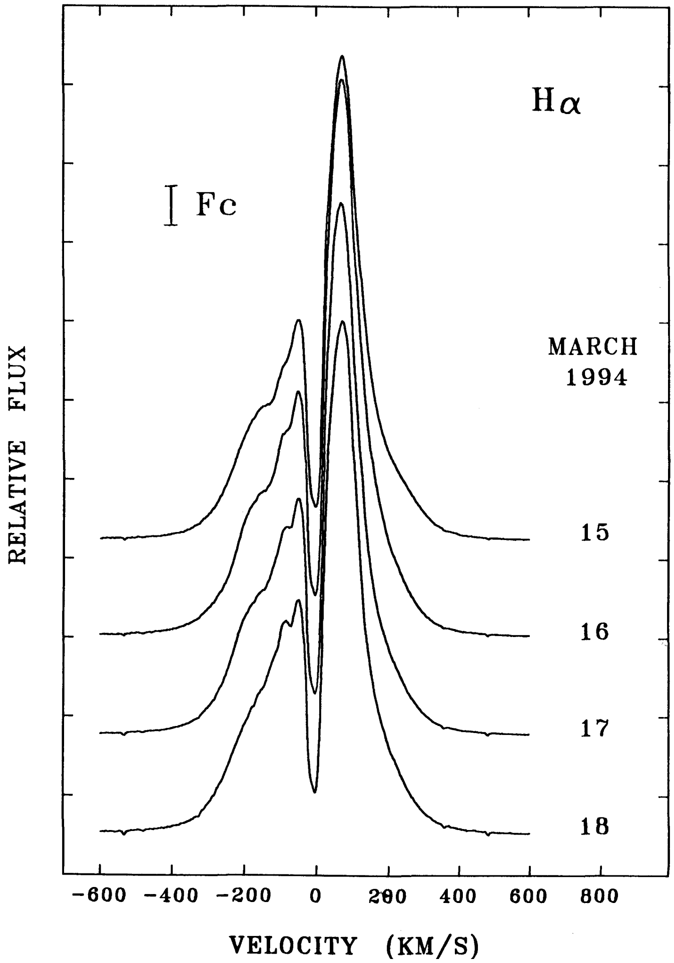

Fig. 1. Nightly mean Hα profiles in the spectrum of HD 50138. The radial velocity scale (RV) is given in the reference frame of the star. The vertical bar provides the flux scale in the units of the continuum, F_C . No attempts have been made to remove telluric water vapour lines.

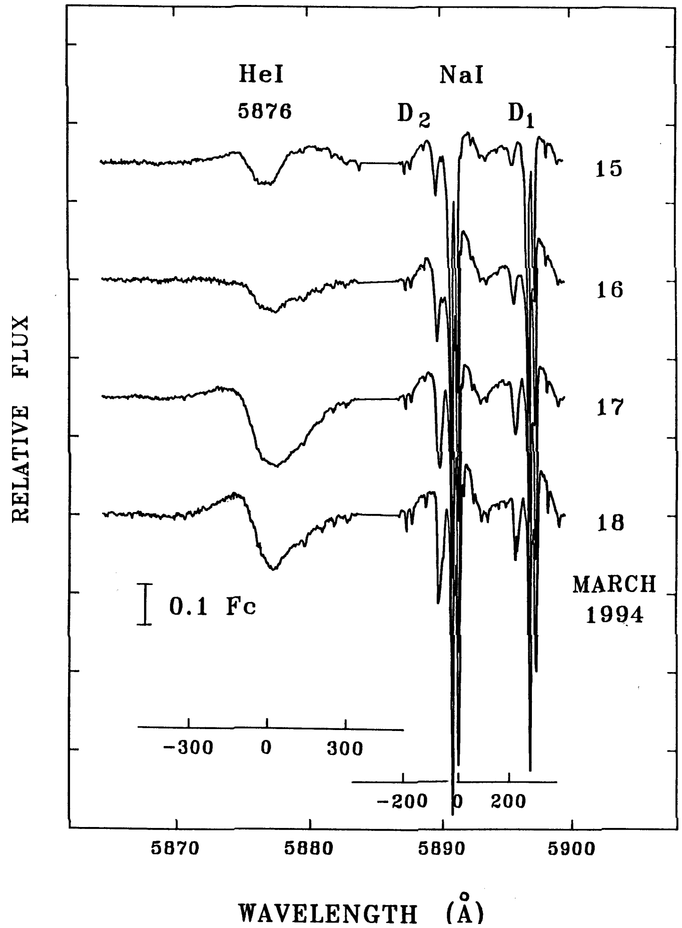

Fig. 2. Nightly mean profiles of He I 5876 and DNa I lines in the spectrum of HD 50138 . The radial velocity scale for He I 5876 and D_2 is the same as in Fig. 1.

the results with those for the HAEBE stars already investigated in the frame of this programme.

