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LOW-METALLICITY MASSIVE SINGLE STARS WITH ROTATION

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Massive low-metallicity stars are essential for understanding cosmic history. These stars are thought to be the progenitors of certain types of supernovae, gamma-ray bursts, and gravitational wave-emitting mergers. These exotic phenomena contribute to their host galaxies through intense ionising radiation and energy and momentum feedback. To better understand the nature of these stars and to quantify the feedback from them to their host galaxies, spectroscopic observations of these stars and their analyses are of great importance.

We focus on a certain type of very metal-poor ($0.02 Z_{\odot}$) hot massive single stars that rotate fast and evolve chemically homogeneously. Combining state-of-the-art theories of stellar evolution and stellar atmosphere modelling, we predict synthetic spectra and wind properties of these stars corresponding to different masses and evolutionary phases. The Hubble Space Telescope's Ultraviolet Legacy Library of Young Stars as Essential Standards (ULLYSES) project will allow us to compare our predicted spectra with observations of stars of similar nature (e.g. metal-poor stars in Sextant A).

Keywords: stars: atmospheres – stars: winds, outflows – stars: evolution – galaxies: dwarf

1. INTRODUCTION

Massive stars with low metal content (also called metal-poor stars) are essential because they provide unique insights into the earliest stages of stellar and galactic evolution, as well as the mechanisms driving the enrichment of the Universe with heavier elements. These stars are laboratories for exploring the

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conditions and processes of the early Universe, helping us to understand star formation, galaxy evolution, cosmic reionisation and the origin of the elements. By studying them, it is possible to piece together a more complete picture of how the Universe evolved from a simple, primordial state to the complex, structured cosmos we observe today.

Massive low-metallicity stars are thought to be similar to the first stars to form after the Big Bang, known as Population III stars [1]. These stars are likely to have had very low or even zero metallicity as they formed from the primordial hydrogen and helium left over from the Big Bang. Direct observations of these stars are not possible. Today we can only observe their supernova remnants [2].

Massive stars generally emit large amounts of ultraviolet (UV) radiation, which can ionise the surrounding gas. During the "Epoch of Reionisation" [3], such radiation reionised the hydrogen in the Universe [4], ending the cosmic "dark ages" and making the Universe transparent to visible light. By studying similar massive low-metallicity stars, we can gain insight into how early massive stars may have ionised the intergalactic medium, a key process in the evolution of the Universe [5].

Massive low-metallicity stars played a key role in the formation of the first heavy elements in the Universe, such as carbon, oxygen, and nitrogen. They are primary progenitors of core-collapse supernovae [6], especially high-energy explosions, because they lose less mass to stellar winds and retain more mass until their end. Low-metallicity stars also shape the formation of the first galaxies by driving gravitational dynamics, turbulence, and feedback, with their radiation and winds influencing gas distribution and cooling [7].

Metal-poor stars are ideal progenitors of long-lived gamma-ray bursts (GRBs) and massive binary black holes (BBHs). Low metallicity minimises the angular momentum loss through winds, enabling the high rotational speeds needed for the collapsar formation, which drives GRBs [8, 9]. In addition, reduced stellar winds in metal-poor environments lead to heavier compact objects and stable close binaries, increasing the likelihood of neutron star or black hole mergers. LIGO and Virgo observations of high-mass BBHs are consistent with these expectations [10, 11].

Metal-poor stars are key to understanding the Universe, yet our limited observational capabilities prevent us from studying the first and second generations of early stars. Even nearby extremely metal-poor stars, such as those in local dwarf galaxies like Sextans A, are rarely observed and analyzed individually [12]. The spectral characteristics of stars with metallicities below $0.1Z_{\odot}$ remain largely unexplored.

The importance of studying low-metallicity stars has been underscored by the Hubble Space Telescope (HST), which has allocated 1,000 orbits to the Director's

Discretionary Time project known as the Ultraviolet Legacy Library of Young Stars as Essential Standards (ULLYSES; [13]).

1.1. ULLYSES and XShootU projects

Stars in the Large and Small Magellanic Clouds (LMC and SMC) are the primary targets observed in the ULLYSES project. These galaxies serve as ideal laboratories for studying massive stars in low- Z regions due to their proximity and metallicity levels, which are 50% and 20% of solar metallicity ($Z_{\odot}$), respectively. These unique features make them ideal targets for investigating spatially resolved populations of low- Z massive stars. A pilot study of stars with sub-SMC metallicities (10% $Z_{\odot}$) in Sextans A and NGC 3109 is also part of the ULLYSES project. ULLYSES seeks to achieve uniform coverage across all spectral subtypes from O2 to B9, while ensuring representation of all luminosity classes for spectral types O2-B1.5 at both LMC and SMC metallicities. This effort encompasses approximately 250 stars Fig. 1.

The UV part of the spectra is key for studying the iron abundance and wind parameters (e.g., terminal velocity v_{∞}) of massive stars. However, the optical wavelengths are crucial for determining stellar properties such as effective temperature (T_{eff}), surface gravity ($\log g$), luminosity (L_*), and abundances. Reliable insights into wind clumping and mass-loss rates ($\dot{M}$) require a combination of optical and near-infrared (NIR) data. To enhance the legacy of ULLYSES, the complementary X-Shooting ULLYSES (XShootU) project was established, which provide high-quality optical and NIR spectra using the broad-wavelength X-shooter spectrograph on European Southern Observatory (ESO) Very Large Telescope (VLT; [15]), complementing UV data and extending the focus to longer wavelengths.

One of the main goals of the XShootU project [16] is to better understand the physics and evolution of low metallicity massive stars and consistently determine of stellar parameters, including T_{eff} , $\log g$, L_* , and abundances, along with wind properties like v_{∞} , $\dot{M}$, and clumping properties as a function of metallicity. The XShootU project aims to deliver a high-quality, homogeneous optical dataset to complement ULLYSES, advancing models and understanding of massive stars in low- Z environments. These datasets are essential for the interpretation of high- Z observations with JWST/NIRSpec.

The UVB and optical X-shooter data collected by the XShootU large programme have been processed in a consistent and systematic manner. The community is provided with various higher-level data products [17]. These high-quality datasets offer lasting value for future research endeavors, including those not yet envisioned.

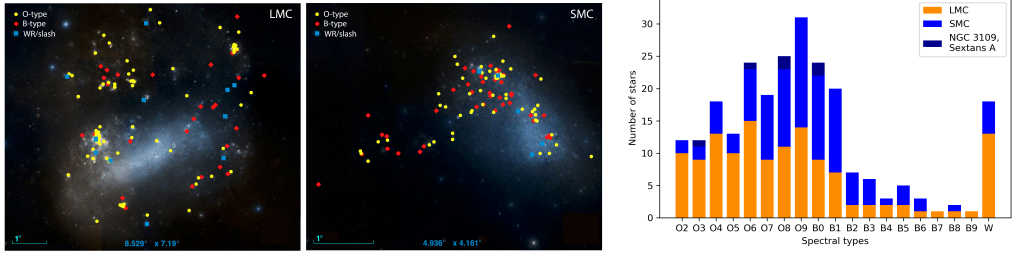


Fig. 1. *Left and middle panels:* The positions of the ULLYSES/XShootU sources in the LMC (left) and SMC (right) are shown, with yellow dots for O-type stars, red diamonds for B-type stars, and blue squares for WR and WR-like Of/WR 'slash' stars. Note the differing spatial scales. The figure uses DSS2 colour images via the Aladin Sky Atlas [14]. *Right panel:* The spectral type distribution in ULLYSES accounts only for the primary components of the ten known binaries in the sample. The category labelled "W" in the x-axes includes WR stars and WR-like "slash" stars. Courtesy: J. S. Vink [16].

2. VERY METAL-POOR MASSIVE STARS WITH ROTATION

To gain a deeper insight into very metal-poor stars, Szécsi et al. [18] modelled the evolution of single massive stars with a metallicity matching *I Zw 18* ($Z \sim 0.02, Z_{\odot}$). They found that rapidly rotating stars evolve chemically homogeneously due to rotational mixing [19] and named them Transparent Wind UV-Intense (TWUIN) stars [20]. These stars exhibit weak, optically thin winds and emit predominantly in the UV spectrum due to their high temperatures. In the Hertzsprung-Russell (HR) diagram, TWUIN stars evolve blueward during core-hydrogen burning (CHB), unlike slower-rotating or non-rotating stars, which move toward the right side of the HR diagram, similar to metal-rich massive stars in our Galaxy Fig. 2.

TWUIN stars remain theoretical predictions based on advanced stellar evolution models. To understand their spectroscopic properties and assess their impact on *I Zw 18* or other metal-poor galaxies, we analyze their spectral features, identify observable signatures, and propose a classification framework.

3. STELLAR EVOLUTIONARY MODELS

Using the 'Bonn' stellar evolution code, we calculated single stellar evolutionary tracks for fast-rotating, low-metallicity massive stars ($Z \sim 0.02 Z_{\odot}$) during the CHB phase (for details on the code and initial parameters, we refer to [18] and references therein). To explore their hydrogen-free evolution, Szécsi et al., 2015

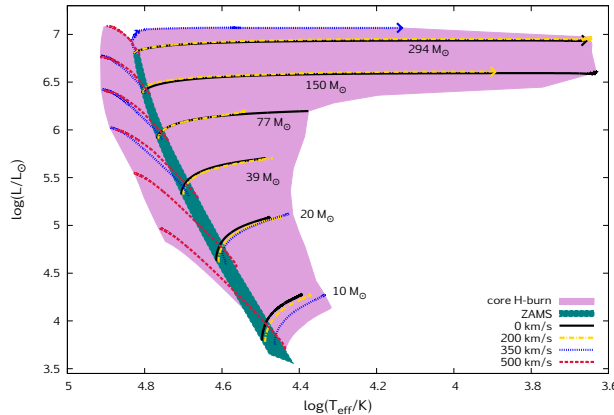


Fig. 2. The HR diagram shows evolutionary tracks during CHB for models with initial masses of 9–300 $M_{\odot}$ and rotational velocities of 0–500 km/s, at 1/10 Z_{SMC} metallicity. The purple region marks the CHB phase, while the green region indicates the zero-age main sequence (ZAMS). CHB stars are expected on both sides of the ZAMS within the purple region, with arrows marking incomplete tracks. Courtesy: D. Szécsi [18].

[20] extended these tracks into the core-helium-burning (CHeB) phase, following them until helium exhaustion in the core.

To represent different evolutionary stages through spectra, we use three chemically homogeneous tracks with initial masses (M_{ini}) of 20, 59, and 131 $M_{\odot}$ and rotational velocities of 450 km/s, 300 km/s, and 600 km/s, respectively (see Fig. 1 in [21]). These sequences assume a fast initial rotation, inherited by the 15 models we compute spectra for. Their rotational velocities range between 400–1000 km/s (see Table 1 in [21]), which remains well below the critical limit for massive stars ($\sim 0.4 - 0.6 v_{\text{crit}}$), ensuring no formation of decretion disks. For each initial mass, five models were computed: four representing the CHB phase with surface helium mass fractions (Y_S) of 0.28, 0.5, 0.75, and 0.98, and one representing the CHeB phase with a central helium mass fraction (Y_C) of 0.1. Further details on these models and their evolutionary tracks can be found in Table 1 and Fig. 1 of [21].

Different mass-loss rate prescriptions were applied depending on the evolutionary stage. For $Y_S < 0.55$, the Vink et al. (2001, [22]) mass-loss rate prescription for hot O-type stars (see e.g. 24 in their paper) was used. For $Y_S > 0.7$, we adopted the WR-type prescription from [23], scaled down by a factor of 10 as suggested by [24]. Throughout the entire CHeB phase, the WR-type prescription was consistently applied.

To address uncertainties in the mass-loss rate predictions, we calculated two sets of synthetic spectra for each model: one using the nominal mass-loss rates

from the evolutionary models, and another with mass-loss rates reduced by a factor of 100. This reduction factor was chosen based on evidence that the WR wind metallicity dependence might be steeper [25]. The values of both the nominal and reduced mass-loss rates used in our computations are given in Table 2 of [21].

4. STELLAR ATMOSPHERE AND WIND MODELS

To calculate synthetic spectra and determine wind parameter stratification, we used the Potsdam Wolf-Rayet (PoWR) atmosphere code [26, 27]. This code models both the quasi-static (photospheric) and expanding (wind) layers of stellar atmospheres, solving the non-LTE radiative transfer in a spherically expanding atmosphere with stationary mass outflow. The radiation field and population numbers are iteratively solved using statistical equilibrium and radiative transfer equations in the comoving frame. The temperature stratification is updated iteratively to ensure energy conservation, using the electron thermal balance method [28] and a generalised Unsöld-Lucy method assuming radiative equilibrium [29]. Line profiles are treated as Gaussians with a Doppler broadening velocity of $v_D = 100$ km/s, accounting for thermal and microturbulent velocities. Once the model converges, the emergent spectrum is calculated in the observer's frame using detailed atomic data and accounting for thermal, microturbulent, and pressure broadening.

