

**THIS ISSUE OF THE AZAJ CONTAINS PART OF ARTICLES THAT
WERE REPORTED AT THE INTERNATIONAL CONFERENCE
“ALIVE UNIVERSE: FROM PLANETS TO GALAXIES” WHICH WAS
HELD IN TUSI SHAMAKHY ASTROPHYSICAL OBSERVATORY ON
OCTOBER 12-14, 2022.**

**Greeting of SOC Chairman of conference, corr.member of
Azerbaijan National Academy of Sciences Namiq Dzhalilov**

Dear conference participants, ladies and gentlemen!

In these beautiful autumn days, October 12-14, 2022, an international conference “Alive Universe - from Planets to Galaxies” has begun its work at the Shamakhy Astrophysical Observatory. We have come together to exchange ideas and experiences related to scientific research, scientific results, and actual problems in astrophysics. At the opening ceremony of the international conference organized by the Shamakhy Astrophysical Observatory, I whole heartedly welcome all the participants and wish them a successful conference. I would like to thank each of you on my behalf and on behalf of the ShAO staff for taking the time to attend this conference in this difficult time.

Following the requirements of the pandemic period, our conference is held online. Of course, holding a conference in this format does not replace live communication. Nevertheless, holding a conference in this way has several advantages - there is no need to make serious financial expenses for tiresome trips. In this format, our main time will be spent listening to interesting reports and discussions. I express my gratitude to each participant of the conference who contributed to today's conference, members of the scientific and local organizing committee of the conference, and the staff of the observatory, and I also want to, especially thank prof. Nariman Ismayilov for his hard work in organizing the conference. The international conference program, which will last three days, includes exciting reports on Solar physics, the bodies of the Solar System, stars, and galaxies with active nuclei, covering modern and actual problems of astrophysics.

In modern times, scientific and technological progress gives a rapid impetus to the development of astrophysical science. Currently, valuable information obtained by various space missions not only enriches our knowledge of celestial bodies but also challenges new scientific research. From this point of view, I can say with confidence that the exchange of experience regarding both theoretical and experimental scientific innovations will open up great opportunities for joint research and the achievement of important scientific achievements in the future. This is one of the objectives of the conference. It is also commendable that, along with well-known scientists from reputable scientific organizations from different countries, young scientists and specialists took part in the conference and made

presentations on priority topics. I believe that the reports presented by leading experts in these fields at the conference will be useful for future scientific research of the participants, especially young scientists. As can be seen from the program, 14 plenary and 34 oral reports will be presented during this period.

I would like to note that the collection of abstracts of the reports presented at the conference is posted on the Internet, and at the same time is prepared for mass printing. Materials presented in the form of articles will be published in the Azerbaijan Astronomical Journal at the end of the conference. Detailed information about this will be given.

For your information, I want to inform you that, despite the long-term aggression of Armenia against our Republic, our state has always cared and cares about the development of astronomy to this day.

Greeting of LOC chairman of the conference, prof. Nariman Ismailov

Dear participants,

An international conference of this range was held in ShAO in 2019, before the Covid 19 pandemic. Despite the various difficulties of our time, the political situation in the region, various social cataclysms and wars, we astronomers are trying to do our favorite work - studying the physical properties of space bodies and in general, our universe.

There is a small team of astronomers in the ShAO, in recent years young people have come to work with us. As the experience of previous meetings shows, the conferences held in our observatory have a significant positive impact on the creativity of our team members. I know that young researchers and students from Russia also are going to join our conference. Therefore, I give great importance to holding such a meeting as our conference. I wish you all a successful conference, health and patience.

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UNVEILING THE ENVIRONMENTS OF EXTREME MASSIVE STARS

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Massive stars are powerful cosmic engines, enriching their environments with energy and mass throughout their lifetime. The post-main sequence evolution of massive stars comprises several distinct states, such as the luminous blue variables, blue supergiants, red supergiants, Wolf-Rayet stars, B[e] supergiants and yellow hypergiants, many of them connected with intense mass loss, embedding the stars in a dense environment. Here we present an overview of our studies for members in three states of evolved massive stars: B[e] supergiants, luminous blue variables, and yellow hypergiants. Combining high-quality spectral and imaging observations over large wavelength regions, we aim to unveil the physical properties and temporal evolution of the ejected material in these types of objects in order to gain insight into their mass loss and mass ejection histories. This information is also vital to constrain the location of these objects along the evolutionary path of massive stars.

Keywords: stars: massive – supergiants – circumstellar matter

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1. INTRODUCTION

Massive stars ($M_{\text{initial}} \geq 8M_{\odot}$) are powerful cosmic engines. Throughout their entire life they enrich their environment with huge amounts of energy and with chemically processed material, triggering the formation of next generations of stars and planets and driving the chemical evolution of their host galaxies. Despite the importance of massive stars for cosmic evolution, their aging process from the cradle up to their death in spectacular supernova explosions is most uncertain. This is due to the lack of reliable values of the total amount of mass the star loses during each epoch of its life.

The evolutionary path of massive stars comprises various extreme transition phases, in which the stars shed huge amounts of material into their environments, typically via episodic, sometimes even eruptive events. These objects are luminous supergiants or hypergiants populating the upper part of the Hertzsprung-Russell (HR) diagram and spreading from spectral type O to F or even later. Sophisticated stellar evolutionary models depend critically on the input physics. Consequently, any inaccuracy of the input parameters can result in large uncertainties of the evolutionary models [1]. As mass loss is one of the most crucial parameters for the evolution of massive stars, it is essential to understand the physical processes behind mass ejections and to properly quantify the amount they add to the total mass loss of the star within each of these evolutionary transition phases.

Some classes of evolved massive stars are particularly puzzling. These are the B[e] supergiants (B[e]SGs), the luminous blue variables (LBVs), and the yellow hypergiants (YHGs). Members of these groups are shown in Figure 1. While stars born with masses in the range $40 - 60 M_{\odot}$ can develop into LBVs directly after they have left the main sequence, lower mass stars ($30 - 40 M_{\odot}$) might reach this stage only in their late, post-red supergiant evolution [3]. In contrast, neither B[e]SGs nor YHGs are currently predicted by sophisticated stellar evolution models. In this work, we present the typical characteristics of these three classes of objects and a brief overview of our studies aimed to deepen our comprehension of their environments and their mass-ejection activity.

2. B[E] SUPERGIANTS

Stars classified as B[e]SGs are luminous B-type emission line stars. The best-known sample resides in the Magellanic Clouds, because these stars have precise luminosity values due to their well constrained distances. B[e]SGs in the Milky Way still face the issue of uncertain distances, although with the upcoming data release from the Gaia mission these uncertainties will hopefully decrease. The

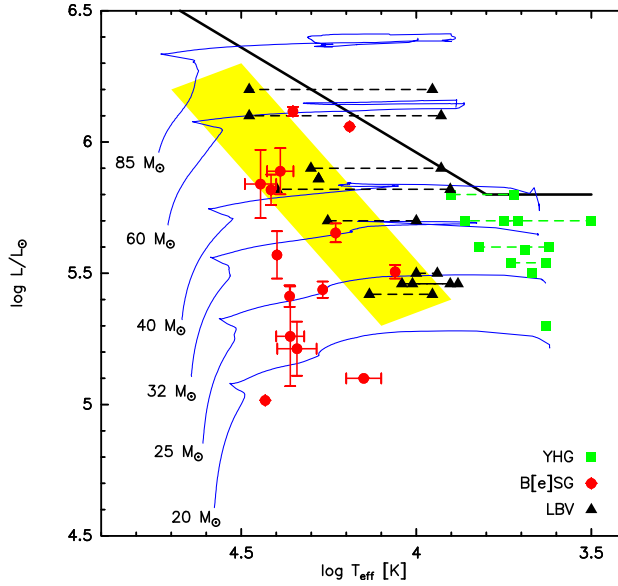


Fig. 1. HR diagram with the positions of examples of B[e]SGs, LBVs, and YHGs indicated. The thick black solid line marks the Humphreys-Davidson limit. The yellow colored domain marks the S Dor instability strip. The hot (quiescent) and cool ("outburst") positions of LBVs and YHGs are connected with dashes in the figure. Evolutionary tracks are for rotating stars at a metallicity $Z = 0.002$ and were taken from [2].

examples shown in Figure 1 are objects in the Magellanic Clouds, and their parameters have been summarized in [4] (Table 1).

The optical spectra of B[e]SGs display intense Balmer line emission along with emission from low-ionized metals such as Fe II as well as forbidden emission lines of [Fe II] and [O I]. The latter is an important classification characteristic as it is only seen in B[e]SGs, but not in other hot supergiant stars such as the LBVs.

The hybrid character of the spectra of B[e]SGs points towards an axis-symmetric wind from these stars, consisting of a hot and fast line-driven wind regime (typical for hot supergiants) in polar direction, traced by the broad P-Cygni profiles of high-ionized metals (e.g. Si IV) in ultraviolet (UV) spectra, and a much slower wind towards equatorial regions, traced by the low-ionized metal lines. A typical example is the star R 126 in the Large Magellanic Cloud (LMC). The P-Cygni absorption components in the UV indicate a polar wind with terminal velocity of about 1800 km s^{-1} , in contrast to the optical Fe II and [Fe II] lines that have full-width at half maximum values of just $20\text{-}30 \text{ km s}^{-1}$ suggesting a much slower wind outflow [5].

Furthermore, the spectral energy distribution (SED) of B[e]SGs displays intense infrared (IR) excess emission due to hot dust [6]. Spectroscopic observations of the dust emission carried out with the *Spitzer Space Telescope* [7] revealed that the dust is composed of silicates, often enriched with polycyclic aromatic hydrocarbons (PAHs). While amorphous silicates can be expected to form in the environments of massive stars due to their oxygen-rich surface composition throughout their evolution, the presence of often crystalline silicates as well as of carbon-based dust particles is surprising, because the chemical reactions needed for their formation can happen only in stable, long-lived environments. The most logical explanation for the detected dust composition is, therefore, that the dust is confined in a circumstellar disk.

A disk structure is also supported by the high intrinsic polarization values measured from B[e]SGs [8]. These measurements agree with the idea of a density contrast between equatorial and polar regions by a factor of 100-1000. Finally, the reconstruction of interferometric observations of the Galactic B[e]SG CPD-57 2847 taken at $10\,\mu\text{m}$ with the ESO instrument MIDI resulted in the first visualization of a dusty disk spreading from about 12 AU to about 130 AU [9].

2.1. Stellar environments of B[e] supergiants on small scales

The existence of stable dusty disks around B[e]SGs poses the question of their formation mechanism and their dynamics. Because dust emission has no clearly defined features that would allow to derive its kinematics, the disks need to be studied using information that can be obtained from the gas component. Assuming that the disks form from the material released from the stellar surface, then molecules should form closer to the star than the location of the inner edge of the dusty disk. And in fact, from some B[e]SG star environments emission from CO molecular bands arising in the *K*-band redwards of $2.293\,\mu\text{m}$ has been reported [10], as well as possible emission from TiO at optical wavelengths redwards of $6160\,\text{\AA}$ [11–13].

To analyze the molecular disks around B[e]SGs in the Milky Way and in the Local Group, we have acquired near-IR spectra in medium- and high-resolution during several observing runs that have been allocated to our projects since 2009. The instruments used were SINFONI ($R \sim 4500$) and CRIFES ($R \sim 50\,000$) at ESO, along with GNIRS ($R \sim 18\,000$), Phoenix ($R \sim 50\,000$), and IGRINS ($R \sim 45\,000$) offered at Gemini Observatory. These IR data were complemented with high-resolution ($R \sim 50\,000$) optical spectra, mostly collected with the FEROS spectrograph attached to the 2.2-m Max-Planck telescope at La Silla, Chile.

Our IR survey revealed several important results. Firstly, CO band emission has been detected in only about 50% of the B[e]SGs, and these stars seem to have evolved from progenitors with initial masses in the range of $20 - 40 M_{\odot}$ [4, 14]. Secondly, from our modeling of the CO emission, we found that the temperature of the molecular gas ($1900 - 3200$ K) is, in all cases, significantly lower than the CO dissociation temperature (~ 5000 K). Because the intensity of the emission increases with the column density of the molecular gas and its temperature, the observed emission bands trace the hottest and densest molecular regions. The absence of emission that could be associated with regions having a temperature close to the dissociation temperature thus implies a lack of molecules closer to the star. Therefore, we conclude that the disks are not continuous structures spreading from the stellar surface to far distances. Instead, the emitting region is found to be confined within a detached narrow molecular ring. Finally, in all CO spectra, we also identified emission from the isotope ^{13}CO in significant amounts [14, 15]. Such intense emission can only be explained with a substantial enrichment of the circumstellar gas in ^{13}C , and this enrichment mirrors the stellar surface composition at the time of the material release [16].

Besides CO, we also detected emission from SiO in the *L*-band spectra of so far four Galactic B[e]SGs [17]. SiO forms at considerably lower temperatures than CO, so that SiO emission traces regions farther out than CO. The high spectral resolution of the observations allowed us to determine the kinematic broadening of both the SiO bands and the CO bands, and the dynamics retrieved from these emission bands result in the conclusion that the molecular gas is revolving around the central object on (quasi-)Keplerian orbits. Further confirmation of Keplerian rotation of the disks of B[e]SGs came from interferometric observations providing spatially resolved emission of the Br γ line [18].

The optical spectra of B[e]SGs also contain emission lines formed in the circumstellar gas disk. These are the forbidden lines of [O I] $\lambda\lambda 5577, 6300, 6364$ [19, 20], and of [Ca II] $\lambda\lambda 7291, 7324$ [21]. Of these, the [O I] 5577 Å arises from a higher energy level that requires a hotter and denser environment to be sufficiently populated. The upper levels of the two [Ca II] lines can be populated either collisionally from the ground level or via emission from the Ca II IR triplet lines. Our general observation is that the [Ca II] lines and the [O I] 5577 Å line (if present in the spectrum) display very similar profile shapes and widths, suggesting close-by (or identical) formation regions that are clearly separated from those traced by the [O I] $\lambda\lambda 6300, 6364$ lines.

Using the velocity information that is preserved in the profiles of these optically thin emission lines and combining it with the velocity information derived from the molecular gas, it is possible to trace the circumstellar disks at various distances from the star. The striking result from such analyses is that each star is

surrounded by a unique set of multiple rings or arcs of atomic and molecular gas [13,22,23], regardless of whether the star is single or part of a binary system. Out of the currently known sample of 33 B[e]SGs (plus 25 candidates), only 7 (plus 3 candidates) are confirmed binary systems. Of these, four have been studied in detail, and for three of them the rings are circumbinary, and for one of them the rings are circumprimary [22], ruling out binary interaction as the most likely disk/ring formation mechanism.

2.2. Large-scale ejecta

Besides the disks and rings on small scales with sizes of several tens of AU, B[e]SGs can also be embedded in large-scale nebulae or ejecta. The most famous object is the Galactic star MWC 137, for which a ring nebula with a diameter of 70" along its major axis has been detected during an H α imaging survey of 25 northern Galactic B[e] stars [24]. Another B[e]SG included in that survey was MWC 349, which displays an H α shell. In total, 12 objects of that sample were found to have nebulae.

Starting from 2018, we have carried out a new H α imaging survey. We have complemented the original B[e] star sample with 9 northern and 23 southern objects and (re-)observed all targets using facilities of the Danish Telescope and of Gemini-South in Chile, and the Nordic Optical Telescope (NOT) and the Isaac Newton Telescope (INT) at La Palma. The aim of this survey is two-fold. On the one hand, we wish to identify more B[e] stars and B[e]SGs with nebulae or ejecta. The detection of circumstellar structures would provide clear proof for past mass ejection activity and would help placing the stars along the evolutionary path - post-red supergiants (post-RSGs) are more likely to be surrounded by expelled matter than pre-RSG objects. On the other hand, for stars with reported nebulosities we aim at detecting possible expansion or changes in nebular morphologies between the old data taken in 2001/2002 [24] and our new observations.

This imaging survey has been completed, but data analysis is still ongoing. However, we can report the detection of nebular features around $\sim 50\%$ of the objects. This is very similar to the fraction reported previously from the northern sample [24]. The structures seen are spherical shells, bipolar or multipolar lobes as well as spiral-arms, bows and rings, filaments and blobs. The catalog with the images is currently in preparation for publication. But results for selected objects have already been published [25], such as for the ring nebula of MWC 137, for which our analysis revealed no measurable expansion so far [26]. However, we resolved clearly more structures inside the ring and detected a new bow-shaped feature at farther distances [27].

Furthermore, we have initiated a spectroscopic follow-up of the objects with clear nebular structures. For this, we have utilized long-slit facilities at the NOT and at the 6-m telescope of the Special Astrophysical Observatory Russian Academy of Sciences (SAO RAS) in Russia to collect spectra across individual nebular features, as well as the scanning Fabry-Perot Interferometer (FPI, [28]) at SAO RAS to map the entire nebulae in selected emission lines. The focus is on $H\alpha$ and the lines of $[N II]$ and $[S II]$. The aim of the spectroscopic survey is to derive information on the nebular dynamics and the physical parameters, such as the electron density distribution across the nebula. This spectroscopic survey is still ongoing, and data could be secured so far for MWC 137, for which we found that generally, the northern nebular regions are approaching while the southern ones are receding with velocities, projected to the line of sight, of more than $\pm 30 \text{ km s}^{-1}$. But the velocities display a complex pattern across the nebular features and a stratification along the line of sight, suggesting that we observe a decrease in radial velocities from inside out that might point towards ballistic expansion. In addition, we found a very inhomogeneous electron density distribution across the entire nebula [27].

3. LUMINOUS BLUE VARIABLES

The second class of objects that we investigate are the LBVs. The classification of a star as LBV is based purely on historical grounds. These stars are luminous blue supergiants displaying specific variability in brightness and colors (see [29] for a recent review on LBVs). The most well-known variability is the so-called S Dor cycle, named after the LMC object S Doradus which has been the first object showing this phenomenon. During such a cycle, the star starts to brighten (1-2 mag) with a simultaneous reddening of its colors. At the same time, the spectral appearance changes from a hot OB-type supergiant in its quiescent stage to a cool AF-type supergiant (often referred to as "outburst"). This means that the star performs an excursion in the HR diagram from the hot to the cool side where it can reside for a significant amount of time (years to decades) before it returns to its original position and state. While its cause is still unclear, S Dor cycle activity is known only from LBVs based on which these objects can be distinguished from other evolved massive stars sharing the same location in the HR diagram. An interesting recent example of an LBV experiencing an S Dor cycle is the object RMC 40 in the Small Magellanic Cloud. It changed its spectral type from a late B/early A-type in 2002 to a late F-type supergiant in 2016 with a simultaneous brightening by more than 1 mag [30].

There is a second type of LBVs, the so-called giant eruption LBVs for which η Car is the prototype. During such eruptions, several solar masses of matter can be expelled.

In the absence of recorded S Dor cycles or a past giant eruption, it is not always easy to unambiguously classify an evolved massive star as LBV. LBVs in their hot, quiescent state share many characteristics with B[e]SGs. In particular, the optical spectra in the blue region of members of both groups are indistinguishable. Only red spectra covering the region of the [O I] and [Ca II] lines can tell the difference. Moreover, because not every B[e]SG displays CO band emission, the near-IR spectra of LBVs in quiescence and B[e]SGs can look identical as well [14]. A robust discrimination characteristic of the two groups is provided by their IR colors. We could show that LBVs and B[e]SGs clearly separate in the 2MASS $J - H$ versus $H - K$ and in the Wise $W1 - W2$ versus $W2 - W4$ color-color diagrams [4]. Moreover, a recent study of emission features in near-IR spectra of quiescent LBVs revealed intense emission of Mg II arising at 2.4047 and 2.4131 μm [31]. These lines are also present in the spectra of B[e]SGs, but with significantly lower intensity. We note, that the presence of intense Mg II lines is a weak classification criterion, but combined with the ones mentioned before, it supported the classification of some LBV candidates, e.g., the Galactic object MN 112 [31]. This object has recently been confirmed as a dormant LBV [32] due to its inactivity for more than a century.

3.1. Nebulae of LBVs

Many LBVs are surrounded by large-scale nebulae detected on optical images taken in $H\alpha$ or in the nebular lines of [N II]. The high mass loss of LBVs in relation with the change in wind conditions during an S Dor cycle leads to wind-wind interaction and consequently to circumstellar structures of swept-up wind material. On the other hand, giant eruptions result in large-scale ejecta. A systematic survey of the nebular structures revealed that their morphology encompasses ring-like shells or triple-ring systems, while about 50% of the LBV nebulae have bipolar lobes [33].

Based on IR archival data retrieved with the *Spitzer Space Telescope*, a great number of IR nebulae have been discovered that host massive stars, many of which have been suggested to be LBV candidates (e.g., [34]). We have already imaged two of them in $H\alpha$ to search for optical counterparts of their IR nebulae. These are the Galactic objects MN 83 and MN 112. Only MN 112 shows large-scale diffuse emission, whereas no emission has been detected from the environment of MN 83 [31]. However, the extinction we derived towards the latter object is with $A_V > 20$ mag much too high to be able to detect any optical signal.

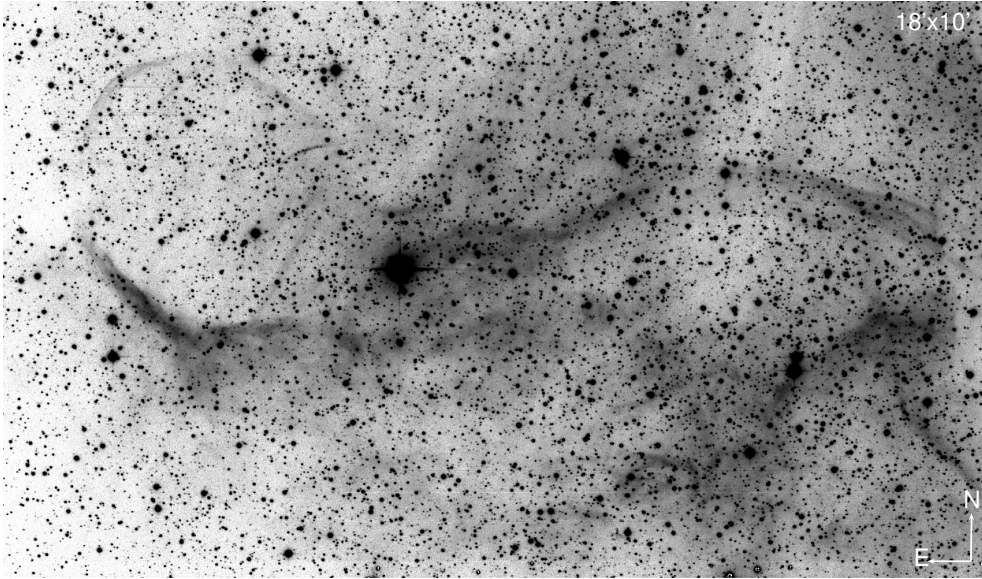


Fig. 2. $H\alpha$ image of the large-scale bipolar nebula of the LBV candidate MWC 314 taken with the INT. The total extent in east-west direction corresponds to 13.2 pc.

Apart from searching for optical counterparts, we also started a detailed investigation of the large-scale bipolar nebula of the Galactic object MWC 314 (Figure 2). It has the status of an LBV candidate (e.g., [35] and references therein), and its nebula has a total extent of 13.2 pc considering a distance of 3 kpc [24]. No measurable expansion of the nebular structures could be detected when comparing $H\alpha$ images taken 18 years apart [25]. We have mapped the kinematics of the nebula in $H\alpha$ using the FPI at SAO in its scanning mode. The analysis of these observations is still ongoing, but first estimates suggest that the southern nebular domains are approaching and the northern ones are receding with maximum values of $\pm 40 \text{ km s}^{-1}$ [25]. This low velocity explains the non-detection of an expansion on the images so far. Follow-up observations with the FPI in the [S II] lines to retrieve the electron density distribution across the nebula are already planned. Furthermore, the surrounding of the nebula is being observed with APEX in the lines of CO(2-1), $^{13}\text{CO}(2-1)$, and $\text{C}^{18}\text{O}(2-1)$. These observations will provide physical parameters such as kinematics, density and temperature, in both the shocked gas at the rims of the bipolar nebula and in the ambient medium, needed to constrain the mass ejection history and the interaction of the ejecta with the ambient interstellar medium.

4. YELLOW HYPERGIANTS

Finally we turn to the YHGs. This class encompasses objects with temperatures of $T_{\text{eff}} = 4000 - 7000$ K and luminosities of $\log L/L_{\odot} = 5.4 - 5.8$. This rather narrow luminosity interval translates into a range of initial masses of $20 - 40 M_{\odot}$ for the progenitor stars. YHGs were proposed to be in their post-RSG evolutionary phase [36]. As such, they have lost a considerable amount of mass during the previous RSG phase. Due to this mass loss, the luminosity over mass ratio of YHGs can easily exceed the critical value of $\log(L_*/M_*) = 4$ (in solar units), above which the strongly inflated envelopes become unstable.

The light curves of YHGs display cyclic, but not strictly periodic variability, which seems to be related to (radial) pulsation activity. Small perturbations within the envelope can develop velocity amplitudes within the outer atmospheric layers exceeding the escape velocity and hence leading to enhanced mass loss or to mass ejections in the form of outbursts. As a result, YHGs can be surrounded by multiple shells of gas and dust. An impressive example is the southern object IRAS 17163-3907. It must have experienced at least three outbursts during the past 100 yr resulting in three distinct dust shells [37]. The appearance of IRAS 17163-3907 and its surrounding dust shells on IR images earned it the nickname ‘Fried Egg Nebula’ [38]. An outburst is usually accompanied by an apparent drop in temperature so that the star shifts to a cooler (redder) position in the HR diagram. As soon as the ejected material expanded and diluted, the star appears back at its previous position. These excursions in the HR diagram are marked in Figure 1 by the connecting lines between the original (warm) and the outburst (cool) locations.

The dust formed from the ejected matter can be traced by its IR excess emission in the SED. An intense IR excess emission has been detected from the Fried Egg Nebula [37] whereas less pronounced emission is seen from three YHGs in the LMC [39]. Nevertheless, the circumstellar matter of the LMC objects is warm and dense enough for molecules to form in substantial amounts, but intense molecular emission from CO has only been detected from two objects [14].

In the northern sky only four Galactic YHGs are currently known, and we spectroscopically monitor them since 2010 with the Perek 2-m telescope at Ondřejov Observatory. Of these, ρ Cas is famous for its outburst activity [40]. The most recent one took place in 2013, during which the brightness decreased by 0.6 mag and we noted a simultaneous drop of the star’s temperature by 3000 K. Furthermore, the spectral lines clearly displayed an enhanced pulsation activity in the star’s atmosphere prior to the outburst [41]. This has been the fourth recorded event during the past 80 yr. Although it turned out to be less pronounced than its progenitors [42], the time interval between the outbursts steadily decreases, sug-

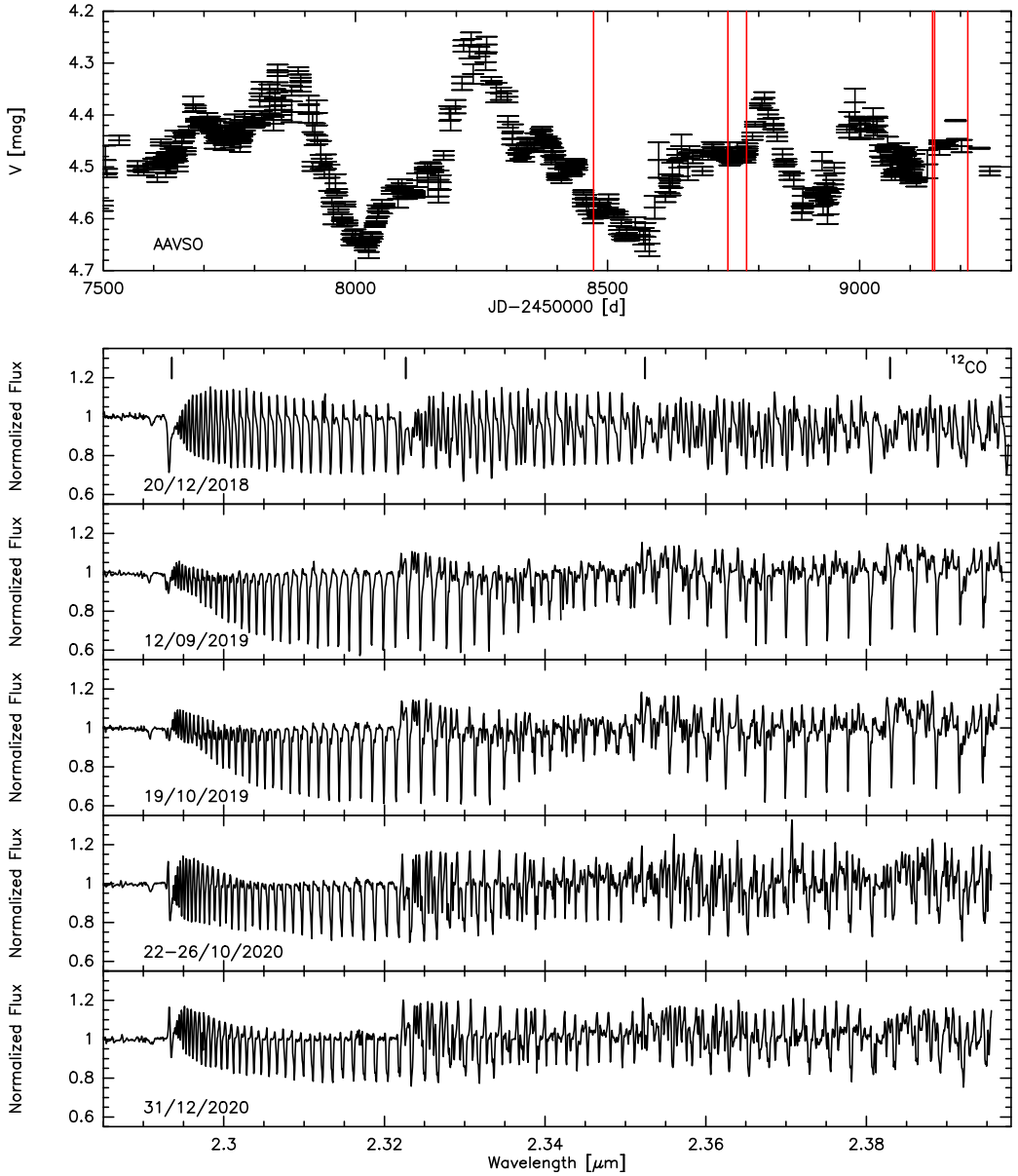


Fig. 3. Top: Light curve of ρ Cas in the years 1966-2021 taken from AAVSO. Red lines mark the dates of the IR observations. **Bottom:** K -band spectra of ρ Cas covering the CO band region at different epochs. The spectra have been obtained with GNIRS at GEMINI-North with a resolution of $R \sim 18\,000$ (IDs: GN-2018B-Q-410, GN-2019B-Q-405, GN-2020B-Q-408).

gesting that the star still has a rather unstable envelope and more mass ejection episodes might be expected in the near future.

So far, it seems that only the eruption that took place in 1946 ejected sufficient material to create detectable dust emission. Since then, this matter is expanding and diluting [43]. However, our careful analysis of the optical spectra revealed static emission in the low-excitation neutral iron line at 6359 Å as well as in the line of [CaII] at 7324 Å [41]. Furthermore, emission from CO has been detected [44], especially during phases of maximum brightness, which correspond to phases of highest temperature. In other phases, the circumstellar emission component is polluted with intense photospheric CO absorption.

We have initiated a *K*-band monitoring campaign with GNIRS at Gemini-North (PI: M.L. Arias) to investigate the physical conditions within the CO emitting circumstellar envelope. So far, we could collect five sets of spectra distributed from December 2018 to December 2020. These are shown in the lower panels of Figure 3. The CO bands display clear variability and changes between emission and absorption. The dates of the observations are marked in the light curve that is shown in the top panel of Figure 3. The photometric data cover the period from 2016-2021 and have been taken from the AAVSO database¹⁾. Due to the highly irregular light curve variability, it is difficult to predict the next epoch with maximum brightness, and so far we have been unlucky and our *K*-band observations fall all on dates with intermediate brightness. Nevertheless, the analysis of the CO band spectra is work in progress, and we expect to gain from them deeper comprehension about the dynamics and physical conditions within the outermost photospheric layers of this fascinating object.

5. CONCLUSIONS

We have presented an overview of our research related to massive stars in three distinct states: B[e]SGs, LBVs, and YHG, representative for classes of extreme massive stars. Members of these classes display outburst activities and/or phases of enhanced non-spherical mass loss, and the released material can be traced both on small (circumstellar rings and disks with extents of a few dozens of AU) as well as on large scales (with sizes of several pc) around the objects. Utilizing high-quality multi-wavelength spectroscopic and imaging data we were able to constrain physical properties of the ejected matter, such as the dynamics, temperature and density distributions in diverse physical states (atomic and molecular gas, and dust).

As a final remark, we wish to address the fact that B[e]SGs, LBVs, and YHG populate a domain in the HR diagram in which stars are generally unstable to non-adiabatic radial pulsations. Such pulsations can develop the right power to

¹⁾ <https://www.aavso.org/>

drive mass loss [45] and even trigger mass eruptions [46]. Theoretical investigations of such pulsation instabilities for our extreme massive stars are work in progress. In case these pulsations turn out to be capable of causing mass loss in amounts similar to the observed values, these instabilities might become the key "missing-link" for understanding the physics behind outbursts and mass ejection events from evolved massive stars. The results from such investigations might then contribute significant, complementary mass-loss rates as input into sophisticated stellar evolution models. These mass-loss rates are crucial for reliable predictions of the final fate of massive stars.

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EXOPLANETS AND POPULATION APPROACH IN PLANETARY DYNAMOS

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Observation of exoplanet systems opens new perspectives in various branches of astrophysics. Here we suggest how to use in future the data concerning the magnetic field of exoplanets to clarify the place of geodynamo among other kinds of spherical dynamos.

Keywords: Exoplanets – Geodynamo – Planetary dynamo.

1. INTRODUCTION

Successful observations of exoplanetary systems open a new and very important page in contemporary astronomy. Available sample of more or less firmly identified exoplanets with estimated mass, orbital radius, orbital period and other relevant integral quantities is already quite large. It looks reasonable now to think how this information can be used to clarify various more general astronomical and paleontological problems. An example of such investigation is presented in a recent paper [1] which demonstrates how data concerning exoplanets and magnetic activity of their host stars allow us to reject the hypothesis that the 11-year solar activity cycle is driven by the effect of Jupiter (corresponding orbital period is also 11 year). The aim of this short note is to suggest one more direction of similar development, i.e. clarification of the place of geodynamo among other dynamos.

2. GEODYNAMO AMONG ANOTHER ASTROPHYSICAL AND PLANETARY DYNAMOS

The Earth's magnetic field is believed to be driven by more or less the same physical process as, say, solar magnetic field, i.e. by a dynamo driven by differential rotation in convective shell and mirror asymmetry of convection. The

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temporal behavior of the Earth's magnetic field is however quite different from that of the solar magnetic field (e.g. [2]). Solar magnetic field oscillates with a period about 22 years, which leads to 11-year oscillations in sunspot numbers. In contrast, the Earth's magnetic field remains almost stationary in times comparable with the human civilisation age and demonstrates in a geological timescale a sequence of abrupt magnetic field inversions which occur in randomly distributed instants. Both types of behaviors can be reproduced in the framework of suitable dynamo models which are however quite different from one another. In particular, a more or less realistic solar dynamo model can be formulated in terms of a mean-field approach with a dynamo saturation presented in terms of magnetic helicity balance while differential rotation is only moderately modified. In contrast, a realistic simulation of geodynamo requires microscopic direct numerical simulations and includes substantial modification of differential rotation in the outer core of the Earth.

Contemporary geodynamo models are quite complicated. Relevant direct numerical simulations became realistic in 90-th of the previous century only. Qualitative analysis of the models is a problematic undertaking. At the previous stage of research, in early 1990th expertis is geodynamo developed a number of less sophisticated numerical models which allow a qualitative analysis which isolated a number of various regimes with various scalings of relevant parameters, say, magnetic and rotational moments (see for review e.g. [3]). Such scalings was discussed in planetary dynamo studies at the early stages of research (e.g. [4]) however do not attract attention in cointemporary models. It is impossible to get such scalings from observations inside solar systems because the Earth seems to be an isolated example here in respect to its magnetic properties and comparison with, say, Jupiter's satellites seems to be of limited importance.

3. POPULATION APPROACH

It looks plausible that observations of magnetic properties for exoplanets could help in understanding of the place which occupies the Earth among various more or less similar planets and understand the place of geodynamo among other regimes of spherical dynamos. One can refer to this approach as a population approach in planetary dynamos. This approach can be compared with similar approaches in stellar activity studies. A more or less rich stellar sample with known magnetic activity was obtained here in 1990th in the framework of so-called H-K project [4] what allow to obtain a scaling between stellar rotational moment J and corresponding magnetic moment M which scale as follows [5]:

$$M \sim \sqrt{J}. \quad (1)$$

Further studies yields in isolation of other stellar populations where scaling (1) is saturated (e.g. [6]). Both scalings admit a qualitative explanation in terms of spherical dynamos.

Our point is that obtaining similar scalings for exoplanet magnetic fields may be an important step to understand the place of geodynamo among other spherical dynamos and isolate particular regimes of planetary dynamos.