2. Background

2.1. Lines in the visible

The most conspicuous envelope lines in the visual spectrum of HD 50138 are those of the Balmer series. The profiles of Balmer lines show two peaks separated by a deep central absorption. Emission is still visible in Hε and, sometimes, in H_8, while the narrow shell absorptions can be usually seen up to H_{30} (Houziaux 1960). The equivalent width of Hα is very large (W = 50–60 Å), and the Balmer decrement is anomalously steep ($I_{H\alpha}/I_{H\beta}$ = 6.5) in comparison with the classical Be stars (Briot 1981). The V/R ratio is about 0.5 for Hα and becomes greater than unity beginning with Hγ (Doazan 1965) or Hδ (Houziaux 1960).

Estimations of the spectral class of HD 50138 are rather contradictory: from B5 III (Houziaux 1960) to B9.5 V (Gao & Cao 1984). This uncertainty seems to be connected with the presence of variable shell spectrum superimposed on photospheric lines.

2.2. Line variability

The envelope lines of HD 50138 display striking variability on time scales from years (first noted by Merrill 1952) to hours (Houziaux & Andrillat 1976). The object episodically exhibits classical shell phases typical for Be stars (Andrillat & Houziaux 1991, Jaschek et al. 1992, Bopp 1993), and outburst-type phenomena (Hutsémekers 1985). A characteristic peculiarity of the Balmer lines in HD 50138 is the appearance of variable violet and red satellite absorptions (Merrill 1952, Doazan 1965), with the violet features being observed more often (Andrillat & Houziaux 1972). The cyclic character of spectral variability in HD 50138 was reported by Merrill (1931) and by Doazan (1965).

It is notable, that violently non-stable behaviour of spectral lines is not accompanied by significant photometric variations. According to Halbedel (1991), ΔV was less than $0\overset{m}{.}2$ during

3 years, in spite of the fact that observing runs included some periods of global spectral changes.

2.3. Near IR spectrum

Observations in the spectral range from 0.7 to 1.1 μ give evidence of the existence of a hot circumstellar region near the star. Similar but not so intensive emission spectrum is typical for chromospheres of Be stars (Marlborough 1982) and regions of accretion shocks in T Tau stars (Hamman & Persson 1992, Guenther & Hessman 1993). The IR spectrum is characterized by intensive emission in $P_7 - P_{20}$, Ca II IR-triplet, O I 7773, 8446 and also by noticeable He II 10123 emission line (Andrillat et al. 1990, Jaschek et al. 1992). The variability of these lines is of intricate character and may be connected with complicated kinematics in the hot region of the envelope.

2.4. UV data

Much information about the circumstellar environment of HD 50138 has been obtained from ultraviolet observations with orbiting satellites starting from the late seventies. Savage et al. (1978) and Sitko et al. (1981) analyzed the extinction curve A_λ and pointed out that it was not similar to the interstellar one. Its shape resembles that of the HAEBE stars with a small depression at λ2175 Å. A noticeable, very variable, minimum near λ2150 Åwas supposed to be a result of blended absorption in resonance Fe II shell lines. The presence of highly ionized species such as C IV and Si IV in the UV spectrum of HD 50138 confirms the existence of hot circumstellar zones (Sitko et al. 1981, Hutsémekers 1985, and Grady et al. 1994). There are only a few emission lines in the UV spectral region: the Mg II doublet and some Fe II multiplets. Besides of that, a great number of absorption lines of neutral (N I , O I , and Mg I) and singly ionized elements (Fe II , Ni II , Cr II , etc.) appear in the spectrum.

The profiles of UV lines indicate both stellar wind and infalling matter in the vicinity of HD 50138 . One of the most striking features is the Mg II resonance doublet with a PCyg profile. This line exhibits variability resembling that of Hα observed in AB Aur, a Herbig Ae star with strong stellar wind, which is characterized by episodical appearance of a secondary blueshifted emission peak on the line profile (Corciulo et al. 1990, Pogodin 1990, Beskrovnaya et al. 1991). On the other hand, Hutsémekers (1985) and Grady et al. (1994) reported strengthening of the red wing for chromospheric Si IV , C IV and Fe III lines, that argues in favour of matter accretion onto the star.

