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VARIABILITY OF Hα LINE IN SUPERGIANT STARS OF SPECTRAL TYPE B, A AND F

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The variability in the profiles of the Hα line profiles in selected $\mathrm{B, A}$ and F spectral class supergiant stars was comparatively analyzed based on the spectra obtained at the 2-meter telescope at the Shamakhy Astrophysical Observatory. This study investigates the variability in the values of the parameters characterizing the profiles of the Hα line and the changes in profile shapes in the spectra of the supergiant stars HD 190603 (B1.5 Ia), HD 208501 (B8 Ib), HD 187982 (A2 Ia), HD 207260 (A2 Iae), HD 195593 (F5 Ib), HD 163506 (F2 Ibe) and HD7927 (F0 Ia). For each star, the reasons for these changes were investigated, leading to general conclusions.
From the study of the selected supergiant stars of spectral type B, A and F, it can be concluded that from the supergiant stars of spectral type B to the supergiant stars of spectral type A and F, i.e., as the effective temperature decreases, the variability in the atmosphere of the star is observed less. In particular, stellar wind is stronger in B spectral type supergiant stars. Some of the ejected matter disperses into the interstellar medium, some returns and falls on the surface of the star, and some collects around the star, and turns into a disk or inhomogeneous cover. In F spectral type supergiant stars, since the temperature is relatively low, the magnitude of the variability in the star atmosphere is small. Therefore, in the studied F-type stars, the profile of the Ha line is often observed as a full absorption profile.
Keywords: supergiant stars – Hα line profile – spectral variability.

1. INTRODUCTION

Supergiant stars are variable stars with an extended envelope and a sparse, non-stationary atmosphere. According to the modern theory of evolution, hydrogen has already burned out in the core of such stars, and the process of burning

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Table 1. Some information about the program stars.

№	Catalog number	Name of the star	Spectal class	Effective temperature T_{eff}, K	Apparent magnitude	Observation period
1	HD 190603		B1.5 Ia	19500	$5^m.65$	2010÷2019
2	HD 208501	13 Cep	B8 Ib	13000	$5^m.80$	2013÷2019
3	HD 187982		A1, A2 Iab	9300	$5^m.57$	2016÷2019
4	HD 207260	υ Cep	A2 Iae	9200	$4^m.29$	2015÷2019
5	HD 7927	φ Cas	F0 Ia	7300	$4^m.98$	1986-2018
6	HD 195593	44 Cyg	F5 Iab	6100	$6^m.2$	2004-2014
7	HD 163506	89 Her	F2 Ibe	6000	$5^m.46$	1975÷2017

helium and heavier elements has begun. Due to the large mass of these stars, their evolution process is fast, their lifetime is short, they are considered young stars and they are mainly located in the Galactic plane. Their age can be about 30÷100 million years, and they are most often observed in active regions - open star clusters, the spiral arms of the Galaxy and irregular galaxies. In random cases, they are observed in the core of spiral galaxies, globular star clusters, and elliptical galaxies. Due to their brightness, these stars are widely used in studying the distribution of chemical elements at long distances from the Sun, as well as within the Galaxy. Therefore, the study of supergiant stars in order to determine the spiral structure, shape and size of our Galaxy, as well as other galaxies, is one of the most pressing issues of modern astrophysics.

In this work, the variability of the Hα line profile in the spectra of B, A, and F spectral class supergiant stars was analyzed comparatively based on the spectra obtained from the 2-meter telescope of the Shamakhy Astrophysical Observatory named after N.Tusi of the Ministry of Science and Education of the Republic of Azerbaijan. The variability in various stars belonging to the mentioned spectral classes has been studied by us as well as by other authors. Table 1. provides the lists of the stars studied in this work and the values of their various parameters.