To account for all significant contributors to opacity, the spectra calculations included key elements such as H, He, C, N, O, Ne, Mg, Al, Si, and Fe, with their abundances derived from stellar evolutionary model sequences. Additional elements not included in these models, such as P, S, Cl, Ar, and K, were incorporated in the PoWR code with abundances set to $Z_\odot/50$ to account for their potential impact on wind driving. The wind density stratification, $\rho(r)$, was determined using the mass continuity equation, $\dot{M} = 4\pi r^2 v(r) \rho(r)$, with the mass-loss rate taken from the evolutionary models. The velocity stratification $v(r)$ followed the so-called β -law, $v(r) = v_\infty(1 - R_*/r)^\beta$ [30], with β set to 0.8 or 1.0 and v_∞ assumed to be 1000 km/s for all models. Wind inhomogeneities (clumping) were modelled using the microclumping approximation [31], assuming optically thin clumps, a void inter-clump medium, and a radius-dependent clumping factor (D , [32]). To assess the impact of clumping on the spectra of metal-poor massive stars, we generated two sets of synthetic spectra: one assuming a smooth wind with $D=1$, and the other using $D=10$.

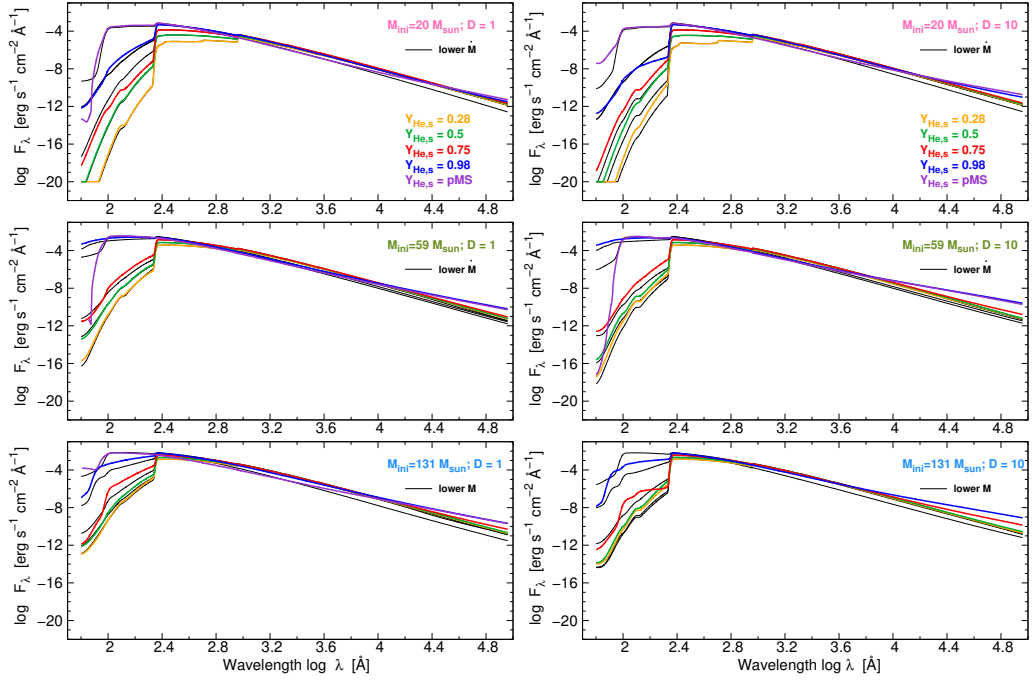


Fig. 3. The continuum SEDs of chemically homogeneous stars are shown for different initial masses (M_{ini}), noted in the top-right corner of each panel) and evolutionary stages (Y_S , indicated in the top-left panel). The coloured lines represent models calculated with nominal mass-loss rates (as used in the stellar evolutionary models) and smooth winds ($D=1$) on the left panels and clumped winds ($D=10$) on the right panels. The black lines show the SEDs for the same models but with mass-loss rates reduced by a factor of 100.

5. RESULTS

We calculated a total of 60 models for stars undergoing chemically homogeneous evolution. These models were based on three different initial masses (M_{ini}), five evolutionary stages defined by the helium fraction (Y_S), and two variations in mass-loss rates and wind clumping. The line profiles were computed while accounting for the effects of radiation damping, pressure broadening, and rotational broadening.

5.1. Spectral characteristics

For each model, we calculated the spectral energy distribution (SED) and found that chemically homogeneous stars emit most of their radiation in the far- and extreme-UV regions. The total flux emitted by these stars is not highly sensitive to changes in mass-loss rates or wind clumping. However, small differences

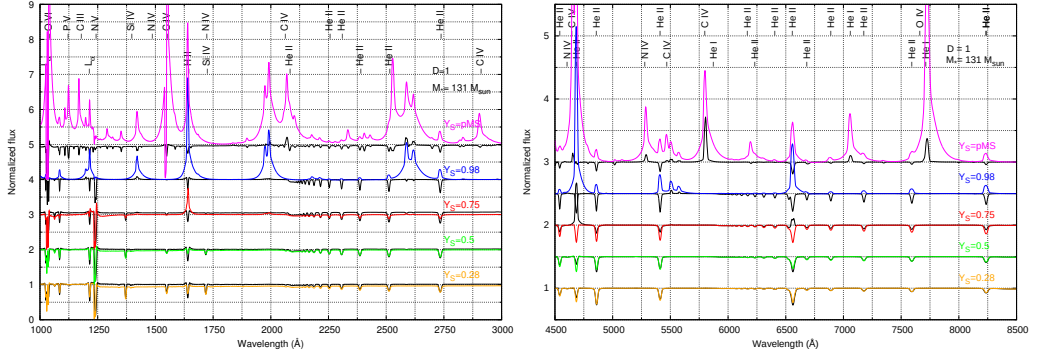


Fig. 4. The synthetic spectra of chemically homogeneous stars with an initial mass of $M_{\text{ini}} = 131 M_{\odot}$ are shown for the UV (left panel) and optical (right panel) regions at different evolutionary stages, indicated by the Y_S values. The coloured lines represent models using the nominal mass-loss rates (as adopted in the stellar evolutionary models) with smooth winds ($D=1$). In contrast, the black lines show the same models but with mass-loss rates reduced by a factor of 100.

in the SEDs appear at wavelengths shorter than $227 \text{ \AA}$ and longer than $10\,000 \text{ \AA}$, especially during the late main sequence ($Y_S = 0.98$) and post-main sequence (CHeB) phases (see Fig. 1). The SEDs also show that radiation with frequencies higher than the ionisation limits of H I, He I, and He II increases with both the star's initial mass and its evolutionary progress. This indicates that more massive and evolved stars emit stronger ionising flux.

In the earlier evolutionary stages ($Y_S < 0.5$), the synthetic spectra primarily show absorption lines, regardless of the star's initial mass. As the stars evolve, emission lines begin to appear, becoming dominant during the CHeB phase, where the spectra resemble those of Wolf-Rayet (WR) stars. Strong helium emission lines are a notable feature during this phase (see Fig. 4).

Based on these spectral features, chemically homogeneous stars in their early phases can be categorised as TWUIN stars, characterised by weak, optically thin winds. In later phases, they develop features typical of WR stars, with strong, optically thick winds (see purple lines in Fig. 4). Detailed spectral calculations in the UV, in the optical and in the infrared wavelength range can be seen in the figures 3, 4, 6 and in the appendix of [21].

5.2. Spectral classification

Using the Morgan-Keenan spectroscopic classification scheme, we assigned spectral classes to the synthetic spectra of chemically homogeneous stars. During the core hydrogen-burning (CHB) phase, these stars exhibit spectra corresponding to spectral class O4 or earlier, with luminosity classes I (supergiant), III (giant),

or V (dwarf). The spectra are characterised by strong He II emission lines and an almost complete absence of metal lines. In this phase, these stars are predicted to be significantly hotter than any O-type stars observed so far, even at metallicities as low as $0.1 Z_{\odot}$).

As the stars evolve into the CHeB phase, they evolve into WO-type WR stars, where ionised oxygen dominates their spectra. These stars' spectra lack nitrogen lines entirely. For more details on the spectral classification, refer to Table 4 and Appendix A in [21].

Due to the limited spectroscopic data available for individual massive stars with metallicities below $0.1 \sim Z_{\odot}$, we couldn't compare our spectra with observations of similar stars. The primary goal of our study was to encourage future observational efforts targeting low-metallicity star-forming galaxies, such as Sextans A or I Zwicky 18.

6. ACKNOWLEDGEMENTS

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INTERNATIONAL CHANGING LOOK AGN MONITORING PROJECT: FIRST RESULTS

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The Changing Look AGNs (CL AGNs) are objects that undergo dramatic variability of the emission line profiles and classification type of which can move from one spectral class to another within a very short time interval (from days to years). We started the project ([1] of spectral and photometric multiwavelength (from IR to X-ray) monitoring which includes the selected set of the CL AGNs. At start we were going to use several telescopes: 2-m (ShAO), 2.5-m, 1.25-m, 0.6-m, 0.5-m (SAI), MASTER global net, and *Swift* (UVOT and XRT) observatories. Then additionally, we used spectral data obtained at the WIRO, SAAO and photometry obtained at the WISE, and some other observatories. The main goal of the project is to investigate the possibilities for the repeating CL events. Investigation of such type of objects can be very informative for understanding the nature of these fast strong variations as well as the physics of the AGNs. We present the first results of our research for several CL AGNs which were mostly published already. We discovered some new CL events in several objects and discussed common properties of the CL AGNs.

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

1. INTRODUCTION

Active Galactic Nuclei (AGNs) are galaxies with incredibly bright cores which concentrate and radiate more energy than most galaxies. It is believed that at

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their centers are super-massive black holes (SMBHs) that are feeding off surrounding stars, dust and gas. The AGNs have different spectral types (see details in [2]) which can be connected with different orientation to the line of sight and existence of dust toruses around the SMBHs (AGN unification schemes [3]). One of the biggest challenge to the simple AGN unification schemes is existence of Changing-look (CL) AGNs. Changing-look AGNs are objects which undergo dramatic variability of their emission line profiles and classification type. They can move from one spectral class to another within very short time intervals (from weeks to years). One of the first known CL – NGC 4151 was discovered by us at 1984 [4], and after that till present time more than 100 CL AGNs have been discovered.

At 2016 we have begun spectral observations of the NGC2617 (a known CL [5]) with 2-m telescope (ShAO) and proposed the project of spectral and photometric multiwavelength (IR to X-ray) monitoring of such objects. The project includes the selected set of AGNs known already as the CL AGNs [1]. The investigation of recurrent CL events is the main goal of the CL monitoring project. First results of the project for several CLs are already published at [1,6–26]. The project includes collaboration with scientists from 11 countries.

2. OBSERVATIONAL DATA AND RESULTS

We are using the 2.5-m telescope of the CMO SAI and 1.25-m telescope of the Crimean SAI observatory (DAS) for IR *JHKL* photometry and optical spectrophotometry, 2.3-m telescope WIRO, 2-m Zeiss (ShAO), 1.9-m telescope (SAAO) and small telescopes 0.6-m (CMO), Zeiss-600, AZT-5 (DAS) for *UBVRI* photometry (and some others). We obtain historical light curves for known and newly discovered objects using the MASTER observations. We apply for X-ray and UV observations of some CL AGNs with the *Swift*.

2.1. NGC 2617

Intensive multi-wavelength observations of NGC 2617 were triggered by the discovery [5] of a CL event in 2013. At 2016 we started our research of the object to trace potential recurrent state changes and published our results of long-term monitoring in [1,6–13,25,26]. We proposed (using the MASTER photometry) [10] that the type change had probably occurred before 2013 – between 2010 October and 2012 February. We found significant variability at all wavelengths and in the intensities and profiles of the broad Balmer lines. We firstly noted presence of the emission peak at the red wing of $H\beta$ [10]. Reverberation mapping was carried out for 8 observing seasons during 2021-2024. We obtained time delays of

~ 4 d for the response of the $H\beta$ line to optical continuum variations. The X-ray variations correlate well with the UV and optical, with a few days lag for longer wavelengths. The K band lagged the B band by ~ 15 d during the last 3 seasons, which is significantly shorter than the delays reported previously by the 2016 and 2017–2019 campaigns. Near-IR variability arises from two different emission regions: the outer part of the accretion disc and a more distant dust component. The HK -band variability is governed primarily by dust. The $H\beta/H\alpha$ ratio variations (for broad components only) correlate with the X-ray and UV fluxes. The spectral type changed from type 1.2 (2016) to type 1.9 (January 2024) and then was a more rapid change to type 1.5 occurred in February 2024. We interpret these changes as a combination of two factors: changes in the accretion rate as a dominant cause but also the sublimation or recovery of dust along the line of sight

2.2. NGC 1566

NGC 1566 is a galaxy with a very well-studied variable active nucleus in the South Hemisphere. It is a nearest AGN and CL AGN. It is one of the first discovered CLs (see details and references in [15]). Our results of the NGC 1566 investigations published in [14, 16, 19, 21, 22]. We presented optical, UV and X-ray light curves of the nearby changing look of the NGC 1566 obtained with the Neil Gehrels *Swift* Observatory and the MASTER Global Robotic Network over the period 2007–2020. We also report on our optical spectroscopy (started soon after the brightening was discovered in July 2018) at the South African Astronomical Observatory with the 1.9-m telescope on the night 2018 August 2–3. A substantial increase in X-ray flux (by 1.5 orders of magnitude), as well as outburst in UV and optical bands were observed at 2018. After the maximum was reached at the beginning of 2018 July the fluxes in all bands decreased with some fluctuations. The amplitude of the flux variability is strongest in the X-ray band and decreases with increasing wavelength. Low-resolution spectra reveal a dramatic strengthening of the broad emission as well as high-ionization [FeX] $\lambda 6374$ lines. These lines were not detected so strongly in the past published spectra. The change in the type of the optical spectrum was accompanied by a significant change in the X-ray spectrum. All these facts confirm NGC 1566 to be a changing look Seyfert galaxy [15]. In the next publications [19, 21, 22] we concentrated on the remarkable post-maximum behaviour of the object after July 2018 when all bands decreased with some fluctuations. We observed three significant re-brightenings in the post-maximum period during 17 Nov. 2018 – 10 Jan. 2019, 29 Apr. – 19 Jun. 2019 and 27 Jul. – 6 Aug. 2019. An X-ray flux minimum occurred in Mar. 2019. The UV minimum occurred about 3 months later. It was accompa-

nied by a decrease of the Luv/Lx ratio. New post-maximum spectra covering (31 Nov. 2018–23 Sep. 2019) show dramatic changes compared to 2 Aug. 2018, with fading of the broad lines and [FeX] λ 6374 until Mar. 2019. These lines became somewhat brighter in Aug.-Sep. 2019. Effectively, two 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 due mostly to fluctuations in the energy generation. The estimated Eddington ratios are about 0.00055 for minimum in 2014 and 0.02.8 for maximum in 2018.