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CHANGING LOOKS OF THE NUCLEUS OF THE SEYFERT GALAXY NGC 1566 COMPARED WITH OTHER CHANGING-LOOK AGNS

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We present results of a long-term optical, UV and X-ray study of variability of the nearby changing-look (CL) Seyfert NGC 1566 which was observed with the *Swift* Observatory from 2007 to 2020. We summarize our previously published spectroscopic and photometric results and present new observations. We reported on the alteration in the spectral type of NGC 1566 in 2018 (Paper I). Moreover, we focused on the exceptional postmaximum behavior after 2018 July, when all bands dropped with some fluctuations (Paper II). We observed four significant re-brightenings in the post-maximum period. We have found differences in X-ray and UV/Optical variability. The $L_{\text{UV}}/L_{\text{X}}$ ratio was decreased during 2018-2020. New post-maximum spectra covering the period 2018 November 31 to 2019 September 23 show dramatic changes compared to 2018 August 2, with fading of the broad lines and [Fe X] $\lambda 6374$ until 2019 March (REF2). Effectively, two changing look (CL) states were observed for this object: changing to type 1.2 and then returning to the low state as a type 1.8 Sy. We suggest that the changes are mostly due to fluctuations in the energy generation.

Variability properties of NGC1566 are compared with our results for other CL active galactic nuclei (AGNs).

Keywords: galaxies – active – X-ray – UV -optical

1. INTRODUCTION

The NGC1566 was discovered in 1826 by James Dunlop but intensive investigations of it were triggered after discovery of the Seyfert phenomenon in this object in 1956 [1, 2] which was confirmed in 1962 [3]. These investigations of

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NGC 1566 have long history (see e.g. references at [4–7]). The NGC1566 is one of the brightest and nearest galaxies with AGN in the South Hemisphere. This object is also nearest Changing Look (CL) AGN [5, 8]. It is one of two (also NGC3516) firstly discovered (soon after discovery of variability of AGNs in continuum by [9]) CL AGNs [10, 11], however this designation came into common use only in the past decade. The CL AGNs are active nuclei of galaxies which undergo dramatic variability of the emission line profiles and classification type, which can change from type 1 (showing both broad and narrow lines) to type 1.9 (where the broad lines almost disappear) or vice versa within a short time interval (typically a few months). This dramatic spectral change in the NGC1566 was correlated with optical variability [12]. Due to the optical monitoring since 1954 about 20 years (first published optical light curve) the object was in bright state during few years till 1962 then it shortly dropped down and shortly moved up to the maximal level at 1963. Such re-brightenings after strong outbursts and CLs probably are typical property of CL AGNs and were fixed in several other ones of them [8, 13, 14]. After 1963 the NGC 1566 was mostly in low state what was a reason to note it as a “weak Seyfert”, however occasional recurrent brightenings of H and optical continuum (not as strong as the outbursts of 1962 and 2018) were observed in the period 1982-1991 [15–19].

The first multi-wavelength (X-ray, UV, optical and IR), UV/optical emission lines investigations of the variability of NGC 1566, as well as the first IR reverberation mapping, were published by [19]. It seems that found IR time delays ($\sim$ several months) was significantly overestimated (see discussion of that in Paper II) and more realistic value for the IR time delay is less than 20 days [20].

NGC 1566 is a galaxy with a very well-studied variable active nucleus, however the spectral and photometric data have big gaps. The most intensive multiwave photometric observations were done during past years after discovery of a new reawakening [7, 21–24] and new CL phase (see [5, 6, 8] and references there). During these few years 2 CLs were discovered in the object: first happened in 2018 when object changed from Sy1.9 to Sy1.2 ([5] = Paper I) and second one in 2019 when object changed back to the low state ([6] = Paper II). This was happened about 60 years after previous CLs [11, 12], but, taking into account too long gaps in the spectral coverage, some other possible CLs could well have been missed. Meanwhile it is entirely possible that CLs of NGC 1566 such as in 1962 and 2018 (see [8] and Paper I) are recurrent events happening on time-scales of several decades.

The spectral transition during the CL events (during 2018-2020) of NGC 1566 not only manifested in dramatic intensity changes of the broad emission lines but also in significant strengthening of the UV Balmer continuum and high-ionisation coronal lines such as [FeX] λ 6374 (Papers I – II). Such variability of coronal lines

was observed also in some other CL AGNs: NGC 4151 [28–32] and NGC 3516 (in preparation). The H/H ratio (for broad components) changed from ~ 2.6 in high state to ~ 6.2 in the low state (see details in Paper II). The variability of the Balmer decrements is a typical property of a CL AGN (see e.g.) [28–32]. After maximum was reached in July 2018, fluxes in all bands declined, with some re-brightenings Event 1 in December 2018 [33], Event 2 in the end of May 2019 [34], Event 3 in August 2019 (Paper II) and Event 4 in May 2020 [34]. This decline was accompanied by a decrease of the $L_{\text{uv}}/L_{\text{x}}$ ratio (Paper II). The estimated Edington ratios were about 0.055% for minimum in 2014 and 2.8% for maximum in 2018.

In [36] and in this paper we present results of the continuation of our multi-wavelength (optical, UV and X-ray) monitoring of NGC 1566 using the data obtained with *Neil Gehrels Swift Observatory* over the period 2007-2020 combined them with published before results in Paper I and Paper II, which include also spectral data obtained with the South African Astronomical Observatory 1.9-m telescope from 2018 August to 2019 September and photometry with the MASTER Global Robotic Network from 2014 to 2020 December. We compare these results with the revealed before facts for other CL AGNs to fix some common properties which can eventually help us to understand better physics of the CL phenomenon.

2. OBSERVATIONAL DATA AND RESULTS

NGC 1566 has been regularly observed by the *Neil Gehrels Swift Observatory* [37] for many years, starting in late 2007 and the results of the monitoring were published mostly by [5–7, 22, 23, 34, 35, 38]. In the present paper we have added to the analysis the most recent data (both from the XRT and UVOT telescopes), using the same methods as in Paper I and II, but we uniformly re-reduced all available data to ensure usage of the most recent versions of the software and calibration files. No significant variations were found between different versions of the reduced X-ray data. Meanwhile last update of the UVOT calibrations can give the difference up to almost 0.3 mag (see details here <http://www.swift.ac.uk/analysis/uvot/>). The new data include 28 dates for interval between 5th December 2019 and 20th October 2020. The data allows us to trace better the long and short term evolution of NGC 1566’s behaviour including post maximum period.

We summarize a study of optical, UV and X-ray light curves of the nearby changing look active galactic nucleus in the galaxy NGC 1566 obtained with the Neil Gehrels Swift Observatory and the MASTER Global Robotic Network over the period 2007-2019 published before in Paper II and new data for the years 2019-

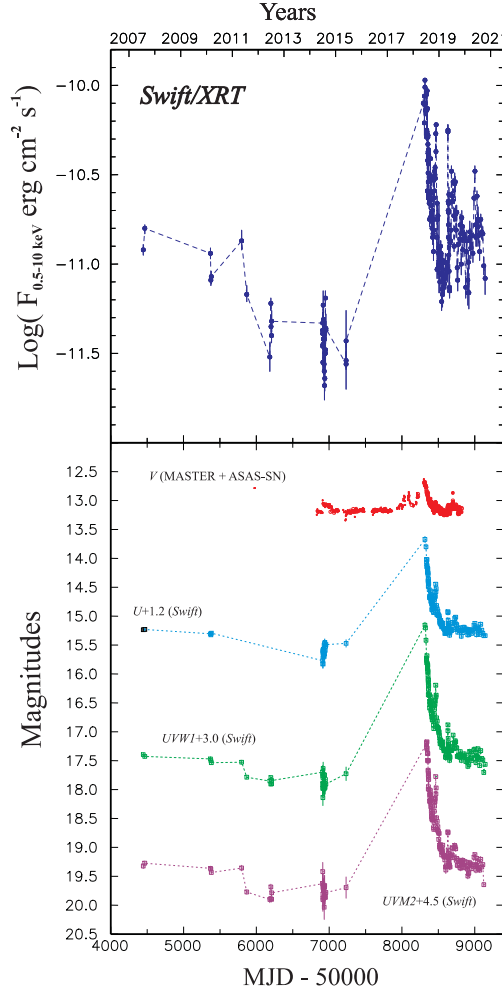


Fig. 1. Multi-wavelength observations of NGC 1566 spanning the period 2007 December 11 to 2020 October 21. *Top panel:* The *Swift*/XRT 0.5–10 keV X-ray flux (in $\text{erg cm}^{-2} \text{ s}^{-1}$). *Bottom panel:* Optical–UV photometric observations. The large open circles represent MASTER unfiltered optical photometry reduced to the *V* system while the points are *V* ASAS-SN (nightly means) reduced to the *Swift* *V* system. The filled circles show MASTER *V*-band photometry. The small open boxes correspond to the *U*, *UVW1* and *UVM2* *Swift*/UVOT photometry.

2020 (see Figures 1– 2). The MASTER observations and results of the ASAS-SN (All-Sky Automated Survey for Supernovae) [39–41] *V*-band magnitudes reduced to the *V* *Swift*/UVOT system are presented in Figures 1 and 2 (till 2019 December 5) as were published before in Paper II. The light curves in the optical *UBV*, *UVW1*, *UVM2* and X-ray bands are well correlated as can be clearly seen in Figure 1 (bottom panel) for 2007–2020 and Figure 2 (bottom panel) for 2018–2020.

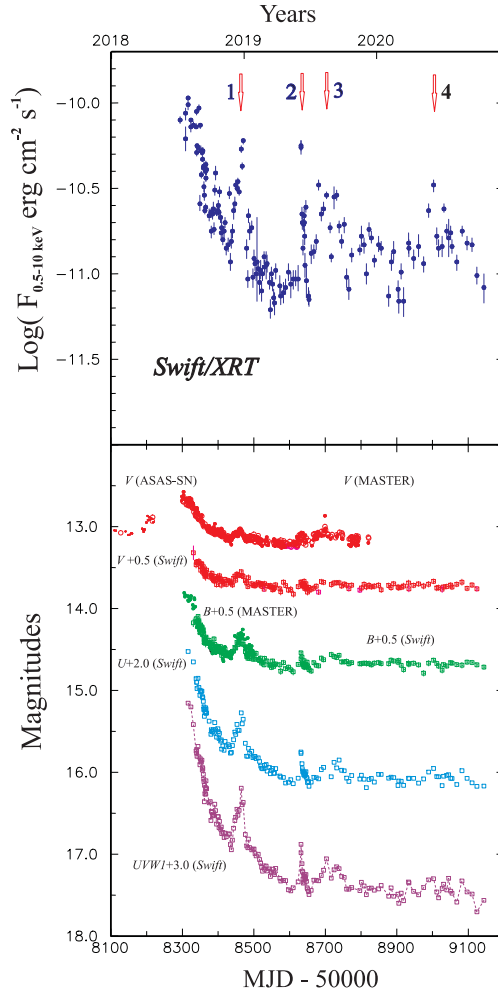


Fig. 2. Multi-wavelength observations of NGC 1566 shown just for 2018–2020. *Top panel:* The *Swift*/XRT 0.5–10 keV X-ray flux (in $\text{erg cm}^{-2} \text{s}^{-1}$). *Bottom panel:* The large open circles represent MASTER unfiltered optical photometry reduced to the *V* system while the points are *V*-band ASAS-SN (nightly means) reduced to the *Swift* *V* system. The filled circles show MASTER *BV* photometry results. The open boxes correspond to the *UVW1* and *UBV* data obtained by *Swift*. The arrows indicate the Events 1, 2, 3 and 4 (see text for the details).

The light curves till 2019 December 5 were discussed in details in the Paper II. There were considered 3 re-brightening Events 1–3. Here in new data we see one more Event 4 (2020 August), which was firstly noted by [35]. The Event 3 was most significant and it happened about one year after the main maxim but was seen mostly from the MASTER data since its maximum was missed by *Swift* observations. We didn't see any clear signature of periodicity of these events as

it was suspected by [35]. The event 2 and 3 were very fast and short and so some other such re-brightening could well have been missed. In the Paper II was firstly found a decrease of the $L_{\text{uv}}/L_{\text{x}}$ ratio at post-maxim decrease. Here that is seen more clear from the Figures 1 and 2: the X-ray flux was in mean grow up after the minimum in 2019 March but UV brightness had tendency to move down in mean. This effect for UV bands is significant, it is smaller for U and not seen for BV variations.

3. DISCUSSION

The properties of multi-wavelength variability of NGC 1566 is not unusual for a CL AGNs. The dramatic changes of factors few tens in the X-ray flux (see Paper I) along with correlated variations at UV and optical wavelengths is a typical property of CL AGNs. However, such a strong correlation of the X-ray and UV/Opt is not common among AGNs (see e.g.) [42, 43], there are exceptions for some other CL AGNs, viz. NGC 2617, NGC 4151, NGC 3516, and NGC 5548 (see e.g.) [13, 39, 44–46]. The UV/Optical variations are typically delayed relative to the X-ray fluctuations by about a few days. These delays correlate with the masses of the supermassive black holes (SMBH). From these results we can conclude that the variability across several wavebands in CL AGNs (spanning from X-rays to the UV/Optical) is driven by variable illumination of the accretion disc (AD) by soft X-rays. We have to determine the most significant common features of such variability. That can help us to find the most likely explanations for the CL phenomenon (see e.g. discussion and references in Papers I–II and below). There are several different possibilities that have been considered: variable obscuration, AD flares, tidal disruption events (TDEs), and supernova event (see e.g. more detailed discussion and references in Papers I – II and below) . In case of NGC 1566 the duration of the rise and decay times for the main brightening in 2018 was about the same (~ 9 months) and much longer than the recurrent brightenings (with lower amplitude) described by [16] (~ 20 days). A similar dramatic brightening was observed previously in 1962, with re-brightening about one year later [47]. Such re-brightenings soon after the main maximum may be common in the variability of CL AGNs. Whilst there is good evidence for obscuration in many of AGNs (see [30–32] and references therein), it is not the dominant variability mechanism. It is difficult to explain the dramatic rise of the X-ray and UV/optical flux by some variable obscuration. The main problem with the obscuration theory is that it would predict much longer time scales for the spectral changes than what is observed in CL AGNs (see e.g.) [48]. For NGC 1566 we expect timescales of more than a few years for a CL event in the obscuration scenario, which is much longer than what is observed. It does not exclude the

possibility of intervening clouds causing variable obscuration, but seems to exclude that as a dominant explanation for the CL mechanism. The more obvious explanation of this, and AGN variability in general, is that it is due to variation of the intrinsic energy-generation rate. These two leading possibilities – intrinsic variability and variable obscuration – do not need to be mutually exclusive. For example, a dramatic change in the energy generation could cause the sublimation of dust in clouds near the central source energy source [13,49]. If such sublimation occurs in some clouds along the line of sight, then the rise in the UV can be explained in part with the change in obscuration. The typical time for the recovery of dust clouds after the UV flux has abated can be several years [13,49,50], but it could be less for NGC 1566 if we take into account the significantly smaller mass of the SMBH compared with NGC 4151. So we could see some increase in obscuration during the time when the energy generation is falling. We do see some differences in variability in different wavelengths after Mar. 2019, which can be explained by variable obscuration since it must be most significant for the UV and less in optical bands, and with hardly any noticeable effect for X-ray flux. Similar decrease in UV/X-ray ratio at post maximum deeming was found by us for NGC 2617 and NGC 3516 (in preparation). That is in agreement with absorbing column variations (more than of a factor of 3 from during 2015 – 2018) found in the NGC 1566 by [35] (however the estimates are model-dependent and the variations can be due to dust sublimation). After the maximum in 2018 the estimated (by Jana et al.) hydrogen column density had tendency to grow up in correlation with variations of $H\alpha/H\beta$ ratio (found in Paper II). Meanwhile there are some other possible explanations for these variations and difference in X-ray and UV variability. For example, the strong change in the $L_{\text{uv}}/L_{\text{x}}$ flux ratio observed in the NGC 1566 after Mar. 2019 (see Paper II) can be connected with changing of the height of the X-ray source that can reduce the amount of UV/optical emission produced by reprocessing in the AD (see e.g.) [51]. Also a transition in accretion mode might explain the observed differences in properties of variability in high and low states (see e.g.) [52]. The most intriguing question is what the mechanism would be for such dramatic switching on or off for the energy generation of CL AGNs. This has been explored in some firsts reports on CL events as well as in recent papers [14, 53–55]. See discussion of the possible mechanisms for CLs in [7, 52, 55–59] and Paper II. The TDE and supernova explanations can be rejected given the differences between expected and observed time scales for such events, as well as their spectral properties and evolution. An alternative theory proposes the tidal stripping of stars [60,61], which could lead to more frequent and recurrent events [62] if these stars have bound orbits similar to some known objects near the SMBH in the Milky Way. However, the mechanism has not been investigated in sufficient details yet. At present we are far from understanding

the CL phenomenon, and many questions remain still.

4. CONCLUSIONS

We summarize a study of the NGC 1566 published before in Papers I–II with new optical, UV and X-ray light curves with the Neil Gehrels Swift Observatory over the period 2007-2020 taking into account most recent versions of the software and calibration files. We found some common properties in variability of the NGC 1566 with other CL AGNs which can be useful for the future models intended to explain the CL phenomenon:

1. CLs are recurrent events [5, 6, 46, 63].
2. After the strong outbursts, as a rule some re-brightenings are happened [7, 13, 14, 36, 64].
3. The $L_{\text{uv}}/L_{\text{x}}$ flux ratio is significantly decreased at post maximum time [6, 36].
4. The UV/Optical variations are delayed to X-ray ones on few days [13, 39, 43, 46].
- 5 The UV and X-ray variations are correlated but some uncorrelated events or trends are typical [13, 46, 65].
6. During the strong outbursts dust sublimates in the clouds. The dust can be recovered if the object moves to a low state at least on few years. That can explain variations of obscuration [13, 50, 66].
7. The $\text{H}\alpha/\text{H}\beta$ is higher in low states (see e.g. [67] and Paper II) .
8. The time delays grow along $\text{H}\gamma$, $\text{H}\beta$, $\text{H}\alpha$ [46, 68]
9. Variability of coronal lines (which are broader than usual forbidden lines) might be common property of CL AGNs [36, 49, 69–72].
10. The significant strengthening of the UV Balmer continuum might be common for CL AGNs [6, 13, 39, 46].
11. CL AGNs have low accretion rate $\ll 1\%$ Edd in minimum and few % in maximum [6, 63] .

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CIRCUMSTELLAR DISKS OF A GROUP OF THE AEBe HERBIG TYPE STARS

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In the work is analyzed the spectral energy distribution (SED) curves for a group of the young Herbig AeBe type stars (HAeBe). It is shown that in the group of 19 HAeBe stars, only 3 stars have signs of a residual disk, and they are classified as type III in terms of spectrum. The rest of the stars show type II SED curves. The main fundamental parameters and the evolutionary status of the sample stars are determined.

Keywords: AeBe Herbig stars–circumstellar disks–fundamental parameters

1. INTRODUCTION

Ae/Be Herbig type stars (H Ae/Be) are known as young objects (ages $t < 10$ Myr), visible in the optical range, they are at the Pre-Main sequence (PMS) stage of evolution. These stars have a typical spectral type A or B, sometimes F, emission lines in the spectrum, masses from 2 to $12 M_{\odot}$, exhibit a circumstellar excess of radiation in the infrared (IR) range. The original list, which contained a dozen sources [1], was supplemented with new following catalogs (for example, [2–6]), and today more than 300 H Ae/Be stars are known. This is much less than the number (more than a thousand) of known T Tauri (TTS) stars, which have smaller masses ($M \leq 2.0 M_{\odot}$). Therefore, statistical studies of H Ae/Be stars are generally less reliable than studies of TTS.

H Ae/Be stars are of considerable interest as possible progenitors of β Pic and Vega type stars [7], which have intermediate masses and already have reached the MS and have residual disks. The interest in H Ae/Be stars is also due to the fact

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that, in comparison with more massive young stars, the evolution of intermediate-mass stars is significantly different. The brighter and more massive stars, due to the processes of photoevaporation, faster dissipates its circumstellar matter. This can lead to the thermal and chemical evolution of the star [8]. Circumstellar disks can significantly affect the formation and evolution of planets [9].

This paper is a continuation of our series of works by Ismailov et al. [10–12] devoted to the analysis of SED curves for young stars of low and intermediate masses. In this paper, we present the results of a study of the SED curves for a selected group of H Ae/Be type stars.

2. OBSERVATION DATA AND RESULTS

19 H Ae/Be-type stars were selected from the catalog [4], their list is given in Table 1. The columns of the table contain: the name of the object, the equatorial coordinates of the equinox 2000.0, the distance to the object given in the SIMBAD database and refined from the Gaia DR3 archive (<https://gea.esac.esa.int/archive/>), interstellar extinction A_v , equivalent width emission line $H\alpha$, spectral types and effective temperatures corresponding to them, adapted according to the version of [13]. The last column of Table1 lists the numbers of the cited literature related to the selected observational data. The list of references to table 1 is given in the note.

The main part of the data on broadband photometry of UBVRI-JHK was collected from the literature, according to the VizieR catalogs (<https://vizier.cds.unistra.fr/viz-bin/VizieR>), the list of references is given in the last column of Table 1. Photometric data in the near and far IR regions were collected from the 2MASS [14], DENIS [15], WISE [16], and IRAS [17] catalogs. For individual stars, the values of interstellar extinction given in the literature by different authors can differ significantly. In such cases, using the B-V color index for normal MS stars, we redefined the value of the A_v parameter, assuming that the normal law of interstellar extinction is observed and the extinction coefficient is $R = 3.1$.

Typical brightness variability for H Ae/Be stars in the V band are $\Delta V \approx 0.1 - 0.5 \text{ mag}$, so the expected maximum change in the flux in this band can be about 35%. The maximum changes in the K band ($2.2 \mu\text{m}$) are about $\Delta K \approx 0.3 \text{ mag}$ [18], which can introduce an error in the fluxes in this band by about 25%. The methodological part of constructing the energy distribution curves in the spectra of stars was described in detail in our papers [10,11]. In the model approximation of the observational data, we assumed that the contribution of radiation in the inner boundary layer of the disk in the R band is negligible (see, for example, [19]), the errors due to interstellar reddening in the VRI bands are

Table 1. List of program stars and some its data collected from literature.

Target name	α (2000)	δ (2000)	D, pc	Av	$W(H\alpha)$ Å	Sp type	T_{eff}	literature
HD 35929	05 27 42.79	-08 19 38.4	380	0.39	7.2	A5	7250	4, 1
HD 36112	05 30 27.53	+25 19 57.0	155	0.155	16.5	A5 V	8080	12, 4
V* BF Ori	05 37 13.26	-06 35 00.5	382	0.33	10.0	A6,9	7800	10, 3,2
HD 37357	05 37 47.08	-06 42 30.2	465	0.5	9.9	A1/2V	9200	12, 16, 1
V* VY Mon	06 31 06.92	+10 26 04.9	800	5.68	50.0	B6-B7	13000	10, 9
HD259431	06 33 05.19	+10 19 19.9	653	1.26	55.0	B6 e	14500	13, 1, 2
HD 52721	07 01 49.51	-11 18 03.3	444	0.868	19.6	B2 Vn	20600	12, 2
HD 85567	09 50 28.54	-60 58 02.9	1047	1	42.8	B5Vne	15700	19, 1, 2
HD 97048	11 08 03.31	-77 39 17.4	184	0.87	38.0	B9.5 Ve	10400	8, 11, 1
HD 100546	11 33 25.44	-70 11 41.2	108	0.15	39.5	B9Vne	10700	14, 5, 2
HD 104237	12 00 05.09	-78 11 34.5	106	0.31	20.0	A7Ve	7800	12, 10, 1
HD 132947	15 04 56.06	-63 07 52.6	379	0.2976	1.6	B9V	10700	15, 1, 4
HD 141569	15 49 57.75	-03 55 16.3	111	0.29	10.4	B9.5V	10400	5, 14, 4
HD 144432	16 06 57.95	-27 43 09.7	154	0.62	11.8	A7V	7800	4, 6, 13
V* V856 Sco	16 08 34.29	-39 06 18.3	158	0.38	7.0	A7 e m iv	7800	10, 5, 20
HD 163296	17 56 21.29	-21 57 21.8	100	0.54	1.6	A1Vep	9200	7, 9
MWC 297	18 27 39.53	-03 49 52.1	417	8.47	594.5	B0e, O9e	31500	18, 1
V* TY Cra	19 01 40.83	-36 52 33.8	159	1.488	19.0	B9, B9e	10700	12, 1, 2
HD 200775	21 01 36.92	+68 09 47.7	354	0.52	63.8	B3	17000	17, 1, 2

Note: literature citations which are presented in the last column of table (1) Cutri R.M. et al., 2003yCat, 2246, 0; (2) Ducati J. R. 2002yCat, 2237, 0; (3) Cutri R.M. et al., 2014yCat., 2328, 0; (4) Høg E. et al., 2000A&A, 355L, 27; (5) Lasker B.M. et al., 2008 AJ, 136, 735; (6) Lawrence A. et al., 2007 MNRAS, 379, 1599; (7) Lucas P.W. et al., 2008 MNRAS, 391, 136; (8) Stelzer B. et al., 2004 A&A, 423, 1029; (9) Mora A. et al., 2001 A&A, 378, 116; (10) Tisserand P. et al., 2013A&A, 551, 77; (11) Irvine N.J. et al., 1977PASP, 89, 347 (12) Vieira S.L.A. et al., 2003AJ, 126, 2971; (13) Houk N., 1982 MSS, C03, 0 (14) Gray R.O. et al., 2017 AJ, 154, 31; (15) Levenhagen R.S. and Leister N.V. 2006 MNRAS, 371, 252; (16) Hsu W.-H. et al., 2013ApJ, 764, 114; (17) Guetter H.H. 1968 PASP, 80, 197; (18) Drew J.E. et al., 1997 MNRAS, 286, 538; (19) Houk N. and Cowley A.P. 1975 MSS, C01, 0; (20) Bessell M.S. and Eggen O.J. 1972 ApJ, 177, 209.

insignificant, therefore, when approximating the observational data, preference was given to data in VRI bands as the points with the lowest IR excess value.

As can be seen from Fig.1, the plotted SED curves show a wide range of infrared radiation characteristics: from an almost flat distribution with a large IR excess radiation extending over the entire spectrum, to a minimum excess in the far IR range. We determined the types of SED curves according to the Lada scheme of the classification [21]. The parameter α , which shows the degree of slope of the SED curves, was determined for the range 2.2 - 12 μm . Of the 19 program stars, 3 have the coefficient α in the range $-3 < \alpha < -2$, which indicates a significant attenuation of gas radiation in the disk (type III). Such stars have a residual disk, and protoplanetary disks are close to complete dissipation. For the remaining stars, $-1 < \alpha < 0$, which indicates an optically thick disk in most program stars (type II). All defined types of SED curves are indicated in the last column of Table 2.

The logarithm of the ratio of the fluxes of the star $F_{2.2}^*$ and the model standard $F_{2.2}^m$ of the same spectral type in the K band [22] (Shtrom et al. 1989) was taken as a possible excess measure in the near-IR range,

$$\Delta K = \log F_{2.2}^* - \log F_{2.2}^m = \log F_{2.2}^* / F_{2.2}^m \quad (1)$$

For the value of ΔK , the expected error of determination should be at the level of errors in the approximation of the observational data of the model curve (± 0.07). Therefore, all stars with $\Delta K \geq 0.07$ will be considered as having a real excess. The results of calculating the parameter ΔK are given in Table 2. As can be seen, except from type III stars, almost all stars have significant excess radiation in the 2.2 μm band.

To quantify the value of the integrated excess radiation in the spectra of H Ae/Be stars, we applied a method that is demonstrated by the example of the SED curves of two T Tauri stars, DoAr 51 and V999 Tau (Fig. 2). On the graphs showing the dependence of the values $\log F^*/F_m \sim \log \lambda$, sections are highlighted that can characterize the amount of total excess radiation in the UV and IR parts of the spectrum, designated as S(UV) and S(IR). To calculate the integral excess radiation in the spectral region $\lambda_2 - \lambda_1$ (where $\lambda_2 > \lambda_1$), one can apply the expression

$$S = \int_{\lambda_1}^{\lambda_2} \log \frac{F_*}{F_m} d\lambda \quad (2)$$

Here λ_1 and λ_2 are the initial and final wavelengths of the excess radiation region. To calculate this integral, it is practically necessary to calculate the areas of the figures on these graphs, marked with a dotted lines. The obtained values of S(UV) and S(IR) are characterize the integral value of excess radiation in the corresponding parts of the spectrum.

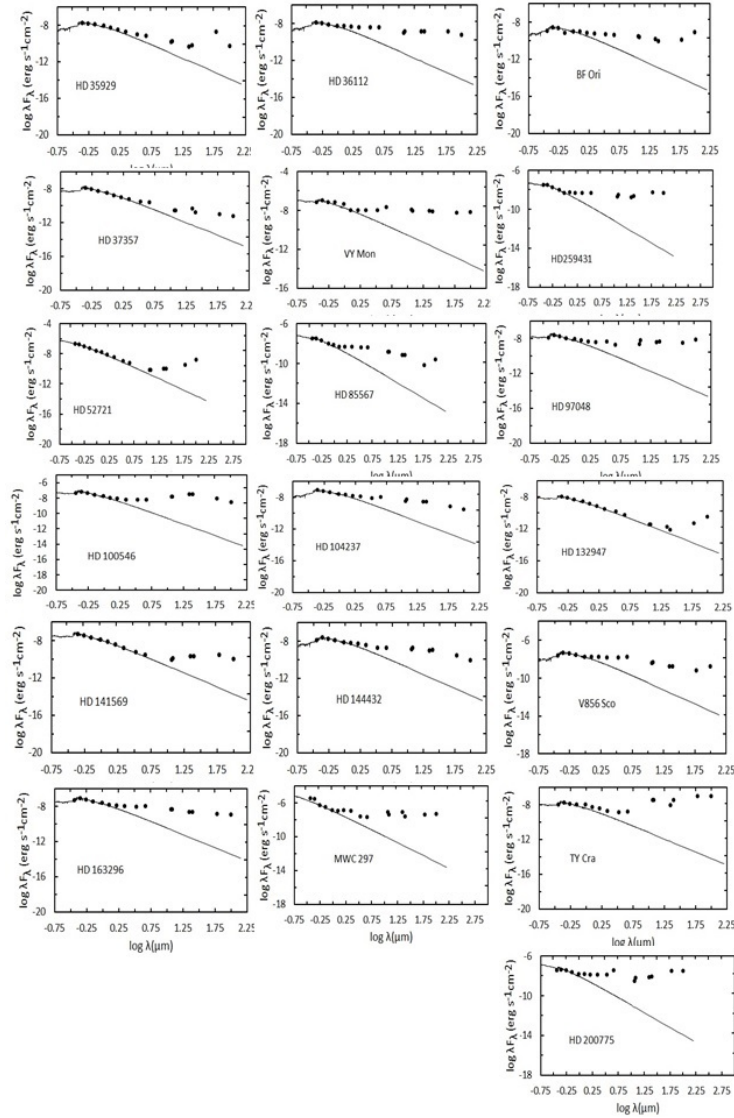


Fig. 1. SED curves of program stars. The solid curves show the distribution of the model star of the corresponding effective temperature according to the model [20].

No excesses are found in our program stars in the UV region. All integral excesses calculated in this way in the IR range of the spectrum $S(\text{IR})$ are given in Table 2.

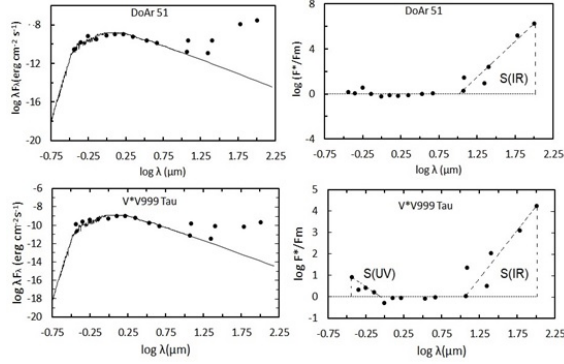


Fig. 2. On the left panel is the SED curve of the star; on the right is the residual between the spectra of the star and the standard model. The dotted line indicates the areas which is characterized the measure of excess radiation.

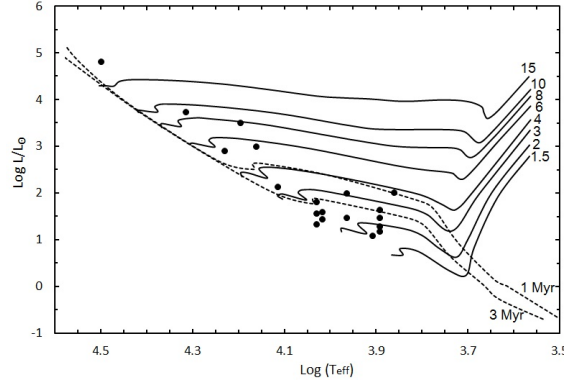


Fig. 3. Location of program stars on the HR diagram with evolutionary tracks according to the data of [23] and [24]. The numbers on the solid lines indicate the masses, and near the dotted lines, the ages (1 and 3 Myrs).

3. PHYSICAL PARAMETERS OF STARS

Based on the V value cleaned of interstellar reddening, the distances to the stars, and bolometric corrections taken from [13], we calculated the absolute bolometric stellar magnitudes M_V . Knowing the absolute luminosity of the sun $M_{V\odot} = 4.83$ mag, we calculated the absolute luminosities of stars in units of solar luminosity $L/L_\odot$. Further, knowing the effective temperatures T_{eff} and luminosity, we calculated the radii of the stars in units of the solar radius $R/R_\odot$. The solar effective temperature $T_\odot$ was taken equal to 5800 K.

Using theoretical evolutionary tracks [23,24], the masses and ages of stars were also determined. All obtained parameters for individual stars are given in Table

Table 2. Calculated parameters of the program stars.

Target name	Mv	$L^*/L_{\odot}$	$R/R_{\odot}$	$M/M_{\odot}$	t, Myr	SQ	ΔK	Type
HD 35929	-0.2	100.9	8.0	3.9	1	2.77	0.28	II
HD 36112	2.1	11.9	2.5	1.8	6	4.30	0.77	II
BF Ori	1.9	14.8	2.9	1.8	5	5.54	0.62	II
HD 37357	-0.1	97.6	6.2	4	1.5	2.37	0.15	II
VY Mon	-0.5	132.0	5.1	3.5	2.8	5.23	0.65	II
HD259431	-2.6	967.0	12.4	5.8	0.5	6.07	0.95	II
HD 52721	-4.5	5325.6	20.5	9	0.4	1.97	0.18	III
HD 85567	-3.9	3132.5	20.7	8	0.3	4.48	0.92	II
HD 97048	0.9	38.5	3.5	2.5	3.4	5.36	0.73	II
HD 100546	0.9	35.8	3.2	2.5	3.2	4.32	0.51	II
HD 104237	1.2	29.3	4.0	2.3	3.3	3.11	0.54	II
HD 132947	0.3	64.9	4.4	2.8	3	1.76	0.07	III
HD 141569	1.2	27.7	2.9	2.4	3.5	2.38	0.05	III
HD 144432	1.6	18.9	3.2	2	3.3	3.74	0.54	II
V856 Sco	0.7	43.9	4.9	2.6	3	4.28	0.79	II
HD 163296	1.2	29.2	3.4	2.3	3.4	4.22	0.62	II
MWC 297	-7.26	64309.1	46.7	19.5	0.2	5.95	1.08	II
TY Cra	1.5	20.9	2.5	2.3	4.8	6.42	0.62	II
HD 200775	-2.4	792.9	9.6	5.5	1	6.31	1.10	II

2. The position on the HR diagram (Fig. 3) shows that the masses of the stars are within $2 \leq M/M_{\odot} \leq 20$. The expected errors of individual parameters are no more than 20%.

The search for a correlation between the parameters of excess radiation and luminosity in the $H\alpha$ line is shown in Fig. 4. The found correlation coefficient between the parameters S(IR) and ΔK is $r = 0.86 \pm 0.12$, and between the parameters $\log(LH\alpha)$ and δK , $r = 0.49 \pm 0.23$.

4. CONCLUSION

We have constructed and classified the SED curves for 19 typical H Ae/Be-type stars. It is shown that among the studied stars only 3 have signs of a remnant protoplanetary disk, they are assigned to type III spectrum (HD 52721, HD 132947 and HD 141569). The remaining objects were classified as type II.

A correlation was found between IR excess radiation in the near ($2.2 \mu m$) and far IR ranges ($25\text{--}100 \mu m$). In this case, a weak correlation is observed between the absolute luminosity in the $H\alpha$ line and the IR excess in the near-IR range. This indicates that the variability in the $H\alpha$ line in such stars is associated not only with a variable stellar wind, but also, possibly, with the disk accretion rate.