2. OBSERVATIONAL MATERIAL AND ITS PROCESSING

Spectral observations of the program stars were obtained using CCD camera installed in Universal Astro Grid Spectrograph (UAGS) with an echelle-spectrometer at the Cassegrain focus of the 2-meter telescope at the Shamakhy Astrophysical Observatory named after N.Tusi. Until 2016, the spectra were obtained with a 530×580 pixel CCD camera, providing a spectral resolution of

R = 14000. The observation materials cover the spectral range $\lambda 3960-6600$. Detailed information about the characteristic and working principle of this camera is given in Mikayilov [19]. Since 2016, spectra were obtained using a 4000×4000 pixel CCD camera at the Cassegrain focus, with resolutions of R = 28000 and R = 56000. The dispersion curve was constructed using the spectrum of the daytime sky. Two or three spectra of the star were obtained in a single night. Since there was no strong variation in the spectrum of the star during the night, the spectra were averaged. The spectra were processed using the DECH-20 and DECH − 20 T software packages presented by [6]. The error in measuring the equivalent width is less than 5%. The error in measuring the radial velocity is not greater than 2 km/s. Observational materials and their processing methodology are described in detail in our previous works Khalilov [18].

3. VARIABILITY IN SUPERGIANT STARS OF SPECTRAL CLASS B

The changes in the values of the parameters characterizing the Hα line profiles in the spectra of supergiant stars HD 190603 and HD 208501, typical representatives of B spectral class supergiant stars, as well as the variations in the shape of the profiles, have been extensively studied in our previous works.

The apparent magnitude of the supergiant star HD190603=HR 7678 varies in the range of $5.56 \div 5.70$, it is a blue supergiant star with a spectral class B1.5 Ia [2]. Its absolute stellar magnitude $M_v = -7.5$. In the Galactic coordinate system, its galactic longitude is l=69°.5, the galactic latitude is $b = +0°.4$ [15] and the distance to the star is1961.5 pc [5].

It was shown in [14], that the Hα line profile consists of weak absorption and emission components on the violet side and is observed in the form of clearly distinguishable P Cygni type profiles. It was found that the emission component of the profile consists of one, two, and sometimes three components (Figure 1 (a)).

It has been proved that the radial velocity and equivalent width of the absorption and emission components of the Hα line change with a period of about 100 - 120 days according to time. These variations have been explained by the pulsation of the stellar atmosphere.

The supergiant star **13Cep = HD208501 = HR8371** is a supergiant star that is included in the group of eruptive (flammable, erupting) stars with an irregular change in brightness with apperent magnitude V = 5.80, spectral type B 8 Ib . Its brightness varies from 5.935 to 5.865. Its absolute stellar magnitude $M_V = -4.25$. In the Galactic coordinate system, the galactic longitude is l = 100°.39, the galactic latitude is b = +1°.68. The distance to the star is 700 pc [21].

In our article mentioned in [17], it was shown that in the spectrum of the supergiant star HD 208501, the shape, structure and the value of the spectral parameters characterizing the profile of the Hα line profile show greater variability. The Hα line profile is observed in the following forms depending on the activity of the star (Figure 1 (b)): a) full absorption profile;

b) normal P Cygni-type profile: absorption and on the red wing emission component;

c) inverse P Cygni-type profile: absorption and on the violet wing emission component;

d) weak emission component on both wings and absorption profile in the center;

e) full emission profile;

f) attenuation of the intensity of the absorption and emission components to the level of the continuous spectrum.

In our previous works [17], it was found that the radial velocity and equivalent width of the Hα line profile change within a week or even shorter intervals. As a result of the study of the Balmer series of hydrogen and the lines of various elements in the spectrum of the star HD 208501, and as a result of the calculations, it was shown that the radial velocities of the elements whose lines are observed in the star's atmosphere are stratified by layers. It was determined that the amplitude and average value of the changes of radial velocities of the lines increase from the lower to the upper layers of the atmosphere.

These observational results prove the existence of a rotating, non-homogeneous density disk-like gaseous envelope around the star HD 208501 directed at a certain angle towards the observer, these changes are explained by the pulsation of the star and the interaction between the star and its circumstellar envelope Khalilov et al., [17].