2.3. NGC 3516

NGC 3516 is not only the first object with detection of spectral variability for Seyfert galaxies but also the first example of a CL AGN (see details and references in [20]). Our results for the object are published in [18–20]. We present the results of photometric and spectroscopic monitoring campaigns of the NGC3516 carried out in 2016 to 2020 covering the wavelength range from the X-ray to the optical. The facilities included the telescopes of the CMO SAI MSU, the 2.3-m WIRO telescope, 2.0-m telescope ShAO and the XRT and UVOT of *Swift* and some others. We found that NGC 3516 brightened to a high state and could be classified as Sy1.5 during the spring 2016, late spring of 2020, and had a deep minimum in 2017–2018. We fixed several transitions of the spectral type and confirm that the object is CL AGNs as it was discovered in [27]. We have measured time delays in the responses of the Balmer and He II 4686 lines to continuum variations. In the case of the best-characterized broad H β line, the delay to continuum variability is about 17 days in the blue wing and is clearly shorter, 9 days, in the red, which is suggestive of inflow. As the broad lines strengthened, the blue side came to dominate the Balmer lines, resulting in very asymmetric profiles with blueshifted peaks during this high state. During the outburst the X-ray flux reached its maximum on 1 April 2020 and it was the highest value ever observed for NGC 3516 by the *Swift* observatory. The X-ray hard photon index became softer, 1.8 in the maximum on 21 Apr 2020 compared to the mean 0.7 during earlier epochs before 2020. We have found that the UV and optical variations correlated well (with a small time delay of 1 – 2 days) with the X-ray until the beginning of April 2020, but later, until the end of Jun. 2020, these variations were not correlated. We suggest that this fact may be a consequence of partial obscuration by Compton-thick clouds crossing the line of sight.

3. DISCUSSION AND CONCLUSIONS

From our 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 [21, 22]). There are several different possibilities that have been considered: variable obscuration, AD flares, tidal disruption events (TDEs), and supernova event. 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 [28, 29], which could lead to more frequent and recurrent events [30] 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.

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TOWARD THE FURTHER UNDERSTANDING OF THE PRZYBYLSKI' STAR PHENOMENON

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This paper proposes an updated scenario, which explains the Przybylski's star phenomenon, based on the assumption that it is a binary star, whose secondary component is a γ -ray source. A number of important additions are made allowing a more critical consideration of the provisions of the paper published earlier by Andrievsky in 2022. First, a new approach is proposed to estimate the number of the γ -quanta emitted by the γ -ray pulsar, and irradiating the Przybylski's star deep atmosphere layers. Second, additional sources of the free photo-neutrons are considered. Third, a critical qualitative analysis is carried out concerning the influence of the Compton effect on the γ -quanta population, which after leaving the γ -ray pulsar magnetosphere as a fan-beam, irradiate the Przybylski's star surface. Specific geometry of this binary system and its physical properties may explain uniqueness of the Przybylski's star.

Keywords: Stars – Chemically peculiar stars – Przybylski's star

1. INTRODUCTION

In [1] a new scenario to explain the unusual properties of Przybylski's star was proposed. This unique star was discovered in 1961 by Polish astronomer Antoni Przybylski in Australia. As is known, in the spectrum of this star one can detect a huge number of lines belonging to s-process elements (rare earth), such as Ce, Pr, Nd, Sm and others. This peculiarity may indicate the high-energy processes affecting the atmosphere of this star (or have affected it in the past), and leading to the generation of free neutrons. Their reactions with the seed nuclei (in particular, iron-peak nuclei) in the processes of the slow neutron captures (neutron capture, and the following β^- decay) gradually produce the nuclei of the above s-process elements. A few hypotheses that were proposed up to date in order

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to explain the Przybylski's star phenomenon, as well as observed properties of this star, are considered in detail in [1]. In addition, [2–4] attempted to search for spectral lines of such elements as deuterium, technetium and promethium, whose nuclei are also formed by the free neutron captures (the last two radioactive elements are usually considered as s-process elements). The search gave the negative results, and this was explained in the above mentioned papers.

2. BASIC MODEL ASSUMPTION

Hypotheses put forward before 2022 failed to explain the Przybylski's star phenomenon. In 2022 [1] described a new scenario, which as seemed to be able to help in understanding this star spectroscopic peculiarity. This scenario was based on a supposition that Przybylski's star is a binary star, whose companion is a low-mass neutron star being the γ -ray source. Specific geometrical and physical features of this binary system made this star an unique object of our Galaxy. Assumptions: first of all, the orbits of both components lie in the plane of the picture. This excludes the detection of the periodical line shift in the spectrum of Przybylski's star (observational fact). Secondly, the rotation axes of both components are nearly collinear (which is a completely natural assumption), and are directed towards the observer. Since in this case we see Przybylski's star polar-on, it makes this star the "very slow" rotator (observational fact).

Secondary component of the binary system is a neutron star. One component of the electric field in the pulsar's magnetosphere is parallel to the magnetic lines. Charged particles, which are born near the neutron star surface, are accelerated in this strong electric field aligned with magnetic field to the high energies, and they can escape the neutron star surface within the outer gap in the magnetosphere. Their trajectories are modulated by the open curved magnetic field lines, and they emit the curvature radiation in the γ -ray range [5]. γ -rays should be produced very close to (or outside) the light cylinder. This radiation can propagate approximately in the orthogonal direction relative to the rotation axis of the neutron star (namely, in the direction of the Przybylski's star) if the rotation and magnetic axes are at a certain angle to each other (see, for example, a very instructive illustration in [6], Fig.1).

In the outer gap model, the γ radiation propagates within a fairly large solid angle, and this fact makes it possible for such a fan-beam to irradiate the surface of the Przybylski's star, even at a fairly large distance between the components. In other words, for the Przybylski's star, a neutron star is a γ -ray pulsar. In contrast, the pencil-beam radiation from the polar cap of the neutron star does not affect the surface of the Przybylski's star atmosphere. The outer gap model was discussed, for example, in [7], Takata et al. [8], [9], [10] etc.

As it was mentioned, in the outer gap model the fan-beam radiation propagates within the rather large angle if the Lorentz factor $\Gamma = \frac{1}{(1-\frac{v^2}{c^2})}$ is not very large (it is true for moderate energies of particles). In this case, for beaming the flat angle $\alpha \sim \frac{1}{\Gamma}$. Of course, the physical parameters of the neutron star, as well as geometrical parameters of the binary system are not known. The angular velocity of the neutron star rotation may vary from 0.1 to 1000 rads^{-1} , magnetic field strength - from 10^5 to 10^{10} Tl, electric field potential drop can be about 10^{16} V. In [11], the Lorentz factor $\Gamma = \frac{e\Delta\phi}{m_e c^2}$ for electrons in extreme case can achieve 10^{10} . This value can be smaller and may change during the pulsar evolution (typical value for electrons is about 10^7). Frequency of the emitted quanta can be found using the following expression:

$$\nu_c = \frac{3c}{4\pi r_c} \Gamma^3 \quad (1)$$

The curvature radius r_c of the open magnetic field lines in this specific case is unknown, but it is known that for mild γ -ray pulsars the energy range is from MeV to about 0.1 TeV.

Solid angle of the γ -ray fan-beam is

$$\Theta = \frac{\pi}{\Gamma^2} \quad (2)$$

and it may vary in the range from approximately 10^{-8} to 10^{-20} . According to [12] the distance between components of a close binary star is $D \approx 3000 R_\odot$. If we adopt this value as an arbitrary parameter of the binary system, and consider the mild energy regime, then the irradiated area on the Przybylski's star surface will be

$$S = D^2 \Theta \approx 5 \times 10^{28} \times 3 \times 10^{-14} \approx 10^{15} \text{ cm}^2 \quad (3)$$

for $\Gamma = 10^7$ (in our model we assume that the fan-beam hits on the surface of the Przybylski's star). In reality, the irradiated spot area can be either larger (say, $\approx 10^{21} \text{ cm}^2$ for $\Gamma = 10^4$), or smaller, depending on Γ value. Note that the total area of the Przybylski's star disc is about 10^{22} cm^2 [13] (gives the radius of the Przybylski's star as $1.3 R_\odot$).

It is known that pulsed energy emitted by the γ -ray pulsar is about $L = 10^{35} - 10^{36} \text{ ergs}^{-1}$ [6]. If this energy is emitted within the discussed outer gap solid angle then the irradiated area on Przybylski's star will be hit by about $10^{36} \text{ ergs}^{-1} / 10^{-5} \text{ erg} \approx 10^{41}$ γ -quanta per sec (for quanta with an energy of about ten MeV, i.e. 10^{-5} erg).

For a rough estimate of the irradiated area 10^{13} cm^2 , we get the γ -ray flux of about $10^{23} \text{ erg cm}^{-2} \text{ s}^{-1}$.

The typical lifetime of a pulsar is about 10^7 years [14], therefore the total fluence (total number) of γ -quanta, which irradiate the certain area on the Przybylski's star surface during this time can be quite large (approximately, 10^{55}).

3. γ -QUANTA AND FREE NEUTRONS

How γ -quanta can produce free neutrons? [1] proposed a mechanism of the free photoneutrons formation in reactions between γ -quanta and α particles in the Przybylski's star deep layers (it is reasonable to limit consideration of particle interactions in the convective zone, since only in this case the convective flows transport the products of the reaction between free neutrons and seed nuclei to the stellar surface, and this makes them accessible to detection by spectroscopic analysis).

The reaction cross-section ${}^4_2\text{He}(\gamma, n){}^3_2\text{He}$ is close to $1 - 2\text{mb}$ in the energy range between 30 and 70 MeV with a peak value of about 3.5 mb at about 30 MeV [15]. The following reactions at the same energy can also contribute to the production of free neutrons:

$$\gamma + {}^{12}_6\text{C} = {}^{11}_6\text{C} + n \quad (4)$$

$$\gamma + {}^{14}_7\text{N} = {}^{13}_7\text{N} + n \quad (5)$$

$$\gamma + {}^{16}_8\text{O} = {}^{15}_8\text{O} + n \quad (6)$$

$$\gamma + {}^{28}_{14}\text{Si} = {}^{27}_{14}\text{Si} + n \quad (7)$$

For instance, the last reaction has a giant dipole resonance at 26 MeV [16]. Despite the fact that these nuclei are less abundant than α particles, the reaction cross-sections are larger than those of the reaction ${}^4_2\text{He}(\gamma, n){}^3_2\text{He}$. The question arises: where in the Przybylski's star the listed above reactions occur? Since we do not know the internal structure of the Przybylski's star, as a very rough approximation we will use the internal structure of the Sun (the difference in the effective temperature is about $600 - 800\text{ K}$, $T_{\text{eff,PS}} = 6400\text{ K}$ from $\text{H}\alpha$ line, and $\log g = 4.2$, [17]; $T_{\text{eff,PS}} = 6600\text{ K}$, [18]; $T_{\text{eff,PS}} = 6131\text{ K}$ from GDR3). According to [19], at the bottom of the outer convective zone (it occupies about 30% of the stellar radius, or even slightly more with overshooting) the density reaches about 0.1 g cm^{-3} . Therefore, the proton concentration there is about 10^{23} cm^{-3} . Since the helium nuclei in the stellar atmospheres, as a rule, are about ten times less abundant than protons, the concentration of the α particles in this zone is $N \approx 10^{22}\text{ cm}^{-3}$. As mentioned above, the cross-section σ for the γ -quanta interaction with α particles is about $1 - 3\text{mb}$, so the optical thickness for the γ -quanta

of about unity will be reached at the bottom of the convective zone in the shell of size:

$$d \approx \frac{1}{\sigma N} \approx 10^5 \text{ cm.} \quad (8)$$

In this shell at the bottom of convective zone γ -quanta can already react with nuclei of the elements mentioned above, thus forming in this way fast free photon-neutrons. Fast neutrons can lose their energy through elastic collisions with protons and become resonant intermediate neutrons, which can react with seed nuclei in the s-process. This can be achieved through the following scheme:

$$\frac{\Delta E}{E} = 1 - \frac{2A}{(A+1)^2}, \quad (9)$$

where A is the mass of target (obviously, the energy loss will be highest for the lower mass targets). ΔE and E are the fraction of energy lost in one collision and the neutron initial energy, respectively. About twenty collisions are needed to reduce the neutron energy from tens of MeV to less than keV (intermediate or resonant neutrons). The energy loss (thermalization) occurs very quickly. Only such intermediate neutrons can be captured by the seed nuclei (for example, the nuclei of iron-peak elements).