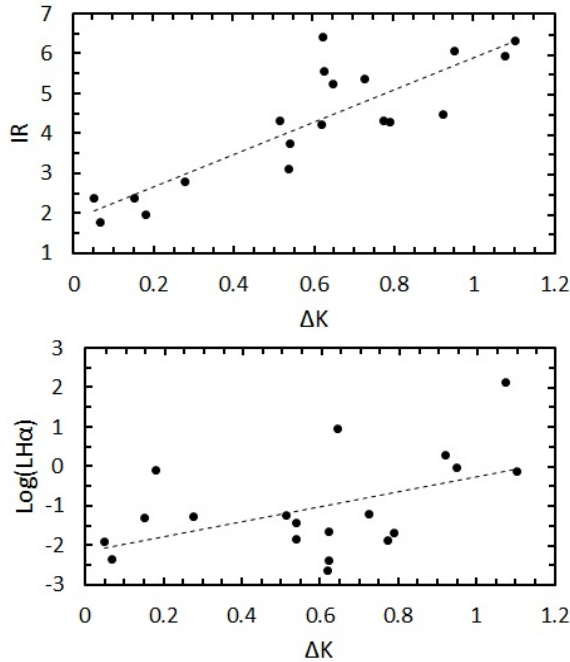


Fig. 4. Relations of the IR excess parameters in the near and far IR range (upper panel). The lower panel shows the absolute luminosity in the $H\alpha$ line versus the excess radiation index in the near-IR range. Dashed straight lines are linear approximations.

The main fundamental and evolutionary parameters of stars are calculated, which agree satisfactorily with the literature data. The masses of program stars determined from the evolutionary tracks mainly lie in the range of $2\text{--}10 M_{\odot}$. Only one of the program stars MWC 297 showed a mass of $19.5 \pm 0.5 M_{\odot}$, which is outside the assumed mass range of H Ae/Be stars. To test this result against an even wider sample of data, we checked the latest data for 318 stars from the new HArchibe archive (<http://svo2.cab.inta-csic.es/projects/harchibe/harchibeCat/index.php?action=search>), whose kernel is based on [25, 26]. In this archive, we found quite a few stars with masses significantly exceeding $\geq 10 M_{\odot}$. It is interesting to study of the physical characteristics of such massive H Ae/Be stars.

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CIRCUMSTELAR PECULIARITIES OF THE HERBIG AE/BE STARS DERIVED FROM HIGH-RESOLUTION SPECTROSCOPY

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An overview of the results of spectroscopic observations of the Herbig Ae/Be stars at different observatories starting from 1986 in the framework of the Pulkovo program is presented. The aim of the program is to study structural, kinematical and physical properties of the circumstellar envelopes around bright objects from the catalogue of candidates to the Herbig Ae/Be stars by Thé et al. (1994). As a result, long-term spectroscopic monitoring of 10 Herbig Ae/Be stars have been carried out. Two main groups of the program objects can be distinguished. The first group includes three yearly type (B0–B3) massive star. All of them have been found to be binary systems and demonstrate some unusual inexplicable phenomena. The second group contains B9–A4 stars with signatures of dense outflowing matter on the line-of-sight between the star and the observer. The analysis of their spectroscopic variability allows to investigate structural and kinematical features of their circumstellar envelopes. A special case is the B6e Herbig star HD 259431. There is good reason to believe that this object is surrounded by a magnetosphere, that is in contrary with earlier predictions by other investigators.

Keywords: stars: pre-main sequence – stars: early-type – techniques: spectroscopy

1. INTRODUCTION

Now it is commonly recognized that Herbig Ae/Be stars are young pre-main sequence objects of intermediate mass. They are surrounded by relict accretion disks responsible for their observational features:

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a) the far IR excess and b) the emission line spectrum [2–4]. The accretion from the disk onto the star takes place near the equatorial plane, where the disk is situated, and then – through the stellar magnetosphere. A matter outflow can be observed at higher latitudes (a so called wind). Several different scenarios of the envelope/star interaction are considered now. Many properties of these objects are already clarified. Nevertheless, some observed phenomena remain unclear. As a practice shows, long-term spectroscopic monitoring of the program objects on the time scales from hours to years is an effective way to collect information on physical processes taking place in the CS envelopes. We started our observations in 1986 at the Crimean astrophysical observatory with different spectrographs of high resolution ($R \sim 20\,000$). Additionally, we carried our observations at such observatories as ESO (Chile), OAN SPM (Mexico), Kourouka AO (Ural FU) and others. About 2000 spectra of 10 objects have been obtained during 35 years. Sometimes the spectroscopic programs were followed by photometric and polarimetric observations. In this paper only several the most interesting results are presented. All objects of our investigation were the brightest stars ($V < 9^m$) chosen from the catalogue of candidates to Herbig Ae/Be stars by The et al. [4]. As it was found, two main sub-groups can be distinguished:

1. Early-type Be stars (HD 200775, HD 53376, HD 52721);
2. Ae stars with signatures of dense wind between the star and the observer (AB Aur, HD 163296, HD 36112, HD 31648, HD 37806, HD 190073).

A special case is the Herbig B6e star HD 259431. It was turned out, that the first sub-group of the most massive and early-type objects demonstrate the most puzzling unresolved properties. In this paper we concentrate our attention on the objects from this sub-group.

2. HD 200775

The first object from this sub-group is the bright northern star HD 200775. It is a well-known Herbig B3e star in the reflection nebula NGC 7023. During 16 years we have observed this object at 6 observatories. There were Crimean AO, Ritter AO (USA), OHP (France), Hawaii and McDonald AO (USA), SAO RAS (Northern Caucasus). About 200 high-resolution spectra near $H\alpha$ have been obtained. The results were presented in Beskrovnaya et al. [4], Pogodin et al. [5, 6]. The $H\alpha$ in the spectrum of HD 200775 is seen in emission. We confirmed earlier result of Miroshnichenko et al. [7], and found, that different parameters of the line demonstrate a cyclic variability with the period about 3.7 years. So, the EW of the emission profile becomes twice greater in its maximum in comparison with

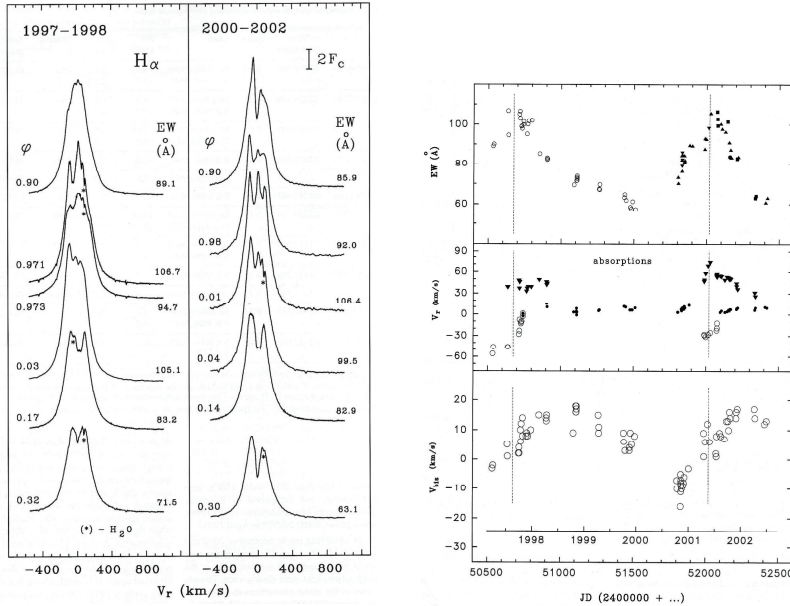


Fig. 1. *Left:* Typical emission $H\alpha$ profiles of HD 200775 at different phases of activity (for $P = 1345$ days) during different observing seasons. The zero phase corresponds to maximum of EW . *Right:* Variations of different parameters of the emission $H\alpha$ profile in 1997–2003. *Top panel:* equivalent width (EW); *middle panel:* positions of local absorption components; *bottom panel:* bisector velocity at the normalized intensity level $1.5\text{--}2.0 F_c$. This parameter corresponding to the velocity of the star was used to obtain the orbital solution for HD 200775 as a binary system.

the minimum (Fig. 1). In the minimum state the profile is double-peaked. But in the maximum it looks as a single profile with a number of local components near the top. The picture of positional variations of these features is rather complex, but it repeats from cycle to cycle. It is remarkable, that the curve of the bisector velocity of the emission profile calculated at the twice the continuum level resembles a curve for radial velocities of components of a binary system. At this level we observe wide emission wings forming in equatorial gaseous disk near the stellar surface. Since the disk is axially symmetric, the bisector velocity corresponds to the velocity of the star itself. We assumed that observed variability of this parameter is a result of binarity of HD 200775. And the temporal curve of this variability can be considered as a radial velocity curve for a component of the binary system surrounded by the gaseous envelope. We derived the orbital solution for the system. The orbital period was determined more correctly. We estimated also the eccentricity and the phase of periastron (Fig. 2). Different symbols on the plot correspond to data from different observatories. Our estimations

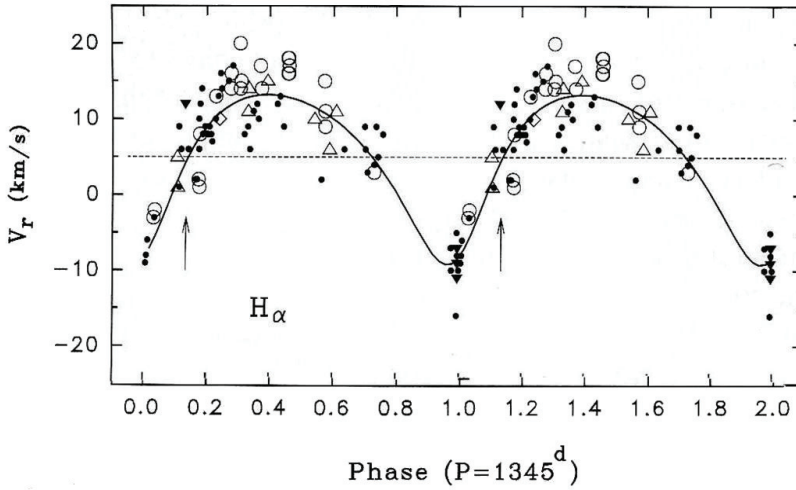


Fig. 2. Orbital solution for HD 200775 on the base of $V_{\text{bis}}(H\alpha)$ at the $1.5\text{--}2.0 F_c$ level. Different symbols correspond to data obtained at different observatories. The arrows indicate the position of the *EW* maximum.

were as follows: $P = 1341 \pm 23$ days, $e = 0.29 \pm 0.07$, phase 0 corresponds to periastron. We were carrying out our observations only in $H\alpha$ and could get no information on the second component of the system. But our study was followed by other investigators. Some years later, the orbital solution for both components was obtained by Alecian et al. [8]. The observations were carried out with the spectropolarimeter ESPaDOns of very high resolution and using the LSD (Least Squares Deconvolution) method. They reconstructed orbital velocity curves for both components. It has turned out that they are stars of similar masses. Their determinations of the main orbital parameters were found to be close to our results: $P = 1412 \pm 54$ days, $e = 0.32 \pm 0.06$. They estimated several parameters of both components of the system (A and B), these values were very similar for A and B components, except $V \sin i$ (26 km/s for A and 59 km/s for B). The most recent and exact estimation of the orbital period of the system has been obtained at Kouroukva Observatory ($P = 1361.3 \pm 2.2$ days, [9]). Alecian et al. [8] constructed also the bisector velocity curve for the $H\alpha$ emission profile, as it was made earlier by us. It turned out that this curve agreed with the curve for the secondary (B). That means, that only the secondary is surrounded by the gaseous envelope. The second surprising fact: only the primary demonstrates signs of large magnetic field of about 1 kG. The distance between the components is about $200R_*$ in apoastron and $100R_*$ in periastron. When the components A and B draw close together, the envelope of B component becomes excited. To

explain what processes take place in the system is a problem of MHD modelling of CS gas.

3. HD 53367

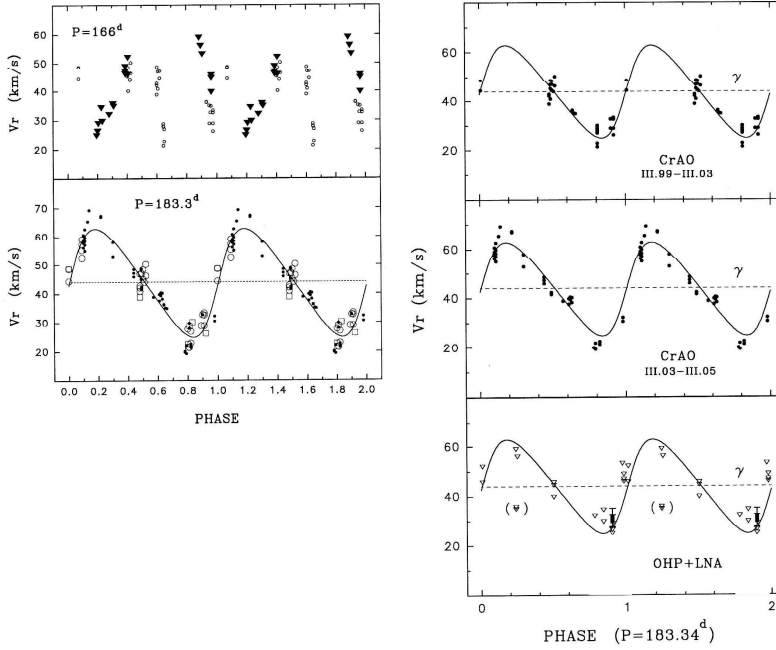


Fig. 3. *Left bottom:* The orbital solution obtained in our investigation. *Left top:* Our data converted with the period $P = 166$ days, obtained in [17]. *Right:* Our data obtained in different seasons from 1999 to 2005 fitted by the orbital curve calculated for $P = 183.34$ days.

It is the brightest B0-type PMS object in the extended star formation region CMar1. The stellar composition of the region was studied in detail by Tjin A Djie et al. [4].

More than 200 $UBVR$ measurements of HD 53367 were collected during 12 years at the Mt. Maidanak Observatory and more recent data were kindly put at our disposal by K.N. Grankin. In addition, spectroscopic observations were carried out at 3 observatories: a) Crimean AO, b) LNA (Brazil), and c) OHP (France). Near 110 high-resolution spectra have been obtained. Results of this program were published in [11].

We have found that HD 53667 is a binary system and derived the orbital solution for this object based on our spectroscopic data using velocities of 2 atmospheric

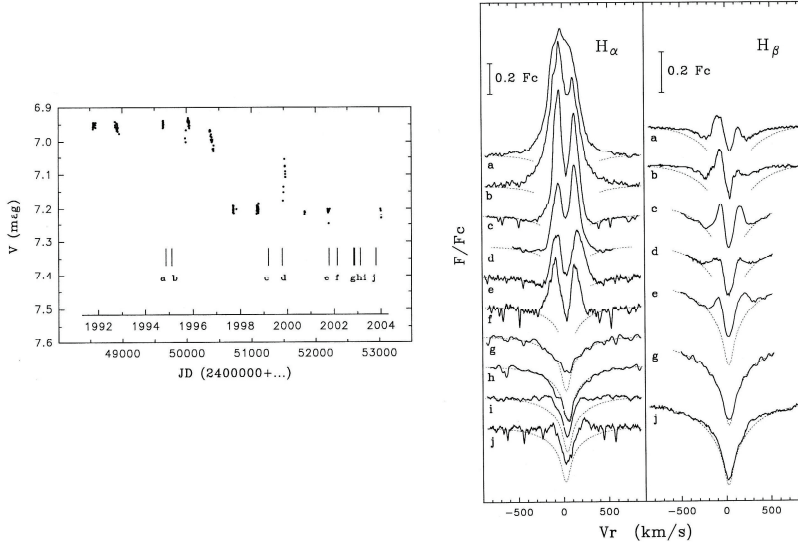


Fig. 4. Left: The V light curve of HD 53365 from 1992 to 2004. Right: The $H\alpha$ and $H\beta$ profile variability in the spectrum of HD 53367 during the dissipation of its gaseous disk-like envelope and the consequent emergence of the new envelope.

lines: OII6641 and HeI6678 (Fig. 3, left bottom). We estimated the orbital period $P \sim 183$ days, which is in contrast with the previous estimation by Corporon & Lagrange [17], where $P = 166$ days. We can see that our observations did not confirm their result (Fig. 3, left top). We believe that it is connected with the fact that Corporon & Lagrange in their calculations used velocities of the HeI, which is strongly under CS influence.

Figure 3 (right) illustrates a satisfactory fitting of our data obtained at different seasons and at different observatories by our orbital curve. The secondary component is likely to be a low-mass star, and its spectroscopic signatures are invisible. The photometric study of this object show that it has a peculiar light curve with 2 states of brightness: high and low (Fig. 4, left). The time scale of their change is several years. This variability is likely to be a result of variations of the amount of emitting gas in the envelope. The inference is based on the fact that the object becomes more red in the bright state.

This conclusion is confirmed also by results of our spectroscopy. It turns accidentally out, that the period of our spectroscopy covers the dates of transformation (see symbols in Fig. 4) of the object from high to low photometric state (Fig. 4, right). In the high state, the emission Balmer line profiles are wide and large in intensity. Then they become more narrow and less intense. At last the emission disappears completely, and we see only the atmospheric profiles. But some time

later an emission component forms again. It is small in intensity but rather broad. Such picture of profile variations corresponds to the situation, when the gaseous equatorial disk starts its dissipation beginning from the most internal region near the stellar surface, where the velocity of rotation is high. Then it transforms into a remote CS ring with small rotation velocity. And, at last, the envelope dissipates completely.

Then, the CS disk-like envelope reappears again, staring its rising from the stellar surface, where the rotation velocity is high and the emission line has to be broadened. This phenomenon is usual for classical evolved Be stars, but was not observed earlier in PMS Be stars.

4. AE STARS WITH SIGNATURES OF DENSE WIND

The second sub-group of objects of our program includes Herbig Ae stars with signatures of a dense wind in the field between the star and the observer. These objects demonstrate P Cyg-type profiles of spectral lines, with $H\alpha$ as the most prominent emission line. The profiles can look as P CygII (or classical P Cyg) profile with a blue absorption component, P CygIII profile with small emission peak at the blue boundary of the absorption component and as a purely single emission profile (Fig. 5). The profiles, as a rule, demonstrate variability on timescale of days in a form of transformations between these 3 types.

We propose a possible interpretation of this phenomenon. Our assumptions are as follows:

- the equatorial accretion disk is inclined relative to the line-of-sight;
- the wind zone is situated at higher latitudes on both sides of the disk;
- the wind is accelerated by the magnetic centrifuge until certain distance R_m , then it moves with deceleration according to the Keplerian law;
- the wind zone increases in its latitudinal distribution with distance (the wind is flared);
- Three cases of intersection of the wind zone by the line-of-sight can be separated: A, B and C. (Fig. 6, *top*).

In this situation, if the wind zone is wide enough and screens the star at all distances from the star, the classical P Cyg-type profile without additional blue emission maximum (P CygII) is observed (A). If the flared wind starts to screen the star only at some intermediate distance $R > R_m$, the stellar emission at high velocities has to be seen in a form of the blue emission peak (P Cyg III) (B). And,

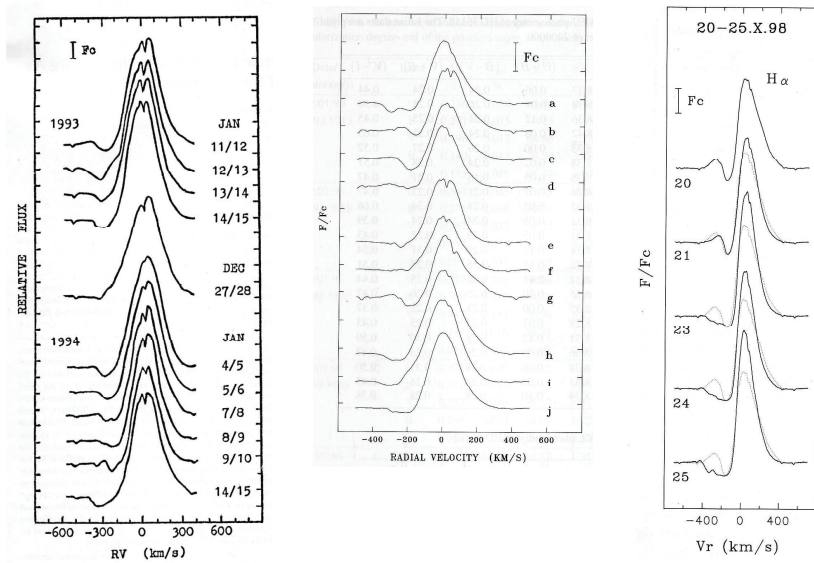


Fig. 5. Typical emission $H\alpha$ profiles in the spectra of AB Aur, HD 36112 and HD 31648 (from left to right) in different observing data. They are taken from Beskrovnaya et al. [4, 6, 9], correspondingly.

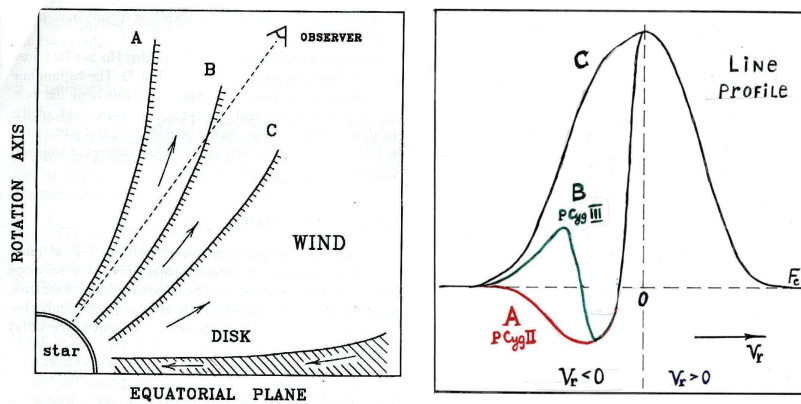


Fig. 6. *Left:* Schematic geometry of the wind zone, and 3 cases (A,B,C) of its intersection by the line-of-sight. *Right:* The line profiles observed in each of the cases A, B and C. The details are given in the text.

at last, if the wind zone is narrow and does not screen the star at any distances, one can see only a symmetric emission profile without absorption component (C) (Fig. 6, *bottom*).

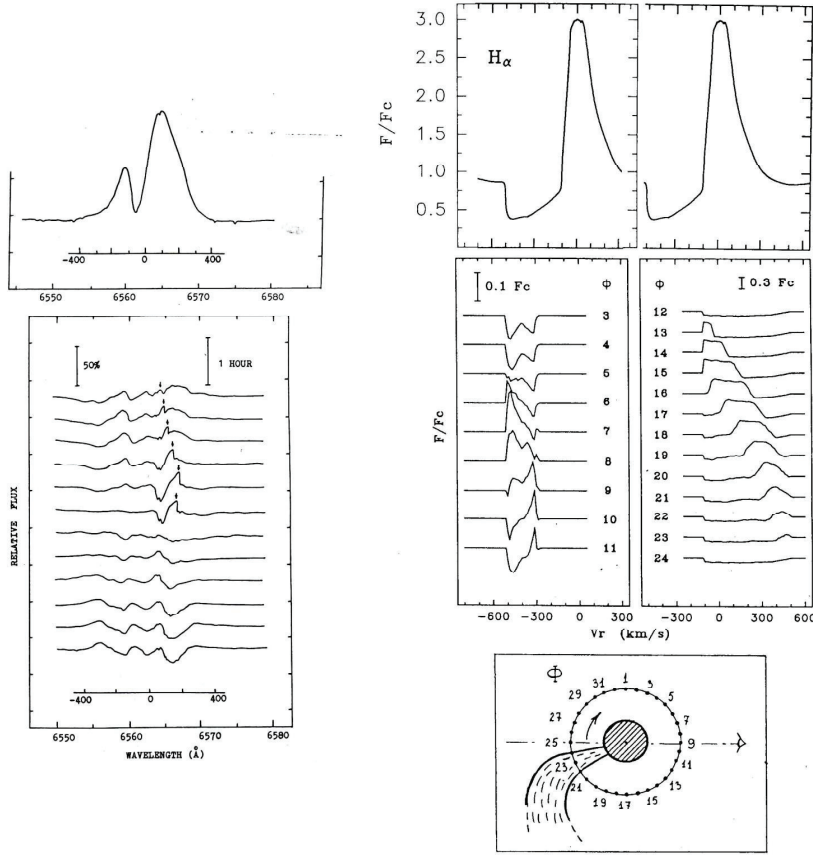


Fig. 7. Left: The nightly mean $H\alpha$ profile observed in the spectrum of HD 163296 on July 26, 1992 [12] and the individual residuals constructed relative the nightly mean profile. The time is directed from top to bottom. Right: The theoretical P Cyg-type profiles and their residuals calculated for different phases of a local stream rotation relative to the line-of-sight. The details are given in the text.

As a result, the observed profile transformation can be explained by a latitudinal re-distribution of the wind zone. The second typical variability of the line profiles in spectra of Herbig Ae stars with signatures of strong wind is appearance of standing waves at the blue part of its P Cyg-type profiles. Figure 7 (left) illustrates residual profiles obtained during one night constructed relative to nightly mean and relates to the Herbig Ae star HD 163296 and its $H\alpha$ line. The spectra were obtained at ESO in 1991 [12]. The short-term variability is seen in the residuals in the form of: a) a standing wave in the region of the blue P Cyg-absorption; b) a running wave in the red parts of the emission profile. Similar character of variability is observed in other Herbig Ae/Be stars of such

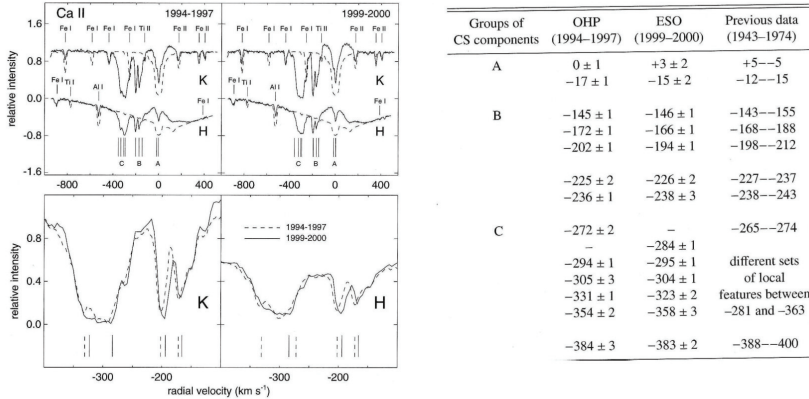


Fig. 8. *Left:* Multi-component CaII K&H profiles in the spectrum of HD 190073. *Right:* The table from [14] presenting velocities of all local wind components observed in the CaII K&H doublet in the spectrum of HD 190073 from 1943 to 2000.

type: AB Aur, HD 36112, HD 31648 and others. Interpretation of such variability is shown in Fig. 7 (right). This is an example of model calculations of the profiles forming in the wind containing a rotating stream at different phases of its rotation. We used the Sobolev's approximation for moving media for calculations of source functions and optical thicknesses and exact numerical integration for profile construction. We can see that when the rotating outflowing stream moves near the line of sight (phase Φ from 3 to 11) the standing waves on the residuals are observed, and when it is far from the line of sight (Φ from 12 to 24) - the waves are running. The parameters of this particular model are presented in [13]. This type of variability speaks in favour of azimuthal inhomogeneity of the wind zones of Herbig Ae/Be stars.

5. UNIQUE HERBIG A2E-B8E STAR HD 190073

In this section we'd like to concentrate our attention on a very unusual Herbig Ae star HD 190073. About 50 spectra of the object were obtained during 9 years at 3 observatories [14]. The most striking peculiarity of the object is the blue-shifted absorption components of the resonance doublet of ionized calcium (Fig. 8, left). These lines are forming in the wind. Their profiles demonstrate a complex multi-component structure, they contain a lot of local lines. Different components of the profiles are collected in several separate groups. It is wonderful that velocities of the local features remain invariant during tens of years (Table in Fig 8, right). Later we carried out new spectroscopic observations at the Crimean AO. 180 high-resolution spectra near the $H\alpha$ line and DNaI doublet have been

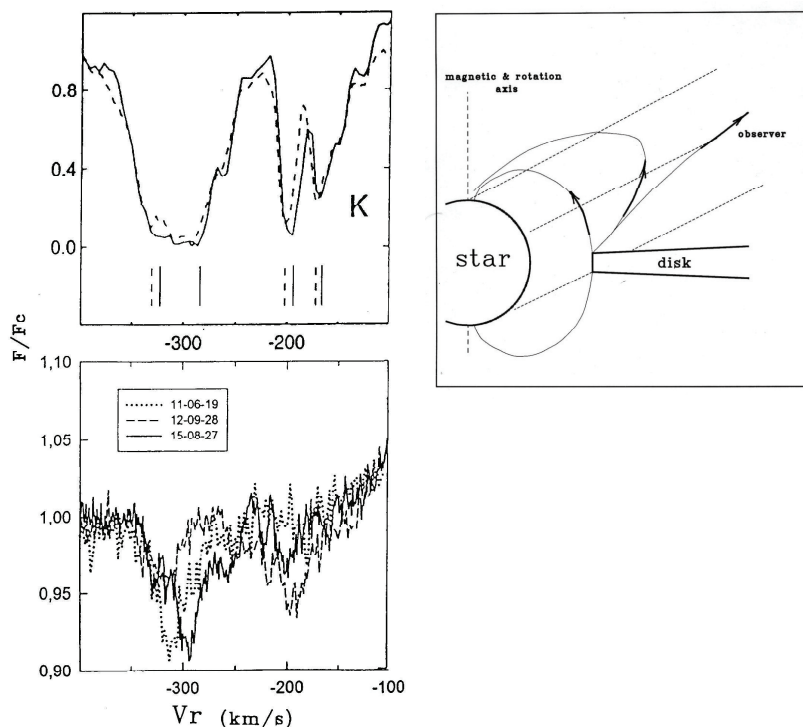


Fig. 9. Left: Comparison of the structure of the multi-component wind profiles of the CaII K&H doublet and of the NaD2 profile in the spectrum of HD 190073. Right: Illustration of a possible influence of the magnetic field configuration in the region of the disk/magnetosphere interaction on a velocity stratification of outflowing streams connected with a stratification of their directions relative to observer.

obtained from 2009 to 2018 [15]. The analysis of the data has shown that these lines also demonstrate multi-component profiles. But, in contrast to the calcium lines, the positions of individual components are variable in time. Nevertheless, they concentrate in the same several groups as the calcium lines (Fig. 9, left). This phenomenon remains unclear up to now. Hypothetically, we connected it with a specific configuration of the global magnetic field of the object. Fig. 9 (right) illustrates a possible influence of magnetic field configuration on the observed velocity stratification of outflowing streams connected with a stratification of their directions relative to the observer. The figure is taken from a paper by Camenzind [16]. But it still remains unclear: a) what is a real nature of such stratification, and b) why local wind components are more stable in the resonance CaII lines than in the resonance DNaI lines and in the $H\alpha$ line.

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COSMOLOGICAL VACUUM AND COSMOLOGICAL-QUANTUM EFFECTS

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The notion of cosmological quantum effect is introduced. These effects depend on the value of the cosmological constant. It is shown that dark matter and energy can be examples of cosmological quantum effects. It is suggested that the irreversibility of time is a cosmological quantum effect.

Keywords: cosmological quantum effect, de Sitter group $SO(4,1)$, dark matter, dark energy, cosmological constant, cosmological vacuum

1. INTRODUCTION

Usually, quantum effects are understood as microscopic and macroscopic quantum effects. As well-known microscopic quantum effects, one can indicate the photoelectric effect or the Compton effect, and as macroscopic quantum effects, the phenomena of superconductivity and superfluidity.

The phenomena of dark matter and energy are topical problems of fundamental science, [1–5]. In the world's leading laboratories, experimenters are trying to find the composition of dark matter from the point of view of elementary particles. Among the known elementary particles, sterile neutrinos are the most probable. Nevertheless, the search for hypothetical particles is also being actively pursued.

In our work, we tried to prove that the phenomena of dark matter and energy are not related to the composition of elementary particles, but are a consequence of a non-zero value of the cosmological constant. It is shown that quantum principles in cosmology can explain the phenomena of dark mass and energy, i.e. we are dealing with cosmological quantum effects.

Fundamental research at the intersection of high energy physics and cosmology is a trend in modern physics.

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2. DE SITTER COSMOLOGICAL MODELS

According to Einstein's general relativity, the metric properties of space-time are determined by the distribution and motion of matter, [6]:

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R_{\lambda}^{\lambda} + \Lambda g_{\mu\nu} = -\frac{8\pi G}{c^4}T_{\mu\nu}; \quad (1)$$

where

$R_{\mu\nu}$ – Ricci tensor, $g_{\mu\nu}$ – metric tensor, Λ – cosmological constant, G – the gravitational constant of Newton, $T_{\mu\nu}$ – energy-momentum tensor and $\lambda, \mu, \nu = 0, 1, 2, 3$.¹⁾

This equation can be rewritten in an equivalent form:

$$R_{\mu\nu} = \Lambda g_{\mu\nu} - \frac{8\pi G}{c^4}(T_{\mu\nu} - \frac{1}{2}g_{\mu\nu}T_{\lambda}^{\lambda}); \quad (2)$$

It is clear from (2) that the Λ -term, even in the absence of matter ($T_{\mu\nu} = 0$), changes the space-time geometry and $g_{kl}\Lambda$ is the energy-momentum tensor of the vacuum.

In the vacuum, the Einstein equations take the form:

$$R_{\mu\nu} = \Lambda g_{\mu\nu}. \quad (3)$$

For $\Lambda = 0$, the solution of (3) is the Minkowski manifold with a group of Poincaré motions.

The histories of the cosmological constant are reviewed in [7]- [8].

In the general case, the solutions of the Einstein (1)-(2) equations do not have a maximal group of motions. But in 1917 Willem de Sitter found two solutions of (3) for $\Lambda \neq 0$ with different global groups of movements, [9–11]:

$$ds^2 = \frac{dr^2}{1 - r^2/R^2} + r^2(d\vartheta^2 + \sin^2\vartheta d\varphi^2) - \left(1 - \frac{r^2}{R^2}\right) c^2 dt^2, \quad \text{if } \Lambda > 0; \quad (4)$$

$$ds^2 = \frac{dr^2}{1 + r^2/R^2} + r^2(d\vartheta^2 + \sin^2\vartheta d\varphi^2) - \left(1 + \frac{r^2}{R^2}\right) c^2 dt^2, \quad \text{if } \Lambda < 0. \quad (5)$$

Here the radius of space R and the cosmological constant Λ are related by the following formula:²⁾

$$\Lambda = \pm \frac{3}{R^2} \quad (6)$$

¹⁾ The attentive reader will notice that, unlike the modern notation, the momentum tensor energy on the right side of the equation appears with a plus sign. The sign depends on the definition of Riemann-Christophel connections and the Riemann tensor. We have chosen to retain the classical form of Einstein's equations since this is not essential for our purposes.

²⁾ It is easy to see that for $\Lambda \rightarrow 0$, i.e. $R \rightarrow \infty$ both solutions (4)-(5) are transferred to the flat world of Minkowski.

Using stereographic projections:

$$\begin{aligned} \xi_1 &= r \cos \varphi; & \xi_2 &= r \sin \vartheta \cos \varphi; & \xi_3 &= r \sin \vartheta \sin \varphi; \\ \xi_4 &= R \sqrt{1 - \frac{r^2}{R^2}} \cosh \left(\frac{ct}{R} \right); & \xi_0 &= R \sqrt{1 - \frac{r^2}{R^2}} \sinh \left(\frac{ct}{R} \right) \end{aligned}$$

and

$$\begin{aligned} \eta_1 &= r \cos \varphi; & \eta_2 &= r \sin \vartheta \cos \varphi; & \eta_3 &= r \sin \vartheta \sin \varphi; \\ \eta_4 &= R \sqrt{1 + \frac{r^2}{R^2}} \cos \left(\frac{ct}{R} \right); & \eta_5 &= R \sqrt{1 + \frac{r^2}{R^2}} \sin \left(\frac{ct}{R} \right) \end{aligned}$$

de Sitter solutions can be isometrically embedded as sub-manifolds in 5-dimensional pseudo-Euclidean spaces:

$$\xi_0^2 - \xi_1^2 - \xi_2^2 - \xi_3^2 - \xi_4^2 = -R^2 \quad (7)$$

and

$$\eta_1^2 + \eta_2^2 + \eta_3^2 - \eta_4^2 - \eta_5^2 = -R^2, \quad (8)$$

respectively.

These spaces have global symmetry groups $SO(4, 1)$ and $SO(3, 2)$ that leave the metrics (7)-(8) invariant. Groups $SO(4, 1)$ and $SO(3, 2)$ are called de Sitter groups. Spaces (4), (7) and (5), (8) are called de Sitter worlds of the 1st and 2nd kind or according to the modern terminology, de Sitter worlds dS and anti-de Sitter AdS , respectively.

3. WIGNER'S ELEMENTARY QUANTUM SYSTEMS

Wigner introduced the concept of an elementary system and showed that irreducible representations of the group of motions of the world correspond to such systems, i.e. the space of these representations has no invariant subspaces, [12]³⁾.

The vacuum solutions of Einstein's equations have a maximal group of motions - these are the Poincaré groups for the Minkowski world and the de Sitter group for the de Sitter worlds, depending on the value of the cosmological constant.

Wigner proved that in the world of Minkowski the mass (energy of rest) and spin of the elementary particle are:

³⁾ It should be clarified that in the case of quantum mechanics we are dealing with projective representations of the Poincaré group $ISO(3, 1)$ or vector representations of its universal covering group $SL(2, C)$.

- invariants of the Poincarè quantum-mechanical group $\overline{P}_+^\uparrow$, which uniquely characterize unitary irreducible representations⁴⁾;
- the consequences of space-time symmetries, i.e. they can be obtained without using the equations of dynamics.