As can be seen, in the spectrum of both stars, a P Cygni-type profile was observed in the Hα line (Figure 1 (a, b)). It is known that the appearance of the P Cygni-type profile in the spectrum proves the presence of an expanding gaseous envelope around the star and a strong matter loss.

It should be noted that the formation of a P Cygni-type profile can be considered characteristic in hot supergiant stars with a wide envelope. Such profiles, which are mainly observed in the Hα line profile, are sometimes also observed in the HeI and HeII lines. In the spectrum of the supergiant star HD 190603 which has a higher effective temperature, a P Cygni-type profile is clearly observed in the Hα, Hβ and helium lines profiles. In the supergiant star HD 208501, whose effective temperature is 6500K lower than that of the supergiant star HD 190603, P Cygni- type profile is only observed in the Hα line profile. Thus, the decrease in effective temperature directly affects the spectral variability of the star. The variability of the mentioned stars is explained by the result of interaction between the envelope surrounding them and the stellar atmosphere. By studying the various spectral lines observed in the spectrum and their parameters, it is possible to explore the interaction mechanism between stellar atmosphere and the surrounding envelope.

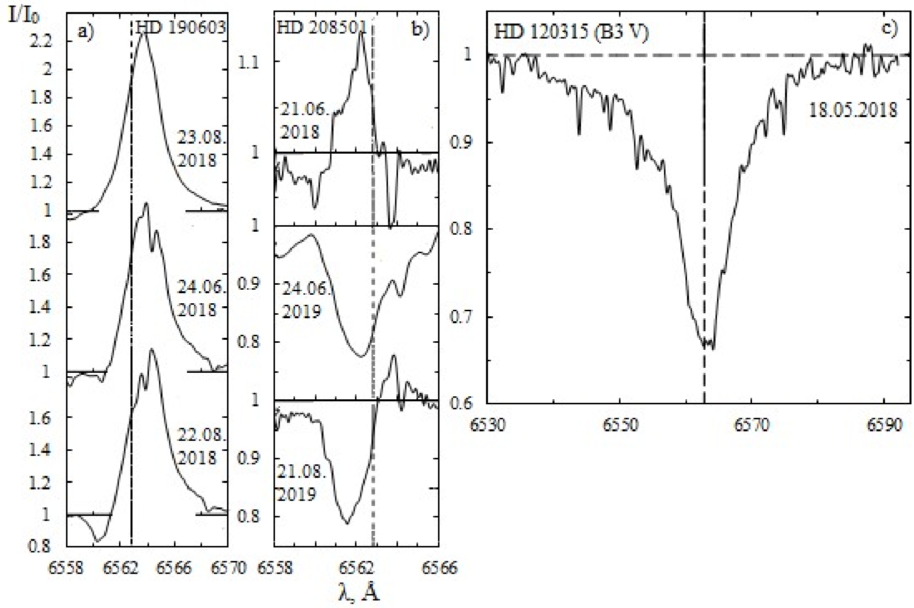

Fig. 1. Profile of the Hα line in the spectrum of stars HD 190603 (a) and HD 208501 (b). On the right, for comparison the spectrum of the Hα line in the spectrum of a standard star HD 120315 (c), of spectral class B.

4. VARIABILITY IN SUPERGIANT STARS OF SPECTRAL CLASS A

Supergiant stars of spectral class A, have a lower effective temperature compared to supergiant stars of spectral class B. From the perspective of spectral variability, they are slightly different stars. In this work, the change in the values of the parameters characterizing the profiles of the Hα line and the shape of the profile in the spectrum of the stars HD 187982 and HD 207260, which are typical representatives of these stars, were comparatively studied.