2.5. Summary

The following conclusions can be made on the basis of observational data already published:

- The gaseous envelope of this object is more extended than the typical one in classical Be and in the majority of HAEBE stars. The presence of forbidden lines and the steep Balmer decrement are likely to result from the fact that the external cool shell contains low-density matter but with concentration higher than expected according to the law: $n(r) \propto r^{-2}$. In this case, collision processes should dominate in excitation of circumstellar gas.
- The envelope of HD 50138 is formed by both stellar wind and matter infall onto the star. The gas expansion is prevailing in the outer regions, while the process of matter infall is predominant near the stellar surface.
- The wind of HD 50138 is obviously of discrete, outburst-type character. Its rather small velocity ($V < V_{\rm esc}$) could cause the formation of an extended remote shell, and interaction of the wind with the shell matter can result in episodic accretion phenomena.

The following envelope lines were selected to study the circumstellar structure of HD 50138 in more detail: a) the He I 5876 line generating in the hot region near the star, b) the DNa I doublet originating in outer parts of the envelope, and c) the Hα emission line, which is forming throughout the envelope.

3. Observations and data reduction

Ninety-two high-resolution (R = 40 000) spectra of HD 50138 were obtained in two spectral regions: a) in the vicinity of the Hα emission line, λ_0 = 6563 Å, $\Delta\lambda$ = 57 Å; and b) centered between the He I 5876 line and the DNa I doublet, λ_0 = 5885 Å, $\Delta\lambda$ = 51 Å. The observations were carried out in March 15–18, 1994 at the ESO (Chile) with the CES spectrograph mounted on the 1.4m CAT telescope and operated with a RCACCD detector. The time exposures were limited to 4 min for Hα and to 15 min for the 5885 region in order not to exceed the saturation level of the CCD detector (16384 counts/pxl). A typical observing procedure during a night was a continuous series of observations in each spectral region with interchange between two spectral bands every 30–40 min. The primary reduction of the observational data was performed with the IHAP image processing system with the use of standard technique (Baade & Stahl 1989, Pogodin 1994).

A continuous series of spectra in each of the two spectral regions was averaged in order to increase the signal-to-noise ratio.

The radial velocity ($V_{\rm r}$) calibration of spectra was carried out after the heliocentric corrections. This was based on the assumption that the longer wavelength narrow absorption component of the DNa I lines is mainly of interstellar origin and is stationary relative to the star. The velocity of this line was determined as +40 $\pm$ 1 km s^{-1} in the solar system frame. According to Bopp (1993) the same absorption was observed at $V_{\rm r}$ = +38 km s^{-1} in 1991. These values are in good agreement with the estimation of heliocentric velocity of +36 km s^{-1} given by the GCRV for HD 50138.

Table 1. Log of observations.

Date (March 1994)	Spectral region (λ_0, A)	Exposure time (UT)	Number of spectra within a series	S/N at the continuum level for mean spectrum
15	6563	0^h27^m - 1^h00^m	10	300
	5885	1 29 - 2 02	2	300
	6563	2 40 - 3 23	10	270
	5885	3 48 - 4 25	2	250
16	6563	23 58 - 0 40	10	270
	5885	0 45 - 1 19	3	280
	6563	1 48 - 2 30	10	280
	5885	2 45 - 3 17	3	270
	6563	3 57 - 4 05	2	100
	5885	4 08 - 4 16	1	100
17	5885	0 02 - 0 34	2	240
	6563	0 44 - 1 16	6	200
	5885	1 35 - 2 07	2	250
	6563	2 11 - 2 47	7	240
	5885	3 11 - 3 42	2	240
	6563	3 46 - 4 07	4	160
18	6563	1 40 - 2 08	6	220
	5885	2 15 - 2 35	2	210
	6563	2 56 - 3 28	6	210
	5885	3 30 - 4 02	2	240