4. POTENTIAL PROBLEMS OF THE PROPOSED HYPOTHESIS

γ -quanta that penetrate into the internal layers of Przybylski's star may lose part of their energy due to the Compton effect. The interaction with free electrons can be characterized by the cross-section:

$$\sigma = \pi a^2 \frac{m_e c^2}{h\nu} \times \left(\ln \frac{h\nu}{m_e c^2} + 3 \right), \quad (10)$$

where a is the electron radius, m_e is the electron mass. γ -ray scattering can reduce the energy of quanta. Such a decrease depends on the angle of scattering:

$$\Delta\lambda = \frac{h}{m_e c} \times (1 - \cos(\theta)). \quad (11)$$

If the angle is small or equal to zero, then the γ -quanta energy loss will be small or absent at all. Of course, this process may decrease the flux of γ -quanta that can penetrate deep enough into Przybylski's star atmosphere. Nevertheless, there are two points that mitigate this possible problem. First, we are interested in γ -quanta that have energies of about tens of MeV (for the reactions listed above to be effective). It is quite possible that γ -quanta born in the neutron star magnetosphere have initially energies of hundreds of MeV, and after the scattering

they gain the energies of tens MeV. Second, the Compton effect has the largest efficiency near the electron energies, which are close to the $m_e c^2$ value, that is 0.5 MeV. Efficiency of the Compton scattering decreases rapidly with energy increase, and become almost negligible at about tens of MeV.

In [20] considered stratification of the elements in the atmospheres of pulsating roAp stars. Since the author considered the Przybylski's star as a coolest representative of the whole class, she indirectly supports an idea of stratification in the Przybylski's star atmosphere as a factor of the chemical peculiarity formation. Perhaps this process can participate to somehow in the Przybylski's star phenomenon. However, regarding the low temperature of this star and an expected strong convection, which should erase any surface chemical anomalies, this explanation does not seem very realistic.

Finally, in case of a certain disposition of the orbits of the binary system components, we should detect the Przybylski's star cyclic proper motion variation. It was not detected from the combined Gaia+Hipparcos data [21]. The possible reason may be as follows. If the binary system under discussion consists of a main sequence component and a neutron star of about half less its mass, then taking into account the distance between the close binary components of about $3000R_\odot$ (see above), we should expect that the distance of the Przybylski's star from the center of mass should be something about $1000R_\odot$. The distance to the Przybylski's star is about 100 pc (SIMBAD, GDR3). Therefore, the spatial angular deviation from the center of mass will not exceed $\approx 2 \times 10^{-5}$ arcsec, while the spatial resolution of Gaia equipment is not better than 2.4×10^{-5} arcsec. Thus, either such a motion was not detected by the Gaia instruments, or it is on the level of the measurement errors.

5. CONCLUSION

Let us summarize the above reasoning. For this the main assumptions of the discussed phenomenological hypothesis can be listed as follows:

1. Przybylski's star is a component of the binary system, where the secondary component is a neutron star. Rotation axes of both components are nearly codirected towards the observer, while their orbits both lie in the picture plane. In such a case we do not register the radial velocity variation for the Przybylski's star. At the same time observationally this star is known as very "slow" rotator.
2. A neutron star is a γ -ray pulsar for the Przybylski's star. If we adopt for such a pulsar the outer gap model, then the emitted γ -rays will be directed approximately orthogonally to its rotation axis (provided there is a corresponding tilt between rotational axis and magnetic axis). In this favorable case, the γ

quanta can irradiate the Przybylski's star atmosphere, causing there the high-energy processes that can lead to the production of free neutrons.

3. The size of the irradiated area on the surface of the Przybylski's star depends on the distance between components and the solid angle of the γ -radiation fanbeam. The latter, in turn, depends on the Lorentz factor.

4. Many of the above-mentioned physical properties of the binary model of the Przybylski's star are unknown and can only be of an estimated nature. If such a system, containing a main sequence star and a neutron star (the source of γ -rays) actually formed tens of millions years ago, an initial "fine-tuning" of its geometrical and physical parameters could lead to the formation of a remarkable chemical peculiarity of the primary component, which is currently considered one of the most unique observed objects in the sky - Przybylski's star.

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VARIABLE STARS AND STAR CLUSTERS

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The brief review of some recent results obtained in search and study of different type variable stars both in star clusters and stellar associations and in general field of the Galaxy, i.e. outside star clusters and stellar associations is presented. In the short excursus we overview the historical grounds on which the nova-day astronomy in Uzbekistan based. The dozens of open clusters of different ages and some unique types of variable stars beyond clusters to compare were observed in the frame of international research project with India. Hundreds of new variable stars in different open star clusters as well as a number of MCV, EB, N, SN and FS beyond the clusters have been discovered and studied using our observational data. Using the Big Data databases of space telescopes, such as Gaia, TESS, Kepler, etc. to search and study variability of stars, the great number of new variable stars were found in selected open star clusters, the basic parameters of them as well as of their host star clusters and associations were determined. Some our suggestions and promising prospects of future collaboration with foreign countries are described and discussed.

Keywords: stars: activity – stars: variables: general – (Galaxy:) open clusters and associations: general – methods: observational – techniques: image processing

1. INTRODUCTION

The processes of non-stationarity of energy and other fundamental astrophysical characteristics of space objects are very important and at the same time quite common phenomena that have not only cognitive value, but also a potential im-

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pact on the environment. For example, our Sun, being a normal star SpG(V) of the Initial Main Sequence (ZAMS i.e. Zero Age Main Sequence), observed from afar as a stationary star, in fact, upon close examination, exhibits noticeable non-stationarity, manifested in powerful flares, emissions of accelerated particles and magnetic disturbances, changes in the spottedness of the photosphere and other manifestations of activity cycles. The processes of non-stationarity are especially strongly manifested in changes in luminosity, other characteristics, and therefore the observed brightness, of the so-called variable stars of a wide and diverse class of variability in physics. A comprehensive study of non-stationarity phenomena in stars, especially those that form physically related groupings (stellar associations, star clusters, both open and globular), is becoming one of the most pressing and topical issues in modern astrophysics [1,2].

Multicolor photometry of variables (e.g., RR Lyrae type) is very important for determining their basic physical parameters (temperature, mass, luminosity, $\log g$, metallicity or chemical composition, etc.), as well as for studying various subtle effects, such as the Blazhko effect. Lyrids (i.e., RR Lyr type variable stars) in globular clusters allow an accurate test of the theory of stellar evolution and the cosmological distance scale. Another important task is the search for and in-depth study of extremely young variables or Pre-Main-Sequence stars (PMS) in groups or regions of modern star formation. In particular, based on the processing and analysis VLDB of very large arrays of Big Data class Databases (VLDB) (2MASS, Chandra, UCAC, USNOB) and the most modern Gaia VLDB (DR1, 2, EDR3, DR3), Spitzer, TESS, Kepler, COROT, AllWISE, PanSTARRS, IPHAS, LAMOST and others, we have already discovered numerous young variable stars in the complex around the open cluster NGC 6823, confirmed later by observations of their spectra [3]. It is known that star clusters are ideal objects for studying the stellar population of our Galaxy, the structure and evolution of stars, the dynamic evolution of the cluster itself, for accurately determining its age and distance from the Sun. Due to the common origin of stars in an open cluster, they have almost the same age, chemical composition and distance at which they are located. Searching for and studying variable stars in open clusters is one of the important tools for testing the theory of stellar evolution, and provides additional information for understanding the structure and evolution of the Milky Way. In solving such problems, it is critically important to determine whether the detected variable stars belong to the open star cluster being studied, which is now becoming possible based on deep analysis of cosmic VLDBs of the Big Data class.

On the other hand, well-known that Uzbekistan has deep ancient roots, traditions and achievements as well as scientific relations with many countries in astronomy, along with other sciences, and impacts on their science and technology in the



Fig. 1. Ancient Koy-Krylgan-kala Observatory

past. Nowadays we continue to establish such a relations and collaborations. Here the recent results of joint project UZB-Ind-2021-99 supported by India and Uzbekistan governments on search of variable stars in star clusters is presented.

2. BACKGROUND

2.1. ANCIENT HISTORY

Ancient astronomy in the territory of Uzbekistan has been proven based on various archaeoastronomical research instruments, and excavations have led to the discovery of many observatories and astronomy-related signs in various regions of the country. The solid evidence of the very ancient roots of astronomy in Uzbekistan is the discovery of very ancient observatories and places with astronomical

signs in Khorezm, between Bukhara and Samarkand, in the Surkhandarya region and other places. As example, Koy-Krylgan-kala was built in 4th-3rd centuries BC and was used until the 4th century AD [4, 5]. Fig. 1 shows a bird's eye view (photograph) of this ancient observatory taken from above.

Medieval Astronomy of Central Asia mainly of Uzbekistan starting about 7th century AD represents the brilliant Eastern Renaissance. We will note here only the most outstanding figures who were encyclopedic scientists and made a worthy contribution to world astronomy (see Fig. 2). Thus, the founder of algebra and algorithms of calculations al-Khwarizmi also significantly improved the tables of planetary motion compiled by Ptolemy and invented the astrolabe. The tremendous fundamental achievements of other great astronomers who worked up to the 15th century (al-Farghani, al-Biruni, ibn Sina and Ulugh Beg) are shown insets in Fig. 2. It is appropriate to note here that there is evidence that Ulugh Beg used the experience of the Maragha Observatory, built by Nasr-at-Din Tusi, when creating his own observatory in Samarqand. In connection with the further description of the principles of our cooperation with our Indian colleagues, it is necessary to especially note that the connection between the astronomy of Uzbekistan and India can be traced back to ancient times: in particular, the experience of the Ulugh Beg's Observatory and his scientific school in Samarqand was used during the construction of the Jantar Mantar observatories in Jaipur, Delhi, Banoras and others that were built in the 18th century India where the strong influence of the Ulugh Beg's school is obvious [6].

2.2. PREAMBLE OF COLLABORATION

Main basic cornerstones of scientific cooperation with Indian astronomers in the modern era, especially, from Aryabhata Research Institute of observational Sciences (ARIES) are described below. In 2004 by invitation of the former director of ARIES, Prof. Ram Sagar Alisher S. Hojaev visited Nainital (for the Asteroseismology workshop) and had a fruitful discussion on possible joint research and collaboration in observational astronomy. After a long break caused by many circumstances beyond our control, Department of Science and Technology, Government of India (DST) together with Ministry of Innovative Development of Uzbekistan in 2019 announced a Call for Proposals under Indo-Uzbek Joint Research Program. There were 170 proposals submitted and passed technical expertise from which 21 were awarded only (mainly in applied sciences and technology).

In the beginnig of 2021 the joint triennial project 'Search for Variable Stars in Star Clusters' [UZB-Ind-2021-99 (INT/Uzbek/P-19)] between ARIES/DST of



Fig. 2. Prominent scholars and scientists of the Middle Ages who lived in the territory of Uzbekistan

India and Ulugh Beg Astronomical Institute, Academy of Sciences of the Republic of Uzbekistan started.

The PIs (i.e., Principal Investigators as well as Project Initiators) are Ramakant Singh Yadav (India) and Alisher S. Hojaev (Uzbekistan). Indian participants were followings: Ramakant Singh Yadav, Jeewan Chand Pandey (included in the proposal), but in actual there were much more collaborators, such as Nikita Agrawal, Sneha Lata, Neelam Panwar, et al.

Uzbek personnel included following people: Alisher S. Hojaev + 7 researchers + 4 Maidanak Astrophysical Observatory operators and staff + 7 undergraduate students.