Invariants of the inhomogeneous Lorentz group, in other words, the Poincarè group $ISO(3, 1)$ (Casimir operators) are constructed using translation generators P_μ and 4-dimensional rotations $M_{\mu\nu}$ as follows, [13, 14]:

$$m^2 = P^\mu P_\mu; \quad w^2 = w^\mu w_\mu = m^2 s(s+1); \quad w_\varrho = \frac{1}{2} \epsilon_{\lambda\mu\nu\varrho} P^\lambda M^{\mu\nu}, \quad (9)$$

where

m – mass, s – spin of the particle, and w_ϱ is the Pauli-Lubansky-Bargmann vector:

$$(m, s), \quad m^2 \geq 0, \quad s = 0, 1/2, 1, 3/2, 2, \dots$$

Important! In the case $m^2 > 0$, there is a third invariant - the sign of energy:

$$\varepsilon = \frac{P_0}{|P_0|} = \pm 1 \quad (10)$$

The application of the Wigner elementary system concept in the de Sitter world leads to interesting results. In de Sitter's world, elementary systems are also characterized by two parameters, [15]:

- The spin s retains its status;
- Instead of mass, a function of the rest energy of the special theory of relativity, spin, and radius of curvature of the Universe appears:

$$m^2 = m_0^2 + \frac{9}{4R^2} - \frac{s(s+1)}{R^2}. \quad (11)$$

It is obvious that $m^2 \rightarrow m_0^2$ at $R \rightarrow \infty$.

Here, the radius of curvature R is determined by a cosmological constant Λ , (6).

Passing to the limit $R \rightarrow \infty$ is an example of a contraction operation for Lie groups, their algebras, and representations in the sense of Wigner-Inönü, [16].

It can be seen from the formula that, in contrast to the Minkowski world, where the mass is a classical quantity in the de Sitter model, the second characteristic of the elementary system has a cosmological-quantum nature.

⁴⁾ $\overline{P}_+^\uparrow$ is isomorphic to $SL(2, C)$.

In this case the role of the contraction operation is similar to that of the Bohr correspondence principle, [17, 19]. The operation of contraction replaces the principle of the correspondence of Bohr, since we do not have a complete theory of quantum gravity.

4. COSMOLOGICAL QUANTUM EFFECTS IN THE DE SITTER WORLD

Maximal groups of motions make it possible to use the well-known methods of relativistic quantum field theory in cosmology. Using the representations of the de Sitter group of motions, it is shown that the phenomena of dark matter and energy are a cosmological quantum effect. In de Sitter's world, gravity and anti-gravity are different states of Wigner's elementary quantum systems. But, in the world of Minkowski, anti-gravity can be excluded because there are no transitions between the two states. Our conclusion is based on the interpretation of the theorem on the contraction of representations of de Sitter group to representations of the quantum-mechanical Poincaré group, which we proved earlier, [20].

The result of the contraction of the UIR's, $T^{(\sigma,s)}(g)$, $g \in SO(4, 1)$, $\sigma = -3/2 + imR$, for $R \rightarrow \infty$ is the direct sum of UIR, $U^{(m,s;\varepsilon)}(g)$, $g \in ISO(3, 1)$, with mass m , spin s and differing in energy sign ε .

In the de Sitter world, elementary Wigner systems are identified by spin and by a parameter, which is the flat limit of a function of spin and mass, with different energy signs. However, unlike the Minkowski world, we can not exclude negative energies from consideration. It is natural to identify states with opposite signs of the parameter ε as gravity and anti-gravity, which are characteristic of dark matter and energy.

But, in the general case, a solution to the problem of quantizing the gravitational field is required. This problem cannot be solved in the same way as an electromagnetic field or a general gauge field. The first main problem is that the general theory of relativity postulates a fundamental experimental fact about the equality of gravitational and inertial mass. According to the well-known work of Bohr-Rosenfeld [21], it is precisely due to a decrease in the ratio of the charge of a test particle to its mass that a consistent interpretation of quantum measurements in quantum electrodynamics is possible. And according to the principle of equivalence, this ratio is always equal to one and cannot be reduced.

Another problem is that all gravitating bodies, including test particles, have a gravitational or Schwarzschild radius.

And this makes the introduction of a local field problematic.

Given these and other difficulties in quantizing the gravitational field, it is usually said that the gravitational field is not quantized. But these problems of

quantization of the gravitational field can be characterized differently: as a result of the unification of the general theory of relativity and quantum mechanics, a new physical object appears, different from the relativistic quantum field.

The next difficulty is related to the non-trivial symmetry properties of the vacuum solutions of Einstein's equations, which create serious difficulties in determining the quantum vacuum. And the principle of general covariance in general relativity makes the interpretation of solutions and the definition of the energy-momentum tensor ambiguous.

Without the maximal group of motions, using the methods of relativistic quantum field theory is impossible. Thus, the gravitational field cannot be quantized, and general relativity is not applicable in the microcosm of quantum particles. A reasonable question arises: is it possible to apply quantum mechanics on the scale of the Universe?

All this forces us to look for other possibilities for solving the problems of high-energy physics and cosmology.

5. ALGEBRA OF OBSERVABLES AND COSMOLOGY

The main reason is the difficulty of applying the principles of quantum mechanics to the Universe as a whole since the measuring device, which should be a classical system, is part of the world.

Historically, three formulations of quantum mechanics are known: Heisenberg's matrix mechanics, Schrodinger wave mechanics, and Jordan's observable algebra. The first two formulations of quantum mechanics are presented in monographs, where it is shown that the influence of the measuring device on the measurement process is manifested in the procedure of wave packet reduction, [?, 27]. J. Neumann focused on the fact that the Schrödinger equation only determines the evolution of the quantum system and does not describe the measurement procedure. The effect of a classical measuring device can be understood as a reduction of the wave function.

To find the correct application of quantum mechanics in cosmology, we have tried to find a representation of observable algebra that describes the interacting classical quantum system. To do this, we used the definition of the algebra of observables by Jordan in the formulation of [29, 30].

We have proved the theorem that an interacting classical and quantum system cannot be Hamiltonian system, [31].

There is not any representation of the observable algebra (1)-(4) corresponding to the interacting Hamilton classical-quantum system.

Bohr's Copenhagen interpretation is usually presented in books on quantum mechanics. But initially, Bohr proposed the idea of a fundamentally uncontrolled

interaction between a classical system (measuring device) and a quantum system in quantum mechanical measurements, [17]. Our theorem shows that Bohr's original point of view reflects the physical side of the measurement process much better.

6. CONCLUSION

In conclusion, we will draw some conclusions and outline promising studies.

Wigner's elementary systems are the only mathematically and physically correct definitions of an elementary particle. But this definition depends entirely on the existence of a maximal group of motion. Maximal groups of motions exist only in the Minkowski world and de Sitter models. But in the general cosmological model, there are no maximal groups of motions. Thus, it is generally impossible to introduce the notion of an elementary particle. The concept of an elementary particle can be used only in the local sense. On the scale of a galaxy or a cluster of galaxies, the concept of an elementary particle is acceptable, because on such a scale Newtonian cosmology can be used in a post-Newtonian approach without applying general relativity. Einstein warned against introducing the concept of a particle into general relativity as early as 1916, [6]. Attempts to represent particles as field singularities cannot be considered satisfactory.

Here it is appropriate to note that in the general theory of relativity, black holes play the role of elementary particles, as in high-energy physics. Indeed, black holes, regardless of their origin, are characterized by only a few parameters, such as mass, angular momentum and electric charge, [11]. And in relativistic quantum mechanics, the basic characteristics of elementary particles, such as mass and spin, according to Wigner's theory, are invariants of kinematic groups of movements, whereas in general relativity, black hole parameters act as integration constants for solutions of Einstein equations. On the other hand, there is still no satisfactory explanation of the electric charge and lifetime of elementary particles.

Hawking showed in his paper [23] that black holes can have a finite lifespan due to quantum evaporation. We are confident that Hawking's work is the beginning of a new physics and will play the same role as Planck's work on blackbody radiation.

This is an example of the fact that the solution to the problems of fundamental physics will be found at the intersection of elementary particle physics and cosmology.

On the other hand, attempts to quantize the gravitational field have also failed, which implies that the synthesis of quantum mechanics with general relativity produces another physical object, differs from the relativistic quantum field of special relativity.

Determining the nature of this object depends on the solution of two problems. First, the reformulation of the principles of symmetry in the general theory of relativity exclusively in terms of invariant geometric objects. In this case, the symmetry properties of the cosmological vacuum play an essential role. Recall that from the constancy of the speed of light, it follows that the laws of physics in a vacuum must be invariant concerning a wider group than the inhomogeneous Lorentz group, namely, concerning the conformal group. H.Weyl wanted to use this fact to construct a unified geometric theory of electromagnetism and gravity but without success, [24, 25]. It's interesting that the Poincaré $ISO(3, 1)$ group and de Sitter groups $SO(4, 1)$, $SO(3, 2)$ are globally subgroups of the conformal group $SO(4, 2)$, [26].

Secondly, our theorem on the application of quantum mechanics to shows that it is necessary to find an adequate generalization of the Hamiltonian formalism to solve this problem. Preliminary results show that such a generalization is possible only if time is irreversible. This result leads to the following hypothesis:

The irreversibility of time is also a cosmological quantum effect.

In the context of our approach, a problem arises that supplements the well-known list of cosmological ones: Can cosmology provide a unique element of the equivalence class or the uniqueness of the nonequivalent classes of the representations of the algebra observed?

This is our program for further research.

This work is the basis of my report of the same name at the International Conference "Alive Universe - from Planets to Galaxies"⁵⁾. Therefore, I considered it necessary to include the questions put to me and my answers in the Appendix.

⁵⁾ 12-14 October, 2022, Shamakhy, Y.Mammadaliyev settlement, ShAO, Azerbaijan

APPENDIX

A. Namig Dzhalilov, Dr.of Sci., Professor.

Question: *It is known that, in addition to mass and spin, elementary particles have different charges. What can you say about the charges?*

Answer: Charges come in different types. The first type of charge was introduced to classify elementary particles. For example, baryon, lepton and other charges. The second type of charge is a source of interaction. For example, an electric charge or color charge. The last type is mass, which is the source of gravitational interaction. Furthermore, according to Wigner, mass and spin are invariants of the kinematic group of motion, whereas for an electric charge there is no similar interpretation.

On the other hand, in general relativity, there are known solutions to Einstein's equations for black holes with mass, angular moment, and charge. Moreover, solutions with Dirac monopoly are also known. These quantities are obtained as integration constants for solutions to Einstein's equations. This is evidence that solutions to fundamental problems can be found after the synthesis of quantum mechanics with general relativity.

B. Janmammad Rustamov, Associate Prof. Dr.

Question: *Are the Void and cosmic vacuum the same?*

Answer: Not at all. The report is not about the cosmic vacuum, but about the cosmological one. The cosmological vacuum is a solution to Einstein's vacuum equations, (3). On the other hand, according to the standard cosmological model, the universe is homogeneous everywhere and isotropic in all directions, which is confirmed by the observed properties of relict radiation⁶⁾. And cosmic voids are local inhomogeneities on the scale of a cluster of galaxies, where general relativity is not needed, a post-Newtonian approximation is enough. And the hypothesis of dark matter in cosmic voids has not been confirmed, [32], ⁷⁾. This proves once again that dark matter is not a local phenomenon, but a cosmological effect.

C. Nariman Ismailov, Dr.of Sci., Professor.

Question: *Currently, even not far from what it was 20 years ago, the field of cosmology is in a perplexed state. Various theories have been put forward,*

⁶⁾ In 1992, the cosmological anisotropy of the cosmic microwave background was discovered.

⁷⁾ I express my deep gratitude to Dr. J. Rustamov, who drew my attention to this site.

sometimes there are ideas that completely contradict each other. In this apparent confusion, what advantages does your cosmological model have, and how does it differ from others? How to get out of such a mess?

Answer: Let me be clear: I am not proposing a new cosmological model. There are standard cosmological models, and well-known models De Sitter, Friedman, Robertson-Walker, etc. Moreover, I propose to be based on the general theory of relativity and on the principles of quantum mechanics and avoid exotic theories such as superstring, multidimensional ones, various modifications of the Einstein's equation and etc. Using the de Sitter model as an example, I showed that, based on the Einstein equations and the concept of Wigner elementary systems, it is possible to explain the phenomena of dark matter and energy as quantum effects. Since these take place at a non-zero value of the cosmological constant, I have defined them as cosmological quantum effects.

The most difficult problem is to construct a representation of Jordanian algebra observed for interacting classical and quantum systems. Solving this problem will allow quantum mechanics to be applied to cosmology. I will prove that such a system cannot be Hamiltonian.

Two representations of the algebra of observables are known: classical and quantum mechanics. Two parameters characterize the equivalence classes of the representation: $\hbar$ and c . Experimental data show that representations with the following values are realized in Nature:

$$\begin{aligned}\hbar &= 1.054\,571\,817... \times 10^{-34} \text{ J}\cdot\text{s} = 6.582\,119\,569... \times 10^{-16} \text{ eV}\cdot\text{s} \\ c &= 299792458 \text{ m/s}.\end{aligned}$$

Newtonian mechanics corresponds to the representation:

$$\hbar = 0; \quad c = \infty.$$

I would like to point out the following. From a philosophical point of view, the observation algebra approach is a mathematical expression of the difference between subjective and objective. The choice of a particular representative of the representation of algebras observed within some non-equivalence class is subjective because it is our choice. But the element of the set of non-equivalent representations is determined by the laws of Nature through universal constants and therefore expresses the objective nature of scientific truths and is not dependent on our will. Whether cosmology limits our choices remains to be seen in future research.

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VARIATIONS OF SOME SPECTRAL LINES IN THE SPECTRUM OF V 1295 AQL

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The results of homogeneous spectral observations of the HAeBe-type star V1295 Aql obtained in 2016–2020 are presented. The variability of the profiles of the $H\alpha$, $H\beta$, FeII, SiII, [OI], D NaI spectral lines is considered. The Fe II lines show two emission peaks with central absorption, with the variable displacement from +15 to -5 km/s in different years. Almost all metal lines show changes in the radial velocity and the equivalent width of the emission components. The profile structure show variability in a complex form, but more often with two peaks superimposed on the line wings. The same structures in profiles also observed in purely absorption lines. [OI] $\lambda 6300$ Å line shows a weak form redshift, indicating the observation of accretion in the outer layers. Despite this, most likely, the star has a strong chromosphere activity.

Keywords: pre-main sequence stars – spectral variations – circumstellar matter – emission lines – Ae stars, individual: V1295 Aql.

1. INTRODUCTION

HAeBe stars [1] defined the massive counterparts of T Tauri stars (TTs) as emission line objects with spectral type A or earlier that locate in obscured regions and illuminate bright and close nebulosities. Currently, Herbig Ae/Be stars (HAeBe) are known as young ($\lesssim 10$ Myr), optically visible pre-mainsequence (PMS) stars with emission lines in their spectra, typical spectral types A and B, stellar masses that typically range between ~ 2 and $\sim 12 M_{\odot}$, and infrared (IR) excesses associated with circumstellar disks. The spectroscopic monitoring of some sources [2–4] revealed that the spectra of HAeBe objects are not only characterized by the presence of emission lines, but also by the complex varia-

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tions observed in both the emission and absorption features. This variability is also characteristic of T-Tauri stars [5,6].

V1295 Agl (HD190073, MWC325, A2IIIe - B9IIep+sh) is a very remarkable early-type object with rich emission lines in the visible spectrum. HD190073 was variously classified as a peculiar Bep star [7] or as an evolved post-main sequence A giant [8]. Recently HD190073 has gained recognition as a young Herbig Ae/Be star [9,10]. Despite being situated in the constellation of Aquila far from wellknown regions of star formation, it displays a large far-IR excess due to thermal radiation of cool circumstellar (CS) dust [11]. The energy distribution of HD190073 in this spectral region is similar to that of well-known Herbig Ae stars, like AB Aur, HD163296 and HD31648 [12].

Alicia et al. [13] identified stellar parameters for V1295 Agl. The star has a magnetic field, $\sim 100\text{G}$, which has been detected and confirmed by many authors over several years [14–16]. As described in [13] from MIKE spectra $V_r = -1.2 \pm 1.3 \text{ km/s}$ and $v \sin i = 3.19 \pm 2.45 \text{ km/s}$. Effective temperature is $T_{\text{eff}} = 9250 \pm 250 \text{ K}$, Mass is $M_* = 2.9 \pm 0.5 M_{\odot}$ radius is $R_* = 3.6 \pm 0.5 R_{\odot}$. Variability was observed, indicating a change in the star’s magnetic field structure.

In this work, we have presented new results of monitoring of the spectral lines $H\alpha$, $H\beta$, FeII, SiII, [OI], D NaI on the spectral observations of the star in 2016-2020.

2. OBSERVATIONS

The spectra were carried out in the 2-m telescope of Shamakhy Astrophysical Observatory of Azerbaijan National Academy of Sciences. We used ShAFES spectrographs that works with CCD $4 \text{ K} \times 4 \text{ K}$, spectral resolution is $R \sim 28000$ in wavelength range $\lambda 3700 - 8000$ [17]. The mean signal-tonoise level is $S/N \sim 100$ in the region of the H_{α} line, and $S/N = 40 - 60$ in the region of the H_{β} line. Wavelength calibration have made on the sky and ThAr lamp spectrum. For calibration and processing of spectrograms used the DECH20T software [18]. We used total of 27 pairs of spectrograms of the star for 2016-2022 years. The mean error of positional measurements in the spectra of standard stars was $0.5 - 1 \text{ km/s}$, and standard deviations in intensities at 0.5% .

3. MAIN RESULTS

Results for the $H\alpha$ line

In this work, we have created average profiles and standard deviation its intensity along the wavelength for the lines H_{β} , Fe II, Si II, [O I], D Na I, for 2016-2020

years. We monitored their variation for each year. In the Fig.1 is presented average profile (solid line) and standard deviation σ of the line intensity for each point along wavelength (dashed line) of H_α line. As it is seen from Fig.1 H_α line is emission line. In 2016 and 2017 years it has got barely distinguished two picks. But in 2018-2022 years it shows only red component. In 2016 and 2018 years standard deviation shows some variations. In 2016 year, it shows variation in red component, but in 2018 in blue component. In the Table 1 is shown radial velocities of H_α line's red, blue component and full wide (FW) at the 10% intensity level and radial velocity of standard deviation in 10% intensity level. Last two rows show average value of radial velocity and standard deviation. As it is seen from Table 1, the full wide of the line at 10% level of intensity is not more than 300 km/s. It means that there is no strong accretion and wind features.

Table 1. Profile parameters of the H_α line's red, blue component and full wide in 10% intensity level and radial velocity of standard deviation in 10% intensity level.

Year	RV_b (km/s)	RV_r (km/s)	FWat 10% (km/s)	σ_b (km/s)	σ (FW) 10% (km/s)	σ_r (km/s)
2016	16.5	52.5	-223	241	-273	231
2017	4.5	7.5	-269	201	-291	121
2018		44	-194	241	-200	187
2019		49.5	-171	214	-174	176
2020		45	-153	220	-207	200
Average	10.5	39.7	-202	223.4	-229	183
rms	8.5	18.3	45.7	17.5	50.3	40.3

The $H\beta$ line

$H\beta$ line is an absorption line with central emission component. Absorption wings are typical photospheric wings. In the Fig. 2, as in Fig.1 is presented average profile and its standard deviation of the $H\beta$ line. From standard deviation of profile, we carried out that there is no obvious change in the wings of line, but we can observe variation in the emission component mainly in 2016 and 2018 year. This variation is synchronous with the variation in profile of the H_α line in 2016 and 2018 years.

In the Table 2 is shown radial velocities of $H\beta$ line's red and blue component and FW in 10% intensity level and FW of standard deviation in 10% intensity

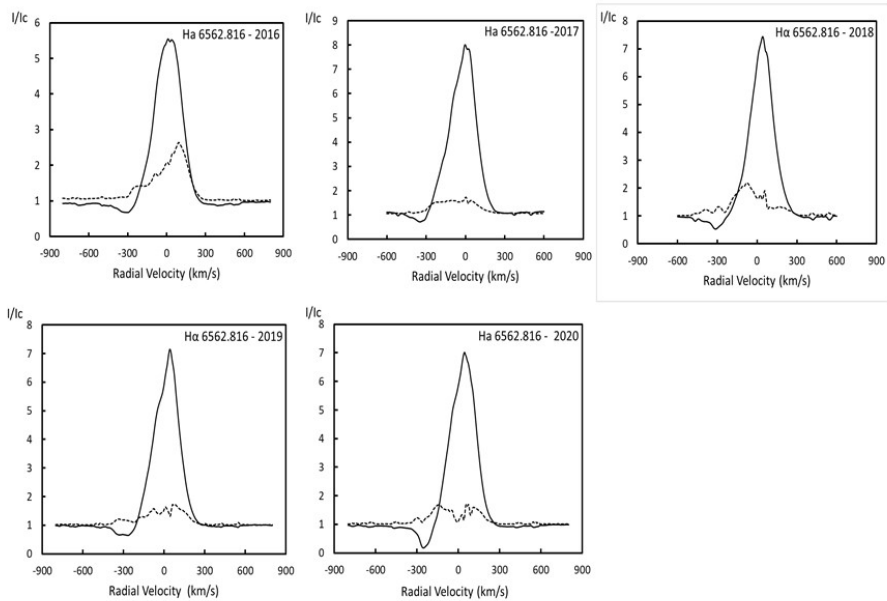


Fig. 1. H_{α} profiles (solid lines) and standard deviation of intensity along the wavelength (dashed lines) for 2016-2020 years.

level. Last two rows show average value of radial velocity and standard deviation.

Table 2. Radial velocity of $H\beta$ line's red, blue component and in 10% intensity level and radial velocity of standard deviation in 10% intensity level.

Year	RV_b (km/s)	RV_r (km/s)	FW10% (km/s)	σ_b (km/s)	σ FW 10% (km/s)	σ_r (km/s)
2016	-76	54.5	-109	103	-219	191
2017	-86	16.5	-173	138	-286	129
2018	-59	50.5	-77	121	-212	8.5
2019	-49	29	-150	89.5	-277	117
2020	-36	60	-110	121	-269	164
Average	-61.2	42.1	-123.8	114.5	-252.6	121.9
rms	20.1	18.5	37.8	18.7	34.5	69.8

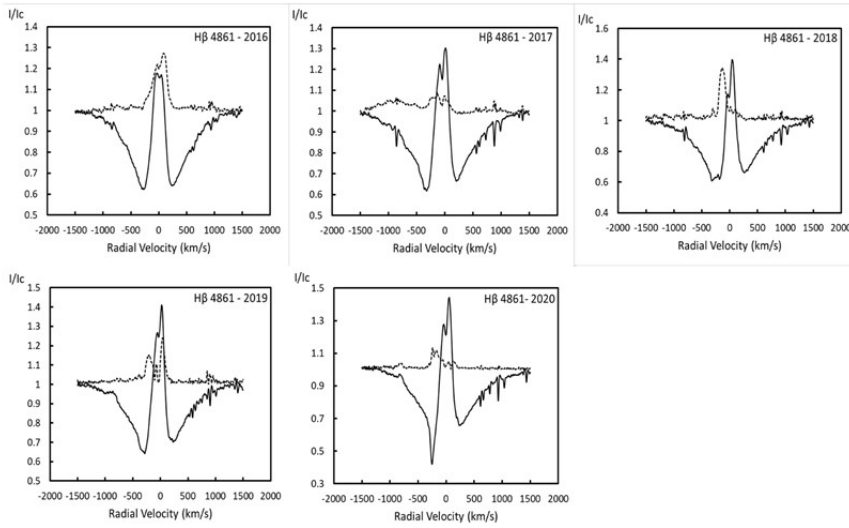


Fig. 2. H_{β} profiles (solid lines) and standard deviation of intensity along the wavelength (dashed lines) for 2016-2020 years.

The line Fe II 4924

FeII $\lambda 4924 \text{ \AA}$ emission line shows 2 emission peaks with central absorption. In the Fig.3 is presented average profile and standard deviation of FeII $\lambda 4924 \text{ \AA}$ line for each year. Standard deviation varies in 2016 and 2019 years. Variation in 2019 is not synchronous with $H\alpha$ line.

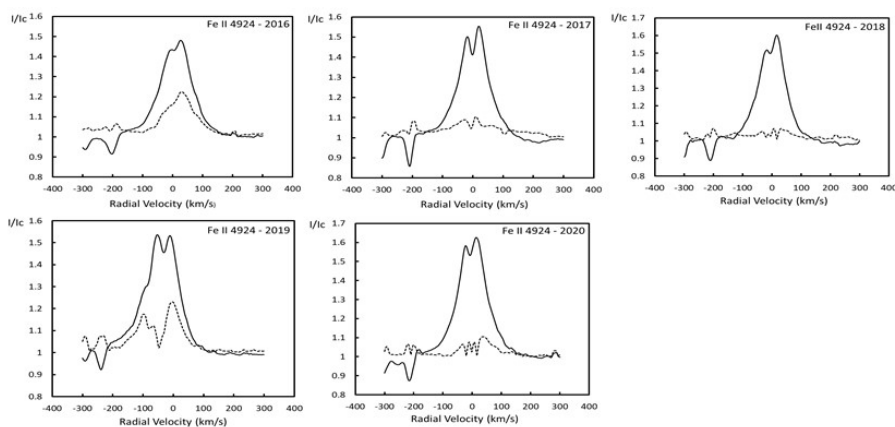
In the Table 3 is shown radial velocities of the FeII $\lambda 4924 \text{ \AA}$ line's red and blue components and FW in 10% of intensity level and its standard deviation parameter FW10%. Last two rows show average value of radial velocity and standard deviation σ .

The line FeII $\lambda 5018 \text{ \AA}$

The FeII $\lambda 5018 \text{ \AA}$ is also emission line with central absorption. Standard deviation of the line profile exhibit some variability in 2019. The character of variations in the FeII lines is similar, but significantly different with the activity dates with of the $H\alpha$ line profiles. It is indicated that variability in profiles of the FeII lines may be results of chromospheric activity. The standard deviation in other years is close to the noise level, which indicates the absence of significant variations in the profile. In the Table 4 is presented radial velocities the of FeII $\lambda 5018 \text{ \AA}$ line's red and blue components and parameter FW10% and its standard

Table 3. Radial velocity of FeII $\lambda 4924$ Å line's red and blue components, FW10% parameter and its standard deviation and its FW10% parameter.

Year	RV_b (km/s)	RV_r (km/s)	FW10% (km/s)	σ_b (km/s)	σ FW 10% (km/s)	σ_r (km/s)
2016	-1.43	24	-112	135	-53	123
2017	-20	24	-106	117	-62	69
2018	-22	21	-105	97	-38	44
2019	-52.2	-8	-147	56	-128	54
2020	-22	10.5	-124	119	-42	78
Average	-23.526	14.3	-118.8	104.8	-64.6	73.6
Standard deviation	18.2	13.6	17.5	30.4	36.7	30.6

**Fig. 3.** Average profiles (solid line) and standard deviation (dashed lines) of Fe II λ 4924 Å line for 2016-2020 years.

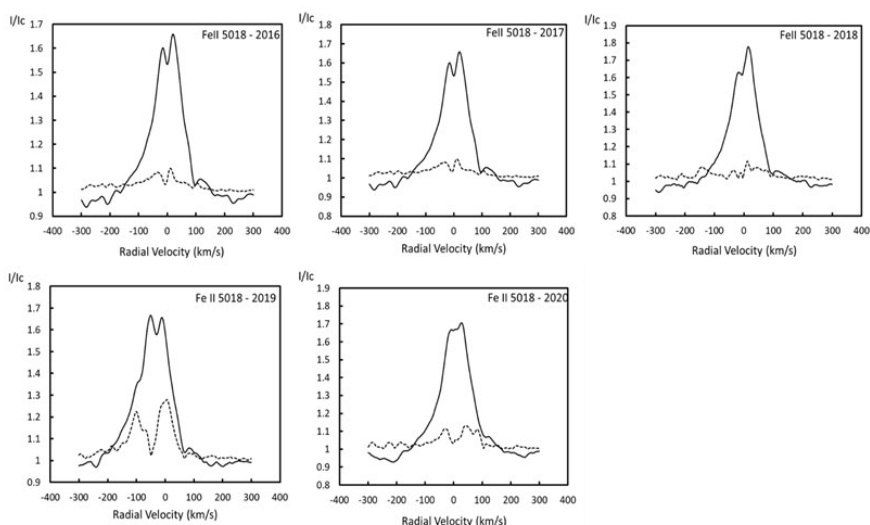
deviation. Last two rows show average value of radial velocity and its standard deviation.

The line FeII $\lambda 5169$

In the Fig. 5 is shown the average profiles of the FeII $\lambda 5169$ Å line for 2016-2020 years. This line shows two emission components in 2017, 2018, 2020 years but one peak in 2016 and 2019 years. Standard deviation of profile exhibit some variations in 2016 and 2019 years. Variation in 2016 year observed in all line's of

Table 4. Profile parameters of the FeII λ 5018 Å line's red and blue components and FW10%.

Year	RVb (km/s)	RVr (km/s)	FW 10% (km/s)	σ_r (km/s)
2016	1	22	-108	99.5
2017	-18.5	18	-132	88
2018	14.5	12	-110	81.5
2019	-47.5	-8	-158	53
2020	-11.5	23	-133.5	138
Average	-12.4	13.4	-128.3	92
rms	23.3	12.7	20.4	30.9

**Fig. 4.** Average profiles (solid lines) and standard deviation (dashed lines) of the Fe II λ 5018 Å line for 2016-2020 years.

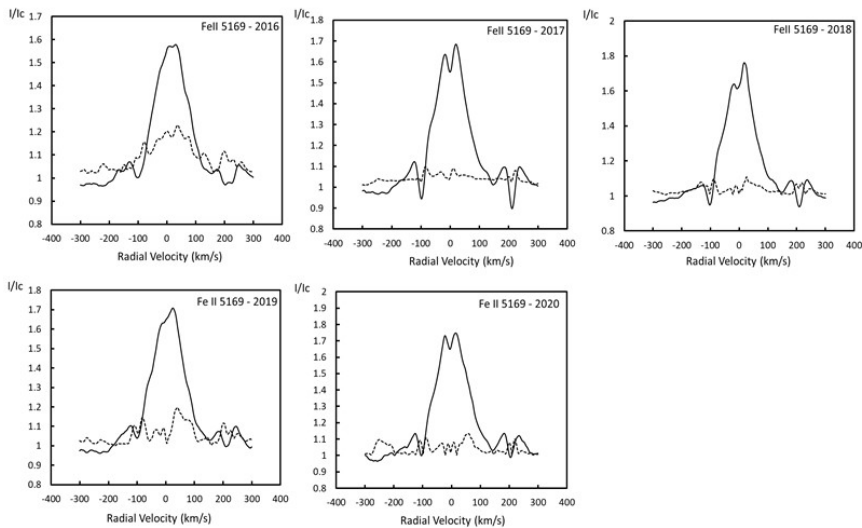
the average profiles. In the Table 5 it is presented profile parameters of the line FeII λ 5169 Å line's red and blue components and parameter FW10%.

The line Fe I λ 4958 Å

As it seen from Fig. 6. Fe I λ 4958 Å is an absorption line. This line is pure photospheric line. Standard deviation of this line shows two picks, so it shown that the line structure changes in its red and blue wings. Rather that we see in the wings some variability due to the star exhibited photospheric activity in this

Table 5. Profile parameters of the FeII λ 5169 Å line's red and blue components and FW10%..

Year	RV_b (km/s)	RV_r (km/s)	FW 10% (km/s)	σ_r (km/s)
2016	15	28.5	-79	122
2017	-15.5	22.5	-83.5	106
2018	-16.5	20.5	-78.5	118
2019	-11	28.5	-74.5	118
2020	-18.5	18	-90	127
Average	-9.3	23.6	-81.1	118.2
Standard deviation	13.9	4.7	5.9	7.8

**Fig. 5.** Average profiles (solid lines) and standard deviation (dashed lines) of the Fe II λ 5169 Å line for 2016-2020 years.

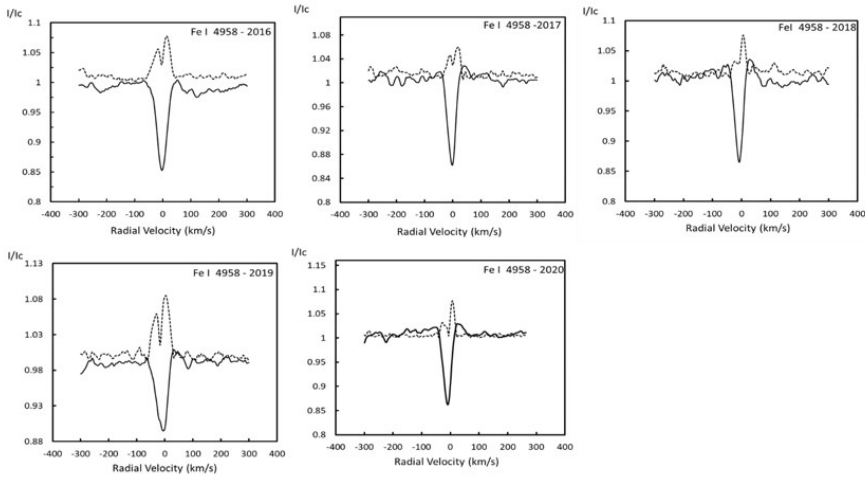
line. Variability dominated mainly in the red wing in all years. In the Table 6 is presented the same profile parameters for the line Fe I λ 4958 Å.

The Si II λ .6371 Å line

In the Fig. 7 is shown the average profile of Si II λ 6371 Å absorption line for each year. It is also absorption line, and its profiles are same to the profiles of

Table 6. Profile parameters of the line Fe I $\lambda 4958$ Å and its standard deviation parameters.

Year	RV_a (km/s)	RV_b (km/s)	RV_r (km/s)	FW10% (km/s)	σb (km/s)	σ FW10% (km/s)	σ_r (km/s)
2016	-5	-14	16	-60	36	-53	40
2017	0	-14	16	-33	21	-31	33
2018	-6	-26	4	-34	14	-35	20
2019	-3	-27	6.5	-48	19.5	-52	48.5
2020	-11.5	-30.5	6	-34	12	-35.5	20.5
Average	-5.1	-22.3	9.7	-41.8	20.5	-41.3	32.4
rms	4.2	7.8	5.8	11.9	9.4	10.4	12.4

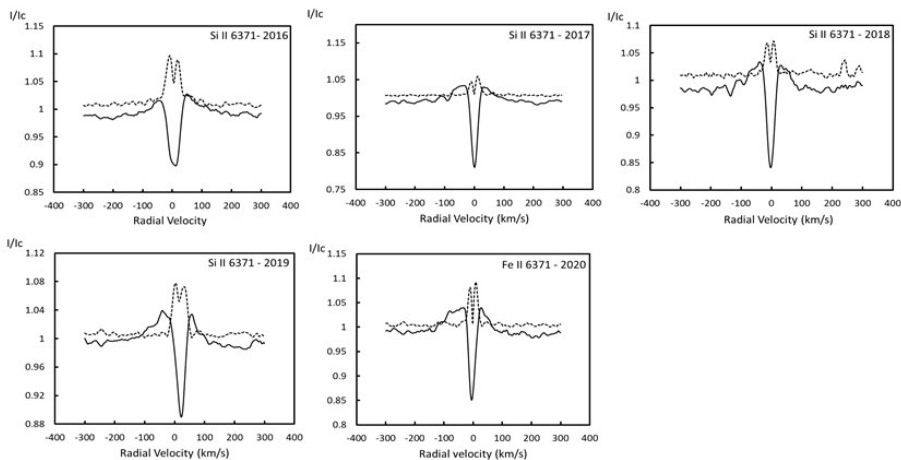
**Fig. 6.** Average profiles (solid lines) and standard deviation (dashed lines) of the Fe I $\lambda 4958$ Å line for 2016-2020 years.

the Fe I $\lambda 4958$ Å line. In all years, in average profile we can see main absorption component, which has weak emission components superimposed to wings. Standard deviation of the profile also exhibit two picks that shows variation in blue and red wings.

Table 7. shows radial velocities of Si II 6371 line's absorption component and in 10% intensity level and radial velocity of standard deviation in 10% intensity level and in picks. Last two rows show average value of radial velocity and standard deviation.

Table 7. Profile parameters of the line SiII $\lambda 6371$ Å and its standard deviation parameters.

Year	RV_a (km/s)	RV_b (km/s)	RV_r (km/s)	FW10% (km/s)	σ_b (km/s)	σ FW10% (km/s)	σ_r (km/s)
2016	13.5	-7	21	-26	34	-32	35
2017	2	-7	13.5	-19	21	-24	41
2018	-1.5	-11.5	9	-24.5	20.5	-28.5	19
2019	24	5.5	33.5	-18.5	54.5	-19	51
2020	-5	-11	11.5	-21.5	28.5	-22.5	23
Average	6.6	-6.2	17.7	-21.9	31.7	-25.2	33.8
rms	11.9	6.9	9.9	3.3	13.9	5.1	13.1

**Fig. 7.** Average profiles (solid lines) and standard deviation (dashed lines) of the SiII $\lambda 6371$ Å line for 2016-2020 years.