4. Results

4.1. The Hα line profiles

During the whole observing run the Hα line in the spectrum of HD 50138 displayed an emission profile with two peaks (Fig. 1), with the red one being more intensive ($V/R \approx 0.5$). Beyond the velocity interval $|\Delta V| \lesssim 200\,\mathrm{km\,s^{-1}}$ the profile shows extended symmetrical wings typical for strong emission lines in Be stars. The bisector velocity of the profile for the region of emission wings is approximately constant ($-5 \pm 1\,\mathrm{km\,s^{-1}}$) and coincides with position of the deep central absorption. A number of absorption features overlaps the blue part of the profile in the range: $-200 < V_\mathrm{r} < +70\,\mathrm{km\,s^{-1}}$. Two weak secondary components stand out against the background of the blue peak. The first of them was almost unnoticeable on March 15, but became visible during the following nights; its positions was shifted from $-77\,\mathrm{km\,s^{-1}}$ (March 16) to $-71\,\mathrm{km\,s^{-1}}$ (March 18). On the contrary, the second feature was clearly seen at the beginning of the run (March 15) at $-130\,\mathrm{km\,s^{-1}}$ then it decreased in intensity and changed its position to $-145\,\mathrm{km\,s^{-1}}$ on March 18. At that time it looked very diffuse. Night-to-night variations of the equivalent width were observed with the amplitude up to 15%: W_min = 49.0 Å (March 15), W_max = 56.2 Å (March 16). As a whole, the observations confirm Bopp's(1993) conclusion that the Hα profile in HD 50138 has been remaining of the same type for many years. But the composition of secondary absorptions is apparently variable on the long time scale.

4.2. The He I 5876 line

In contrast to Hα, the profile of He I 5876 line differs from night to night (Fig. 2). It was double-peaked on March 15 with two emission components situated at -125 and $+170\,\mathrm{km\,s^{-1}}$ and an absorption at zero velocity. On March 16 the profile looked as an asymmetric absorption line centered at $+10\,\mathrm{km\,s^{-1}}$ with the red wing being stronger. During the next two nights the profile became similar to inverse PCyg-type with a redshifted absorption centered at $+17\,\mathrm{km\,s^{-1}}$ and emission peaks at $-165\,\mathrm{km\,s^{-1}}$ on March 17 and $-135\,\mathrm{km\,s^{-1}}$ on March 18. According to Bopp (1993) the same profile was observed in 1991. The line profile ranged from $-360\,\mathrm{km\,s^{-1}}$ up to $+360\,\mathrm{km\,s^{-1}}$ (at the continuum level) during the whole observing run.

4.3. The DNa I doublet

The lines of this emission doublet are very asymmetric in the range: $-200 < V_\mathrm{r} < +100\,\mathrm{km\,s^{-1}}$, with three narrow absorption components overlapping the emission peak. Two of them are deep and stable: at zero velocity and at $-23\,\mathrm{km\,s^{-1}}$. They were observed by Bopp (1993) in 1991 at the same positions ($0\,\mathrm{km\,s^{-1}}$ and $-20\,\mathrm{km\,s^{-1}}$). These lines seem to be of both interstellar (IS) and circumstellar (CS) origin. The third absorp-