3. RATIONALE AND OBJECTIVES

Stars are the main population of galaxies, and they typically form in groups from molecular clouds. Star clusters are ideal laboratories for testing theories of stellar evolution [7], since all member stars emerge from the same parent molec-

ular cloud, and therefore have approximately the same age, distance, and chemical composition [8], but evolve slightly differently due to their different masses. Very young open star clusters bear the imprint of star formation processes, while middle-aged and old clusters, whose locations, metallicity and age are well determined, allow us to study the processes of stellar evolution and chemical enrichment in the galactic disk [7]. Moreover, open star clusters are very convenient for studying stellar variability and exoplanets in them [9, 10], especially since the main properties and evolutionary status of individual member stars can be inferred from the properties of the cluster [9]. In addition, it is known that by comparing the color-magnitude diagram of a star cluster with theoretical evolutionary models, one can quite accurately estimate its age and obtain information about the evolution of stars of almost the same age and chemical composition. Thus, the search for and study of stellar variability in clusters by obtaining and analyzing homogeneous photometric time series (Time Domain Astronomy) is a completely modern and very relevant direction of astronomical research.

Photometric analysis is an effective method for identifying stars of interest in studying stellar structure and evolution [11]. The source of stellar photometric variability is, among other things, magnetic activity generated by dynamo and stellar pulsations. However, variability observations require long-term extensive monitoring of objects with high accuracy and a limited achievable magnitude [9]. This strict requirement can explain the extremely small number of searches and studies of variability among several thousand cataloged star clusters.

Based on the above, we have carefully selected star clusters that are poorly studied in terms of variability, but interesting in their physics and morphology and promising for further study. We selected clusters of different age ranges, morphological structures, different levels of population, located at different distances from the Sun.

So the main objective of the present project is to obtain high-quality time series of observations of star clusters and to study the nature of known and newly discovered variable stars. The available telescopes on both sides allow us to observe the clusters widely. These telescopes are equipped with CCD cameras, which are very suitable for the proposed study. For example, the recently installed 3.6-meter ARIES telescope is very effective in spectroscopic study and in obtaining images with quite high spatial resolution due to the excellent quality of its optics and depth of stars' brightness coverage (up to 24 stellar magnitude). This allows detecting variable stars even in a densely populated region of the cluster. Observations by foreign authors were usually carried out irregularly and also had low search depth parameters ($V < 8.5$ mag and $D < 40$ pc).

Despite significant progress in detecting variable stars in clusters, many questions about the variability and their causes remain quite uncertain. Detect-

Table 1. Observation statistics of clusters and associations

Cluster	Telescope	Nights
NGC 6611	0.6 m Zeiss600NT	8
NGC 6705	0.6 m Zeiss600ST	18
NGC 6705	0.6 m Zeiss600NT	5
NGC 6791	0.6 m Zeiss600NT	31
NGC 6791	0.6 m Zeiss600ST	3
NGC 6823	1.5 m AZT-22	8
NGC 6823	0.6 Zeiss600NT	12
NGC 6871	0.6 m Zeiss600NT	10
NGC 7772	1.5 m AZT-22	3
IC 1396	1.5 m AZT-22	4
IC 1396	0.6 m Zeiss600NT	6
IC4996	1.5 m AZT-22	3
IC4996	0.6 m Zeiss600N	5
Berkeley 55	1.5 m AZT-22	3
Berkeley 55	0.6 m Zeiss600NT	2
Berkeley 98	1.5 m AZT-22	5
King 1	0.6 m Zeiss600NT	5
King 13	1.5 m AZT-22	6
King 13	0.6 m Zeiss600NT	2
King 18	0.6 m Zeiss600NT	6
BRC 5	0.6 m Zeiss600NT	1
BRC 7	0.6 m Zeiss600NT	3

ing stellar variability is usually difficult due to spatial resolution, photometric accuracy, limited time and depth of monitoring. Thus, among the fundamental tasks are the search for new variable stars, determination of the initial mass function, age, chemical composition of clusters, search for supermassive stars, and brown dwarfs. As the array of observations accumulates, it becomes possible to solve questions related to the galactic structure, the reddening law in the part of the Galaxy covered by the survey.

4. OBSERVATIONS, PROCESSING AND ANALYSIS

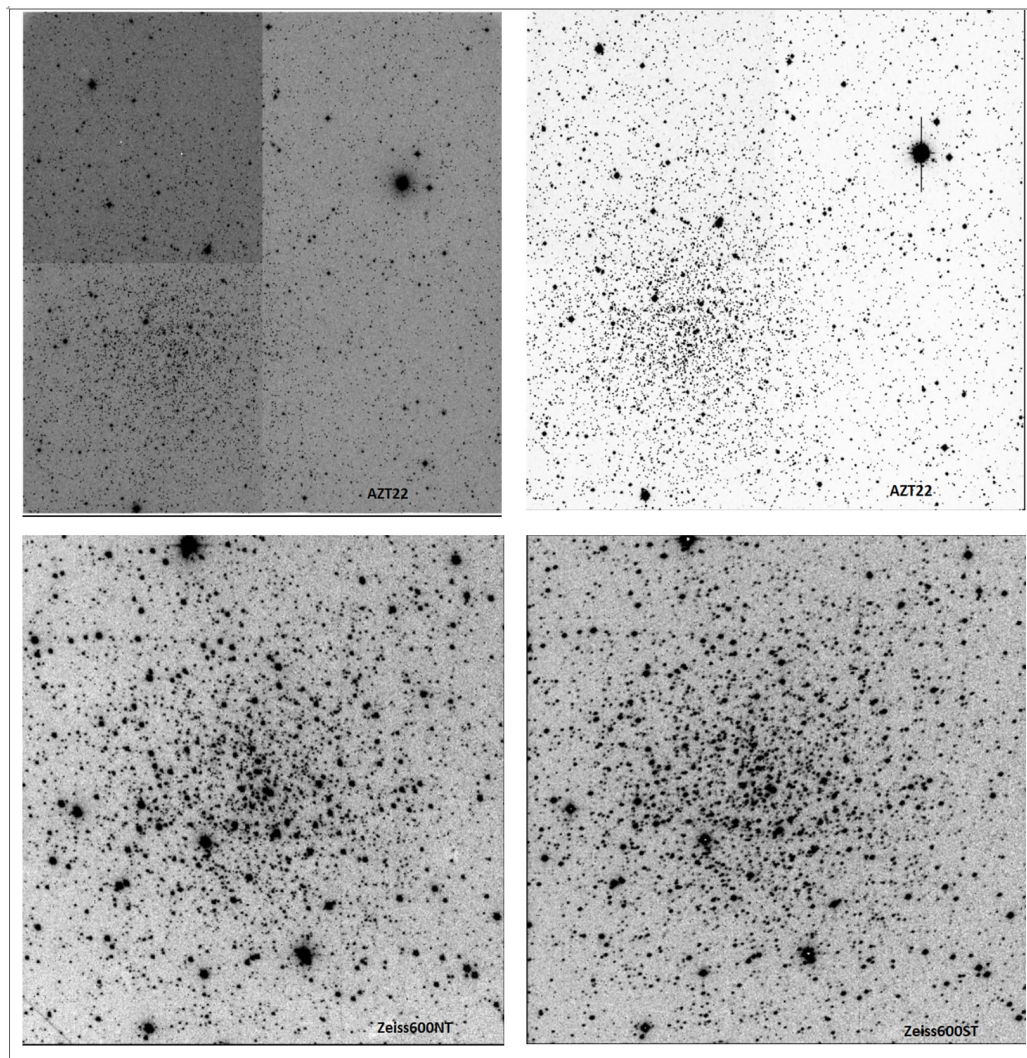


Fig. 3. Mosaic of original observational image-frames of open star cluster NGC 6791 obtained at different telescopes of Maidanak Observatory

The main part of photometric observations were obtained using the astronomical instrumentation installed at the high-mountain Maidanak Astrophysical Observatory (Uzbekistan, Longitude: $66:53:04$ E Latitude: $38:40:22$ N, Altitude: $2\,593$ m), located in the western spurs of the Pamir-Alai mountain system in Central Asia. Now it is well-known that the observatory site has one of the highest astroclimate indicators worldwide (median seeing is about 0.68 seconds of arc).

The observations were carried out using 1.5 m telescope AZT-22 and two 60 cm telescopes Zeiss-600, equipped with CCD cameras Andor iKon-XL (4096×4112 pixels) [or sometimes SNUCAM (4096×4096 pixels)], Andor iKon-L (2048×2048 pixels) and Apogee Aspen CG230 (2048×2048 pixels), respectively. The exposure time was selected every case according to the astroclimatic conditions, the observed brightness of the object and the S/N ratio. As an example, Fig. 3 shows in the form of a mosaic the images of the open star cluster NGC 6791 that we obtained using the telescopes of the Maidanak Observatory. Data reduction, calibration and further processing was carried out using standard IRAF/NOAO packages. We have also already started using original pipelines (software conveyors) for automatic data processing and identification of variables in clusters, including those developed in ARIES. It is necessary to especially note here that, in fact, the cluster monitoring program was started by us back in 2001-2003 [12] when we observed 7 open star clusters.

Thus, over the course of three years (2021-2023), we have obtained good photometric time series of 15 open clusters and stellar associations of our Galaxy of different ages, located at different distances from the Sun. The log of these observations is presented in Table 2. A total of 12,051 CCD frames with observational images of sky areas covering clusters and their surroundings were obtained. In addition, fairly dense time series were also obtained for 7 star clusters (NGC 7801, IC 4996, Berkeley 55, King 1, King 13, King 18, King 20) in July-August 2003 with the 60-cm Zeiss-600 telescope of the Maidanak Observatory using the Apogee 10 CCD camera [12]. It is very important that some of the clusters (IC 4996, Berkeley 55, King 1, King 13, King 18) were observed in both monitoring campaigns, which will provide data on variability on a long time scale, with an epoch difference of 20 years.

5. VARIABLE STARS IN CLUSTERS

Based on our original observations and combined processing and analysis with existing databases, including TESS data, we have been enabled to discover a significant number of new variable stars and to study in detail known variables that had only been discovered in small numbers in these clusters before. We have conducted a thorough study of the young cluster NGC 6823, associated with a star-forming complex that includes molecular clouds, an OB association (Vul OB1), and the bright nebula NGC 6820. Eighty-eight variable stars were identified and described, of which only 14 had been previously recognized; 72 variable stars were found to be members of the clusters, of which 25 Main-Sequence stars (β Cep, δ Scuti, slowly pulsating B type, and new class variables) and 48 Pre-Main-Sequence (8 Classic T Tauri Stars, 4 HAe/Be Stars, 36 Weak-lined T Tauri

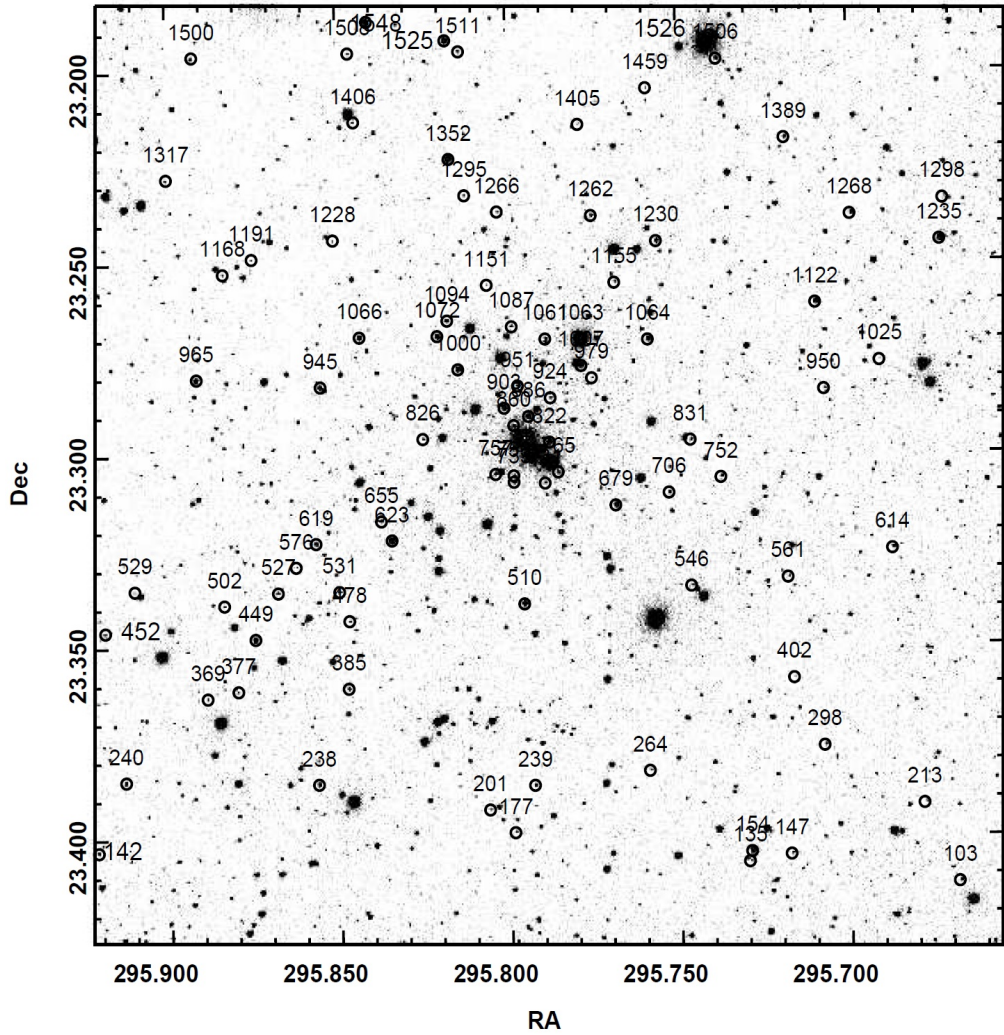


Fig. 4. The identification of variable stars in open cluster NGC 6823 and surroundings

Stars) [10]. The Fig. 4 taken from this our paper [10] shows the observed region of open star cluster NGC 6823, in which all variable star identified by us are encircled. Preliminary analysis of open star cluster NGC 6791 data obtained at Maidanak Observatory revealed more than 430 variables in the region, covered by our observations : there characterization and preparation for publication are in a progress.