The supergiant star HD 187982 HR 7573 has an apparent magnitude of V = 5.57, according to [3], and a spectral class of A1-A2 Iab. The HD 187982 supergiant star is the brightest star of the Vul OB4 star cluster. The HD187982 supergiant is the brightest star in the Vul OB4 star cluster. In the Galactic coordinate system, the galactic longitude is 1 = 61°.89, the galactic latitude is b = −1°.04, and the distance to the star is 1095.77 pc [4].

In our previous work [13], time-dependent changes in spectral parameters and shape of profiles of Hα and other lines of the Balmer series were studied based on observations of the supergiant star HD 187982 in 2016-2018.

It has been shown that the profile of the Hα line changes over time with a quasi-period of 25-29 days [13].

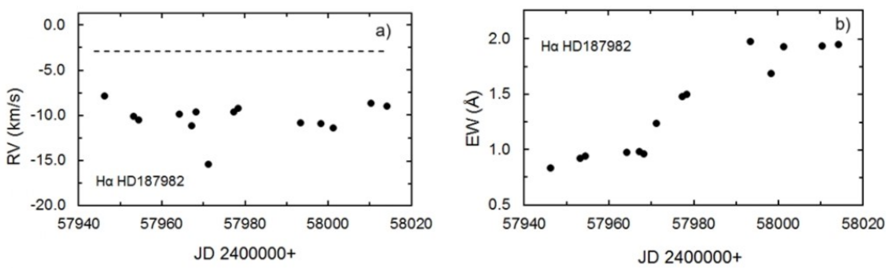

Fig. 2. (a). Radial velocity variations of the Hα line in 2017. For the date JD 2457971.340 a displacement with an amplitude of ∼7 km/s is observed. The dashed line indicates the velocity of mass center of the star. (b). Time variations of equivalent widths EW of the absorption line Hα in 2017

As can be seen from Figure 2 (a), on the date JD 2457971.340, a sudden shift of the Hα line to the violet side with a velocity of -12 km/s relative to the velocity of the mass center of the star, was detected, and then return to its initial position. On the same date, an increase in the equivalent width of the line was also observed, and this increase gradually continued until the end of the observation season, Figure 2 (b). Simultaneously with these events on the indicated date, until the end of the observation season, the strengthening of the emission components of the Hα line was observed, Figure 3 (a). These changes indicate that the stellar wind spreading in the stellar atmosphere is not stable and occurs in the form of mass ejections from the surface of the star. This leads to an increase in the amount of atoms contributing to the radiation lines and the equivalent width of those lines. The increase in the intensity of the emission components in the violet and red wings of the line indicates that the ejected mass is collected in the stellar environment and a part of it slowly disperses into the interstellar medium over time, while another part collects around the star, forming a gas disk, and a certain portion falls back onto the surface of the star.