The D1, D2 Na I lines

Both of sodium lines exhibit two strong emission peaks with the dib central absorption. In the Fig. 8 and Fig.9 is presents average profiles of the D1, D2 Na I line. Radial velocities of the central absorption peak shows stability, because we suggested that the central absorption component is formed in the photosphere. As it is seen from profiles, there are variation in all years mainly in blue and more intensive red component.

In the Table 8 and Table 9 it is presented radial velocities of both doublet lines red and blue components and FW in 10% intensity level. Last two rows show average value of radial velocity and standard deviation (rms).

Table 8. Radial velocities of D2 Na I line's red and blue component and in 10% intensity level line.

Year	RV_b (km/s)	RV_r (km/s)	FW10% (km/s)	σ FW (km/s)
2016	-34.5	41	-91	86.5
2017	-30.5	27	-91.5	77
2018	-38	41.5	-95	82
2019	-35	28.5	-63.5	64
2020	-39.5	27	-102	75.5
Average	-35.5	33	-88.6	77
rms	3.5	7.5	14.7	8.5

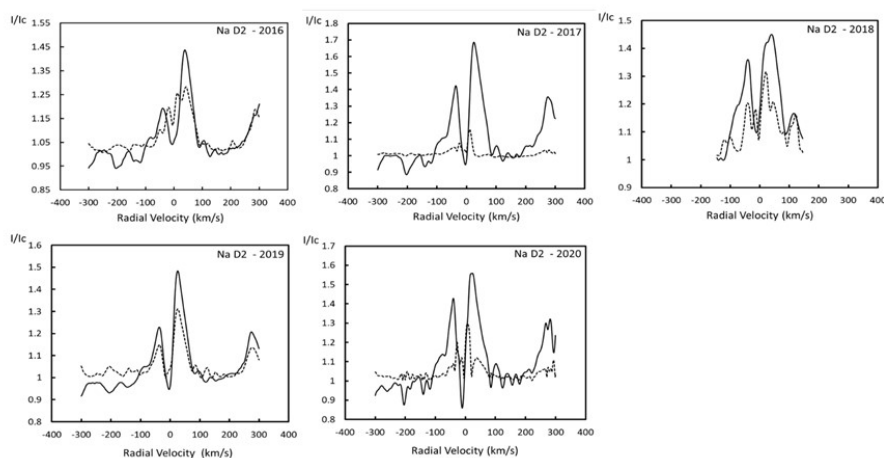


Fig. 8. Average profiles (solid lines) and standard deviation (dashed lines) of the D2 Na I line for 2016-2020 years.

Profile and structure of Na D1 line's standard deviation is similar with D2 Na I line (Fig.9). In 2016 it shows only one emission component but in other years two emission picks with central abortion is observed.

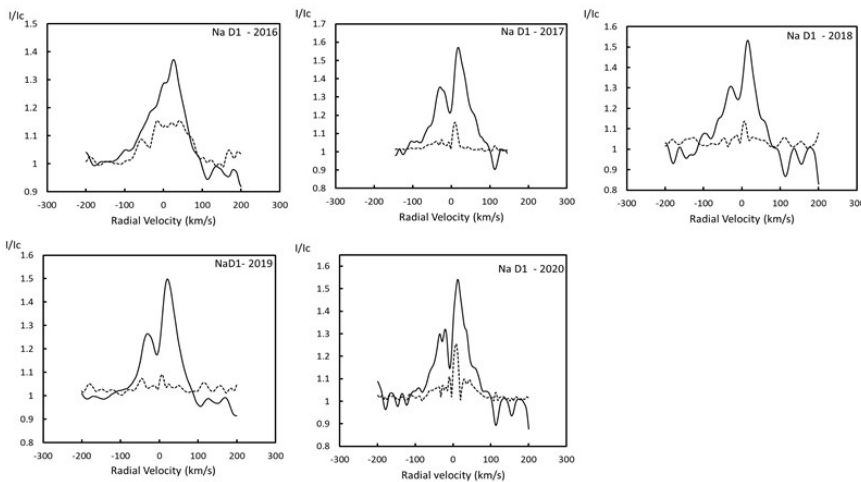


Fig. 9. Average profiles (solid lines) and standard deviation (dashed lines) of the D2 Na I line for 2016-2020 years.

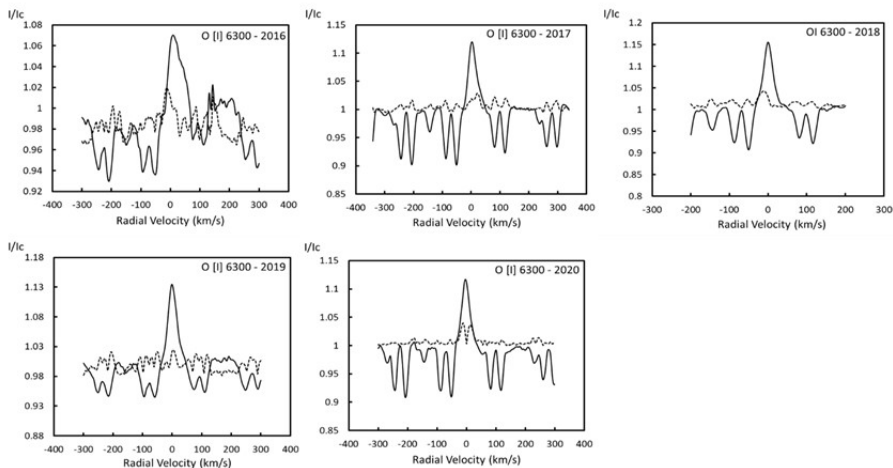


Fig. 10. Average profiles (solid lines) and standard deviation (dashed lines) of the [OI] λ 6300 Å line for 2016-2020 years.

The [OI] λ 6300 Å line

As seen from figure 10 [OI] λ 6300 Å the line is in emission and shows little variations in radial velocities. Standard deviation of average profiles mainly is stable, except of weak form variability in data of 2016 and 2020.

Table 9. Radial velocities of D1 Na I line's red and blue component and FW in 10% intensity level line.

Year	RV_b (km/s)	RV_r (km/s)	FW10% (km/s)	σ FW (km/s)
2016	5.5	26.5	-62.5	80
2017	-25.5	20.5	-73	81.5
2018	-19	17	-73.5	69
2019	-28	23.5	-55	65
2020	-21	13.5	67.8	73
Average	-17.6	20.2	-39.24	73.7
Standard deviation	13.4	5.1	60.3	7.0

Table 10 shows radial velocities of [OI] $\lambda 6300$ Å lines in pick and FW in 10% of intensity level and its standard deviation.

Table 10. Radial velocities of [OI] $\lambda 6300$ Å line's in pick and FW in 10% intensity level.

Year	RV (km/s)	FW 10% (km/s)	σ FW (km/s)
2016	13.5	-18.5	65.5
2017	6.5	-21	50
2018	2	-30	29.5
2019	-0.5	-22.5	24.5
2020	-1.5	-27.5	37
Average	4	-23.9	41.3
rms	6.1	4.7	16.6

4. CONCLUSIONS

The average profile and structure of the $H\alpha$ line show strong variability in 2016 and 2018 years but in other years variability of the profiles is weak. Significant accretion and wind features are not observed, since the full wide of the line at the 10% intensity level are less than 300 km/s.

Variability in $H\beta$ and $H\alpha$ lines are similar, but obviously observed blue and red components in the $H\beta$. As well for emission component width of the $H\beta$ line is thinner than the width of $H\alpha$.

The activity observed in the metal lines does not coincide with the cycle of activity in the hydrogen lines in different seasons. It also shows that the reason for the activity in metal lines can be related to chromosphere activity (magnetic spots on the surface, flares). A variation with a two-peaked structure was found in both the red and blue wings of each metal lines with an absorption profile and with visible emission component in their wings. This indicates possible frequent flares in the star's photosphere. of the star. The strong variation has not observed in this line. Only weak accretion is defined from the outer layers.

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SPECTRAL VARIABILITY OF SUPERGIANT HD 21389

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Late B- and early A-type supergiants are interesting evolved stars exhibiting photometric variability accompanied by spectral changes. Particularly interesting is a group of pulsating stars named after Deneb as α Cyg variables. Deneb-type variables are known for decades to show variability in both brightness and radial velocities. Despite this group of stars undergoing continuous observations, the mechanism responsible for such changes is not yet well understood. In order to better understand and possibly describe this mechanism, the continuous spectral monitoring of early-type supergiants is still a topical task. The main goal of our work is to characterize the spectral variability of one of the Deneb-type variables – HD 21389. We carried out the spectral variability analysis of its spectra taken within 6 years from 2017 up to now.

Radial velocities and lines' profiles of HD 21389 show variability across the whole observational period with the most prominent variability in the H α line. Among other things, we captured the final phase of the High-Velocity Absorption event (HVA) which HD 21389 underwent in 2018, and observed broad emission features around Balmer lines.

Keywords: stars: early-type – stars: massive – stars: individual: HD 21389 – stars: atmospheres – techniques: spectroscopic – techniques: radial velocities

1. INTRODUCTION

Late B- and early A-type supergiants represent a progressive evolutionary phase of massive stars that are evolving redward after they leave the Main Se-

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quence (MS) or already underwent the Red Supergiant (RSGs) stage and moving blueward in their second crossing of Hertzsprung–Russell (H–R) diagram.

Among these stars is a group of variables, called Deneb (or α Cyg) type variables named after its prototype, and exhibiting low amplitude photometric variability ($\Delta V \leq 0.1$ mag) and variability in radial velocity with period 1.2 – 100 days, as well as the variability of spectral lines’ profiles [1]. With their quite short lifetime (ranging from several to tens of millions of years), which leads to an unbalanced final stage in form of a core-collapsed supernova (SN), these objects are rare. Because of their significant variability, we need to know more about them.

HD 21389 is an A0 type supergiant located in Cam OB1 association (e.g., [2]) and included in a list of Galactic α Cyg variables (e.g., [3]). The main parameters of HD 21389 are listed in Table 1.

The story of the HD 21389 started more than one century ago, in 1910 when Mr. Young performed spectroscopic observations and analysis of its spectra ([4]). Based on these results, the star was suggested as a spectroscopic binary [5]; however, its binarity has never been reliably confirmed. The vast majority of previous studies (e.g., [7–9]) discuss variability in radial velocities and profiles of Balmer lines (mainly $H\alpha$ and $H\beta$) that is strongly tied to the active phase. Some studies (e.g., [6, 7, 10, 11]) also revealed variability in metallic lines.

The most extended spectral study of this star was performed by Corliss et al. [14]. Authors analyzed 152 spectra taken with the 1-m telescope of Ritter Observatory between 1993 and 2007 and detected High-Velocity Absorption (HVA) events in spectra from the years 1993-1994. Their study also presents results based on simultaneous photometric observations, that show a strong correlation between photometric and spectroscopic variability with active and quiescent phases of the star. In this paper, we study the spectroscopic variability of HD 21389 using a set of new spectral observations covering 6 years. Our analysis revealed variability in radial velocities, and lines’ profiles, and also brought new results such as the presence of extended emission wings around the $H\alpha$ line, as well as the detection of another episode of HVA.

2. OBSERVATIONS AND SPECTRAL DATA REDUCTION

Optical spectroscopic observations of HD 21389 mainly in $H\alpha$ region were performed during 6 years from 2017 up to 2022 at the Perek 2-m telescope of Czech Academy of Science and AZT-12 1.5-m telescope of Tartu Observatory, University of Tartu, Estonia. Spectroscopic observations performed at the Perek 2-m telescope were done using two spectrographs: Single order spectrograph (CCD700) [15] and Ondřejov Echelle Spectrograph (OES) [16, 17].

Table 1. Stellar parameters for HD 21389.

Parameters	Values	References
Names	HR 1040, CE Cam, BD+58 607	
RA (J2000)	$3^h 29^m 54.74^s$	[17]
Dec (J2000)	$58^\circ 52' 43.5''$	[17]
M_V [mag]	-7.56	
V [mag]	4.54	[29]
B [mag]	5.10	[29]
Spectral Type	A0 Ia	[2]
Parallax [mas]	0.930 ± 0.119	[17]
T_{eff} [K]	9730	[31]
M [$M_\odot$]	19.3	[31]
R [$R_\odot$]	97	[31]
$\log L/L_\odot$	4.87	[33]
$\log g$ [cgs]	1.7	[28]
v_{esc} [$\text{km} \cdot \text{s}^{-1}$]	233	[12]
$v \cdot \sin i$ [$\text{km} \cdot \text{s}^{-1}$]	53	[31]
$\dot{M}$ [$M_\odot \cdot \text{yr}^{-1}$]	$-4.2 \cdot 10^{-7}$	[32]
Distance [pc]	1084^{+124}_{-112}	[30]

Both spectrographs are connected to the primary focus by optical fiber and placed in separate rooms. Observations at the Tartu observatory were carried out using a Single slit spectrograph (ASP-32) that is directly attached to the Cassegrain focus [18]. The information about spectra used in the work is given in Table 2.

Data from ASP-32 and OES spectrographs were processed using standard IRAF tasks, while spectra taken by the CCD 700 instrument were reduced using a dedicated IDL-based package including all standard steps. Additionally, the telluric correction was done using MOLECFIT 1.5.1. software [19, 20]. All spectra are normalized and corrected for barycentric velocity.

Table 2. Summary of spectral data used in present work. R is spectral resolution, N is number of spectra.

Telescope	Instrument	R	Sp. range [Å]	Obs. period	N
Perek 2m	CCD700	13 000	6260 – 6730	Aug 2017 - Aug 2022	86
	OES	50 000	3965 – 8740	Jul 2021 - Oct 2021	10
AZT-12	ASP-32	10 000	6300 – 6580	Aug 2018 - Nov 2021	30

3. RESULTS

In total, we performed a spectral analysis of 126 spectra of HD 21389. The sample spectrum taken on Sep 26, 2018, may be seen in Fig. 1. We mainly focused on the study of the variability of H α line profile, but we also measured radial velocities of selected absorption lines listed in Tab. 3 to test possible binary behavior and to trace the motion of matter in the atmosphere of the star.

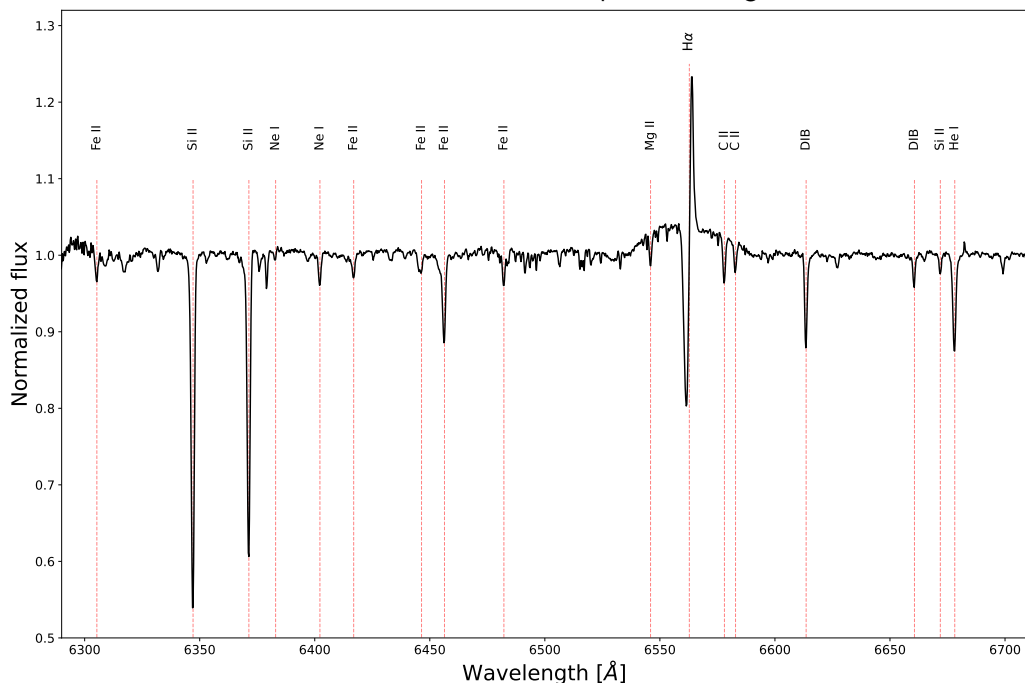
Fig. 1. Spectrum of HD 21389 taken on Sep 26, 2018 in H α region with Perek 2m, CCD700. Telluric lines are removed from the spectrum using MOLECFIT.

Table 3. List of spectral lines of which the radial velocities were measured (λ is air wavelength).

Spectral line	λ [Å]	D700	ASP-32	OES	Spectral line	λ [Å]	D700	ASP-32	OES
Si II	6347.11	✓	✓	✓	DIB	6613.56	✓		
Si II	6371.37	✓	✓	✓	DIB	6660.64	✓		
Fe II	6456.38	✓	✓	✓	H β	4861.32			✓
Mg II	6545.94	✓	✓	✓	H γ	4340.46			✓
H α	6562.80	✓	✓	✓	H δ	4101.73			✓
C II	6578.05	✓		✓	Na I	5889.95			✓
C II	6582.88	✓		✓	Na I	5895.92			✓
He I	6678.15	✓		✓					

3.1. Variability in H α line

As it is known, the best indicator of stellar wind in B- and A- type supergiants is H α line [22]. H α line in HD 21389 spectrum has a complex structure and displays significant variability across all our observations. Pure absorption, normal and inverse P Cyg, and double-peaked profiles were observed. Sometimes highly asymmetric profiles appear, but in our case, that was associated with fading of the HVA event (the left panel of Fig. 2). Selected lines' profiles are shown in the right panel of Fig. 2.

3.1.1. High-velocity absorption event

As was already mentioned in the introduction, HD 21389 is one of the rare stars showing high-velocity absorption events (HVAs) [14]. HVA event is the occasional appearance of deep and highly blue-shifted absorption component detected only in the H α line. The kinematic properties of the HVAs are completely different from those of Discrete Absorption Components (DACs) observed in the ultraviolet spectra of O-type and early B-type stars. HVAs do not propagate outwards, but instead, extend to zero velocity and even indicate mass infall [21].

α Cyg variables with HVA events are rare. This behavior was already observed in a few late B- and early A- type supergiants HD 91619 (B7 Iae), HD 96919 (B9 Iae), HD 34085 (B8 Iae), HD 197345 (A2 Ia), HD 207260 (A2 Iab), and HD 199478 (B8 Iae) [24], [25], [21], [26], [27]. Such events are reported to last

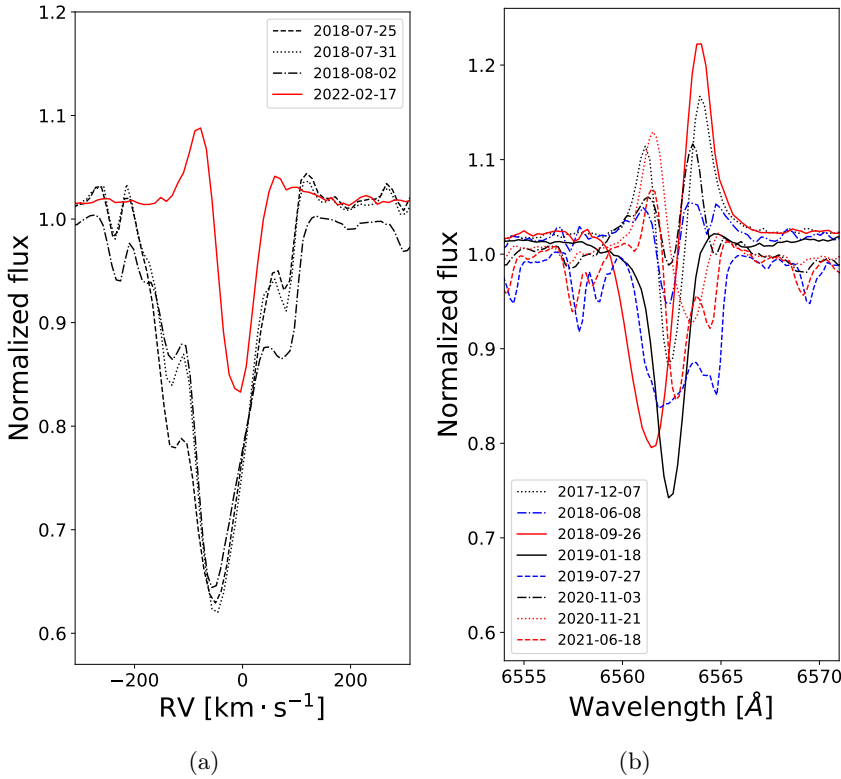


Fig. 2. (a) Lines' profile appearance during final phase of HVA event is demonstrated by black lines. Red solid line is to compare the intensity with profile taken out of HVA event. (b) Selected lines' profiles of H α line.

from dozens of days to several months [21]. There is currently no proper explanation for the formation of HVAs. Israelian, Chentsov, & Musaev [23] attributed them to the effects of magnetic fields, but these stars do not have a such strong magnetic field to fit the observational properties of HVA.

Our data taken during July and August 2018 revealed the presence of **highly asymmetric**, unusually deep and blue-shifted absorption component of H α line profile when the intensity reached 0.6 of continuum level (Figure 3). We detected only one HVA event in our spectra of HD 21389 acquired over 6 years. This indicates that conditions in the atmosphere of HD 21389 necessary for the appearance of HVA events require at least several years to form. However, there is evidence of two consecutive HVA for Rigel (HD 34085) just several months apart [23].

Since these events are associated with significant variability in the H α line without any correlation in other lines, it may be said that the star switches between active phases represented by HVAs and quiescent ones containing no such

events.

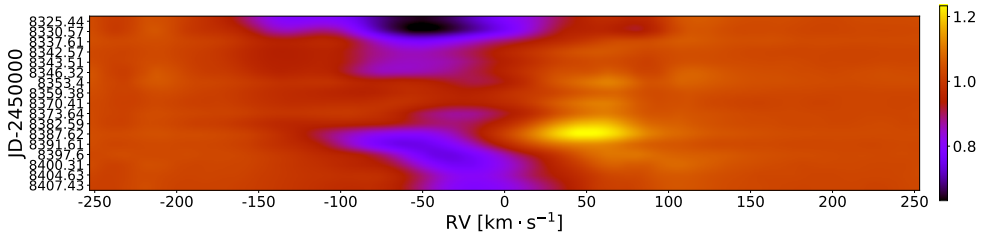


Fig. 3. Dynamic spectrum intercepting final phase of HVA that HD 21389 underwent during July and August 2018. Color bar at the right side represents the flux, thus the darkest part (top black region) shows HVA.

3.1.2. Broad emission wings around $H\alpha$ line

All data contains a prominent feature of extended emission wings around the $H\alpha$ line. Although HD 21389 has been spectroscopically studied many times before, especially the $H\alpha$ region, no one has mentioned this feature. The emission wings extend to about $\pm 1400 \text{ km} \cdot \text{s}^{-1}$ as shown in Fig. 4. We performed the analysis of this feature. Broad emission wings in a few spectra were fitted with Gaussian profile and it turned out that this feature varies on a timescale of a few weeks and from time to time appears asymmetric without any pattern.

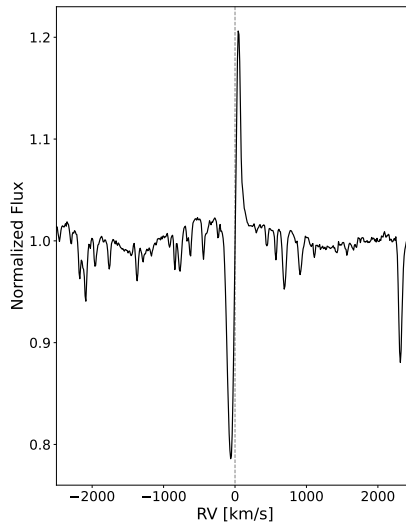


Fig. 4. Extended emission wings around $H\alpha$ line.

3.2. Variability in other lines

All studied lines listed in Tab. 3 display variability in radial velocities (except the interstellar Na II doublet) across the whole observational period and also show asymmetries in lines' profiles while the most striking changes are recorded in Balmer lines, especially in the $H\alpha$ line (Fig. 5).

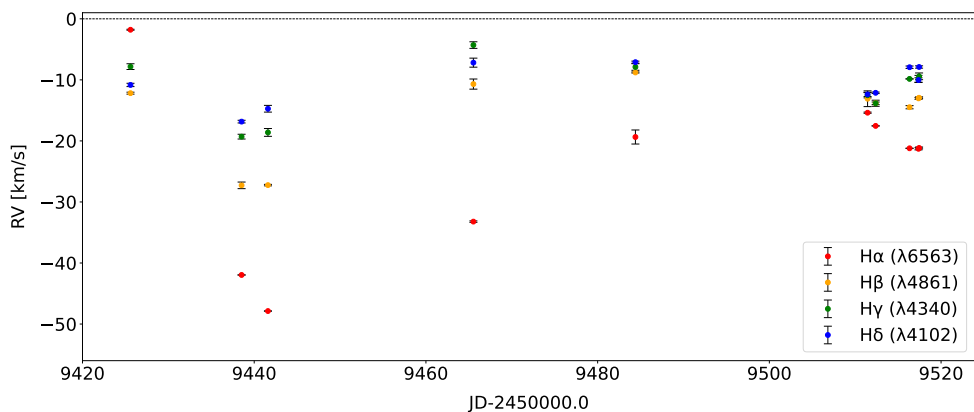


Fig. 5. Radial velocities of Balmer lines measured from OES spectra taken from July to October 2021.

In a study by Abt [11], the radial velocities of selected lines were measured. Among others, the surprising results were obtained for Si II $\lambda 4028$, $\lambda 4030$ and Fe II $\lambda 4508$, $\lambda 4515$, $\lambda 4520$, $\lambda 4522$ lines. Both velocity curves were almost the same in shape but slightly shifted in radial velocity. The same result may be seen in Fig. 6.

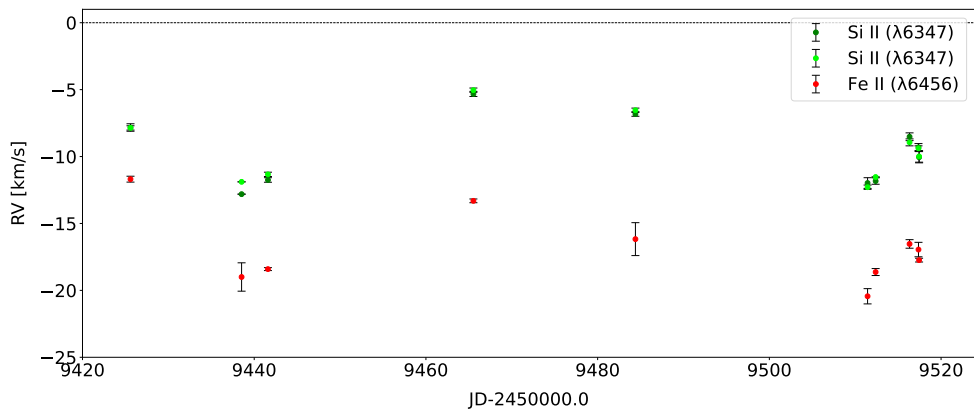


Fig. 6. Comparison of radial velocities of Fe II $\lambda 6456$ and Si II $\lambda 6347$; $\lambda 6371$ lines measured from the OES spectra.

Interesting results were obtained from the analysis of radial velocities of Mg II $\lambda 6546$ line, see Fig. 7. The observations taken with AZT-12 telescope point to some signs of binarity with the period around 400 days, but we need more observational data to be sure.

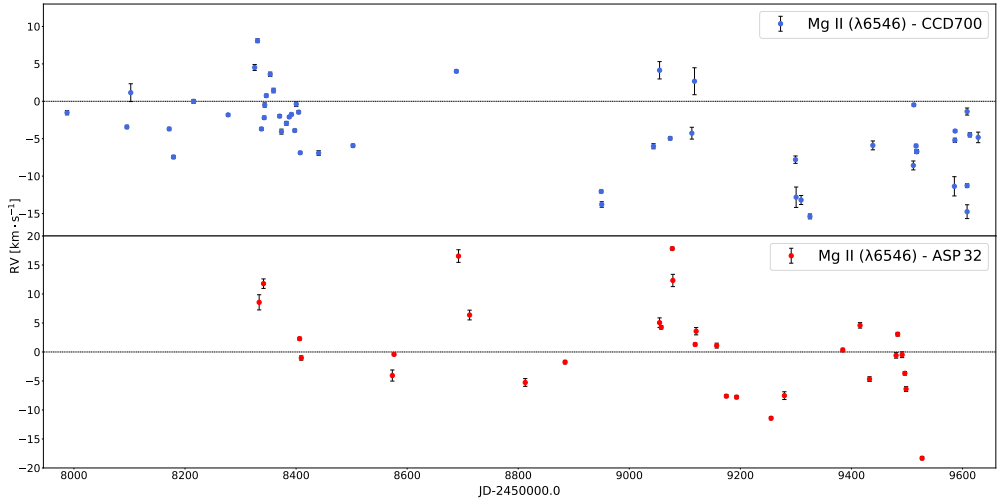


Fig. 7. Measured radial velocities of magnesium line Mg II $\lambda 6546$. Blue dots represent data from CCD700 and red ones are data from ASP-32.

Spectra taken with OES have the largest wavelength coverage in our data set, which allows us to analyze other Balmer lines ($H\beta$, $H\gamma$, $H\delta$, $H\epsilon$). A sample of lines' profiles variability in OES spectra is shown in Fig. 8. As mentioned above, noticeable asymmetries are clearly seen in the $H\alpha$ line profile (Fig. 8 (c)).

4. CONCLUSION

We analyzed spectral variability of A-type supergiant HD 21389 based on medium- and high-resolution spectra collected during 6 years. HD 21389 shows long-term variability (longer than a month) and variability on a short time scale (tens of minutes or several days) in both radial velocities and lines' profiles. The most striking changes were recorded for the $H\alpha$ line. We observed variability with no obvious pattern in the width of extended emission wings and detected HVA (July and August 2018) during which the depth of the $H\alpha$ line reached its maximum. All other measured lines show variability too. Asymmetry in lines' profiles reflects the actual condition of the $H\alpha$ line which is associated with active or quiescent phases of the atmosphere.

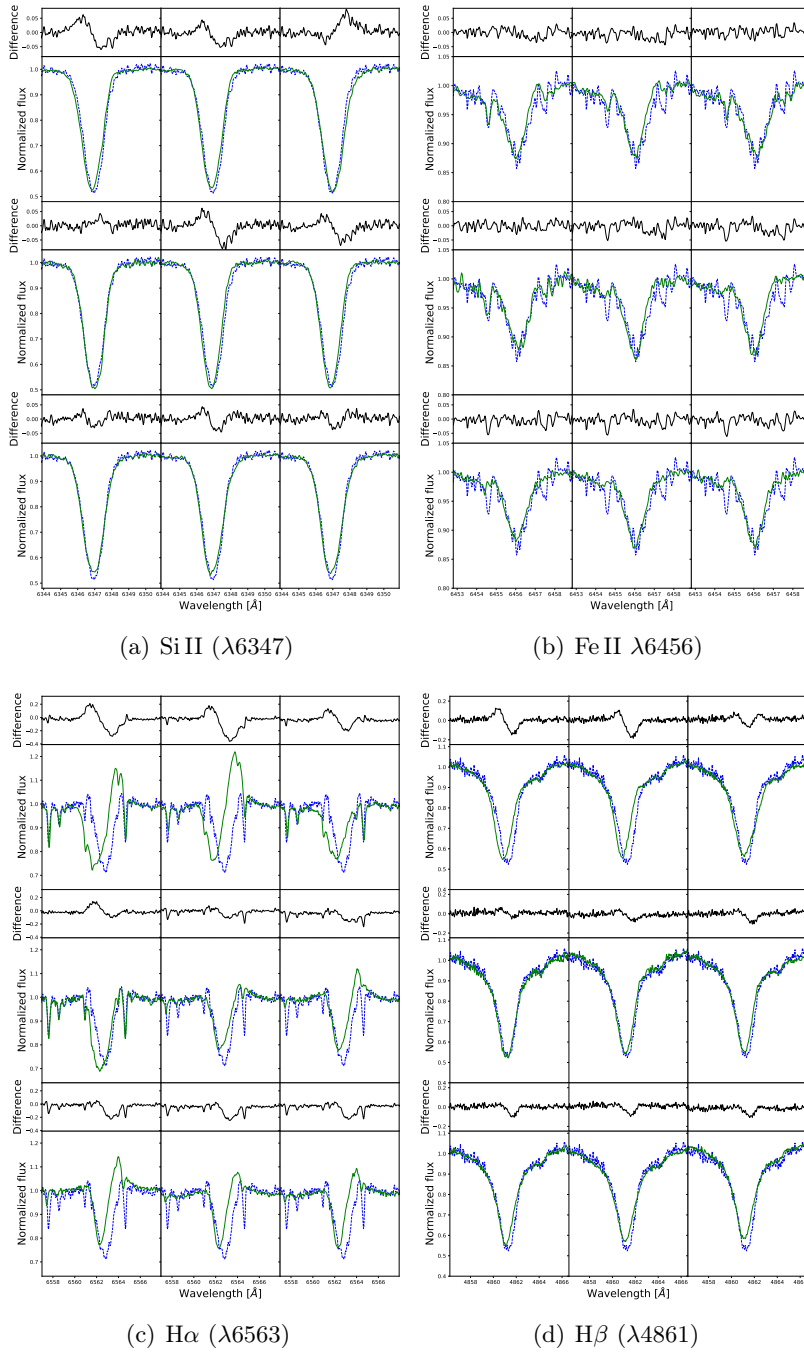


Fig. 8. Line profile variability of Si II, Fe II, H α and H β lines. The blue dashed profile is a reference and the rest of the spectra compared to it are green. Their asymmetry is seen above (black line).

5. ACKNOWLEDGEMENT

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LIGHT CURVES AND FREQUENCY ANALYSIS OF HYBRID δ SCT- γ DOR STARS

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Space observations have greatly improved our knowledge of stellar oscillations since they allowed us to discover many oscillation frequencies with small amplitudes that used to be hidden from the ground observations. One of the interesting phenomena revealed was a large number of hybrid δ Sct- γ Dor stars discovered. These objects are low-mass main sequence stars oscillating in radial and non-radial pressure (p) and gravity (g) modes. The simultaneous presence of p - and g - modes in these stars makes them excellent targets for asteroseismology since these modes together allow to probe both the external and near-to-core layers of the stars. Nevertheless, their location at the Hertzsprung-Russel diagram indicates they might have surface activity (spots) hindering the correct classification of oscillation modes in the frequency spectrum, especially at low-frequency ranges. Additionally, these objects might be in binary systems, which makes mode classification, and thus the explanation of the origin of their light curve variability, an even more complex task. In this work, we present a frequency analysis of the hybrid δ Sct- γ Dor star CoRoT-102314644 and summarize the difficulties that arise when classifying the origin of the light curve variations in this type of objects.

Keywords: Asteroseismology – low-mass stars – main sequence stars – spots

1. INTRODUCTION

Space missions have greatly improved the asteroseismology field, allowing the discovery of even more types of pulsating stars and exciting new features for the already known types of variable stars. Such is the case for hybrid δ Sct- γ Dor stars, for which space observations suggest that the hybrid feature is common among δ Sct and γ Dor stars. This article focuses on hybrid δ Sct- γ Dor stars

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and the challenges we can face when analysing their light curves and frequency spectrum.

δ Sct stars usually have masses between 1.5 and 2.5 $M_{\odot}$ and can be found in the Main Sequence (MS) and post-MS with spectral types between A2 to F5. They oscillate in radial and non-radial modes, which corresponds to spherical harmonics degree $\ell = 0$ and $\ell \neq 0$, respectively. Among the non-radial modes, δ Sct stars show low- to intermediate-order (k) p -modes and low-order g -modes with frequencies in the range [5-70] c/d approximately. These modes are thought to be driven by the κ mechanism in the He II partial ionization zone [1] and it has been proven that the turbulent pressure in the hydrogen ionisation zone also plays an essential role in the excitation mechanisms of these modes [2]. Given that p -modes in δ Sct stars propagate in the external layers of the star, they allow us to explore the external regions of the star.

γ Dor stars, on the other hand, can be found also in the pre-MS and their masses are usually lower, between 1.5 and 1.8 $M_{\odot}$. They show high-order ($k \gg 0$) g -mode periods between 8h and 3 days. These modes propagate in the deep interior of the star, close to the convective core, and are apparently driven by the convective blocking mechanism [3], [4]. They allow us to explore the deep internal layers of the star.

The aforementioned distinction between δ Sct and γ Dor stars has been called into question since diverse studies on samples of γ Dor and δ Sct stars suggest that the hybrid behaviour on these stars is very common [5], [6], [7]. Moreover, apparently, the κ mechanism operates significantly in warm δ Sct and γ Dor stars while the coupling between convection and oscillations is the mechanism responsible for the excitation in cool stars [8].

Hybrid δ Sct- γ Dor stars have been known since 2002 [?]. They are pulsating low-mass stars in the MS but also pre- and post-main sequence) and they offer a unique opportunity to explore the stellar interiors from the deep interior to the surface due to the simultaneous presence of p - and g -modes.

Fig. 1 shows an HR diagram with a sample of γ Dor, δ Sct and hybrid δ Sct- γ Dor stars taken from [5] along with evolutionary tracks from [10]. Violet and green dashed lines represent the boundaries for the theoretical instability strip of δ Sct and γ Dor stars, respectively, according to [11]. From this figure, we can see that the instability strip for δ Sct and γ Dor stars partially overlap suggesting the existence of hybrid stars in this region. Additionally, we can see that there is no delimited region in this diagram for none of the three types of stars and their regions overlap.