Besides we use the Big Data databases of space telescopes, such as Gaia, TESS, Kepler, etc. to search and study variability of stars, the basic parameters

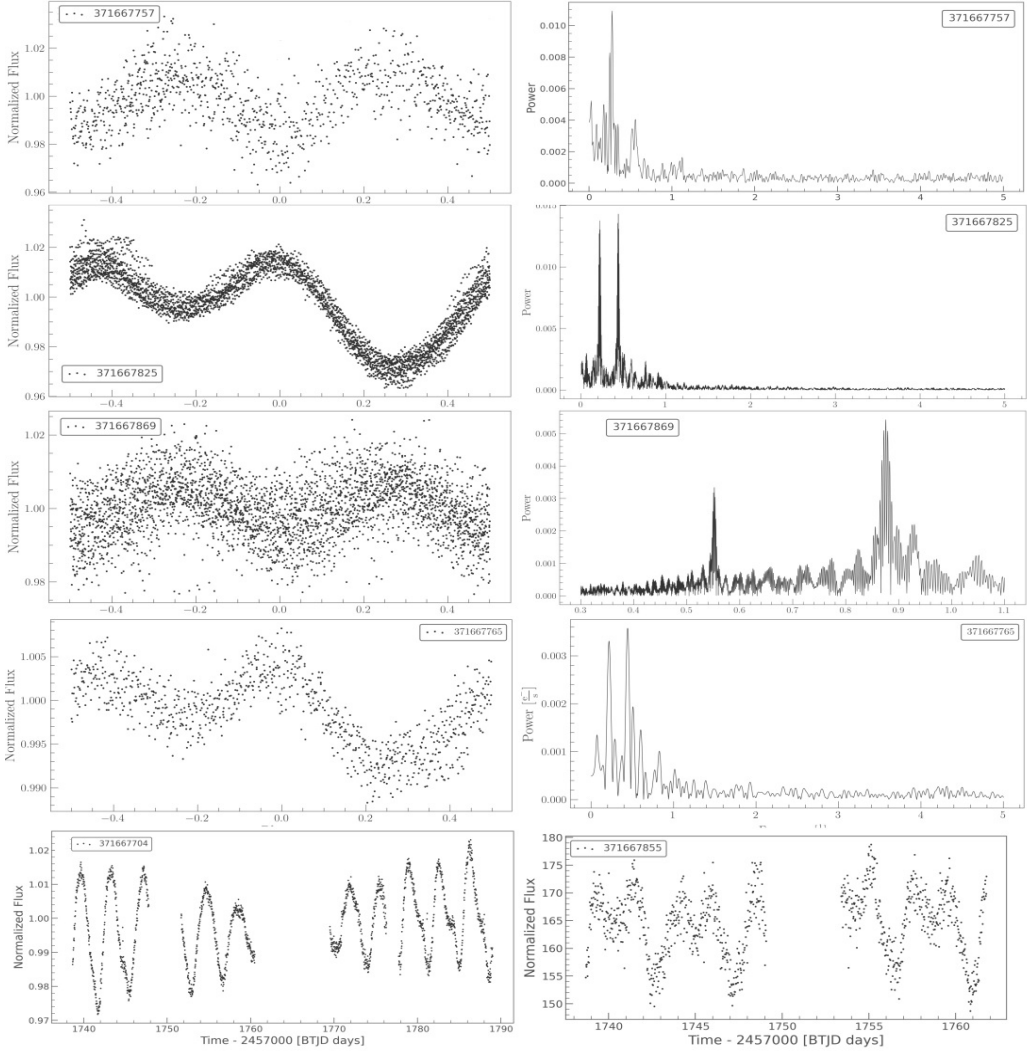


Fig. 5. Phased light curves and periodograms for new variable stars in open star cluster King 18

of them as well as of their host star clusters and associations if any, to analyse their distribution and other features of variables and clusters.

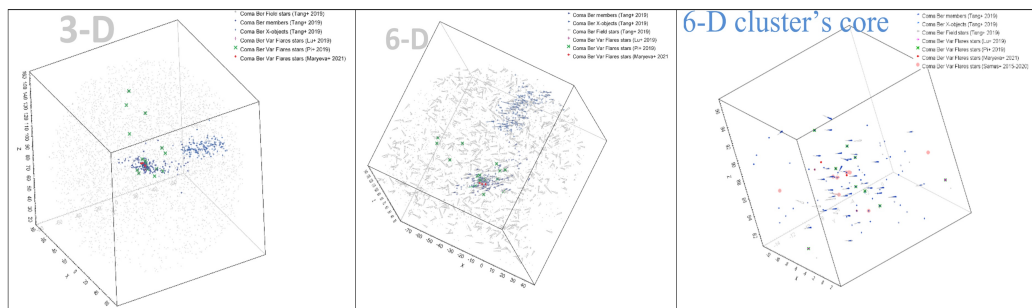
In parallel with the processing and analysis of our own observation databases, we processed and analyzed photometric monitoring databases, in particular the TESS data bank. We have detected 65 variable stars from 1579 checked in open cluster Gulliver 35 , 136 from 1340 checked in NGC 6871, 43 from more than 76 checked possible variables in King 18 and 26 from 260 most probable cluster members in Berkeley 98 (see, for instance, [13]). In Fig.5 the phased light curves

Table 2. New variable stars in open star clusters

Open Cluster	Variables
NGC 6871	136
NGC 6823	88
Gulliver 35	65
King 18	43
Berkeley 98	26

with frequency analysis results for new variable stars discovered by us in open star cluster King 18 are shown. It is also noteworthy that part of these clusters were photometrically monitored at Maidanak Observatory, and the combined analysis of space and ground-based data sets is planned.

Table 2 contains data on the number of variable stars that we discovered during our search for them in star clusters.

**Fig. 6.** 3-D and 6-D modelling of variable stars in open star cluster Melotte 111

Using Gaia data and observational data from other sources to examine the spatial distribution of variable stars in star clusters allowed us to construct their multidimensional distributions. For example, examining the Melotte 111 = Collinder 256 cluster, which is also called the Coma star cluster, allowed us [14] to construct three- (3-D) and six-dimensional (6-D) distributions of variable stars in the cluster and its core, shown in Fig. 6. The 3-D distribution implies a volumetric distribution over three spatial coordinates, while the 6-D distribution includes, in addition to three spatial coordinates, also three vectors of spatial velocities of the star.

Table 3. Observations of cataclysmic variables (MCV)

Variable Star ID	Telescope	Nights
V533 Her	0.6 m Zeiss600NT	41
V533 Her	0.6 m Zeiss600ST	8
RX J0153.3+7446	1.5 m AZT-22	3
RX J0953-1458	0.6 m Zeiss600NT	9
1RXSJ1743-0429	0.6 m Zeiss600NT	12
Swift J2241+5644	1.5 m AZT-22	1
Swift J2237.2+6324	1.5 m AZT-22	2
SDSS J204827.91+005008.9	1.5 m AZT-22	1
1RXSJ174320.1-042953	1.5 m AZT-22	3
1RXSJ174320.1-042953	0.6 m Zeiss600NT	5
RXJ0953-1458	1.5 m AZT-22	1
1RXSJ163100.5+695000	1.5 m AZT-22	3
LAMOST J071553.88+581606.4	0.6 m Zeiss600NT	1
2MASS J18560806+4537400	0.6 m Zeiss600NT	7
SwiftJ2116	0.6 m Zeiss600NT	5
RXJ0153	1.5 m AZT-22	5

6. OTHER SELECTED VARIABLES

Simultaneously with the search for and study of variables in clusters, we also observed other individual, selected variables, the study of which is important for comparison and application to cluster variables. Particular attention was paid to a large sample of magnetic cataclysmic variables (MCV), consisting of a number of cataclysmic variable stars recently discovered by space telescopes, mainly in the X-ray range, supplemented by spectral and polarimetric observations from foreign observatories in order to determine the physics of these variable stars, study the geometry of the accretion flow in these systems and their belonging to the class of *magnetic polars*. In total, 14 MCVs were patrolled for 170 nights with a cadence of more than 4 hours per night. The generalized log of these observations, carried out at the Maidanak Observatory, is given in Table 3. The number of CCD images of sky regions covering wide areas with MCVs is 6,539 .

The phase light curve of the star 1RXS J174320.1-042953 (J1743) in the R-bandpass, obtained from our observations at Maidanak Observatory in 2021–2022, is presented in Fig. 7 together with its frequency analysis. It demonstrate the pre-

cision of data is sufficiently high to make analysis and modelling of the star. We could confirm two MCV as polars [15], namely 1RXS J174320.1-042953 (J1743) and YY Sex .

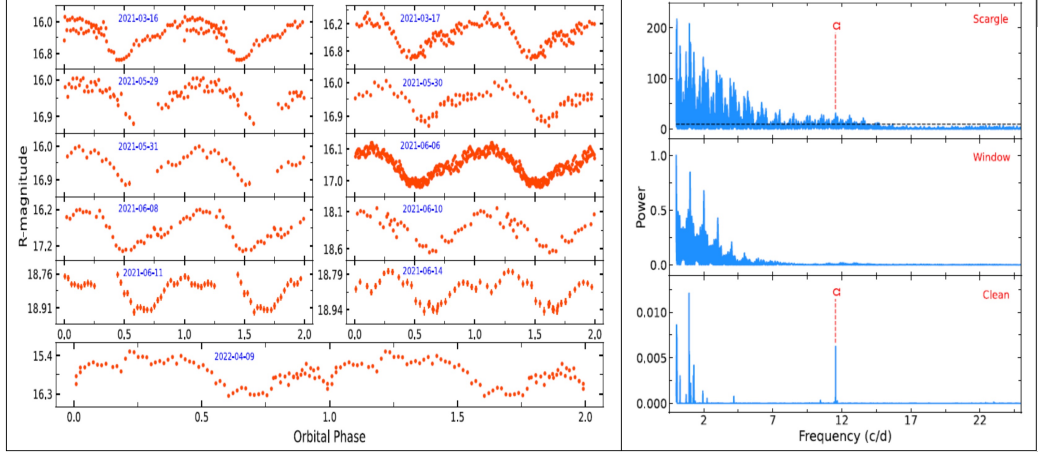


Fig. 7. Phased light curves and frequency analysis for MCV polar 1RXS J174320.1-042953 (J1743)

Observations of a number of eclipsing binary systems HS Hya, V699 Cyg, VV Ori, 2MASSJ23194851+3603503, TYC3224-1304-1, of the repeated nova RS Oph (about one and a half months), of the flare star GJ 3147=LP 245-10 (as part of the international multi-site multi-wavelength synchronous photometric and polarimetric monitoring campaign) and of many other variables were also obtained. We should especially point, that 7 major astronomical observatories from Taiwan, mainland China, India and Uzbekistan took part in that flare star monitoring campaign. The results are in preparation for publication.

7. DISCUSSION AND CONCLUSIONS

The successful development of research in the field of modern and future observational astronomy and especially astrophysics, as in no other scientific field, makes it extremely necessary to create and intensively develop broad international cooperation, both as a multisite and a multimessenger. The unique Maidanak Astrophysical Observatory may take a special place in this unification of efforts of world astronomy. The conjunction of outstanding astroclimatic properties, which despite global climate changes are still present at the Maidanak Observatory (stable atmosphere above the site, providing good seeing, quite small background of the night sky and extinction in optical range, a large number of clear nights, etc.)

and the relatively good quality of the used telescopes/CCD cameras allow us to obtain a quite high photometric accuracy, cadence, time resolution and a fairly deep limit on faint stellar magnitudes (see, for example, [12, 16]). These conditions are suitable not only for time-domain study of different types of variable objects (NEOs, solar system planets, asteroids and comets, stars and star clusters, associations, star forming regions, galaxies, quasars, transients, GW source optical counterpart, etc.) but to detect and characterize of extrasolar planets (exoplanets) too.

For instance, the existing extensive observational material (e.g., obtained within the star clusters and variable stars study project described earlier) is of sufficiently high accuracy, cadence and Field of View of each image frame (about 20×20 arcmin) and also makes it possible to search for transits of probable new exoplanets which along with various other detected at our ground-based observatory unique objects might become as targets for sharp-sighted James Webb Space Telescope (JWST) [17] or another telescope facility in the space or on the ground.