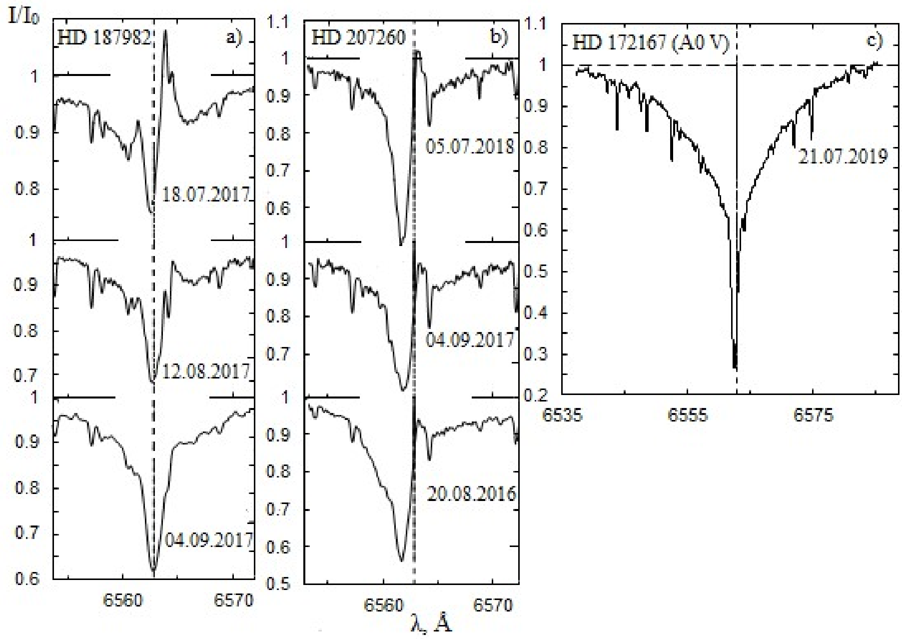

Fig. 3. Examples of the Hα line profile in the spectra of the stars HD 187982(a), HD 207260(b) and standard HD 172167(c).

The apparent magnitude of the supergiant star **vCep = HD207260 = HR8334** is V = 4.29 [3], the spectral class is A2 Ia. [8]. In the Galactic coordinate system, the galactic longitude is l = 102°.3, the galactic latitude is b = +5°.93 [21], the distance to the star is 2083 pc [26].

In [11], based on the comparative study of the emission and absorption components of the Hα line profiles observed on the basis of 25 spectra of the star HD 207260 in 2016 2019 , it was found that the value of the spectral parameters characterizing the shape, structure and profile of the Hα line profile exhibit variability. The Hα line profile is observed in the form of a full absorption profile and a normal P Cygni-type profile, figure 3 (b). As a result of the calculations, it was determined that the radial velocity of the absorption and emission components of the Hα line, as well as the equivalent width of the absorption component, varies with a quasi-period of 35-40 days. An increase in the absolute value of the radial velocity in the absorption component of the Hα line is observed with a decrease in the value equivalent width and that of the emission component. That is, this event occurs synchronously. Researches show that this variation occurs as a result of the pulsation of the star and the interaction between the stellar atmosphere and the circumstellar envelope.

Figure 3 presents the profile of the Hα line in the spectra of the supergiant stars HD 187982 (A1-A2 Iab), HD 207260 (A2 Iae) and the standard star HD 172167 = αLyr (A0 Va) of spectral class A. It is clearly seen from the profiles that in the standard star αLyr, the Hα line profile is observed in the form of a smooth full absorption profile. In supergiant stars, however, the Hα line profile is observed in various forms, including inverse and normal P Cygni types. The reason for the P Cygni-type profile is the result of the presence of an expanding gas envelope around the star, or the ejection of matter in the form of a strong stellar wind as in the case of B spectral type supergiant stars.

As seen, the shape and spectral parameters of the Hα line profile in the spectra of supergiant stars of spectral class A vary with time. However, since the effective temperature of these stars is relatively low, their variability scale is also smaller compared to that in B spectral class supergiant stars. Despite the fact that the Hα line is observed in the form of a P Cygni-type profile in the spectra of supergiant stars of spectral class A, the profile of the Hα line does not weaken to the level of a continuous spectrum in these stars. At the same time, P Cygni-type profile is not observed in other lines of the Balmer series of Hydrogen and in the Helium line formed in deeper layers.

5. VARIABILITY IN SUPERGIANT STARS OF SPECTRAL CLASS F

Supergiant stars of spectral class F have lower effective temperatures than supergiant stars of spectral class B and A.

The study of the F spectral class stars HD 7927 and HD 195593, along with the star HD 163506 located at high latitudes, is of significant importance for evolutionary theory. For this reason, this work presents a comparative analysis of the values of the parameters characterizing the profiles of the Hα line in the spectra of these stars and the changes in their profiles. The work primarily utilizes results mentioned in published articles based on research conducted in previous years.

The star φ Cas HD 7927 = HR 382 is one of the brightest hypergiant stars in our Galaxy. Spectral class is F0 Ia, apparent magnitude is $V = 4.98$ [25]. In Galactic coordinate system, the galactic longitude is $l = 127°$, the galactic latitude is $b = -4°$ [22]. The star is located at a distance of z = −150pc from the Galactic plane. The yellow hypergiant star φCas is a member of the NGC 457 open star cluster.