To date, a significant number of δ Sct- γ Dor stars are known, but still, the analysis of their low-frequency range represents a challenge due to the variety of phenomena that can manifest in this region. In this article, we will highlight the

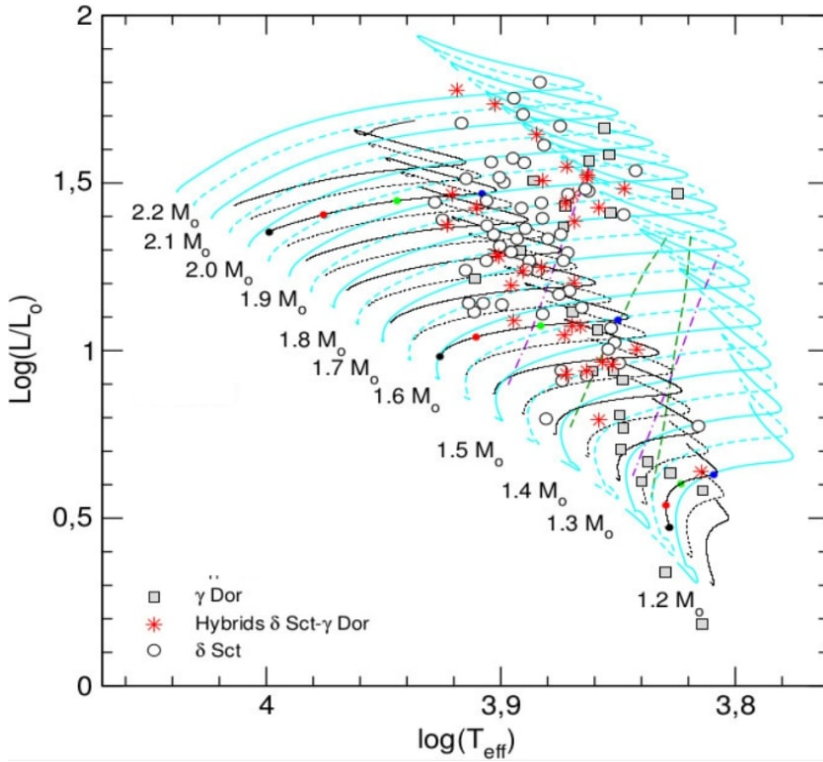


Fig. 1. HR diagram showing the position of a sample of δ Sct (open circles), γ Dor (grey squares) and hybrid δ Sct- γ Dor stars extracted from [1]. Evolutionary tracks for $(Z, f_{OV}) = (0.01, 0.03)$ (in cyan) and $(0.015, 0)$ (in black) were extracted from [10].

most important features to consider in this region with the aim to properly classify and model hybrid δ Sct- γ Dor stars, by following as an example the case of CoRoT ID 102314644. A more detailed analysis of this interesting object is soon to be published in A&A; Sánchez Arias et al. A&A, accepted under revision.

2. COROT 102314644

CoRoT 102314644 was observed by the CoRoT satellite [12] for 148 days. It has a magnitude of $V \sim 12.2$ and its coordinates are $\alpha = 6^{\text{h}}10^{\text{m}}26.73^{\text{s}}$ and $\delta = +4^{\circ}18'12.19''$. In order to analyze its light curve, we first cleaned the data from outlier measurements (usually due to the impact of cosmic rays) and then we removed those frequencies below 0.25 c/d, which print a slope in all CoRoT light curves [13] and the orbital frequency from the satellite ($f_{\text{sat}} = 13.97$ c/d) and its harmonics.

As a result, we obtained a typical light curve of a hybrid δ Sct- γ Dor star, depicted in Fig. 2, where both long- and short-term variability can be observed.

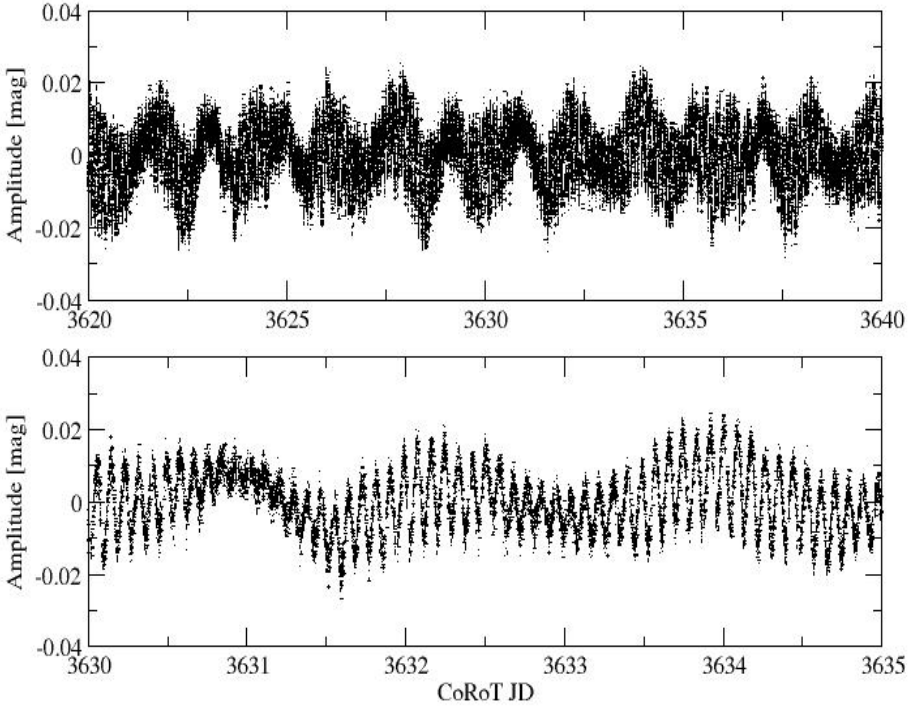


Fig. 2. Light curve of CoRoT 102314644 after correcting it for long-term trends and outliers for different light timescales. A subset over 20 days at the top and a zoom into 5 days subset at the bottom.

The frequency content of this light curve was derived with the package *Period04* [14]. We performed a pre-whitening procedure until a signal-to-noise ratio (S/N) of 5.2 was reached for each frequency, as recommended in [15] for space data. The frequency spectrum obtained is shown in Fig. 3. As expected, two groups of frequencies can be distinguished, one at low frequencies in the γ Dor domain, $[0.3262, 3.6631]$ c/d, corresponding to g -modes and another at high frequencies in the δ Sct domain, $[8.6295, 22.9278]$ c/d, corresponding to p -modes. With the aim to properly identifying each frequency and extract all possible information from the frequency spectrum, a detailed analysis should be performed

in each domain.

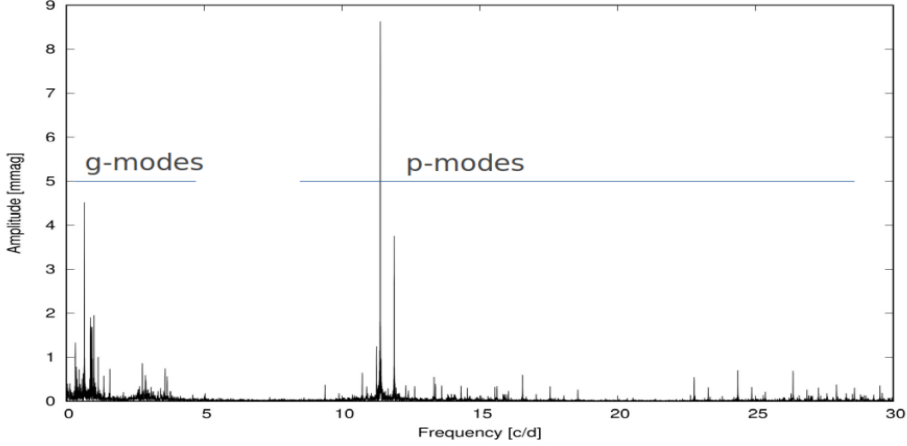


Fig. 3. First Fourier transform showing two separate domains: δ Sct and γ Dor domain indicated by p - and g -modes, respectively.

2.1. γ Dor domain

As mentioned earlier, hybrid δ Sct- γ Dor stars oscillate in high order g -modes. According to the asymptotic theory [16], the difference between two consecutive g -modes with the same harmonic degree l tends to be constant for high radial orders. Therefore, we searched for equally spaced periods in the γ Dor domain, and we found a series of six equally spaced periods with a mean separation of $\Delta\Pi = 1621s \pm 20s$. This quantity is extremely useful to determine the evolutionary stage of the star [17]. As the star evolves in the MS, for masses higher than $\sim 1.5M_{\odot}$, the convective H-core shrink and its edge moves inward. In the asymptotic regime ($k \gg 0$), the period spacing of g -modes tends to be constant and can be written as:

$$\Delta\Pi_l = \frac{\Pi_0}{\sqrt{\ell(\ell+1)}}, \quad (1)$$

with

$$\Pi_0 = 2\pi^2 \left(\int_{r_1}^{r_2} N \frac{dr}{r} \right)^{-1}, \quad (2)$$

where N is the Brunt Väisälä frequency and r_1 and r_2 are the boundaries of the propagation zone of g -modes, which are non-convective zones. Thus, the integral expands over wider regions during the evolution and as a result, $\Delta\Pi$ decrease

during the evolution and can be used as an indicator of the evolutionary state of the star (see, [18]).

There are other features to consider and carefully inspect in the frequency spectrum of hybrid δ Sct- γ Dor stars. It is important to distinguish between 'pure' mode frequencies and harmonics or frequency combinations because for the asteroseismic modelling of the star, only 'pure' frequencies can be used to compare with the theoretical/numerical model. Therefore, we looked for frequency combinations in the γ Dor domain but did not find any. Nevertheless, we detected that the highest amplitude frequency in this domain ($F_2 = 0.65259$ c/d) has a half frequency harmonic ($f_{rot} = 0.3263$ c/d) with lower amplitude. This peculiar arrangement of frequencies usually corresponds to spots or surface activity. The effect of this frequency arrangement in the light curve can be observed in Fig. 4, where we plot the phase diagram using the frequency $f_{rot} = 0.326$ c/d after removing all the pulsational content and only keeping $F_2 = 0.65259$ c/d.

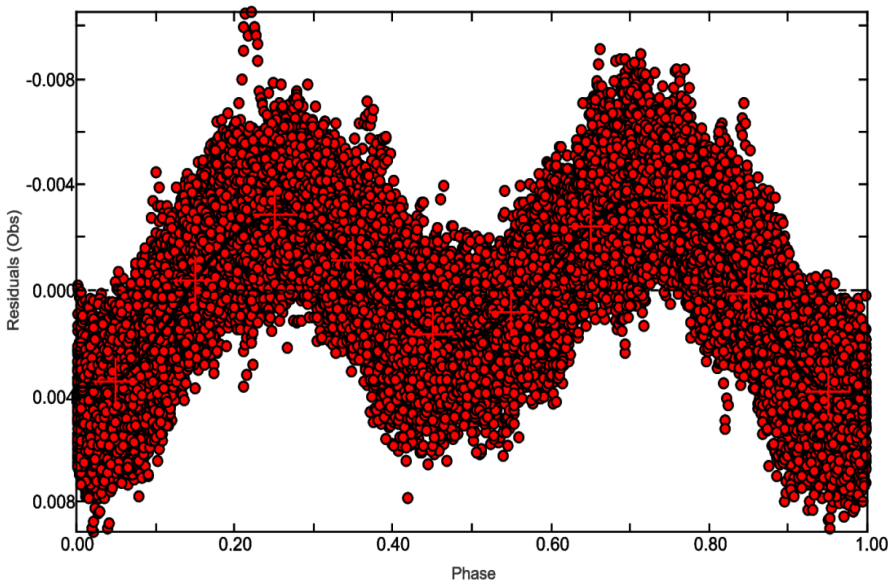


Fig. 4. Phase diagram using the frequency $f_{rot} = 0.326$ c/d after removing all the pulsational content from the light curve.

The double wave depicted in this figure can also originate from a companion forming an ellipsoidal variable system, as shown in [19]. These binary systems are non-eclipsing close binary with $i \approx 0$, whose components are distorted by their mutual gravitation. Assuming a binary system with an orbital frequency equal to f_{rot} and following the method presented in [20], we found possible solutions for the orbital parameters, such as $M_2 = 0.7M_\odot$ and $A = 12R_\odot$ for $M_1 = 1.75M_\odot$

and $R_1 = 2.27R_\odot$, where A is the semimajor axis. Therefore, in order to properly classify this system, it is imperative to obtain spectroscopic data, which is not available yet for this star.

In total, for the γ Dor domain, we found 24 pure frequencies in the range $[0.32, 3.66]$ c/d.

2.2. δ Sct domain

We searched for frequency combinations and harmonics by carefully inspecting the frequency separations, as it was performed in the γ Dor domain.

Another feature to explore while inspecting the frequency spectrum are rotational splittings induced by stellar rotation. Assuming, rigid rotation and considering up to the first order in the perturbations, the components of the rotational multiples are given by:

$$\nu_{nlm} = \nu_{nl} + m(1 - C_{nl})\frac{\Omega}{2\pi} \quad (3)$$

where ν_{nlm} is the central mode of the multiplet, $\frac{\Omega}{2\pi}$ is the rotational frequency and C_{nl} is the mode splitting coefficient which is $C_{nl} \sim 0$ for p -modes [21]. Remarkably, we found one quintuplet in the δ Sct domain centered on $p_1 = 11.39107$ c/d with $\frac{\Omega}{2\pi} = f_{rot}$. The components of this quintuplet are listed in Table 1. This would suggest that f_{rot} is the rotational frequency and CoRoT ID 102314644 is a single spotted star. Nevertheless, another possible explanation for this splitting would be tidally deformed oscillation modes that have variable amplitude over the orbit, in the case that 0.32629 c/d is indeed a binary orbital frequency. Therefore, only time series spectroscopic measurements would allow us to distinguish between these two cases, in order to measure possible radial velocities from a binary system or to distinguish changes in the line-width corresponding to spots over a rotational period.

Additionally, we found several combinations between p - and g - modes. Such combinations of frequencies indicate that their p - and g - modes originate in the same stars. The coupling between p - and g - modes have been proposed by [22] as a way to explore g -modes in the Sun. Interestingly, these combinations of frequencies have been found in other hybrid δ Sct- γ Dor stars namely, CoRoT-100866999 and CoRoT-105733033 studied in detail in [13] and [23], respectively, suggesting that the coupling mechanism proposed by [22] also operates for hybrid δ Sct- γ Dor stars.

In total, for the δ Sct domain, we found 14 pure frequencies in the range $[8.62, 22.92]$ c/d.

Table 1. List of frequencies of the quintuplet.

Quintuplet			
Frequency [c/d]	A [mmag]	Ident.	$p_1 - F_i$ [c/d]
10.73844	0.667	$p_1 - 2f_{rot}$	0.65263
11.06506	0.081	$p_1 - f_{rot}$	0.32601
11.39107	8.680	p_1	—
11.71775	0.083	$p_1 + f_{rot}$	-0.32668
12.04353	0.133	$p_1 + 2f_{rot}$	-0.65246

3. SUMMARY AND CONCLUSIONS

Hybrid δ Sct- γ Dor stars are excellent targets for asteroseismology. Their rich frequency spectrum harbours simultaneously p - and g -modes which allows exploring the deep interior as well as the external layers of the star. A detailed study of its frequency spectrum must be carried out in order to distinguish characteristics of this type of star that helps to extract valuable information. In this article, we mentioned some of them such as the mean period spacing, rotational splitting and signatures of surface activity or a companion.

Our main findings for CoRoT ID 102314644 are the following:

- Two separate frequency domains were found. In the γ Dor domain, [0.3262, 3.6631] c/d, we detected 24 pure frequencies and in the δ Sct domain, [8.6295, 22.9278] c/d, 14 pure frequencies.
- We found an asymptotic series of 6 equidistant periods in the γ Dor domain, with a mean separation of $1621\text{s} \pm 20\text{s}$.
- In the δ Sct domain, we found a quintuplet centred on the highest amplitude frequency of this domain. The splitting in the frequencies suggests that $f_{rot} = 0.32629$ c/d is the rotational frequency.
- The phase diagram corresponding to f_{rot} suggests the presence of surface activity or a companion forming an ellipsoidal binary system.
- We found couplings between p - and g - modes in the δ Sct domain. This phenomenon should provide information about their internal structure and the resonant cavities in these kinds of stars.

In order to properly classify CoRoT ID 102314644 as a single star or a binary system, follow-up spectroscopy measurements are required. Additional information about this star and our analysis will be soon accessible in Astronomy & Astrophysics.

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UNUSUAL CHANGES IN THE SPECTRUM OF AE HERBIG STAR HD 179218

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The results of homogeneous spectral observations of the Herbig Ae-type star HD179218, which were obtained in 2018 on the 2-m ShAO telescope with a spectral resolution of $R=28000$, are presented. The variability of the profiles and parameters of the $H\alpha - H\gamma$ hydrogen lines has been studied. The emission line $H\alpha$ is characterized by two absorption peaks and a central absorption. The ratio of the intensities of the blue component to the red shows variability with a characteristic time of ~ 100 days. We confirmed our previous result, discovered for this star in 2015 on the smooth variation in the profile structure of the $H\alpha$ line. We assume that the observed phenomenon is related to the inhomogeneity of the circumstellar disk of the star.

Keywords: variables:Herbig Ae/Be-stars: circumstellar matter-stars: individual-HD179218

1. INTRODUCTION

HD 179218 (MWC 614, Sp B9-A2) is an isolated Herbig Ae (HAe) type star. The circumstellar surroundings of the star were studied by IR photometry and speckle interferometry by [5, 7], which did not reveal closely spaced components. Spectral studies of the star were performed by [9] and in more detail, in [3, 4].

According to the classification of [10], the spectral energy distribution (SED) of the star belongs to group I, i.e. starting with the infrared band K and further there is an excess of radiation excited in the dust. On the [11] the profile of the line $H\alpha$ is consisting of a stable single-peak structure. Perhaps the star has a close companion, about 2.5 arcsec apart [13]. In the work [1] showed that the star has two dust rings at distances of 1 AU and 20 AU, and the space between from 1 to 6 AU from the star filled with gas. The magnetic field of the star was measured by [6] where on the data 2008 they have got about 51 ± 30 G.

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Our previous studies of this star based on hydrogen lines were published in the work [12]. In this work, we discovered for the first time a wave-like variability in the parameters of the emission component of the $H\alpha$ line on a time scale of about 40 days. In addition, in our work, we have shown the appearance of additional emission and absorption components in the $H\alpha$ line profile, which gradually disappear at the time of the minimum. The aim of this work is to monitor the spectral variability of the star based on new observational data obtained in 2018.

2. OBSERVATIONS

The spectra were carried out in the 2-m telescope of Shamakhy Astrophysical Observatory of Azerbaijan National Academy of Sciences. We used ShAFES spectrographs that works with CCD $4K \times 4K$, spectral resolution is R-28000 in wavelength range $\lambda 3700- 8000 \text{ \AA}$ [8]. The mean signal-to-noise level is $S/N \sim 100$ in the region of the $H\alpha$ line, and $S/N = 40-60$ in the region of the $H\beta$ line. Wavelength calibration have made on the sky and ThAr lamp spectrum. For calibration and processing of spectrograms used the DECH20T software [2]. The method of observations and material processing is described in more detail in the work of [12]. We used 10 pairs of spectrograms of the star for 2018 year. The mean error of positional measurements in the spectra of standard stars was 0.5-1 km/s, and standard deviations in intensities at 0.5%.

In the Table 1 is presented the log of observations, where in columns are respectively presented the names of the spectrum, Julian dates (JD) and the signal-to-noise ratio at the line $H\alpha$. Observations were conducted for the season May-August 2018. For to control of instrument stability and position measurements the spectra of standard stars for each night were obtained.

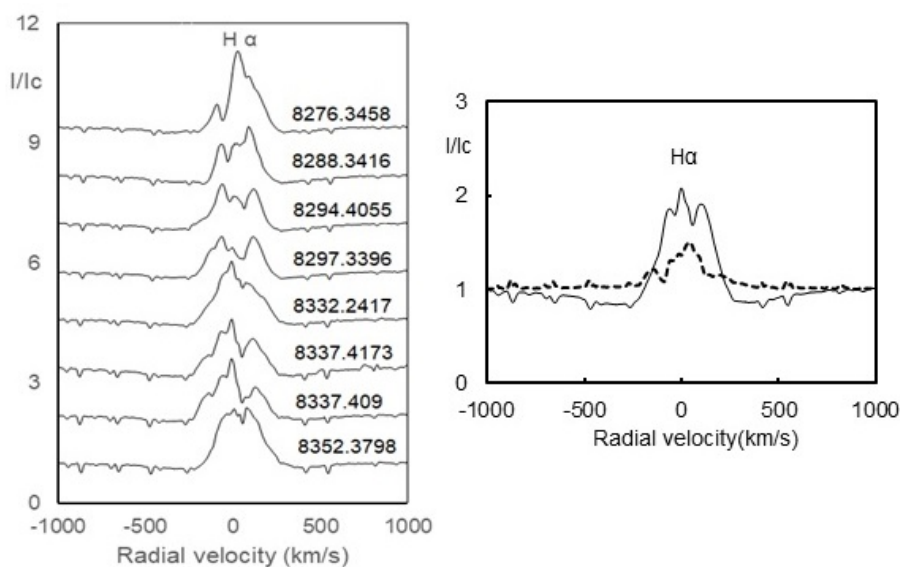
3. MAIN RESULTS

The line $H\alpha$

This line has a complex structure, which consists of an emission component that is superimposed on the core of broad photospheric absorption. The structure of the emission component varies from night to night, sometimes in both the red and blue wings of the line, additional emission components appear and disappear. In the Fig.1 shown all overlaying profiles of the $H\alpha$ line (solid lines), as well as the variation in the root-mean-square (r.m.s) deviation σ (dashed lines) from the average in intensity for a given value of the radial velocity. Here (and further for other line profiles) the ordinate is given by the ratio relative intensity I/I_c , where I - the intensity at a given wavelength of the spectrum, and I_c -the continuum

Table 1. The log of observations of the star HD 179218

JD 2450000+	Sp	texp (sec)
8240.620	KF2253-54	2700s
8276.346	KF2461-62	1920
8288.342	KF2484-85	2400
8294.406	KF2563-64	2400
8297.340	KF2648-49	2500
8327.283	KF3029-30	2500
8332.242	KF 3080-81	2500
8337.417	KF 3124-25	3000
8338.409	KF 3136-37	3000
8352.380	KF 3243-44	2700
8338.409	KF 3136-37	3000
8352.380	KF 3243-44	2700

**Fig. 1.** All profiles, obtained for 2018 of the line $H\alpha$ (left panel). In right panel is presented average profile (solid line) and its standard deviation σ (dashed line).

intensity at the same wavelength. Hence it can be seen that the main variability in the central emission occurs at the peak, and also to a lesser extent on both

wings. It is also seen that the intensity varied on the blue wing is noticeably larger than on the red wing.

As can be seen from Fig.1 in JD 2458276 the $H\alpha$ line has a weak blue emission component, which for next nights show a gradual increase in intensity. Simultaneously, the intensity of the red component gradually decreases. At the end of the season, for about 112 days, the profile of the line $H\alpha$ has the invers form with of the first date profile. In the right panel, rms structure σ of the profile is exhibit variability mainly at the red component and in weak form in the blue component. The same variability in the $H\alpha$ line profile we have observed in our previous work for the star HD 179218 9 (Ismailov et al. 2019). Such type profile variations in the $H\alpha$ emission line obtained in that work the same time was accompanied with variations of spectral line radial velocity and equivalent widths of the line in time scale at 40 days. In the Fig.2 shown the diagram of variations

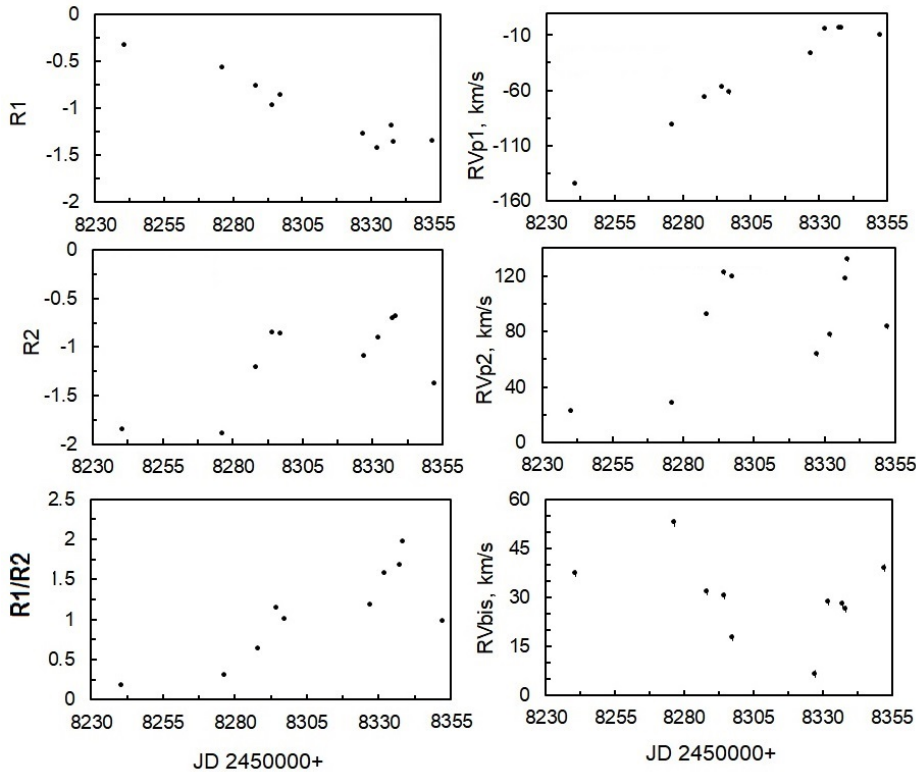


Fig. 2. Time variation of some parameters for the emission line $H\alpha$ and in 2018. From left to right, depths R1 and R2 and accordingly its radial velocities RV_{p1} and RV_{p2} , and in bottom relative intensities R1/R2 of emission peaks and whole bisector radial velocity RV_{bis} of the $H\alpha$ line.

of the time variation of some parameters for the emission line $H\alpha$ and in 2018. From left to right, emission peaks blue and red peaks intensities (depths) $R1$ and $R2$ and accordingly its radial velocities RV_{p1} and RV_{p2} , and in bottom relative intensities $R1/R2$ of emission peaks and whole bisector radial velocity RV_{bis} of the $H\alpha$ line. As can be seen from this diagrams, showed profile variations of the line simultaneously exhibit of the intensity and radial velocity variations of emission peaks, relation of peaks intensities $R1/R2$ and RV_{bis} parameters. Wave-like variation of the parameter RV_{bis} is occurred nearly for 112 days. This result on a smooth variation in the profiles and spectral parameters of the $H\alpha$ emission line confirms our first result and shows that the variability in the line possible is due to the inhomogeneity in the circumstellar disk.

The $H\beta$ Line

In the line $H\beta$ we have observed mainly as a wide photospheric wings, on which at some nights are superimposed weak emission which causes wing asymmetry (Fig.3). From the fig.3 seen that, intensities of the emission components show variations from night to night.

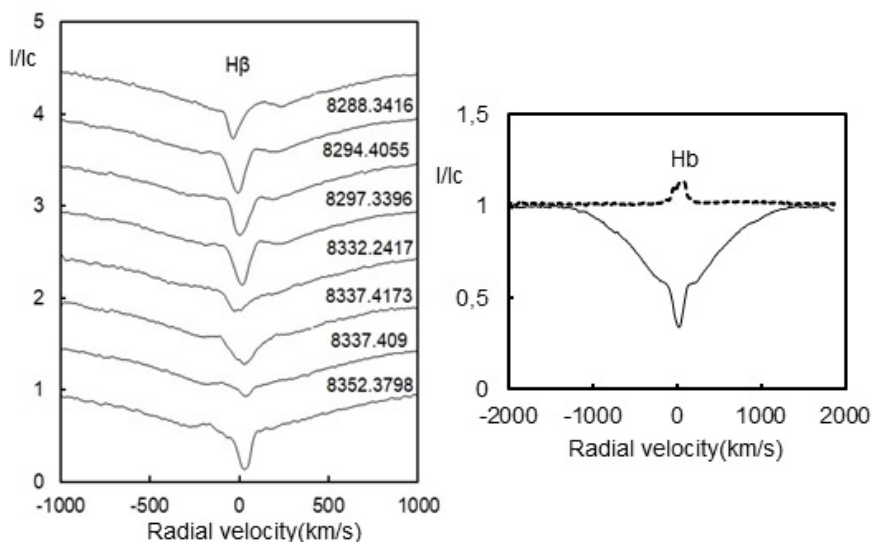


Fig. 3. The profiles of the line $H\beta$ (left panel) obtained in 2018. On the right panel average line profile (solid line) and its standard deviation (dashed line).

In the Fig.4 is presented the diagrams of time variations in the spectral parameters EW(equivalent width), FWHM (half-width), RV_{bis} (radial velocity at half

intensity) and peak. RV_p – radial velocity of the deepest absorption component. As seen from the Fig.4, σ structure of the line (dashed lines) the peak of the line $H\beta$ exhibit similar variation with the line $H\alpha$.

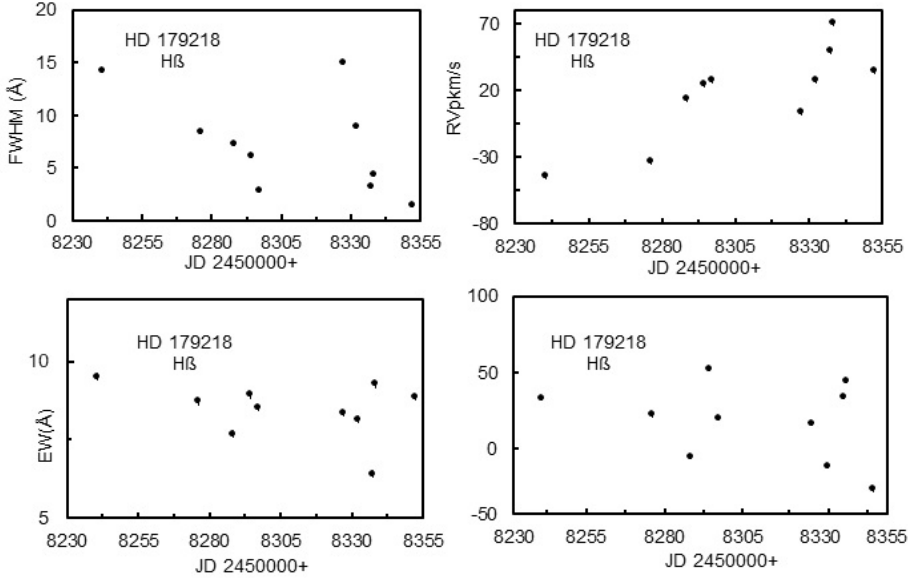


Fig. 4. The profiles of the line $H\beta$ (left panel) obtained in 2018. On the right panel average line profile (solid line) and its standard deviation (dashed line).

The $H\gamma$ Line

The $H\gamma$ line has a similar profile to the $H\beta$ line (Fig.5): the profile is purely absorption, and the weak emission component superimposed on the wings slightly distorts the symmetry of the wings.

In the Fig.6 is shown time variation of parameters of the $H\gamma$ lines. As seen from Fig.6, the spectral parameters EW(equivalent width), FWHM (half-width), RV_{bis} (radial velocity at half intensity) and peak RV_p – radial velocity of the deepest absorption component mainly not exhibit strong variations. Only the parameter FWHM is demonstrated some decreasing at JD 2458327, perhaps due to increasing emission component.

4. CONCLUSIONS

The 40-day cycle in the $H\alpha$ line was detected from richer spectral material, according to observations in 2015 (Ismailov et al. 2019). It was shown that the

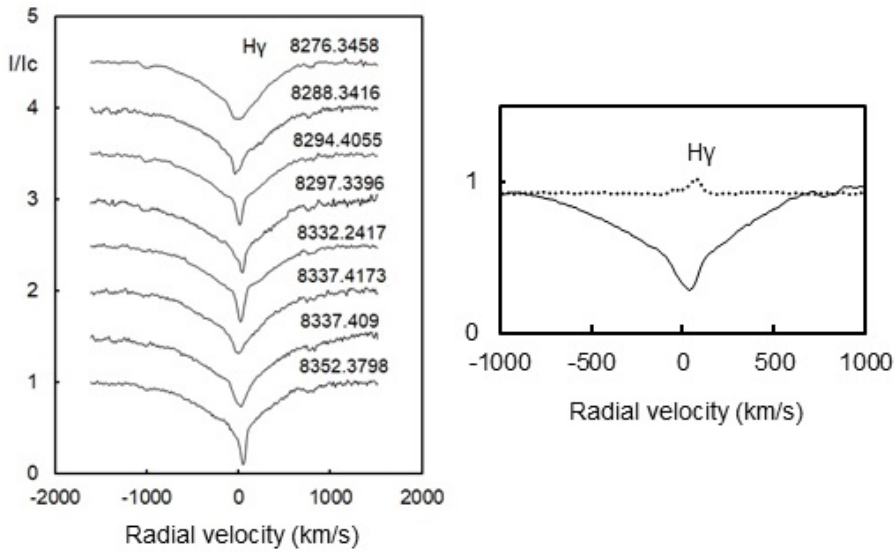


Fig. 5. Time variation of parameters of the absorption lines $H\beta$ for the data 2018.

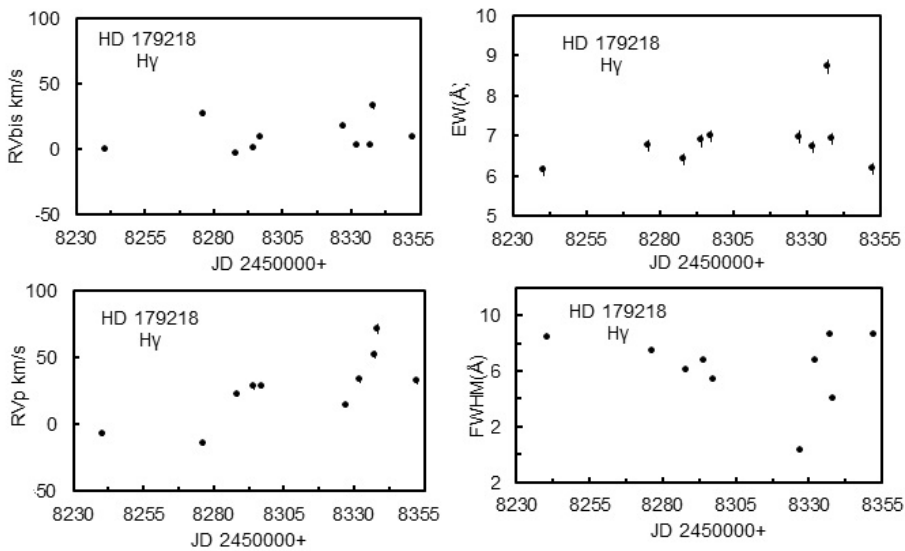


Fig. 6. The profiles of the line $H\gamma$ (left panel) obtained in 2018. On the right panel average line profile (solid line) and its standard deviation (dashed line).

equivalent widths and radial velocities of the emission component in the $H\alpha$ line demonstrated variation with a characteristic time of 40 days. During this cycle,

the line profile changes simultaneously: an unusual variation in the profile of the $H\alpha$ near the minimum on the descending and ascending the leading branches of the first wave of changes in the spectral parameters. Despite the fact that the observational data in 2018 are small, the obtained variability in the $H\alpha$ line confirms our previous results. Here, the RV_{bis} parameter indicates a variations in a sinusoidal shape that lasts about 112 days. Perhaps the star exhibit a certain quasi-cyclic variability in the emission component.

Based on the results obtained in this paper, we can draw the following conclusions:

1. For the 2018 data the spectral parameters of the lines $H\alpha$ and $H\beta$ are demonstrated synchronous variation in the form of smooth wave for 112 day;
2. For 112-days we have observed two invers structure of the $H\alpha$ line profile. Intensities and radial velocities of Ib/Ir components is exhibited smooth variations.
3. We assume that the observed variability is due to rotational modulation, which is facilitate by asymmetry in the circumstellar disk. Such disk asymmetry in disk may be a result of presence another circumstellar bodies in keplerian orbit of the star.

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RESULTS OF SPECTRAL STUDY OF SEVERAL PECULIAR GALAXIES

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We present results of our investigation of several peculiar galaxies (IC 883, UGC 1198, UGC 4261) chosen from the catalog of the polar ring galaxies. This research was based on the detailed analysis of long slit and 3D spectral data obtained with the 6-m telescope (using the integral field and high resolution long-slit spectroscopy) for these objects. We revealed that all galaxies have the complex structure and kinematics of both gaseous and stellar components. As a result of observing the distribution of stellar age and metallicity in galaxies, we could assume their type and get an understanding the processes in these objects. We found that all objects under study do not belong to classical galaxies with polar rings, and they are going through different stages of the merging at present.