Summarizing the results described in the sections above, we can conclude that the search for and study of variable stars in a large number of star clusters and beyond have been quite productive. In total, 12,051 image frames were obtained covering the clusters with their surroundings, 6,539 image frames covering the MCV with wide areas around, and many frames of other types of variable stars with their surroundings. We discovered, classified and characterized many new variable stars along with several known ones in star clusters. Selected peculiar variable stars outside the clusters (in the general field of the Galaxy) were also carefully studied and their new properties were discovered. The current processing and deep analysis of this material is ongoing jointly with our foreign partners and colleagues from Belgium, China, India, Italy, South Africa, Spain, Taiwan, USA, etc. A very important practical output of the project is the huge observational data bank created within the project, which can be very useful as a by-product for searching for interesting targets for other projects at large ground-based facilities and space observatories (for example, for the JWST programs). Dedicated observations at Maidanak Observatory would also be useful in supporting major programs at these facilities, such as JWST and others.

Another practically important result of the international project with Indian partners was that, in addition to new scientific results, we have also received an educational outcome. For example, during the visits of the project team members to the ARIES in India, we became thoroughly acquainted with modern telescopes at the Devasthal and Manora Peak observatories, such as the 4 m International Liquid Mirror Telescope (ILMT), 3.6 m Devasthal Optical Telescope (DOT), 1.3 m Devasthal Fast Optical Telescope (DFOT), etc., and took part in observations on them. The experience and knowledge gained on the 3.6 m telescope, an ana-

logue of the planned 4 m telescope in Uzbekistan, are especially useful.

The large astrophysical project of a novel state-of-the-art 70 m radio telescope (or even a network or array of small antennas) of the millimeter range on the Suffa plateau (Uzbekistan) is very promising and relevant; its completion will bring our astronomy to a new level in understanding the Universe [18–21]. We have prepared programs for observing molecular clouds and star-forming regions (see, for example, [22]), the implementation of which would allow us not only to study the physics of these objects as well as the processes of birth and initial evolution of stars, protoplanetary disks, exoplanets, exoasteroids and exocomets, but also to deeply study the scenario of star clusters' formation and their evolution from the moment of their appearance in molecular clouds. It should be noted that a detailed study of variable and non-stationary stars in stellar groups and outside them, as well as a number of star clusters and associations themselves in the millimeter range of radio waves, has been included in these research programs [22]. Thus, the study of these intriguing objects in the optical range will be supplemented by observations in the radio range.

Resuming the above-said, in conclusion, we can state now that the current astronomy collaboration with India may soon evolve into a much broader, more extensive and intensive collaboration with many other astronomical centres in India (e.g. Indian Institute of Astrophysics (IIA) and CHRIST University both in Bangalore, Tata Institute of Fundamental Research in Mumbai, Physical Research Laboratory in Ahmedabad, Bose Institute in Kolkata etc.). For example, our partners from IIA are planning to join our scientific collaboration with ARIES and build, in cooperation with other co-investigators, a new imaging polarimeter for use at Maidanak Observatory in Uzbekistan for novel joint projects.

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NON-STATIONARY UNIVERSE

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The main steps on our path from the models of Stationary Universe to the models of evolving one are mentioned in this paper. The most significant theoretical models and experimental results that confirm the fact that our Universe is evolving are listed.

Keywords: stationary Universe – counts of sources – cosmic microwave background

Many people know that over the last hundred years our ideas about the world around us have changed significantly. In this work I will try to list the main stages of the transition from ideas about a stationary World to an understanding that the Universe is significantly evolving.

By the beginning of the twentieth century, the dominant view among experts was that the Universe was infinite, homogeneous and isotropic on large scales, and stationary. To a large extent, based on precisely these ideas, which were commonly called the Absolute Cosmological Principle, Albert Einstein introduced into the equations of the General Relativity Theory (GRT), the so-called lambda term, in the presence of which stationary solutions appeared for these equations.

However, already in 1922, Alexander Friedman drew attention to the fact that even without this non-obvious term, the equations of General Relativity have quite elegant solutions that describe a gradually expanding or contracting Universe. Einstein's initial reaction to Friedman's work was negative. However, after a couple of years, he agreed with A. Friedman's arguments and subsequently

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noted more than once that it was Friedman who was the first to propose a model of the expanding Universe.

Let us note, however, that by the time A. Friedman's work appeared, neither the author of this work nor his opponents had any serious arguments either for or against the non-stationary model of the Universe. At the same time, astronomers already understood that our Galaxy is not at all alone, and beyond its borders there are other giant star systems similar to it. Working during the 1920s at Mount Wilson Observatory and using the largest 2.5-meter telescope at the time, Edwin Hubble did a tremendous job of identifying extragalactic nebulae. Using the already known period-luminosity relationship of long-period cepheids, he was able to estimate the distances to several dozen galaxies and obtain the spectra of these nebulae. As a result, a linear correlation was discovered between the redshift of lines in the spectra of about 30 galaxies with the distances to these objects. This meant that either our Galaxy is located at some singular point in space, from which all surrounding galaxies are moving away, or the entire Universe surrounding us is expanding.

Since in subsequent years the law of increasing red shift of lines in the spectra of extragalactic nebulae with increasing distances to these objects, discovered by Hubble, covered more and more galaxies, the probability that our Galaxy is located at some special point became less and less. However, it was also not easy to give up the idea that our Universe is eternal and unchanging. As a result, several very original explanations of Hubble's law appeared within the framework of a model of an unchanging and stationary Universe. Let's mention two of them here.

The first such explanation was put forward at the very beginning of the 1930s by the outstanding astrophysicist Aristarkh Belopolsky. He doubted that the redshifts observed in the spectra of distant galaxies were caused by the Doppler Effect. Considering that the radiation from the vast majority of objects observed by E. Hubble reaches the observer after millions of years, Belopolsky put forward the hypothesis of "aging of photons". Based on the data Hubble had on distances to galaxies, then to explain the pattern he found by "aging of photons", it was necessary that for every million years a photon would lose 1/600 of its energy (if we use modern data on the distance scale, then this value will decrease by about 7 times). Therefore, allowing for the possibility of such "aging of photons," one could remain a supporter of a stationary Universe.

The second proposal was put forward around the late 1940s by the English astrophysicist Fred Hoyle, who agreed that the Universe was expanding. However, as he pointed out, this expansion occurs so slowly that in order to keep one of the basic parameters of the Universe constant, namely the average density of matter, it is enough to assume that on average, in every cubic kilometer of the Universe 1 hydrogen atom is spontaneously born in every thousand years. It is hardly

possible to verify such a possibility even today, and therefore this hypothesis was also difficult to reject.

Thus, the further development of ideas about the expanding Universe required new bright experimental facts, which began to appear only towards the end of the 1950s, and were associated with the development of radio astronomy. Although Karl Jansky's discovery of cosmic radio emissions took place in the very early 1930s, serious development of radio astronomy research began only after the end of World War II. But by the mid-1950s, when optical identifications of dozens of radio sources located at high galactic latitudes were made, it became clear that radio astronomy makes it possible to probe the distant Universe. Already the first extensive catalogs of radio sources, including many hundreds, and some even more than a thousand, objects, made it possible to perform statistical studies of the distribution of these objects by flux densities. It is not difficult to show that, within the framework of a uniform distribution of radio sources in space, one would expect that the number of objects with flux densities exceeding a certain fixed value (S) would be proportional to $S^{-3/2}$. Approximately this distribution was obtained by a group of Australian radio astronomers led by B. Mills. Another group of radio astronomers, namely, the group at the University of Cambridge (England) led by Martin Ryle, having carried out a survey at a very close frequency, initially obtained the dependence $N(> S) \sim S^{-3}$. However, having soon discovered many false objects in their survey, they modernized their radio telescope, and, having completed a new survey, on the basis of which they compiled the widely known Third Cambridge Catalog (3C-catalogue), already at the very beginning of the 1960s they obtained a new dependence $N(> S) \sim S^{-1.8}$. After several heated debates, Mills's group agreed with this new Cambridge result.

But what could this insignificant but reliably established difference in the exponent from $-3/2$ indicate? No one began to explain it by the special position of our Galaxy, and all experts agreed that this is another evidence that the Universe is evolving, namely, that in cosmological epochs preceding the present one, the spatial density of powerful radio sources was higher.

Further studies of counts of increasingly weaker radio sources, which made it possible to determine the cosmological epoch in which the spatial density of radio galaxies and quasars was maximum, are described in detail in the papers and books by Malcolm Longair and the other authors. But we will not delve so deeply into the study of specific models of the evolution of radio galaxies, and will move on to other evidence of the radical evolution of the Universe.

Almost in parallel with the development of more and more detailed analysis of counts of radio sources, searches were undertaken for changes in other parameters of radio sources as their flux densities systematically decreased, and hence the distances to them increased. One of the most convenient parameters for extragalactic

radio sources for these purposes was the spectral index, which characterizes the dependence of the flux density of each source on frequency. For the overwhelming majority of extragalactic radio sources, this dependence in a wide frequency range was close to a power-law dependence of the type $S \sim \nu^{-\alpha}$, where α is this spectral index. In fact, it all came down to searching for any noticeable correlation between the spectral indices and the flux densities of the sources.

The first such attempt was made in the work of Conway, Kellerman and Long [1]. The authors had used almost all estimates of flux densities available at that time in a wide range of radio frequencies, obtained by numerous radio astronomers from many countries using a variety of telescopes. It was not possible to find the desired correlation in this work. A second similar work soon followed [2], in which Kenneth Kellermann made another attempt to search the same correlation, using almost the same huge array of data, but only after some adjustment of individual works in order to bring all data to a single scale of flux densities. And, although such correction of the data undoubtedly reduced the systematic errors of various reviews, it was not possible to detect a noticeable dependence of the average values of spectral indices on the flux density of the sources this time either. Finally, in 1968, another similar attempt followed by Kellermann, Pauliny-Toth & Williams [3], in which, in addition to the previous ones, data from the most recent years were used, but it also turned out to be unsuccessful.

In 1964, observations began with the East-West antenna of the cross-type radio telescope of Pushchino Radio Astronomy Station (now Observatory) of the Lebedev Physical Institute. As one of the tasks, it was decided to use this wide-band meridian radio telescope to measure the flux densities of all radio sources of the Third Cambridge Catalog (3C-catalogue) at several meter wavelengths. By the end of 1967, the flux densities of many radio sources in this catalog were measured at 38, 60 and 86 MHz. The most complete and carefully calibrated survey was carried out at a frequency of 86 MHz [4]. It was the data from this survey that was decided to be used for statistical analysis of the distribution of spectral indices of the 3C catalogue's radio sources. For this analysis, we involved only the results of measurements of flux densities of the same sources at frequencies of 750 and 1400 MHz, carried out at the US National Radio Astronomy Observatory [5], as well as data from the 3C- catalogue itself at a frequency of 178 MHz. The results of this analysis are presented in Figures 1 and 2, borrowed from [6]. As can be seen from Fig.1, the spectral indices of radio sources α increase, as the flux densities of radio sources decrease. And from Fig.2 could be seen that this trend is relatively weakly traced for sources identified with radio galaxies, somewhat stronger for those not identified with optical galaxies at that time, and very brightly for sources identified with quasars. From this, we had concluded that the most objects in the group of unidentified radio sources are more distant radio

galaxies. Later, when the all radio sources in the 3C-catalogue were identified, this conclusion was confirmed, because the all sources from this unidentified group at the time of preparation of the work [5] were identified with radio galaxies.

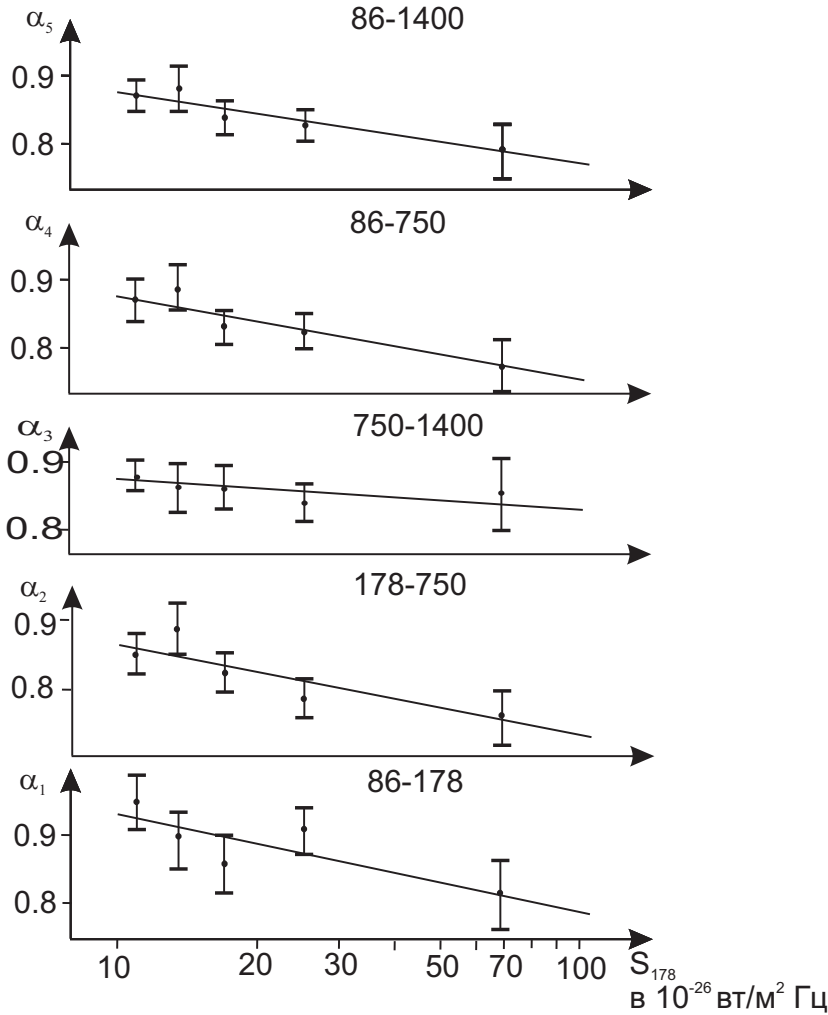


Fig. 1. Dual-frequency spectral indices of 3CR sources as a function of S_{178} .