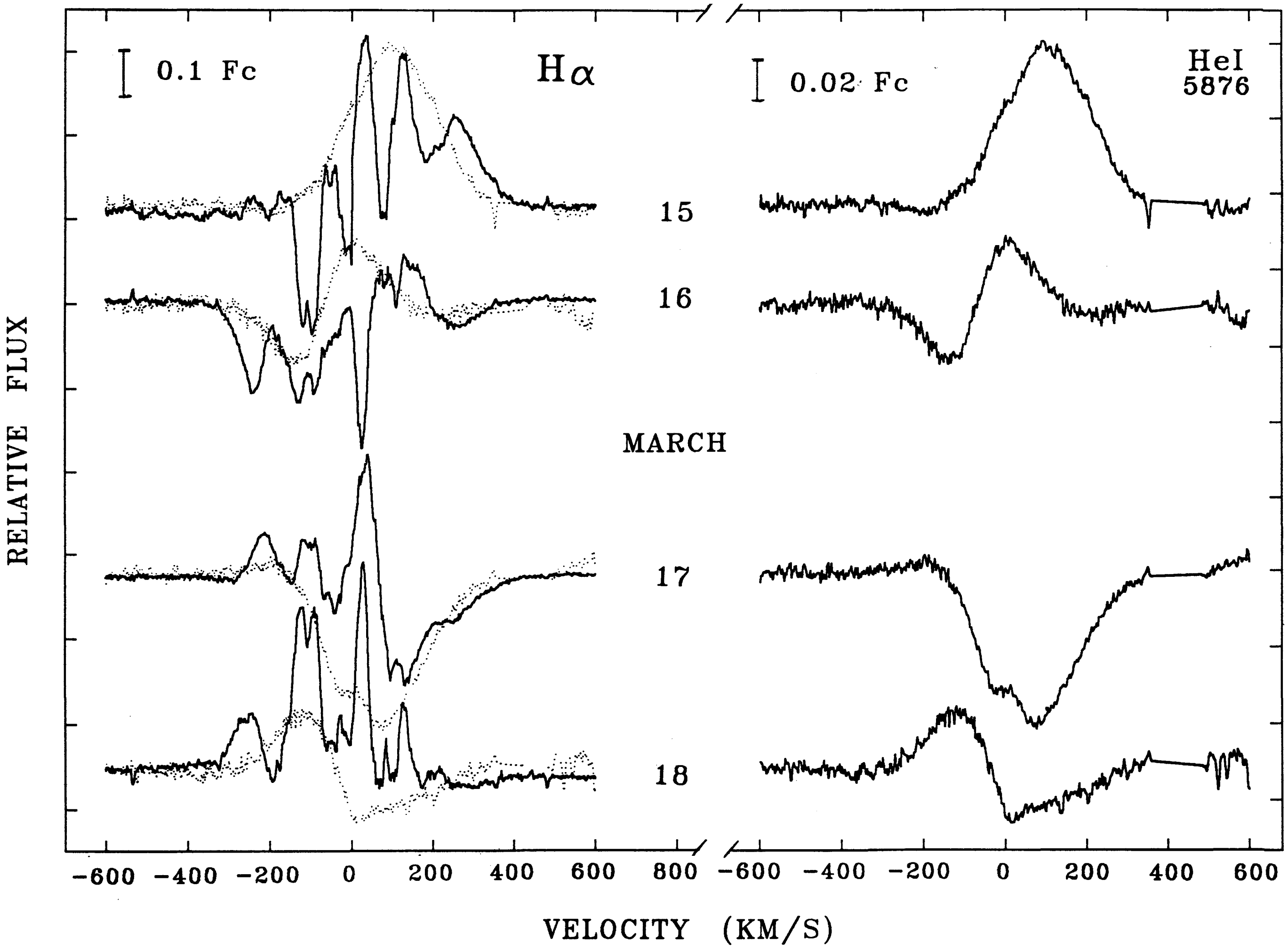

Fig. 3. Night-to-night residuals of Hα (left) and He I 5876 (right). A dotted line illustrates He I 5876 residuals in comparison with those for Hα .

tion component is less intensive and more variable in comparison with the first two. It was not observed in 1991. During this observing run, the position of this component changed from $-85\,\mathrm{km\,s^{-1}}$ (March 15) to $-77\,\mathrm{km\,s^{-1}}$ (March 18). Undoubtedly, it is connected with the corresponding feature observed in Hα at the same velocities, while the stable IS/CS absorptions indicate velocities of the outer parts of the circumstellar feature responsible for the central absorption on the Hα profile, ranging from -50 to $+70\,\mathrm{km\,s^{-1}}$ (see Fig. 1).

In order to examine the character of line profile variability in more detail, two types of residual spectra were constructed: a) individual residuals relative to the nightly mean for each observing night, and b) nightly mean residual spectra relative to the mean for the whole observing run.

4.4. Residual spectra

The night-to-night residual spectra of Hα and He I 5876 lines are presented in Fig. 3. It is difficult to analyze and to interpret the complicated behaviour of He-residuals because of a small number of observations. However, one can see that they resemble the residuals for the HAEBE star AB Aur (Catala et al. 1993) and clearly demonstrate the maximum amplitude of variability in the red part of the line profile.

The residuals of Hα exhibit a multicomponent structure. At least three components of the Hα profile variability can be distinguished. As measurements show, relative intensity ($F/F_{\rm c}$) along the Hα profiles exhibits night-to-night variations with the amplitude up to 15%, while the ratio $F/F_{\rm max}$ remains practically constant to within 1–2% during the whole observing run. Three alternative explanations of this fact can be considered: a) effects of errors in normalization, b) photometric variations of the star itself, and c) real line emission variability. The first possibility should be rejected because of a high S/N value in all the spectra (see Table 1) and a good agreement between spectra obtained during a night. The second hypothesis is hardly probable since HD 50138 is likely to be photometrically invariable (Halbedel 1991). The third assumption is thought to be more realistic provided the absorption features are not the result of