In [12], the spectral study of this star has been discussed. As a result of the research, it was found that there were no significant changes in the Hα line profiles and values of the equivalent width in the spectrum of the φCas star. No asymmetry has been observed in the Hα line profiles, proving the presence of the stellar wind and mass loss. However, variations in the radial velocity of the Hα

and H_β lines over time have been detected. In the H_β line, it has been determined that the value of the radial velocity defined according to the center of the profile is lower than the radial velocity according to the half-width of the line. This proves that the velocity of the stellar wind decreases in the upper layers of the atmosphere where these lines effectively form. Based on the results of the calculations conducted, the authors explained time-dependent variation of the equivalent width and radial velocity in the $H\alpha, H_\beta, H\gamma$, and etc. by the pulsation of the star.

The star 44 Cyg=HD 195593 = HR7847 has an apparent magnitude of $V = 6.2$, a spectral class of F5 Iab, and a galactic latitude of $b = -1^\circ.4$, a galactic longitude of $l = 76^\circ.4$. The star is located at a distance of z $= -34$pc from the Galactic plane [22].

In [10], the spectral study of the star HD 195593 is discussed. The profiles of the $H\alpha, H_\beta$, $H\gamma$ and H_δ lines observed in the spectrum of the star have been constructed, the value of the parameters characterizing these lines: the equivalent width (W_λ), the line depth (R_λ) and the halfwidth of the line ($\Delta\lambda(R/2)$) have been calculated. It has been shown that, as in star HD 7927, the $H\alpha$ line profile in the spectrum of the supergiant star HD 195593 does not change its shape significantly over time and is observed only in the form of a full absorbtion profile. However, the radial velocity of the $H\alpha$ line changes depending on time.

Among A and F spectral type stars, particularly significant are the post-AGB type stars located at high galactic latitudes. These stars are of great importance from the point of view of evolution, because according to evolutionary theory, supergiant stars should be young and massive, but according to the same theory, young and massive stars should be located close to the Galactic plane [1], for the first time in 1951, observed the existence of A and F type supergiant stars located at latitudes of 22° or higher far from the Galactic plane. Despite over 70 years having passed, the evolutionary stages of such stars have not yet been clearly explained. There are several hypotheses about the evolution of high-latitude supergiant stars:

1) A group of young, massive stars formed in the Galactic plane, later left the Galactic plane and moved away;

2) A group of old, low-mass stars with high luminosity at the end of evolution;

3) Stars formed through the evolution of binary systems.

Most of the results obtained from the observation prove the truth of the second hypothesis. The observation of A and F type supergiant stars in some old globular star clusters far away from the Galactic plane has already become the focus of many scientists. Note that such supergiants are sometimes called post-AGB (Asymptotic Giant Branch) stars.

Post-AGB stars are luminous objects of low to intermediate initial mass ($M_* \leq 8 - 9M_\odot$) in the final stage of evolution: they have completed their

Asymptotic Giant Branch (AGB) evolution with a period of intense mass loss $\left(10^{-7} - 10^{-4} M_{\odot} yr^{-1}\right)$. These stars evolve rapidly toward hotter effective temperatures while maintaining roughly constant luminosity, but they are not yet hot enough to ionize the circumstellar material and emerge as a Planetary Nebula (PN), before eventually cooling down to become a white dwarf (WD).

Post-AGB stars cover a wide range of effective temperatures, from extreme AGB stars just after the superwind [9], to objects like AFGL 618, which are on the verge of inonizing the circumstellar matter. The star HD 163506, which is a representative of this type of star, has been studied in this work.

The star 89 Her = V441 = HD 163506 (spectral class F2 Ibe, V = 5.46 mag) behaves like a pulsating variable star and is the strongest example of a UU Her type star [24].