Keywords: galaxies; peculiar galaxies; interaction of galaxies — structure, kinematics, stellar population, metallicity, age

1. INTRODUCTION

The study of the processes of formation and evolution of galaxies is one of the most actively developing areas of modern astrophysics. Various types of interaction between galaxies (approach, merging, collision) occurring in the process of evolution lead to the occurrence of structural and kinematic features in galaxies (bars, warped disks, inner and outer rings/disks, multispin components, etc.). The first works on the study of peculiar galaxies with a multicomponent structure date back to the 80-90s of the last century. A program for the photometric and spectral study of polar ring galaxies (PRGs) included in the Whitmore catalog [1] was launched In Scientific Research Astronomical Institute of St. Petersburg University named after V.V. Sobolev. An analysis of the work carried out in subsequent

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years by various scientific groups, including our own, showed that, along with classical PRGs, there are a large number of peculiar galaxies with a multicomponent structure. To date, numerous surveys have been carried out using multicolor photometry and panoramic spectroscopy for hundreds of galaxies. However, the study of the photometric structure, kinematics, stellar composition, and star formation processes of individual objects makes it possible to reveal a more complex pattern of peculiarities. This article is part of our project for a detailed study of peculiar galaxies in which photometric signs of interaction are observed or a multicomponent kinematic structure is suspected.

2. OBSERVATIONS AND REDUCTION

The observations of IC 883, UGC 1198, and UGC 4261 were performed at the prime focus of the 6-m telescope at the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS) with the SCORPIO focal reducer [2] in the modes of “direct imaging”, Fabry-Perot interferometer (FPI), and long-slit spectroscopy as well as with the Multi-Pupil Fiber Spectrograph (MPFS) (see the SAO RAS site¹⁾, [3]). The detector was an EEV 42-40 2048 × 2048-pixel CCD-array (the pixel size is 13.5 × 13.5 μm). A log of observations for galaxies under study is given in the Table 1.

For the galaxies’s central regions, the spectroscopic observations in the green range were obtained with the MPFS, which allowed the velocity fields of both gaseous and stellar components to be constructed.

The large-scale velocity fields, velocity dispersion fields, and monochromatic images of the ionized gas were constructed from observations with the FPI, using gaussian fitting of the H α and/or [NII] λ 6584Å emission line profiles.

For all galaxies, long-slit spectra along their inner features or outer filaments were obtained with SCORPIO + long-slit mode in red and/or green spectral regions.

To analyze the velocity fields, we used the “tilted-ring” method ([4], [5]). It allows one to determine the positions of the dynamical center and the dynamical axis, to refine the galaxy’s inclination to the plane of the sky, and to construct the rotation curve.

The ULySS²⁾ software package was used to obtain information about the stellar population of galaxies. This package is based on simple stellar population (SSP) models constructed with a high spectral resolution [6]. The models were computed with an initial mass function from [7]. From the full range of metallic-

¹⁾ http://www.sao.ru/hq/lsvfo/devices/mpfs/mpfs_main.html

²⁾ <http://ulyss.univ-lyon1.fr>

Table 1. Log of observations.

Spectroscopic observational material				
Object	Instrument	Field	Spectral range, Å	Spectral resolution, Å
IC 883	FPI	$6' \times 6'$	H α	2.5
			[NII]6584	2.5
	MPFS	$16'' \times 16''$	4428–5963	2.5
	Long slit	$1'' \times 6'$	5700–7400	5
UGC 1198	Long slit	$1'' \times 6'$	3900–5700	5
			3100–7300	10
			4800–5570	2.2
UGC 4261	FPI	$6' \times 6'$	H α	2.5
	Long slit	$1'' \times 6'$	5700–7400	5
			3900–5700	5
			4800–5570	2.2
	MPFS	$16'' \times 16''$	4431–5966	2.5

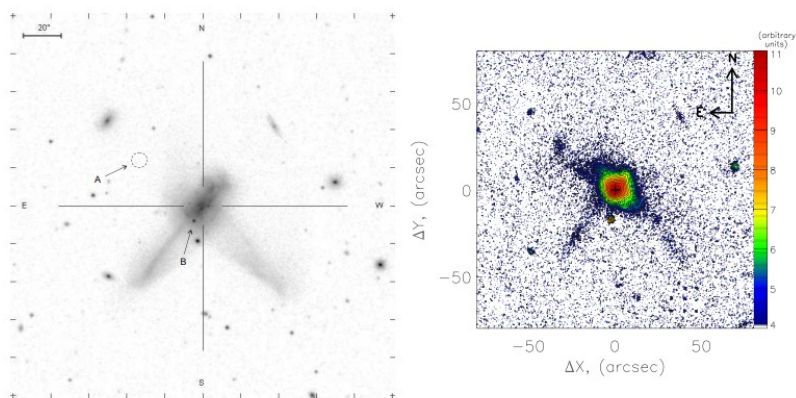


Fig. 1. Left: the *gri* image of IC 883 from the Sloan Digital Sky Survey (<http://www.sdss.org/>). Arrows indicate the “A” and “B” regions discussed in the paper. Right: an image of IC 883 in the H α + [NII] emission lines with the subtracted continuum. $1''$ corresponds to 0.5 kpc ($H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$).

ities and ages we picked the most suitable model with one stellar population to each long-slit spectrum. In the cross-correlation we used the spectrum obtained by convolving the model with the instrumental profile and took into account the kinematic parameters (the velocity and velocity dispersion). Since there is strong emission in the galaxies's spectra, the Balmer emission lines and [OIII] and [NII] lines were also included in the model spectrum.

To analyze the photometric structure of galaxies, photometric observations in the Johnson B and V bands and the Cousins R_c band as well as with a pair of medium-band filters were carried out with the SCORPIO + “direct imaging” mode. As a result, images of UGC 1198 in the B, V, R_c bands and IC 883 in the $H\alpha$ + [NII] emission lines without any continuum were constructed.

3. RESULTS AND DISCUSSION

3.1. IC 883

The galaxy IC 883 (UGC 8387, ARP 193, VV 821, etc.) is an inclined peculiar disc galaxy with a long, almost linear southeastern tail and a faint diffuse southwestern tail (Fig. 1). At the distance of $\approx 8.5''$ from the galaxy center to the southeastern direction, one can see a compact brightening indicated by the letter “B” in Fig. 1. This feature presents in broadband optical and IR images too (see, for e.g., Fig. 1 from [8]) and coincides with the compact X-ray SE-source by the position [8]. The high infrared luminosity of IC 883 and the existence of two tidal tails are explained by the recent merging of two disc galaxies (e.g., [9]). The optical spectra of the galaxy also pointed on the AGN activity, and it was classified as AGN + starburst composite in [10].

As a result of the analysis of the large amount of our material for IC 883, it was ascertained the following. (The detailed results of observations and their analysis have been published in [11]).

In general, the velocity field of the main body is typical for disc galaxies: the ionized gas and the stars rotate around the galaxy minor axis. The position difference of dynamic axes of the stellar and the gaseous disks was found. This indicates that the system is still in the perturbed state. The youngest stellar population ($2-5 \times 10^8$ years) has the metallicity $+0.3 \pm 0.1$ dex and belongs to the circumnuclear region. The age and metallicity of the stellar disk at $r \geq 5''$ are 1 ± 0.1 Gyr and -0.4 ± 0.3 dex. Regions with signs of shock waves in a gas medium ($[\text{NII}]/H_\alpha > 1.5$) are observed in the main body of IC 883 along the minor axis. At the same region the gas component shows large velocity dispersions up to 250 km/s. The processes of star formation are going on all over the disk especially in the central region of the galaxy ($r \leq 3''$) and in the tails.

Romero-Cañizales with co-authors in [12] revealed great nuclear star formation activity $\text{SFR} = 157 M_{\odot} / \text{year}$ with $\text{SN} = 1.1$ per year and detected a number of radio sources in the nuclear region and consistent with AGN and SNs. Based on the X-ray and VLBA data, there were discovered the core-jet structure in the radius about 1 kpc and the jet have subluminal proper motion [13]. Based on the VLT observation, Herrero-Illana with co-authors in [14] proved the SFR for the IC 883, estimated the contribution of AGN energy to the all luminosity of this object and found that it is not more than 5%.

We have found that forbidden lines are very intensive and the H_{α} line is in absorption in the center of the compact “B” region. Furthermore, it has been ascertained the kinematic decoupling of this area — its counter-rotation with respect to the main body with a velocity range ~ 120 km/s. We determined its age and metallicity (4 – 8 Gyr and $-1.7 - -1.$ dex), as well as a lower mass estimation of this region within a radius of $1''.5$ ($8.4 \times 10^8 M_{\odot}$). Our analysis of kinematics, age, metallicity, and mass of the “B” region indicates that it is neither globular cluster nor HII region of the galaxy main body, but represents a separate system and can be a dwarf Im galaxy or a remnant of spiral companion galaxy destroyed during the merging.

The velocities in the southeastern tail do not correspond to the circular rotation around the minor axis of the galaxy, therefore this structure can be either a remnant of a destroyed satellite or a fragment of the unwound bent spiral arm. The second variant seems to us the most likely. The similarity of the chemical composition of the galaxy main body and the southeastern tail as well as simulations of similar structures [15] evidence in favor of this assumption.

On the continuation of the northeastern protrusion the weak region “A” radiating in emission lines (Fig. 1) but invisible in broadband images of IC 883 was detected.

The observed peculiar structure of the object under study was, probably, formed as a result of the merger of two galaxies. The morphology and kinematics of the tidal tails and main body of the galaxy, concentration of the gas to the center point out on the middle/late stage of the merging. Based on our results one can say that the “A” region, SW-tail, and NE- and SW-protrusions apparently form a system of the ionized gas which has a complex knotty appearance and a large spread of line-of-sight velocities and moves approximately along the minor axis of the galaxy. Perhaps, this gas was pulled off from a companion galaxy. The resulting cumulative distribution of velocities in this structure does not allow to say that there is a formed polar ring in the galaxy; thus, at present IC 883 does not belong to the class of galaxies with polar rings. The “B” region is perhaps a dwarf Im galaxy or a remnant of spiral companion galaxy destroyed during the merging. The gas of the cloud “A” and SW-tail can be ionized by an

active nucleus.

3.2. UGC 1198

UGC 1198 is a small galaxy which shows a slight enhancement along the minor axis in the inner region, especially toward the north [1], and two linear structures elongated approximately along the main body of the galaxy (Fig. 2). A slight dust lane is present on the east side. A bright spot (indicated by the

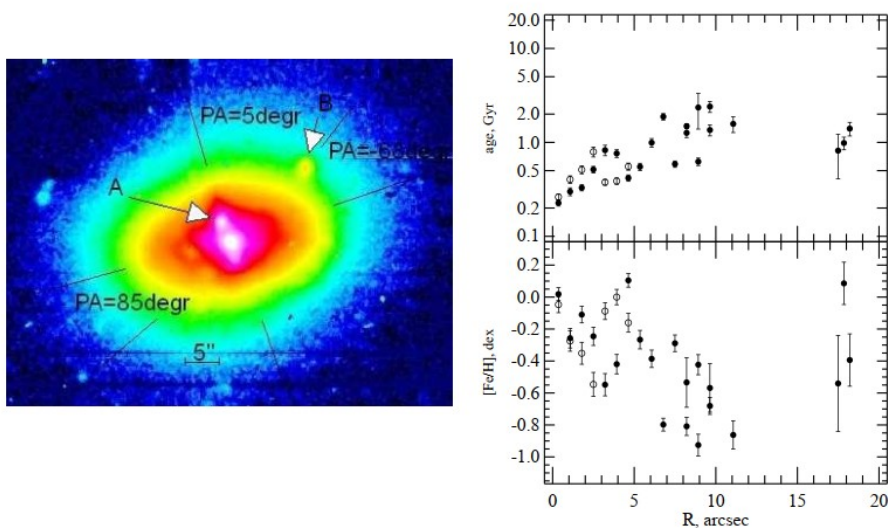


Fig. 2. Left: The image of UGC 1198 in B -band taken from: <http://www.astro.spbu.ru/PolarRing/prg.html>. The positions of the slit during our observations are shown. Arrows indicate the “A” and “B” objects discussed in the paper. North is up and east is to the left. $1''$ corresponds to 0.9 kpc, $H_0 = 72$ km/s/Mpc. Right: Dependences of age (top) and metallicity (bottom) of the stellar population of UGC 1198 on distance along $PA = -68^\circ$.

letter “A” in Fig. 2) is observed at $5''$ to the north approximately along the minor axis. A faint elliptical object (the letter “B” in Fig. 2) is located $17''$ NW of the galaxy center. The observed morphology and the $B - V$ color index distribution of UGC 1198 suggest that the slight enhancement along the minor axis can be an almost edge-on warped disk or ring [16].

As a result of the analysis of our material obtained for UGC 1198, it was ascertained the following. (The detailed results of observations and their analysis have been published in [17]).

Based on our study, we can conclude that UGC 1198 is a dwarf elliptical galaxy (dE) with evidence of interaction. This is suggested by the relative com-

pactness of the object ($R \approx 3.5$ kpc at a level of $\mu_B = 26.0$ mag/□") and its basic photometric and kinematic characteristics.

Our study of the kinematics of UGC 1198 showed that we observe at least two systems. One of them is associated with the stellar system of UGC 1198 itself with weak rotation (40 km/s) around the minor axis of the galaxy. The second system is associated with the gaseous disk/ring rotating with a velocity of ~ 110 km/s at an angle of 72° to the equatorial plane of the galaxy. The dynamical centers of both systems coincide within the error limits.

The gaseous polar disk/ring could be formed during the merging of a dwarf elliptical galaxy characterized by a small amount of gas with a galaxy of approximately the same or lower mass containing the gas. The fact that almost all of the gas is concentrated within the central kiloparsec suggests the accretion of gas onto the dynamical center of the system as the companion is disrupted. This process led to strong star formation at the center and in the regions of dynamical contraction in the accreting matter itself. The brightening "A" which is distinguished photometrically and spectroscopically at a distance of $5''$ to the north of the galactic center and has a size of ~ 300 pc can be such a region. The colors of this region ($B - V$ and $V - R_c$ are $0^m.32$ and $0^m.85$, respectively) point to active star formation in it. The difference between the line-of-sight velocities of region "A" and those of the gaseous disk/ring at this distance (by about 20 km/s) is most likely related to the intrinsic noncircular motions.

At the galactic center there is good agreement between the metallicities of the gas and young stars (the metallicity is, on average, -0.3 dex, the age is 2×10^8 yr; Fig. 2). The stars with an age of 2×10^9 yr make a major contribution (90%) to the luminosity at $r > 5''$. The merging of galaxies that gave rise to UGC 1198 can be assumed to have occurred less than one billion years ago.

3.3. UGC 4261

The galaxy UGC 4261 was included by [1] into the catalog of PRGs into the group of possible candidates for such objects under the number C-21 due to its peculiar morphology (Fig. 3). The extended structure crossing the irregular body of this object looks like an open ring. Spectral observations confirmed the existence of two kinematic almost orthogonal subsystems [18]. In their photometric study of UGC 4261, Reshetnikov with co-authors [19] suggested that the galaxy was formed as a result of the destruction of a less massive, gas-rich companion near the spiral galaxy.

The galaxy UGC 4261 turned out to be a more complex system than previously thought, which has been found out thanks to recent spectral and photometric data. As a result of the analysis of our new material for UGC 4261, it

was ascertained the following. The detailed results of our observations and their analysis are being prepared for publication.

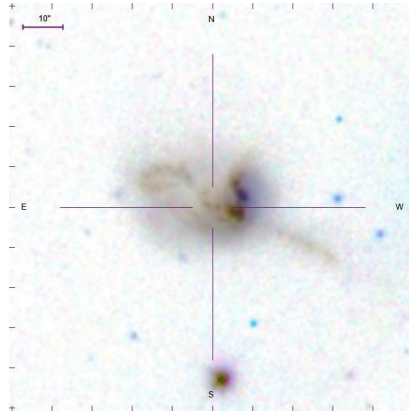


Fig. 3. The *griz* image of UGC 4261 from the Sloan Digital Sky Survey (<http://www.sdss.org/>).

We have discovered that the main body of the object consists of two nuclei of the interacting galaxies. They have different kinematics, age and metallicity. The both nuclei have almost the same size of about 4 kpc according to the photometrical data, but the northern one has steeper stellar velocity gradient along its major axis ($\Delta V = 200$ km/s, 21 km/s/kpc) and R_{max} of the line-of-sight velocity curve is about 5 kpc (it means that the northern nuclear has diameter about 10 kpc). The stellar velocity dispersion σ is about 90 km/s. The obtained ages of stars are $5 \pm 0.2 \times 10^7$ years with the solar metallicity and $8 \pm 1.5 \times 10^9$ yrs with $[\text{Fe}/\text{H}] \approx -1.5 \pm 0.05$ dex. The stellar component of the southern nucleus has very slow rotation velocity component along major and minor axes: $\Delta V = 20$ km/s and $\sigma = 80$ km/s. There, too, two stellar populations with age of $4 \pm 0.5 \times 10^7$ and $10 \pm 2 \times 10^9$ years and with solar metallicity and $[\text{Fe}/\text{H}] \approx -2.2 \pm 0.07$ dex, respectively, were found.

There were revealed many stars around the nuclei which have age of not more than 1 Gyr and kinematics close to the shells.

The gaseous component demonstrate complex kinematics which doesn't coincide with the stellar component one anywhere except for the region of the loop. There are bright gaseous bridges between the nuclei and, perhaps, several loops. Due to their line-of-sight location, these components produce a complex velocity field. We just estimated the distance to the galaxy about 98 Mpc ($H_0 = 65$ km/s/Mpc) and the mass of $1.5 \times 10^{10} M_\odot$ at $R_{max} = 28''$ (13 kpc). Although the shock excitation of gas was not detected in the galaxy, the FeI emission lines ($\lambda 4958, 5015, 5035, 5070 \text{\AA}$) were detected in the region of the

northern nucleus. UGC 4261 was inspected to the existence of AGN by many authors [20] – [22]. They refer the galaxy to starburst galaxies and its SFR rate is $0.6\text{--}0.8 M_{\odot}/\text{yr}$. Also we obtained the gas metallicity which is $12+\log[\text{O}/\text{H}] \sim 8.7$ (sub-solar).

According to results of our investigation (the length of the tidal structures (larger than 10 kpc), type of the old stellar population and metallicity of the gas), UGC 4261 is on the early stage of merging of two spiral galaxies with close masses. Perhaps, they made one-two turnover around each other.

Possibly, the amount of matter in the northern core region is not yet enough for the active core to enter to the active phase, but the presence of emission lines of neutral iron indicate a high temperature in this region. Maybe, this system will become a galaxy with an active core after some time.

4. CONCLUSIONS

Based on the results presented in this paper, all three objects in the Polar Ring Galaxies catalog are interacting systems and each of them is at a different stage in the merging process. UGC 1198 is a dE galaxy. It has already formed the polar ring from the gas of a dIrr companion galaxy. In spite of the large gas mass $M_{\text{HI}} = 0.13 \times 10^9 M_{\odot}$, there is no evidence of the AGN. IC 883 is a spiral Sc galaxy. It is at the earlier stage of merging of two spiral galaxies than UGC 1198. There are a lot of gas concentrated in the central part of the galaxy. The nucleus of IC 883 is an AGN + starburst composite. UGC 4261 is the youngest merging system of Sc/Sd galaxies. The gas mass is also significant ($M_{\text{HI}} = 8 \times 10^9 M_{\odot}$). But the gas is not so strongly concentrated towards the center yet, and the merging galaxies are far enough to each other. There are no sign of AGN by the radio, IR and X-ray observations but the FeI emission lines demonstrate high temperature in the region of the northern nucleus. Perhaps, it can be observed the starburst with AGN in future.

5. ACKNOWLEDGMENTS

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NON-STATIONARY PROCESSES IN THE ATMOSPHERE OF THE SUPERGIANT HD 190603 (B1.5IA)

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By using the spectrograms obtained at the 2-m telescope of the Shamakhy Astrophysical Observatory for the period of 2010÷2019 the variation of a profile and spectral parameters of $H\alpha$ and $H\beta$ lines of the supergiant HD190603 have been investigated.

It was found that the profiles, radial velocities and equivalent widths of the $H\alpha$ and $H\beta$ lines in the spectrum of the supergiant star HD190603 vary in time. The $H\alpha$ line profile consists of an absorption and an emission component. The emission component, depending on time, consists of one, two or three components. It was assumed the absorption and emission components radial velocity and equivalent width of the $H\alpha$ and $H\beta$ line vary in time with a quasi-period approximately of 100 - 120 days.

Keywords: stars supergiants—the profile of $H\alpha$ line, radial velocities

1. INTRODUCTION

Hot supergiants are among the brightest stars in our Galaxy, as well as in other galaxies. These stars are young and mostly located in the Galactic plane. The supergiant stars are bright, they are indicators of the distribution of chemical elements at large distances from the Sun and the distance to it. Supergiants help study the distribution of chemical elements in the Galaxy and therefore test models of the chemical evolution of the Galaxy. These stars are widely used in determining the spiral structure, shape and size of a galaxy. Therefore, the study of a typical representative of such supergiant stars as the stars HD190603 (B1.5Ia) is of great importance from the point of view of evolu-

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tion. For this purpose, we have received spectra of supergiant HD190603. Based on the received spectra, were studied changes in the profiles and spectral parameters of the $H\alpha$, $H\beta$ and HeI ($\lambda 5875.618$) lines.

The apparent magnitude of the supergiant star HD190603=HR 7678 varies between $5^m.56 \div 5^m.70$, the spectral class is B1.5Ia [1]. Its absolute stellar magnitude $M_V = -7.5$ [2]. Mass $M/M_\odot=27$, radius $R/R_\odot = 44$, luminosity $\log(L/L_\odot) = 5.41$, $\log g=2.38$, temperature $T_{eff} = 19500K$. The mass loss rate of the star is estimated at $\dot{M} = 2.4 \times (10^{-6} M_\odot yr^{-1})$ [3]. It's a blue supergiant star. The star is located at a galactic latitude $b = b = +0^\circ.4$ and longitude $l = 69^\circ.5$ [4]. The distance to the star is 1961.5 ps [5].

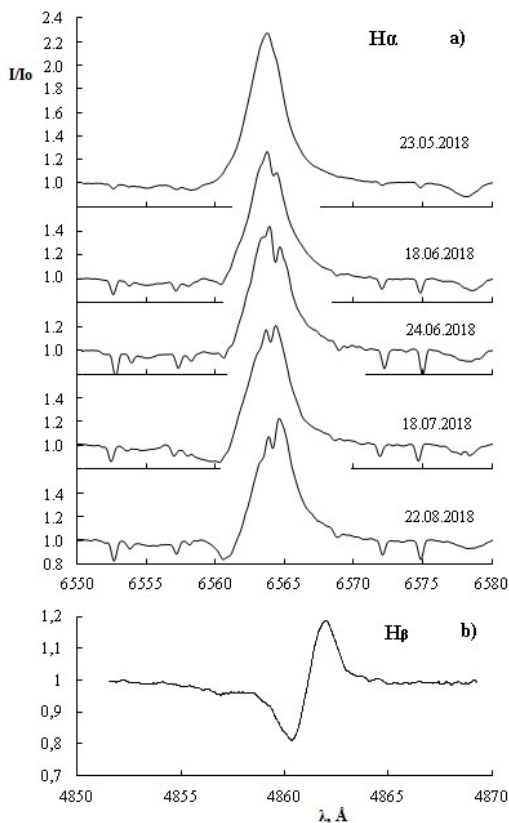


Fig. 1. Line profiles of the $H\alpha$ (a) and $H\beta$ (b) obtained in 2018.

2. OBSERVATIONAL MATERIAL AND ITS PROCESSING

Spectral observations of HD 190603 star were obtained in 2010-2019 by CCD camera installed in classic spectrograph of diffraction grating (UAGS) which was

Table 1. Values of some parameters of the $H\alpha$ lines in the spectrum of the supergiant HD190603.

JD 2400000+	$H\alpha$, abs.			$H\alpha$, emis.				
	W, mÅ	Vr, km/s	R	W, mÅ	Vr 1-komp km/s	Vr 2-komp km/s	R_1	R_2
58261.51	79	-190	0,06	79	59		2.27	
58276.44	249	-156	0,11	249	63	86	2.10	1.99
58288.39	37	-98	0,05	37	56	87	2.07	1.88
58291.39	146	-128	0,09	146	56	84	2.02	1.89
58294.25	49	-98	0,06	49	56	91	2.05	1.87
58304.38	205	-115	0,14	205	56	85	2.06	1.96
58318.36	110	-105	0,10	110	46	78	1.96	2.00
58347.38	110	-119	0,10	110	39	72	2.02	2.13
58353.20	209	-107	0,17	209	41	76	1.86	2.02
58360.26	197	-145	0,10	197	41	74	1.91	2.02

Table 2. Values of some parameters of the $H\beta$ lines in the spectrum of the supergiant HD190603.

JD 2400000+	$H\beta$, abs.			$H\beta$, emis.		
	W, mÅ	Vr, km/s	R	W, mÅ	Vr km/s	R
58261.51	372	-44	0.19	228	58	1.19
58276.44	410	-46	0.18	195		1.17
58288.39	413	-57	0.19	146	54	1.15
58291.39	543	-57	0.25	173	62	1.14
58294.25	439	-49	0.25	145	54	1.14
58304.38	494	-55	0.22	159	62	1.15
58318.36	511	-68	0.26	178	67	1.16
58347.38	655	-56	0.26	195	63	1.18
58353.20	467	-52	0.26	190	69	1.16
58360.26	451	-31	0.20	181	68	1.14

done by using Escelle spectrometer at the Cassegrain focus of 2- meter telescope of Shamakhy Astrophysical Observatory named after N. Tusi. Since 2016, spectra have been obtained by CCD camera with sizes of 4000×4000 pixels that are installed at the Cassegrain focus with spectral resolution of $R=28000$ and

$R=56000$ and wavelength range of the spectrum ($\lambda 9000\text{-}3600 \text{ \AA}$) at the same time in -1 frame. Spectrum of the day sky was used in order to set up the dispersion curve. DECH-20 and DECH-20T and DECH-30 packet programs presented by [6] have conducted the processing of spectrums. Two or three spectra of the star were recorded on each observational night. No rapid variations throughout the night were discovered. For this reason, the profiles obtained during one or several consecutive nights were averaged. The dispersion curves were constructed using the sky spectrum. A detailed description of the observational material and its processing is given in our previous studies [7,8]. The presented work mainly uses the spectra of the star obtained in 2018. In 2018, the spectra of the star were

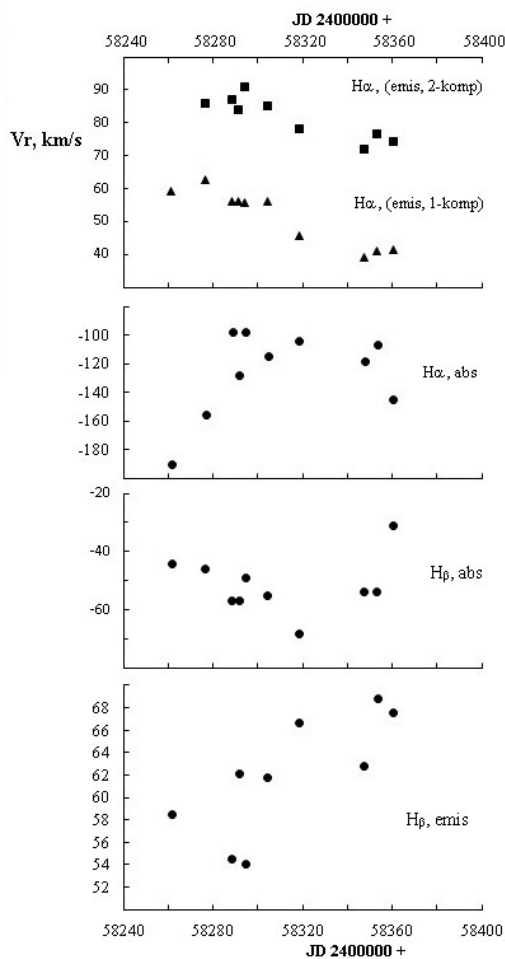


Fig. 2. Time variations of the radial velocity of the absorption and emission components in the $H\alpha$ and $H\beta$ line profiles obtained in the spectra 2018.

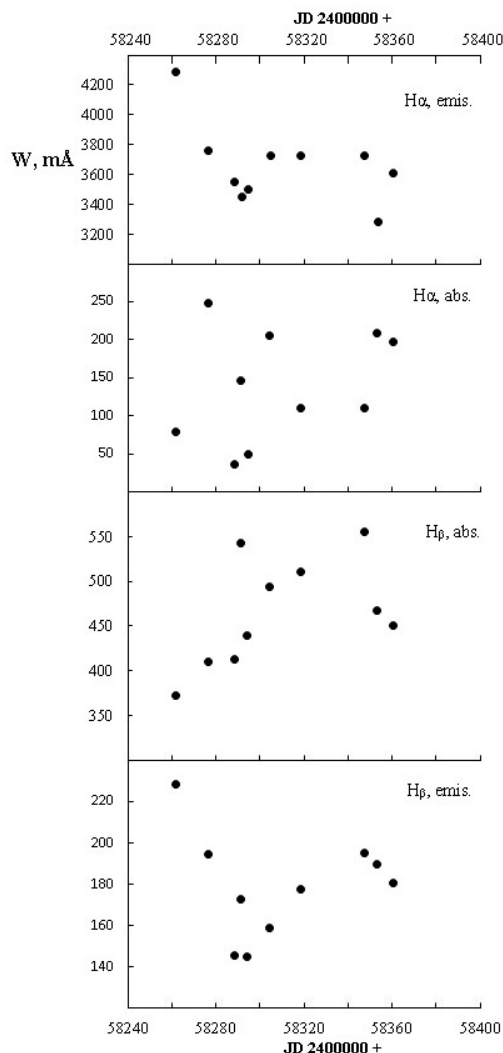


Fig. 3. Time variations of the equivalent width of the absorption and emission components in the $H\alpha$ and $H\beta$ line profiles obtained in the spectra 2018.

obtained over 10 nights. In these spectra were measured, the equivalent width (W) of the $H\alpha$ and $H\beta$ lines, the central line depth (R), and the radial velocity (V_r). The results obtained are shown in Table 1 and Table 2. The mean error of determining the equivalent widths was 1-5%. The error of the radial velocity measurements did not exceed 50 – 100 m/s. All radial velocities heliocentric.

Figure 1 shows that the $H\alpha$ line profile consists of an absorption and an emission component. In the profile of the emission component are observed one, two and sometimes three components. The $H\beta$ line profile consists of one absorption

and one emission component, figure 1 (b). Figure 1 shows clearly the P Cygni character of $H\alpha$ and $H\beta$. The profile and parameters of the absorption and emission components of the $H\alpha$ line change with time. Figure 2 and 3 shows time variations of the radial velocity values V_r of the absorption and emission components of the $H\alpha$ and $H\beta$ lines. It can be seen that a 100 - 120-day quasi-period in 2018 is observed in the change in the radial velocity and equivalent width of the absorption and emission components of the $H\alpha$ and $H\beta$ lines. It should be noted that in the $H\alpha$ and $H\beta$ lines, the change in the radial velocity and equivalent width in the absorption and emission components occurs in antiphase.

3. CONCLUSION

Spectral observations of HD 190603 star were obtained 2010-2019 in of 2- meter telescope of Shamakhy Astrophysical Observatory named after N. Tusi. Based on the obtained spectra, in 2018, changes in the profiles and spectral parameters of the $H\alpha$ and $H\beta$ lines were investigated. The following results were obtained:

1. It was assumed that the radial velocity and equivalent width of the absorption and emission components of the $H\alpha$ and $H\beta$ lines varies with time with a approximately quasi-period of about 100-120 days.
2. The change in the radial velocity and equivalent widths of the absorption and emission components of the profiles of the $H\alpha$ and $H\beta$ lines with time occurs in antiphase. However, variations in time of the value's equivalent widths of the lines of the absorption and emission components of $H\alpha$ and $H\beta$ occur synchronously.
3. It is estimated that, variations in the radial velocity and the equivalent width of the absorption and emission components in the $H\alpha$ and $H\beta$ lines a result by the pulsating of the stellar atmosphere.

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SEARCH FOR CHAINS OF RESONANCES IN THE COMPACT PLANETARY SYSTEM KEPLER-51

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We consider the compact three-planetary system Kepler-51 and search for resonance chains within the errors of determining the orbit periods from observations. To determine the resonant combinations of the semi-major axes of the orbits, the ratio of the mean motions of neighboring planets was represented as a segment of a sequence of convergent fractions. We have shown that the planetary system Kepler-51 evolves outside the low-order resonant chains.

Keywords: Exoplanetary system – Resonances – Dynamic evolution – Stability

1. INTRODUCTION

At present, several dozen compact planetary systems containing more than two planets with masses of the order of the Earth's mass are known¹⁾. It is shown that the stable evolution of compact planetary systems requires the presence of resonances that prevent close encounters of planets moving in neighboring orbits (see, for example, the five-planet systems Kepler-80 [1], K2-138 [2] and the seven-planet system TRAPPIST-1 [3]).

We consider the compact three-planetary system Kepler-51 and search for resonance chains within the errors of determining the periods from observations. Antoniadou and Voyatzis [4] demonstrate three possible scenarios safeguarding Kepler-51, each followed by constraints. Firstly, there are the 2 : 1 and 3 : 2 two-body mean-motion resonances (MMRs), in which eccentricity $e_b < 0.02$, such that these two-body MMRs last for extended time spans. Secondly, there is the 1 : 2 : 3 three-body Laplace-like resonance, in which $e_c < 0.016$ and $e_d < 0.006$ are necessary for such a chain to be viable. Thirdly, there is the combination comprising the 1 : 1 secondary resonance inside the 2 : 1 MMR for the inner pair of

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¹⁾ <http://exoplanet.eu/catalog/>

planets and an apsidal difference oscillation for the outer pair of planets in which the observational eccentricities, e_b and e_c , are favored as long as $e_d \approx 0$.

For compact systems, an important factor affecting evolution is tidal interaction; therefore, when analyzing the feasibility of the proposed resonance chains, we will model dynamic evolution taking into account tides. We introduce the resonant angles in Section 2. We will describe the technique for searching for resonant chains in Section 3. We will search for resonant chains in the Kepler-51 system in Section 4.

2. RESONANT ANGLES

When analyzing the resonant properties of planetary systems, the behavior of resonant angles is studied. For two planets i and $i + 1$, which are in resonance of mean motions $k_i : (k_i - l_i)$, the resonant angle can be set as follows [5]:

$$\varphi_{i, i+1, i+s} = (k_i - l_i)\lambda_i - k_i\lambda_{i+1} + l_i\varpi_{i+s}, \quad (1)$$

where l_i is the resonance order, λ_i , λ_{i+1} are the mean longitudes of planets i and $i + 1$, ϖ_{i+s} is the longitude of the periapsis of planet i ($s = 0$) or $i + 1$ ($s = 1$) orbit. For the next pair of planets $i + 1$ and $i + 2$, which is in resonance $k_{i+1} : (k_{i+1} - l_{i+1})$, the resonant angle

$$\varphi_{i+1, i+2, i+1+s} = (k_{i+1} - l_{i+1})\lambda_{i+1} - k_{i+1}\lambda_{i+2} + l_{i+1}\varpi_{i+1+s}. \quad (2)$$

Instead of two resonances between two neighboring pairs of planets, three-body resonances can be considered. In this case, the three-body resonance is a chain of two two-body resonances $k_i : (k_i - l_i)$ and $k_{i+1} : (k_{i+1} - l_{i+1})$ with a resonant angle that does not depend on the periapsis longitude [5]:

$$\Phi_{i, i+1, i+2}^{p, p+q, q} = p\lambda_i - (p + q)\lambda_{i+1} + q\lambda_{i+2}, \quad (3)$$

where $p = l_{i+1}(k_i - l_i)$, $q = l_i k_{i+1}$.

3. SEARCH FOR POSSIBLE CHAINS OF RESONANCES

The search for chains of resonances was carried out for the values of the semi-major axes of the orbits of the planets, which varied within the standard deviation $a_i = a_{0i} + \sigma_{ai}$. Here a_{0i} is the nominal value of the semi-major axis of the orbit, σ_{ai} is the standard deviation of the determination of the semi-major axis. To determine the resonant combinations of the semi-major axes of the orbits, the

ratio of the mean motions n_i and n_{i+1} was represented as a segment of a sequence of convergent fractions

$$\frac{n_i}{n_{i+1}} = \left\{ \frac{b_1}{d_1}, \frac{b_2}{d_2}, \dots, \frac{b_j}{d_j} \right\}, \quad b_j < b_{max}. \quad (4)$$

where b_{max} is the maximum value of the numerator. We obtain a rational approximation of the real ratio of mean motions

$$\frac{n_i}{n_{i+1}} = \frac{k_i}{k_i - l_i} = \frac{b_j}{d_j}. \quad (5)$$

After the sets of relations of the form (5) are obtained for all pairs of neighboring planets, possible chains of resonances are formed (if the resonance values of the semi-major axes of the outer and inner orbits in neighboring pairs coincide). The final selection of potential resonance chains is based on an estimate of the frequency of the resonant angle

$$\nu_{i, i+1, i+2}^{p, p+q, q} = |pn_i - (p+q)n_{i+1} + qn_{i+2}| < \varepsilon, \quad (6)$$

where the values are chosen as a criterion $\varepsilon \sim 10^{-4} - 10^{-5} \text{ day}^{-1}$.

The algorithm showed high efficiency in searching for resonance chains in the compact planetary system K2-72 [6].