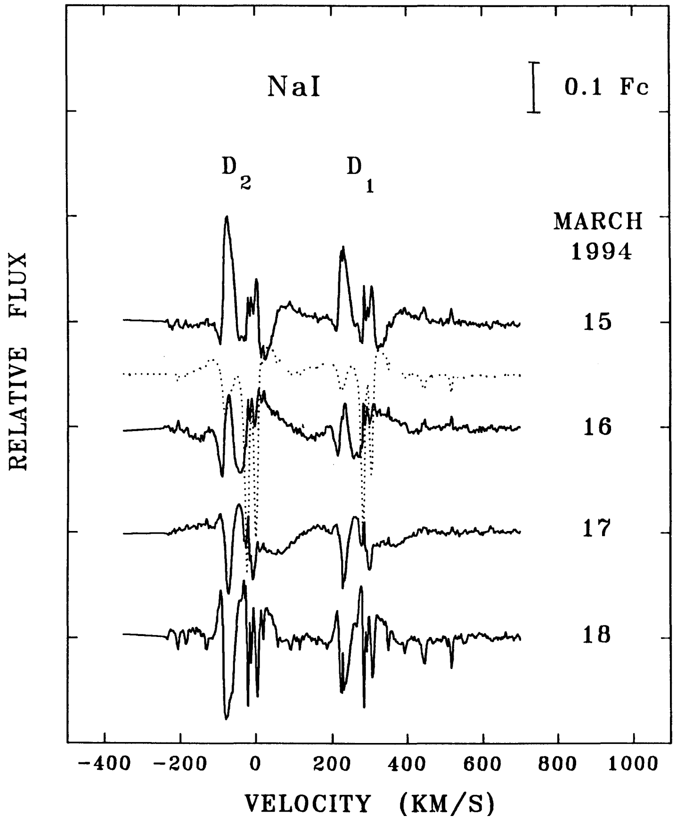

Fig. 4. Night-to-night residuals of DNa I in comparison with the mean spectrum for the whole observing run (dotted line). The radial velocity scale is given for D_2 line.

self-absorption in the emitting envelope, but are forming in a more external region where circumstellar activity is weaker.

The residuals of Hα presented in Fig. 3 (left) were constructed after removing the variability component connected with intensity changes of the whole emission line. This was performed by multiplying of each profile by a corresponding coefficient equal to $(\overline{F_{\rm max}} - F_{\rm c})/(F_{\rm max} - F_{\rm c})$, where $\overline{F_{\rm max}}$ is the maximum intensity value of the mean spectrum for the whole observing run. Fig. 3 (left) shows that as a first approximation two types of profile variability can be noted: i) one resembling in shape the residuals of He I 5876 (Fig. 3, right), especially in the region of red wing, and ii) the second component, which looks like a series of local spectral features overlapping the wide residual spectrum.

These local components are stronger in the blue and central regions and are evidently connected with monotonous intensity variations in different parts of the profile without change in velocity position. It is remarkable, that the same type of variability was reported for some HAEBE stars (Pogodin 1995). The most conspicuous features observed during the whole run are placed at: -236, -108, +30, +128, +171, and +260 km s^{-1} . The maximum amplitude of variations was detected at +30 km s^{-1} and at -108 km s^{-1} .

A similar picture of local intensity bumps is seen on individual residuals of Hα during a night (Fig. 5) and on night-to-night differential spectra of the DNa I doublet (Fig. 4). The amplitudes of "standing waves" on Na-residuals are smaller than of those for Hα . They reach their maximum in the wings of deep absorptions. The behaviour of these residuals give confidence to the notion that the redshift of the component near -80 km s^{-1} is a result of combination of a raising bump at -95 km s^{-1} and a dropping bump at -74 km s^{-1} .

5. Discussion

Spectroscopic observations of HD 50138 confirm a stratified spatial structure of stellar wind, which is clearly observed in Hα and DNa I . The comparison with previous results by Bopp (1993) shows that a new shell layer was formed in the outer envelope region during the last three years. At present, it is seen in the velocity range from -120 to -50 km s^{-1} . Besides, one more condensation centered at -140 km s^{-1} is likely to have generated more close to the star.

Several inferences can be made on the basis of new observational data.