It is located at a galactic latitude of $b = 23°19'$ and a longitude of $1 = 51°43'$ [20], at a distance of $z = 2.2$kpc from the Galactic plane. [16] presents the following results.

The Hα line contains one, two, or three absorption components, while the emission component is consistently observed in the red wing of the Hα line. The third most blue shifted component was observed by Sargent and Osmer [23] on July 17, 1962, and by the authors on August 26, 1975 with maximum radial velocities of -150 km/s and -180 km/s, respectively. The radial velocity of the first absorption component of the Hα line for these dates is several times lower and equals -10 km/s and -55 km/s, respectively. It can also be seen from Table 1. that the velocity of the emission component of the Hα line changes significantly. The radial velocity varies from $+56$ km/s on July 17, 1982 [16], to $+12$ km/s on August 26, 1975. The obtained spectra of the supergiant 89 Her of the Hα absorption line in the period 1955-2017, showed that the three components were observed only twice, on July 17, 1962 and August 26, 1975. The remaining observations indicate that the absorption profiles of the Hα line contain only one or two components. For the study, we focused exclusively on only the second component. At the same time, the values of the radial velocity of the emission component vary from $+60$ km/s for on April 30, 1966 [23] to $+7$ km/s on July 10, 2010. Figs. 3 and 4 illustrate, on the basis of the spectra obtained by us between 2000 and 2017, and by Gangi et al. [7] between 1993 and 2018, the changes over time in the values of the radial velocities Vr and terminal velocity of the Hα absorption component V^{∞}, and simultaneously, the equivalent widths W . It can be seen that the radial velocities, terminal velocity, and equivalent widths exhibit periodic changes with a period of approximately $P = 5000$ d. The studies have shown that, in addition to the short-period variations found earlier by various researchers, there are also long-period variations in the atmosphere of this star. It has been found that the radial velocity and equivalent width of the NaI D absorption line vary with a period of approximately 5000 days. This is interpreted as the motion of the binary system 89 Her around an invisible component. The orbital elements of the system were determined within the model of a spectral-binary system with a period of 5000 days. In figure 4, the Hα line profiles in the spectra of the F spectral class