4. POSSIBLE RESONANT CHAINS IN A COMPACT PLANETARY SYSTEM KEPLER-51

Table 1 shows the parameters of the Kepler-51 system. Star mass m and radius R are given in solar mass $M_\odot$ and radius $R_\odot$, correspondently. The masses m_{pl} and radii R_{pl} of the planets are expressed in Earth's mass $M_\oplus$ and radius $R_\oplus$, respectively. The orbital elements T , e , and g are the period, eccentricity, and periapsis argument, correspondently. The moment T_{conj} corresponds to the conjunction of the planet with the star.

We used the data to search for resonant chains in the Kepler-51 system. We concluded that the system does not contain resonances of the 1st, 2nd, and 3rd orders, for resonant numerators not exceeding $b_{max} = 10$. We did not find confirmation of the realization of a resonant chain $2 : 1 - 3 : 2$ in a compact three-planetary system Kepler-51. For compact systems, an important factor affecting evolution is tidal interaction; therefore, we considered a number of scenarios for the evolution of the Kepler-51 system over 100 Myr using the Posidonius software [8], which takes into account tidal interactions. We concluded that the system can have a stable evolution over long-time in the absence of low-order resonances.

Table 1. Parameters of the compact three-planetary system Kepler-51 [7]

Parameter	Kepler-51	Kepler-51b	Kepler-51c	Kepler-51d
$m [M_{\odot}], m_{pl} [M_{\oplus}]$	$0.894^{+0.036}_{-0.048}$	$2.48^{+1.23}_{-1.04}$	$3.14^{+0.50}_{-0.48}$	$5.22^{+1.17}_{-1.07}$
$R [R_{\odot}], R_{pl} [R_{\oplus}]$	$0.841^{+0.023}_{-0.021}$	$6.62^{+0.19}_{-0.17}$	$8.98^{+2.84}_{-2.84}$	$9.04^{+0.25}_{-0.23}$
T [day]		$45.15393^{+0.00036}_{-0.00038}$	$85.31553^{+0.00138}_{-0.00109}$	$130.1827^{+0.0009}_{-0.0009}$
$e \cos g$		$-0.019^{+0.009}_{-0.010}$	$0.024^{+0.014}_{-0.014}$	$0.014^{+0.011}_{-0.011}$
$e \sin g$		$-0.059^{+0.019}_{-0.022}$	$-0.048^{+0.027}_{-0.029}$	$-0.037^{+0.022}_{-0.024}$
T_{conj}		$-1285.4040^{+0.0006}_{-0.0006}$	$-1274.4886^{+0.0030}_{-0.0030}$	$-1304.0693^{+0.0009}_{-0.0009}$

5. DISCUSSION AND CONCLUSIONS

We implement a method for searching for chains of resonances within the limits of errors in determining the values of the periods of planetary orbits. We concluded that the compact tree-planetary system Kepler-51 evolves outside the low-order resonant chains. We modeled the dynamic evolution of the Kepler-51 system using the Posidonius software, taking into account tides. We showed that the system can have a stable evolution in the absence of low-order resonances. In the future, we plan to refine the initial configurations of orbits and planets that ensure the stable evolution of the planetary system over long-time.

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SUPERFAST LINE PROFILE VARIATIONS IN STELLAR SPECTRA

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The regular line profiles variations (LPVs) with periods ranging from a few hours to days in spectra of stars are well investigated. At the same time the LPVs at minute time scale are badly known. In order to study the spectral variability on such short timescales, we launched Large Project to search for the superfast line profile variations (sfLPVs) in spectra of bright stars. By the end of 2022 year we have obtained over 20000 spectra of selected OBAFGKM stars at the 6-m and 1-m telescopes of the Special Astrophysical Observatory (Northern Caucasus, Russia) and at the 1.25-m telescope of Crimean Astronomical Station of the Sternberg Astronomical Institute (Moscow State University, Russia). Both regular LPVs with periods from 2 to 140 minutes and non-regular LPVs with amplitudes of 1-3% of the continuum level were detected for all studied stars. Such short-term spectral variability was not studied systematically in the past, while it can be crucial for the future theoretical understanding of the stellar physics and for modeling the stellar evolution. We plan to use additional telescopes for spectral observations with an ultra-high temporal resolution and in particular the Shamakhy Astrophysical Observatory (SHAO) 2-m telescope. In future we are also going to study the sfLPVs for bright stars at the pre-main stage of stellar evolution.

Keywords: Stars – Spectra – Line Profiles variations

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1. INTRODUCTION

Houtgast [1] first argued that line profiles in the solar spectra are variable and depend on the location of the studied region of the solar disks. Later, nearly 50 years ago line profile variations in the stellar spectra were detected [2]. 50 years of LPVs investigations showed that the main causes of them are the rotational modulations and non-radial pulsations (NRPs). The typical time scales of LPVs in spectra of OBA stars vary from days to hours [3, 4].

For example, for bright A0 supergiant HD 92207 Kaufer et al. [5] detected the NRPs with a period of 27 days, and no shorter periods were revealed. Searching for fast and super-fast LPVs appeared to be far from the main scientific interest. Surprisingly, the short time-scale line profile changes in the spectra of HD 92207 were recently discovered by Hubrig et al. [6].

These authors detected clearly visible LPVs for different elements in individual subexposures up to 3% in intensities (in continuum units) and up to 30 km/s in radial velocities. Such short-term LPVs were not previously known for non-radially pulsating supergiants. These observations gave an impetus to our research of the superfast line profile variations in spectra of early-type stars at minute and even seconds time scales. Such line profile variations remain practically uninvestigated until now. In order to guess whether the short-term LPVs are typical for all OBA and stars of later spectral type, we launched in 2015 the Large Observational Program to analyze the LPVs with high temporal resolution.

In the present paper we describe our Large Program and review the main results of our fast LPVs investigations at the moment. The program and the observations are reviewed in section 2. In section 3 the selected results of analysing our new observational data are discussed. Some conclusions are given in section 4.

2. OBSERVATIONS

The main goal of our program is to study the super-fast variations of the line profiles in the spectra of OBA stars at time scales of second and minute and to develop the models explaining such variations. We also plan to investigate the dependence of the super-fast LPVs parameters on the spectral type, rotation velocity, chemical abundances, and other stellar parameters.

The list of program stars includes all bright stars for which it is possible to get high temporal resolution and to obtain the signal to noise ratio $S/N > 300$. The list of the proposed targets contains all bright stars with $V \leq 4^m$. The catalog of bright stars¹⁾ was used as a source to choose the targets. It means that the

¹⁾ <http://tdc-www.harvard.edu/catalogs/bsc5.html>

sample of the program stars will be complete up to $V \leq 4^m$. Among the more weak targets with $V > 4^m$ the massive OB stars will be predominantly included in the list.

Our experiences show that the sfLPVs in spectra of bright stars at minute or second time scales can be detected for $\Delta T < 30$ s and $S/N \geq 300$. Here ΔT is the time interval between successive observations. That is a sum of exposure and CCD matrix readout time. The selection of telescopes and spectrographs has to be made to provide such parameters of observations as given above.

Table 1. O stars

Star	Sp.type	V	N_{sp}	Exp (s)	Tele- scope	Spectro- graph	Dates
ξ Per	O7.5III	4.06	1249	15	1.25-m	A-Sp	07.10.2021
α Cam	O9Ia	4.29	434	15	Z-1000	UAGS	29-30.10.2021
19 Cep	O9Ib	5.11	390	2	BTA	SCORPIO	17-18.08.2021
			225	10	1.25-m	A-Sp	21.09.2020
ζ Ori A	O9.2I	1.88	76	90	BTA	MSS	19.02.2019
HD 93521	O9.5III	7.03	529	3	BTA	SCORPIO	19-20.01.2015
			28	900	BTA	MSS	30.12.2021-2.2.2021
HD 34078	O9.5V	5.96	27	300	BTA	MSS	5-8.1.2020
HD 45314	O9:npe	6.64	209	600	BTA	MSS	5-8.1.2020

This means that the diameters of the telescopes used for observations must be in any case greater than 1 meter. To provide the ratio $S/N \geq 300$ for 1-2 meter telescopes it is necessary to use spectrographs with low resolving power $R \sim 1000/2000$. Higher spectral resolution can be only reached with very large telescopes with a diameter $D > 5$ meters. For making the polarization observations and measuring the magnetic field strength one needs to use telescopes with a diameter of at least 5 meters.

Our observations of the program stars were made with the 6-m telescope BTA (Big Azimuthal Telescope), the 1-meter telescope Zeiss-1000 (Z-1000) of Special Astrophysical Observatory, and the 1.25-m telescope of the Crimean Astronomical Station (CAS) of the Sternberg Astronomical Institute (SAI) of the Moscow State University.

For our observations at the BTA telescope we used both low resolution spectrograph SCORPIO [7] and the medium resolution Main Stellar Spectrograph (MSS) [8]. The observations at the 1.25-m telescope were made with a low-resolution A-spectrograph (A-Sp) [9]. Up to the present day more than 20 000 spectra of OBAFGM stars have been obtained.

Table 2. B stars

Star	Sp.type	V	N_{sp}	Exp (s)	Tele- scope	Spectro- graph	Dates
β Cep	B0.5III	3.21	74	60	BTA	MSS	30.12.2020-2.2.2021
			1576	2	1.25-m	A-Sp	13-14.9.2020
γ Cas	B0.5IVpe	2.39	138	60	BTA	MSS	1-2.2.2021
			2460	1.5	1.25-m	A-Sp	7-8. 9.2021
SAO 49725	B0.5III/IVe	9.27	432	5	BTA	SCORPIO	17-18.08.2021
			1271	1	BTA	SCORPIO	19-21.01.2015
ρ Leo	B1Iab	3.87	80	90	BTA	MSS	19.02.2019
			263	10	1.25-m	A-sp	26.10-2.11.2019
π Aqr	B1III-IVe	4.64	1250	5	1.25-m	A-sp	10.10.2021
HD 45995	B1.5Vne	6.14	208	30	BTA	A-sp	10.10.2021
V2156	CygB1.5Ve	8.91	7	20	BTA	SCORPIO	18.08.2021
α And	B8IV	2.06	2611	2	1.25-m	A-sp	13-14.9.2020
	-VHgMn		709	10	Z-1000	UAGS	28-30.10.2020

Table 3. AFGM stars

Star	Sp.type	V	N_{sp}	Exp (s)	Tele- scope	Spectro- graph	Dates
α^2 CVn	A0spe	2.90	866	1	BTA	SCORPIO	21-22.01.2015
			71	90	BTA	MSS	5.1.2020
HD 21389	A0Ia	4.54	330	11	BTA	SCORPIO	25-26.09.2016
γ UMi	A2III	3.00	249	20	BTA	SCORPIO	25-26.09.2016
β Cep	A8Vn	2.46	641	10	Z-1000	UAGS	28-30.10.2020
V388 Cep	F0IV	5.55	505	20	1.25-m	A-sp	13.09.2021
π , Peg	F5III	4.29	1302	5	1.25-m	A-sp	7+9.09.2021
β Cam	G1Ib	4.02	1159	4	1.25-m	A-sp	12.09.2021
51 Peg	G2IV	5.46	400	20	1.25-m	A-sp	7.10.2021
4 Cas	M1III	4.96	488	10	1.25-m	A-sp	13.09.2021

Our large program was started in 2015-2017 from the observations of fast rotating O9.5III star HD 93521, BIa supergiant ρ Leo, A0I supergiant HD 21389, A0V magnetic standard α^2 CVn, and A2III giant γ UMi with the 6-m BTA telescope.

Firstly, we investigated the LPVs in spectra of HD 93521. We reveal the fast profile variations with periods of 4-5 and 32-36 minutes [10]. The possible origin

of short time-scale spectral variations was discussed.

The fast variations in spectra of a slow-rotating [11] star ρ Leo were reported by Kholtygin et al. [12]. They detected short-period transient regular variations of the H and He lines with periods from 2 to 90 minutes. These results were later confirmed by Kholtygin et al. [13]. The authors explain the presence of these transient components assuming that the high modes of non-radial pulsations (NRPs) are unstable and can either disappear or be generated on short time scales ranging within 10-100 minutes.

An analysis of the spectra of the γ UMi in January 2017 with the BTA telescope equipped with the SCORPIO spectrograph showed the presence of the LPVs' harmonic components with periods within the 10 – 65 minute interval [14].

In a recent paper by Kholtygin et al. [15] the authors analyze α^2 CVn observations carried out on January 20 – 21, 2015 using the BTA telescope with the SCORPIO spectrograph. Short-term regular variations in the Balmer H lines and HeI lines with periods ranging from about 30 to 135 minutes were detected.

LPVs in spectra of this star were additionally investigated using the observations carried out with the 6-meter BTA telescope on January 6, 2020 using the MSS spectrograph. Regular short-term periodic variations of the H_β , FeII, and CrII lines with periods ranging from 4 to 140 minutes were registered [16].

Spectra of the chemically peculiar (mercury-manganese overabundant) B8IV-V star α And, characterized by its spot activity [17] and belonging to the group of α^2 CVn type star, were also obtained at the 1.25-m telescope on 13/14.9.2020. Our CLEAN analysis shows the presence of regular LPVs in the α And spectra with periods of 4.93 ± 0.60 , 18.38 ± 8.36 and 20.74 ± 10.64 minutes at a False Alarm Probability (FAP) level of 10^{-3} [18]. These periods are close to those for α^2 CVn mentioned above.

Our observations of the B0.5IVpe star γ Cas at the 1.25-m telescope on the Crimean station of SAI are analysed by Kholtygin et al. [19]. The regular components of LPVs with periods from 4 to 37 minutes are registered. This telescope was also used to observe another γ Cas type star π Aqr [20] on October 10/11, 2021. The regular LPVs at the short-time scale with periods from 4 to 136 minutes in spectra of π Aqr are revealed.

Analysing the X-ray spectra of the stars opens an opportunity to study their fast variability. A comparison of periods of the X-ray flux variations for selected γ Cas type stars shows that these periods correspond to those obtained from an analysis of the optical spectra of such stars [18]. This means that the regions where the optical and X-ray spectra are formed close to the stellar surface.

3. LINE PROFILE VARIATIONS

Line profiles in spectra of all observed by us stars appeared to be variable. The typical amplitude of LPVs is about 1-3% in the continuum units as it is shown in the Fig. 1 for normalized H_β and H_α line profiles in spectra of δ Scuti type variable star V388 Cep.

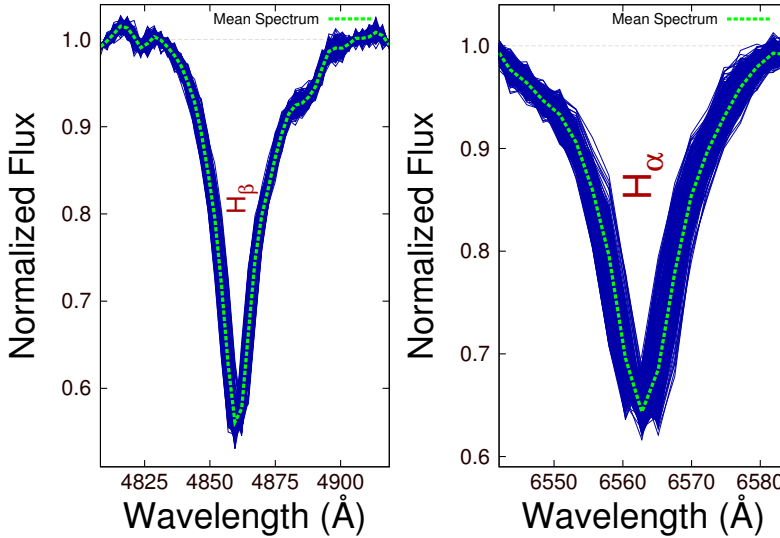


Fig. 1. Line profiles in spectra of V388 Cep, obtained on 13.09.2021 at the 1.25-m telescope.

In order to look for regular components of profile variations, we determine the difference line profiles. Let one have N observed spectra of the studied object. Denote by $F_i(\lambda)$, $i = 1, \dots, N$ the continuum-normalized flux in the i -th stellar spectrum at wavelength λ . Let $\bar{F}(\lambda)$ be the line flux at the wavelength λ averaged over all observations. Then the difference line profile

$$d(\lambda) = F_i(\lambda) - \bar{F}(\lambda) \quad (1)$$

To analyze the difference line profiles, it is more convenient to use the Doppler shifts V with respect to the laboratory wavelength λ_0 of the line:

$$V = c(\lambda/\lambda_0 - 1),$$

where c is the speed of light.

For spectra of different quality, one could use different profile weights g_i , which are proportional to the square of S/N ratio in the continuum region near the line, when calculating the average and difference line profiles.

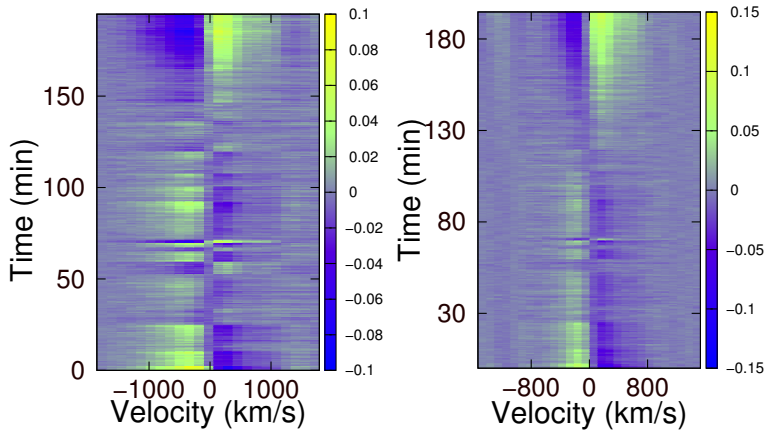


Fig. 2. Dynamical spectra of the H_{β} (left panel) and H_{α} (right panel) LPVs in spectra of V388 Cep.

3.1. Regular LPVs

We detect the regular components of LPVs with periods from 3-4 to 90 minutes for bright OBA stars. Periods of the regular LPVs depend on the spectral type of stars. The shortest periods down to 3-4 minutes are detected for O and early B stars [14]. Such short-time periods of regular line profile variations can be connected with the high modes of the non-radial pulsations (NRP). We supposed that detected LPVs are connected with p modes of NRP with values of $l \sim 50 - 200$. Such high NRP modes are well known in the solar 5-minutes oscillations [21].

For late B and A stars the shortest periods of LPVs seem to be larger than for O and early B stars [13]. In order to understand the tendency for the line profile variation period to increase from the early to late spectral type stars, we analyzed the LPVs in spectra of the F0IV star V388 Cep. We obtained 505 spectra of this star (see Table 3). The dependence of the values of $d(V, t)$ on the time of observations (dynamical spectra) for H_{β} and H_{α} lines in spectra of this star is plotted in Fig. 2. One can see the similarity of the LPV pattern for both lines.

We tried to detect regular components in the LPVs in spectra of V388 Cep using the CLEAN Fourier analysis method by Roberts et al. [22]. In Table 4 we present the frequencies and periods detected from the analysis of the LPVs (2nd and 3rd columns). In the last column the False Alarm Probability (FAP) level is given.

The standard top estimate of the frequency error $\Delta\nu = 1/T$, where $T = 194.8$ minutes is the total observation time [23], is too big. Our numerical experiment shows that the value of $1/3T$ is more realistic.

Table 4. Frequencies and periods of regular components for LPVs in spectra of V388 Cep

No.	ν , min ⁻¹	P , min	FAP
1	0.005335 ± 0.00171	187.4 ± 60.1	10^{-6}
2	0.006669 ± 0.00171	149.9 ± 38.5	10^{-2}
3	0.011070 ± 0.00171	90.3 ± 14.0	10^{-4}
4	0.074026 ± 0.00171	13.5 ± 1.0	10^{-2}

The components 2 and 4 correspond to the value $FAP = 10^{-2}$ and should be confirmed by future observations. The components 1 and 3 are larger than 1 hour. That is, the minimum periods of LPVs in the spectrum of F stars are significantly longer than those of OBA stars. This confirms our conclusion that the periods of LPVs are to increase from early to late spectral types.

One can compare our data with those obtained by other authors. A detailed analysis of the photometric variability of V388 Cep in the B and V bands has been done by Hao et al. [24]. A total of 156 hr of data in the U, B, and V bands were obtained in the 17 days campaign in 1994 September-October using the 60 cm reflector at the Xinglong Station, Beijing Astronomical Observatory (China) and the 48 cm Cassegrain telescope of Ege University Observatory (Turkey).

As a result of their frequency analysis five frequencies $f_1 = 3.617$, $f_2 = 3.655$, $f_3 = 4.286$, $f_4 = 2.385$, and $f_5 = 5.847$ c/d were detected. Mode identification showed the first four frequencies to be interpreted as the $l = 2$ mode of the non-radial pulsation (NRP) with the rotational frequency splitting identified with $m = -2, 1, -1, 2$, and 2 respectively.

A comparison of these frequencies with ones obtained by us and given in Table 4 shows that the frequency 2 could be the 4-th harmonic of the frequency $f_4 = 3.617$. The frequency 1 can be (taking into account errors of its determination) the 2nd harmonic of the frequencies f_1 or f_2 . This confirms the reality of detecting regular components of LPVs in spectra of V388 Cep.

4. CONCLUSIONS

The present study allowed us to make the following conclusions:

1. Our observations with the SCORPIO spectrograph on the 6-m BTA telescope and 1.25-m SAI telescope show the presence of short-period LPVs for all studied stars never known previously for OBA stars.

2. Fast variations of the line profiles in the spectra of studied stars are probably associated with the high modes of NRP.
3. The periods of LPVs increase from early to late spectral types.

In future we suppose to use the additional telescopes for the spectral observations with the ultra-high temporal resolution and in particular the SHAO 2-m telescopes. We are also going to study the sFLPVs for bright Ae/Be Herbig stars and T Tauri stars to study super-fast spectral variability for the pre-main sequence stars.

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STATISTICALLY OPTIMAL PHENOMENOLOGICAL MODELLING OF VARIABLE STARS

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A set of algorithms and programs is reviewed, which are most effective for statistically optimal mathematical modelling of various types of variability. Although these methods were proposed and applied for photometry and polarimetry of 2000+ variable stars, as excellent laboratories to study various processes, they may be applied to signals of any nature, e.g. technical, medical or social. For "mono-periodic" stars (with high level of coherence), "global" approximations are most effective - either a trigonometric polynomial of statistically optimal order (mainly for pulsating stars or for eclipsing binaries with smooth curves (EW, EB), or for stars with elliptic variability. However, for Algol-type variables or transits of exoplanets, a "special shape/pattern" approximations superimposed onto the second-order trigonometric polynomial are recommended. For quasi-periodic variations, the wavelet analysis may be used (in some programs, with an adaptive effective width determination), or the scalegram analysis with further local weighted approximation with an optimal width. This method may be effective even in a case of strong flickering, fractal variations, red noise. Wavelet and (especially) scalegram analysis (some modifications are called "multi-resolution", "multi time-scale") may separate variability at different time scales. Particularly, some types suggest long-term aperiodic variability, which may be effectively modelled by an algebraic or trigonometrical polynomial. In a case of trends, the periodogram analysis is to be made using a complete mathematical model instead of super-simplified "detrending" or "pre-whitening", which may cause wrong (biased) results. Some algorithms are illustrated by application to the observations.

Keywords: methods: data analysis – methods: statistical – astronomical databases – AstroInformatics – stars: variables – stars: binaries

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Dedicated to the memory of
 Prof. Vladimir Platonovich Tsesevich
 (11.10.1907 – 28.10.1983),
 A great Scientist, Lecturer,
 Popularizer and Organizer of Science

1. INTRODUCTION

Variable stars show a wide variety of types of variability. According to the "General Catalogue of Variable Stars" [1], there are 70+ "main" types of variability and hundreds of "mixed" types with two or more types of variability.

This makes impossible to apply a single algorithm to all these signals, e.g. the most popular Fourier Transform (FT) and few its variations (FFT, DFT, DCFT etc.) and improvements based on the mono- or multi-harmonic approximations. It is necessary to have a set of numerous algorithms to apply one or few of them to a concrete object.

For the illustration of some algorithms, we have used the data from the AAVSO International database [2] and the "Open European Journal on Variable Stars".

Recent reviews on these and other methods are in [3], [4], whereas some highlights of the results on pulsating [5] and interacting binary [6] stars are published.

The studies by our group (there are many other co-authors of other published papers) were named in 1983 as an "Inter-Longitude Astronomy" (ILA) project [7], [8] in a collaboration with the "Ukrainian Virtual Observatory" (UkrVO) and "AstroInformatics" projects [9].

In this paper, we show references for original papers with a complete description of the algorithms and/or applications to concrete objects.

2. ALGORITHMS AND SOFTWARE FOR THE DATA ANALYSIS

2.1. General approach

We prefer to use (linear or non-linear) least squares (LSQ) approximations

$$x_C(t) = \sum_{\alpha=1}^m C_{\alpha} lpha \cdot f_{\alpha} lpha(t) \quad (1)$$

with an improved version of the test function [10]

$$\Phi(x_k; C; f) = \sum_{\alpha, \beta=1}^m p(t_k, t_j) \cdot w_{kj} (O - C)_k (O - C)_j, \quad (2)$$

where x_k , $k = 1..n$ are observed ("O") values of the signal at the moment (argument) t_k , $x_C(t_k)$ are calculated (C) values at the same moment, weights $w_{kj} = \sigma_0^2 \cdot \mu_{ij}^{-1}$, μ_{ij} is a covariation matrix of errors of observations. The classical approach is to use only diagonal matrices $w_{kj} = w_{kk} \cdot \delta_{kj}$. In this case, $w_{kk} = \sigma_0^2 / \sigma_k^2$ (σ_0 is called "the unit weight error", σ_k is a statistical error estimate of x_k). A simplified version $w_{kk} = 1$ is used very often in electronic tables and many papers. The weight (or "filter", or "kernel") function is dependent on the dimensionless "distance" $z = (t - T_0) / \Delta t$, where, according to the "wavelet terminology" [11], T_0 is "shift" and Δt is scale. In the "scalegram" terminology, they are called "trial time" and "filter half-width", respectively [10].

2.2. Periodic Signals

The Fourier Transform (FT) as well as its modifications suggest that the data are distributed "evenly" ("equidistantly", $t_k = t_m + (k - m) \cdot \delta$, $k, m = 1..n$, δ is time resolution. The duration of observations $D = (t_n - t_1) \cdot n / (n - 1)$, as one may formally extend $t_{k+l \cdot n} = t_k + l \cdot P$ for any integer l . The test periods are restricted to $P_j = D / j = P_1 / j$, $j = 1..\text{int}(n/2)$. However, the observations of a star during the night (D) do not generally cover an integer number of periods. This causes a lot of peaks at the periodogram [12], which is computed at a grid of trial frequencies differing with a step of $\Delta f = \Delta \phi / (t_n - t_1) / s$, where $\Delta \phi$ is a phase shift between the first and last observations, s is the degree of the trigonometric polynomial ($s = 1$ for a sinusoid), and is recommended to be in the interval $[0.04-0.06]$ (anyway, < 0.1). The Fortran program [12] was later realized in the program MCV ("Multi-Column Viewer") [13], [14]. Moreover, the program MCV has additional features like a periodogram analysis using a polynomial trend superimposed on a trigonometric polynomial of power s , a multi-periodic multi-harmonic approximation with trend, an algorithm of the "artificial comparison star", et al.

Instead of using trigonometric polynomials, one may split observations into L subintervals (for each trial period) and use approximations with spline functions of different order and defect (see [15] for a review and a comparative study).

An alternate group of methods for searching for periodicity is called the "non-parametric" (or "point-point") methods, contrary to "parametric (or "point-curve") methods mentioned above (see [16] for a comparative study).

2.3. Quasi-Periodic and-Aperiodic Signals

[16] There are three main methods to study such signals. The autocorrelation methods are widely used for regularly spaced data (e.g. [17]). Detailed modelling

of the autocorrelation function bias owed to a limited number of de-trended observations was presented by [18], with applications to autoregressive models with noise.

Four-component model of the auto-correlation function for the X-Ray (Chandra) data of the prototype polar AM Her lead to the discovery of the two-component shot noise from the accretion column above the white dwarf. This was interpreted by cutting of the column into 17 pieces due to the magneto-hydrodynamic instability [19].

Wavelet analysis of the irregularly spaced time series by the least-squares method with supplementary weights was introduced by [20], who described spectral and statistical properties of the trial and smoothing functions are studied, and optimal argument and frequency steps are suggested.

This method was applied to almost two hundred semi-regular variables [21]. The decay coefficient of the exponent in the weight function significantly influences of results of the data with long seasonal gaps. Some stars show drastic changes of the amplitude, like transitions between the Mira-type variations and constant stars.

The "scalegram analysis" may be based on any weight function. E.g. the Morlet-type wavelet, which is mentioned above. However, for a strong cycle-to-cycle variability, one has to choose shorter effective intervals. So sines of small angles may be replaced by a line, and cosines - to parabola.

The method of "Running Parabolae" was proposed in [22] as a generalization of the method of "running approximation" ("running mean", "moving average". The weight function for the observation x_k at time t_k was chosen as $p_k = (1 - [|t_k - t_0|/\Delta t]^\alpha)^\beta$. The weight function is zero outside the interval $[t_0 - \Delta t, t_0 + \Delta t]$.

The values $\alpha = 2$ and $\beta = 2$ are sufficient to avoid the discontinuity of the smoothing function and its derivative. The systematic error for the method of "running parabolae" is much smaller as compared with that for "running mean" with the same filter half=width Δt .

The analytical accuracy estimates for the generalized smoothing function, its derivative and the extrema for any basic and weight functions are presented by [23]. Particularly, this formalism was extended to the wavelet analysis [20].

There was introduced a " σ " – scalegram anslysis, where σ is an unbiased weighted mean squared deviation of the observations from the approximation. For nearly periodic signals, it has two characteristic "standstills" at $\Delta t \ll P$ and $\Delta t \gg P$ with a linking part inbetween. This allows to determine an effective period or a quasi-period ("cycle length") and a corresponding semi-amplitude.

The statistically optimal value of Δt may be determined using the " x_C -scalegram, i.e. the dependence on Δt of the r.m.s. accuracy estimate of the observations at times of these approximations. However, for noisy observations, there may be a local minimum at $\Delta t \approx 0.5P$, then a hump and decrease to a lower asymptotic value $\Delta t/P \rightarrow \infty$, which corresponds to global parabolic approximation using a rectangular weight function. This is an often case for visual observations of semi-regular variables and low-amplitude Mira-type stars. Then one may recommend to use the "S/N=SNR" (amplitude "signal-to-noise" ratio. The value of Δt , which corresponds to a maximum of SNR, is typically close (within a few per cent) to a (global or local) minimum of x_C .

In the case of multi-periodic variations, there may be corresponding "stairs". Extremely interesting is a case of fractal variations, which was discovered in a cataclysmic variable AM Her [24]. One may see similar variations in flickering of cataclysmic or symbiotic variables, but for much smaller intervals of Δt .

In the majority of our programs dealing with the "weight" function, the "bisquare" ($\alpha = 2, \beta = 2$) version is used. Obviously, there may be other pairs for the approximation, starting from a rectangular ($\alpha \rightarrow \infty, \beta > 0$, or, alternately, $\alpha > 0, \beta = 0$), triangular ($\alpha = 1, \beta = 1$). In the algorithm LOWESS, different sets of parameters (α, β and the degree of polynomial) may be used [25]. E.g. [26] recently used ($\alpha = 3, \beta = 3$).

2.4. Times of Extrema

The studies of period variations are done using either the complete light curve (rare) or the moments of the characteristic events (minima, maxima of brightness, or crossing some value (e.g. the γ - velocity by a radial velocity). Recently, there is an often abbreviation ToM (Time Of Maximum/Minimum). The deviation ($O - C$) from a linear ephemeris is often interpreted by the presence of the third (etc. body) around the eclipsing binary (LiTE - Light Time Effect), apsidal motion, mass transfer between the components of eclipsing systems or periodic (the Blazhko effect) or aperiodic variations ([27]). Such studies use only one ToM from a complete night (or even a season), thus needs much smaller number of observations - only a small part of the light curve near an extremum.

An old method was a graphic one based on the hand-drawn light curve. It is not accurately repeating, and there is no correct error estimate. Kwee & van der Woerden [28] proposed a numerical method, based on a search of the point of "symmetry" (or "reflection"). This method was popular for decades. However, it produces a "saw-like" test function, so may produce an underestimated accuracy of ToM, which corresponds to a local minimum (which may be different from the global one because of fluctuations of the test functions).

A parabolic approximation was mentioned in [29]. For asymmetric curves (e.g. of the pulsating variables), a high-order polynomials (of a statistically optimal order) may be recommended [12]. They were used e.g. for determination of the 6509 extrema of 147 semi-regular variables [30].

High-order polynomials may be good at the center of the interval, but may produce formal waves closer to the borders of the interval, and gaps in the observations. Cubic splines seem better than the polynomials with the same number of parameters [15].

Local "asymptotic parabola" fits of signals with almost linear ascending and descending branches connected by relatively short parabolic transitions at maximum or minimum were proposed by [31], [32] and further realized by [33]. This is a kind of spline with a changing fixed order ($1 + 2 + 1$).

Non-polynomial approximations for generally asymmetric shapes were reviewed by [34]. New "Wall-Supported Polynomial" algorithms [35] may be effective for modelling flat eclipses and exoplanet transitions. Finally, these and other algorithms for statistically optimal determination of phenomenological parameters of extrema were realized in the software MAVKA [36] – totally, 11 classes of functions with 21 individual functions, with automatic determination of the degree of symmetrical or (generally) asymmetrical polynomials.

3. CATAclysmic AND SYMBIOTIC VARIABLES

Cataclysmic variables were intensely studied in our group polarimetrically in 1989-2014, based on observations at the Shain 2.6m telescope and the telescope AZT-11 of the Crimean Astrophysical Observatory, by S.V.Kolesnikov and N.M.Shakhovskoy (1931-2011). The history of polarimeters were reviewed by [37], [38], the program for the data reduction was described by [39] and the highlights were briefly listed in [40], [6].

CCD observations were performed within an international campaign ILA ("Inter-Longitude Astronomy") in many countries. The orbital and spin variability of the intermediate polars BG CMi [41], MU Cam [42], V405 Aur [43], V2306 Cyg [44] were studied. All these systems show a spin-up of the magnetic white dwarf due an accretion torque.

"The Noah" project ("40 nights of observations") was performed to study switches of the accretion from one pole to another in an asynchronous polar BY Cam [45], as was theoretically suggested by [46]. During the "Noah-2" project, a third bright accretion region was detected [47]. It may be located near the threat point, similar to another synchronizing polar V1432 Aql [48].

The low-field magnetic dwarf nova DO Draconis exhibited a new type of variability - "transient periodic oscillations" TPO [49], which are distinctly different

from the "quasi-periodic oscillations" seen in "non-magnetic" Nova-like stars like TT Ari [50].

Long-term photometry of the symbiotic nova V1329 Cyg [51] and V1016 Cyg [52] was analyzed.

4. PULSATING VARIABLES

Long-period pulsating variables (LPV) were studied on old photographic plates from the Odessa "7-camera" astrograph, as well as on published photometric surveys, mainly from the AFOEV and AAVSO databases.

The catalogue of main characteristics of pulsations of 173 semi-regular stars was published by [30] and based on the observations of the AFOEV [53] database, which were previously cleaned from obvious outliers. The catalogue contains results of the periodogram, scalegram and the wavelet analyses.

A series of papers was on Mira Ceti-type variables with H_2O maser emission [54], [55], [56], [57]. For relatively stable light curves of M-type variables, the trigonometric polynomials of statistically optimal order were computed, and the Fourier-related coefficients were published [58], [59].

Phase plane analysis of the photometrical variations of long-period variables was proposed by [60]. Some asymptotic giant branch stars showed a linear decrease of the period [61], [62].

Periodogram analysis of RV Tau-type stars and their classification was presented by [63].

5. ECLIPSING AND "HEART-BEAT" VARIABLES

Phenomenological modeling of the light curves of Algol-type (EA) eclipsing binary stars may be optimally done using the NAV ("New Algol Variable") algorithm instead of using (very high order) trigonometrical polynomials with dozens of parameters [64]. However, it may be applied also to β Lyrae and W UMa-type stars with much smoother light curves [65], which are classically supposed not to have distinct begin and end of eclipses [1]. The accuracy of the period and other parameters may be better by a factor of few times (or even dozens times) than compared to harmonic or multi-harmonic approximations.

The analysis of the ($O - C$) diagrams was performed to study effects of the mass transfer and presence of the third components in eclipsing systems with circular or elliptic orbits [66], [67], [68],

In the binary system 14 Pegasi a reflection effect due to a highly eccentric orbit was detected [69] "Heart-Beat" variable.

An extreme "Direct Impactor" model was proposed for the system V361 Lyr, where the accretion stream impacts the star, which nearly fills it's Roche lobe without formina a bright accretion disk [70].

6. NEWLY AND RECENTLY DISCOVERED VARIABLE STARS

A new software FVSE (Flexible Variable Star Extractor) for variable stars detection using various variable detection indices was elaborated [71]. The phenomenological approximations of newly discovered eclipsing binaries using the NAV algorithm allows to make estimates of the parameters of these systems, which may be used for further physical modelling [72], [73], [74]. A new variable TIC 230386284 combines EA+UV types [75].

7. CONCLUSIONS

We presented some results of our studies of variable stars of different types with an extended list of references to original papers.

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