5.1. Equatorially concentrated envelope

The configuration of the Hα absorption components is situated within the velocity interval from -200 to +70 km s^{-1} , while the maximum wind velocity is about 400 km s^{-1} . Therefore, zone of the most high-velocity wind ($200 < V < 400$ km s^{-1}), which is located in the active circumstellar region near the star, is not screened by the outer absorbing shell on the line-of-sight. This situation is often met in the HAEBE stars and can be easily explained using the following assumptions:

- an internal part of the envelope forming by non-stable wind is equatorially concentrated with an intermediate tilt of the equator relative to the observer;
- an active wind region is surrounded by a shell with wider latitudinal distribution of circumstellar gas than the internal zone (see Pogodin 1992, 1994).

5.2. Matter infall onto the star

While the lines originating in the outer envelope show direct traces of stellar wind, the behaviour of He I 5876 line is more complex. The line profile is to a great extent affected by circumstellar kinematics with radial motions since its width ($\pm$360 km s^{-1}) is much greater than the rotational velocity of the star 150 ± 20 km s^{-1} (Houziaux 1960). The profile variability is stronger in the red side. This effect is rather unexpected for a stellar wind, taking into account that the He-line can be formed only near the star, and the wind moving away from the observer should be screened by the stellar disk. Thus, it is necessary to assume matter infall in the envelope of HD 50138 . This assumption is in agreement with the conclusions of previous investigations (see Sect. 2).