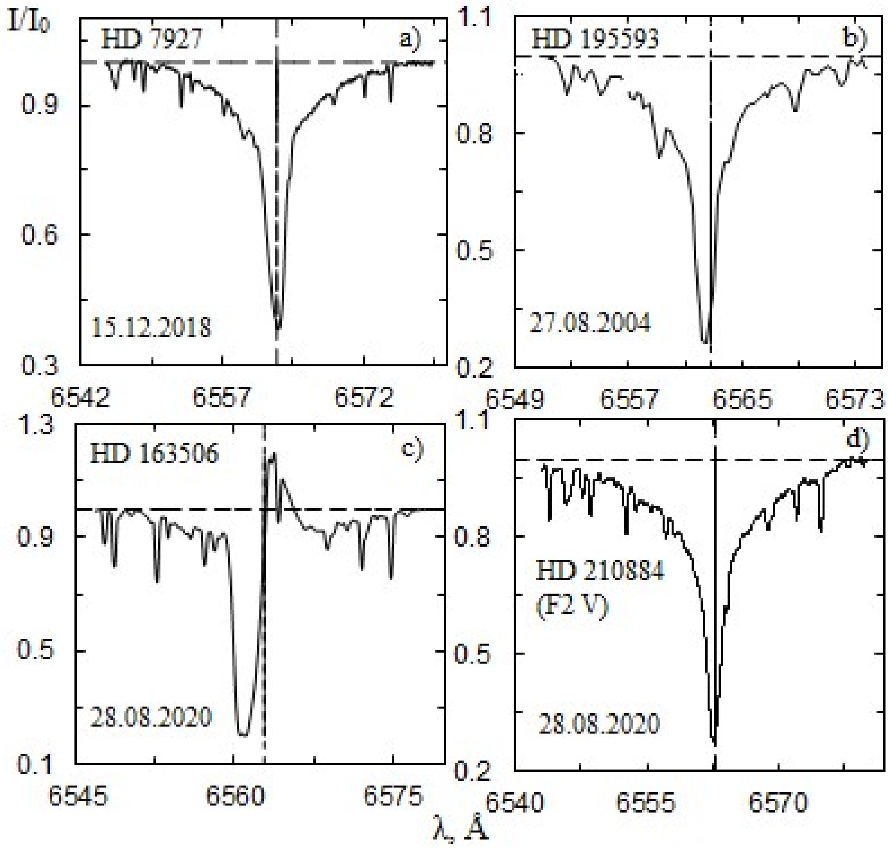

Fig. 4. Examples of the Hα line profile in the spectra of stars HD 195593(b), HD 7927(a), HD 163506(c) and the standard star HD 210884(d).

supergiant stars HD 7927 (F0 Ia) and HD 195593 (F5 Iab), the high-latitude Post AGB star HD 163506 (F2 Ibe), and the standard star HD 210884 (F2 V) are presented. It is clear from the examples that Hα line profile is observed in the form of a smooth full absorption profile in supergiant stars of spectral class F and in the main sequence star. In contrast, a P Cygni-type profile is observed in the high latitude Post AGB star HD 163506.

Summary. Apparently, in the spectrum of supergiant stars of spectral class F, the shape of the Hα line profile does not change depending on time and is observed in the form of an absorption profile. However, radial velocity of the Hα

line varies with time. The fact that the profile of the Hα line is observed only in absorption indicates that the stellar wind in these stars is much weaker compared to B and A type stars. Therefore, as the effective temperature of a supergiant star decreases, the scale of variability in its atmosphere also decreases. Nevertheless, in the high-latitude F spectral class Post AGB star HD 163506, the H α line profile is observed in various forms, and is of the P Cygni-type. As a result of research, it became clear that this variability is related not to physical processes occurring within the star, but rather to the binarity of the star.

6. CONCLUSIONS

At the conclusion of the conducted research, the following results were obtained:

1. In B spectral class supergiant stars, the Hα line profile can be observed in the following forms depending on the phase of the activity of the star (Figure 1):

a) full absorption profile;

b) normal P Cygni-type profile: absorption and on the red wing emission component;

c) inverse P Cygni-type profile: absorption and on the violet wing emission component;

d) weak emission component on both wings and absorption profile in the center;

e) full emission profile;

f) attenuation of the intensity of the absorption and emission components to the level of the continuous spectrum.

It is characteristic for hot supergiants of spectral class B to have a surrounding extensive envelope or disk. The conducted studies indicate that the higher the effective temperature of the star, the greater the scale of variability.

2. In the spectra of the A spectral class supergiant stars, the form the Hα line and spectral parameters change over time. However, the scale of this variability is weaker compared to B spectral class stars. The conducted studies indicate that the Hα line profile in A spectral class supergiant stars is observed in the form of a P Cygni-type profile; however, the profile does not show a decline to a continuous spectral level in these stars.

3. In the spectra of F spectral class supergiant stars, the form of the Hα line profile does not change over time and is observed in the form of a full absorption profile. However, the radial velocity of the Hα line varies with time.

4. In the high-latitude F spectral class supergiant HD 163506, the Hα line profile is observed in the form of P Cygni-type. This is explained by the fact

that the star being in its final evolutionary stage, that is, in the post-AGB stage. The 5000-days periodic variability in the profile of the Hα line is explained by the binarity of the star.

5. Our investigations have revealed that in the studied stars, from B spectral class supergiant stars to A and F spectral slass supergiant stars, which corresponds to a decrease in the effective temperature, the variability observed in the Hα line profile in the spectrum becomes less pronounced (excluding the case of the binarity of the star).

Also, as a result of non-stationary processes occurring in the stellar atmosphere with a decrease in the effective temperature of the star: the stellar wind, the loss of matter weakens, variability is less observed.

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