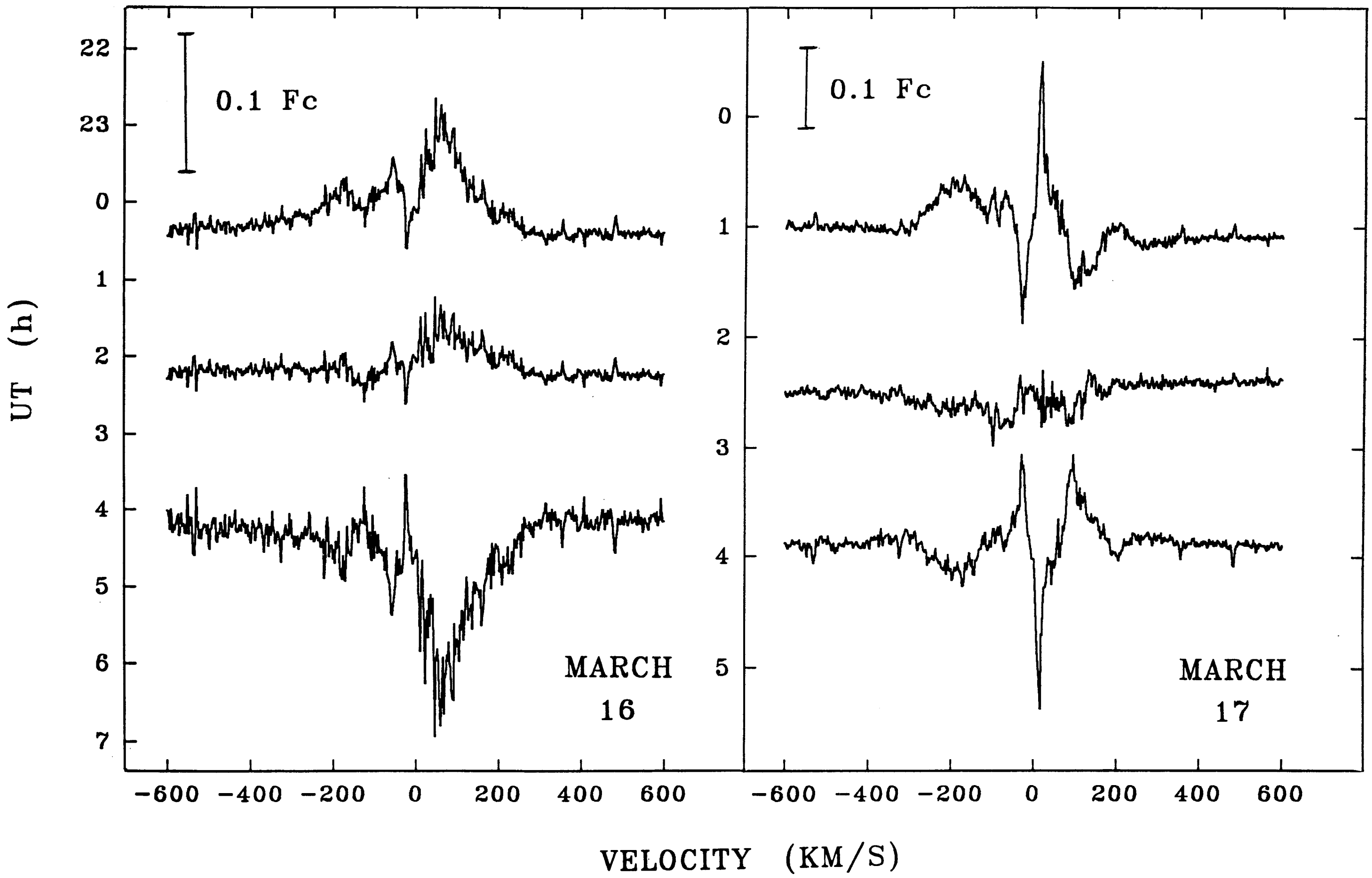

Fig. 5. Individual Hα residuals obtained on March, 16 and 17.

5.3. Equatorial circumstellar disk

Since the DNa I lines originate in an extended region far from the star, screening effects of the stellar disk are evidently negligible. In this situation the visible asymmetry of the emission profile with the blue part being much stronger, can be interpreted as an indicator of dense circumstellar disk, which screens the gas responsible for the red part of the line.

Such disk might be either a remnant of a protostellar accretion disk like those near young TTau stars (Basri & Bertout 1989, Bertout et al. 1988), or generated by flattened equatorial wind of low velocity ($V < V_{esc}$). Comparison of the observed V_{max} = 400 km s^{-1} with V_{esc} expected for B5–B9 III–V star confirms a probability of the latter suggestion.

5.4. Circumstellar inhomogeneity

The appearance of positionally stable narrow features is one of the main types of variability of the Hα line profile and the only type observed in DNa I . The experience in study of the HAEBE stars shows that rapid spectral variations on a time scale compatible with the period of stellar rotation P_{rot} (typically, 1–2 days) can be satisfactorily explained in the framework of a model for circumstellar inhomogeneities moving in the envelope (Catala et al. 1993, Beskrovnaya et al. 1995, and references therein). As one can see in Figs. 3–5, two distinctive kinds of bumps appear on the residuals: a) low-amplitude variations during a night (only for Hα), and b) high-amplitude monotonous changes during the whole observing run. The first type of variations is completely similar to that observed in the HAEBE stars. As it was shown by Beskrovnaya et al. (1995), such features can be a result of long-lived streams rotating in the wind. If the stream is forming near the stellar surface, the variations should be periodic with $P = P_{rot}$, since the phase angular velocity of the stream is constant. From the other hand, the night-to-night monotonous intensity trend within local velocity bands is likely to be connected with slower motion of dense circumstellar condensations forming in more remote regions of the envelope.

At the same time, the night-to-night variability of He I 5876 (displayed also in Hα) arises in circumstellar gas near the star, which contains infalling component. Fig. 3 (right) demonstrates a noticeable difference of residual spectra from night to night. On March 15/17 variations are seen mainly in the red velocity range from -200 up to +360 km s^{-1} with the maximum amplitude at +100 km s^{-1} . On the other two dates there are two peaks of variations centered at -120 and +10 km s^{-1} . The number of observations is insufficient to search for cyclic phenomena, but preliminary analysis of the data allows to propose a hypothesis which must be tested in future observations.

The spectroscopic period of 50 hours was reported by Doazan (1965) and interpreted as a result of radial pulsations in the envelope. However this value proves to be close to P_{rot} expected for a B5III–B9.5V star with $v \sin i = 150\,km\,s^{-1}$. This makes reasonable another interpretation of cyclic spectral variability assuming azimuthal inhomogeneity of the rotating envelope. In the frame of this hypothesis night-to-night variations of He I 5876 profile are connected with its modulation by rotation of inhomogeneities with different kinematics (the phase shift between observations on March 15/17 and on March 16/18 correspondingly is close to 0.5, provided P_{rot} = 50 hours).

6. Conclusions

The detailed spectroscopic investigation of the Be star HD 50138 shows that a number of its circumstellar peculiarities are very similar to those observed in the HAEBE stars:

1. The envelope around HD 50138 is likely to be flattened near the star and possesses a wider latitudinal gas distribution in its external part.
2. The signs of both a stellar wind and infalling matter are seen in the envelope lines.
3. HD 50138 is probably surrounded by an opaque circumstellar disk. It may be of protostellar origin, but other hypotheses cannot be excluded either.
4. The circumstellar gas around HD 50138 contains local inhomogeneities.

Long continuous series of spectral observations is necessary for reconstructing more detailed structural and kinematical picture of this unique object as a basis for forthcoming physical modelling.

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