Since redshifts there were known for all quasars, the distribution of this group radio sources on the $z - \alpha$ plane was also studied, which is presented in Fig. 3 from [7]. This diagram confirms the main conclusion of the studies described, which is that at large cosmological distances the objects with steeper spectra are dominate. Research on the dependence of spectral indices on flux density was continued 12 years later by Indian colleagues. The first of their paper [8], published a dozen years after [6], completely confirmed the dependence presented in Fig. 1,

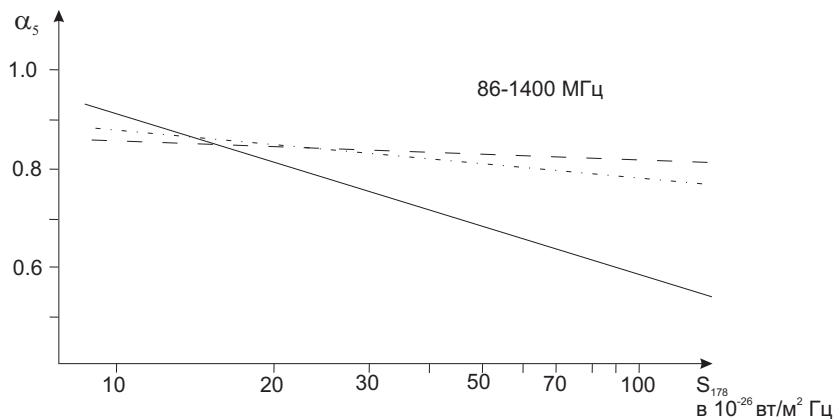


Fig. 2. Dual-frequency spectral indices – flux density relation for radio galaxies (dash line), unidentified sources (dash-dotted line) and quasars (solid line).

and subsequent articles extended this dependence into the region of weaker flux densities.

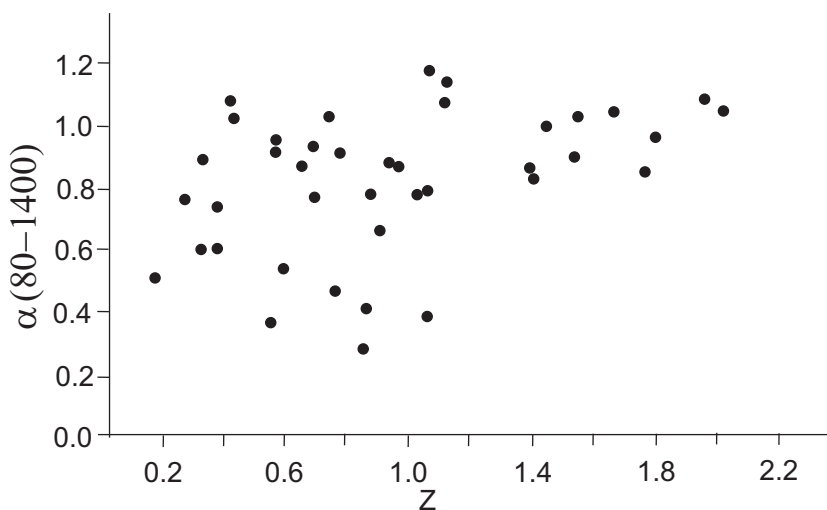


Fig. 3. Dual-frequency spectral index $\alpha(86 - 1400)$ of quasars as a function of their redshift z .

While we were studying the spectra of radio sources, another remarkable discovery was made in 1965. While studying the characteristics of horn antennas, American engineers Penzias and Wilson discovered very weak background radiation. Further discussion had shown that this background radiation could correspond to the residual radiation of the very intensive radiation that filled all the space in the early stages of the hot Universe model suggested back in the

1940s by G. Gamow. Gamow had proposed this model to somehow explain the relative abundance of a number of light chemical elements observed in the world, those could not be formed in the process of nuclear reactions occurring inside the stars. At an early stage in the evolution of such hot Universe the space was filled with very hot ionized plasma and radiation at the same temperature. But, as the Universe expanded, the temperature decreased, and when it reached a value of about 3000 K, the era of recombination began, when electrons combined with atomic nuclei, forming electrically neutral atoms. From that moment on, the Universe became transparent to the cooled radiation, which began to expand without interacting with matter. Gamow had predicted the approximate temperature (several degrees Kelvin) that this residual weak thermal radiation should have in the modern era.

The fact that the cosmic microwave background radiation, which we will further call CMB (Cosmic Microwave Background) was discovered completely by accident (as an interfering factor during purely technical measurements), is due to the fact that in the middle of the last century the opinion of a cold expanding Universe dominated among astrophysicists, and the paper by G. Gamow was almost forgotten. When the nature of this weak thermal radiation with a temperature of about 2.7°K was understood, it became clear how important it was to study all its characteristics. Indeed, the spectrum of spatial fluctuations of the CMB should also carry information about the spectrum of spatial fluctuations of all matter in the Universe during the era of recombination. And although the expected root-mean-square amplitude of such fluctuations was estimated by experts of only 10^{-5} from the average temperature (that is from $\sim 3^{\circ}\text{K}$), several groups of scientists immediately began to work on special projects to estimate the amplitude and spatial distribution of these fluctuations.

Since the maximum thermal radiation with a temperature of about 3°K occurs at a wavelength of $\sim 1\text{ mm}$, the corresponding measurements were carried out only from spacecraft. Before moving on to measurements of weak spatial fluctuations, it was necessary to take into account the contribution of the background radiation of our Galaxy and the dipole component of the CMB, that is due to the relative speed of our Solar system in outer space. The remarkable space projects WMAP (2001) and Planck (2009) made it possible to investigate the distribution of CMB fluctuations.

Even before the discovery of the CMB, A.D. Sakharov calculated the spectrum of quantum density fluctuations for the model of a cold expanding Universe. And these so called “Sakharov oscillations” look like some kind Bessel-functions depending from the parameters of the Universe. Fortunately, in a model of a hot Universe, this spectrum should look almost the same. It is with these “Sakharov oscillations” that the results of numerical processing of data from the WMAP

and Planck projects are now compared in order to determine specific values of the parameters of hot Universe model.

So, we briefly discussed how our ideas about the surrounding World have changed over the last hundred years, mainly in terms of the fairly reliably established continuous evolution of this World. Over approximately the same years, serious changes have occurred in our understanding of the average density and composition of the matter filling our Universe. Such concepts as “dark matter” and “dark energy” appeared. But talking about this goes far beyond the scope of this article. Therefore, we will end this work with a strong statement: “And yet, our Universe is evolving!”

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HIGH-RESOLUTION SPECTROSCOPIC OBSERVATIONS OF HERBIG STARS V1295 AQL. II.

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In this work we continue the spectral study of the unusual Ae Herbig star HD 190073 with pole-on orientation of the rotation axis. In the second part of spectral studies of the HD190073, we examined long-term spectral variations for 2016-2023. Using synthetic spectra of standard stars, extracted profiles of the circumstellar structure for the hydrogen and H and K CaII lines were obtained. All of these lines are show a P Cyg profile in which the deep absorption on the blue wing is highly variable. Long-term variability of spectrophotometric parameters is detected for the lines of hydrogen, helium and other elements. On the character of the long-term variability over time, there is a general cycle of about 38-12 years. A stellar companion or massive planets may cause the reasons for such variations.

Analysis of the Fourier spectrum showed a complex nature of variability. Some periods found in the spectrum and brightness are close and determined with high reliability. From short periods $P_2 = 4 \pm 0.5$ days, and from relatively long periods $P_3 = 97 \pm 3$ days are reliably established. The fundamental parameters and evolutionary status of the star have been determined.

Keywords: Pre-Main Sequence stars – circumstellar disks – disk accretion – individual: HD 190073

1. INTRODUCTION

For the Pre-Main Sequence (PMS) stars with low (T Tauri Stars, TTS) and intermediate mass (Herbig Ae/Be stars, HAeBes) magnetic fields play an important role in the course of evolution. Magnetic fields can be involved in the transfer of angular momentum from the disks themselves at very early stages of starformation, which can change the initial conditions of the star evolution. It is assumed

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that accretion from the disk onto the stellar surface occurs along magnetic field lines [12, 18, 25].

The interaction of the star with its surrounding disk in classical T Tauri stars (CTTS) is well described by the magnetospheric accretion (MA) models [5]. However, it is unclear how well this model can be applied to H AeBes, whose magnetic fields are about an order weaker [3, 13, 14].

To diagnose the magnetosphere in H AeBes type stars, a method is often used that is based on searching for the cyclic variability of the parameters of spectral lines formed in the near region of interaction of the accretion disk with the star. A review of such methods is given, in particular, in the work of [28]. In this work we continue the spectral study of the unusual Ae Herbig star HD 190073 with the orientation of the rotation axis relative to the observer close to the pole $v \sin i = 3.19 \pm 2.45$ km/s, $i = 34 \pm 2^\circ$, [1]. It is from this angle that one can observe the circumstellar envelope, where the gas has the least studied structure and kinematics. This is the boundary region between the wind zone and the accretion flow falling on the star at high latitudes [19–27].

Our first article [4] was devoted to the search for rapid spectral variations in a star based on homogeneous spectral material obtained at the 2 m telescope of the Shamakhy Astrophysical Observatory of Azerbaijan Ministry of Science and Education for 2015–2023 [4]. In this paper, we present the results of observations for 2016–2023, based on materials obtained with a resolution 28000. Detailed information about the observational spectral material is given in the first part of our work.

2. FEATURES OF THE H AND K CaII LINES

First of all, we note that the profiles of the H and K CaII lines in the spectrum of the star HD 190073 have always aroused great interest due to their unusual structure. Thus, [23] drew attention to the complex absorption structure of the lines of this doublet. In the work [27] presented in detail the results of studies of the unusual structure of these lines. Both doublet lines have several strong absorption components, which are variable, but quite stably maintain their position both in intensity and wavelength over a period of tens of years.

[27] showed that the multicomponent absorption structure is variable with characteristic times ranging from a month to ten years. [29] showed that the radial velocities of the faster component are related to the velocities of the second component in a 2 : 1 ratio. He proposed a pure scattering model to explain the emission of CaII ions from the stellar atmosphere, following a scenario developed by [37]. However, [33] concluded that such ratios do not appear to be sufficient. Only part of the characteristics correspond to the ratio, and these absorptions are

not the strongest among other blue-shifted components of the profile. [33] analyzed 24 samples of the spectrum of HD 190073 obtained from 1943 to 1974 and found a correlation between the structure of the H, K CaII profiles and P Cyg absorptions in Balmer line profiles. They found that the fusion between the two components CaII at -180 and -300 km/s tended to appear and the first of them became stronger than the second when the Balmer line absorption components were deep and broad in the blue-shifted profiles. They explained these correlations within a model based on the selective effects of radiated energy [34, 35].

Figure 1 shows averaged over all dates the H and K CaII line profiles obtained in our observations in 2016-2023. The individual components of the doublet are designated by the symbols H1, H2, H3 and K1, K2, K3, respectively. Solid lines show average profiles, dotted lines show standard deviation from the average intensity. As can be seen from Fig.1, each doublet line has 3 relatively stable absorption components. For the first component, both H1 and K1 have peak shifts of -0.5 ± 2 km/s, i.e. close to the velocities of the star's mass center. The remaining two components H2, H3 and K2, K3 have approximately the same displacement, equal to -180 and -300 km/s, respectively, with a standard deviation from the average ± 6 km/s. The same H and K line profiles of CaII were previously observed by [36] and [32].

As can be seen from Fig.1 as a whole, the observed three absorption components of the doublet have the same displacements, which are consistent with the data of the above-mentioned works. The standard deviation from the average intensity shows that the strongest change in intensity is observed in the component (K3, H3) which has a displacement of about -300 km/s. In addition, the structure of the standard deviation line (dotted line) forms two peaks with an attenuation in the center corresponding to each absorption peak. This is especially clearly visible from the K line profile CaII. In addition to photospheric absorption lines, doublet lines H, K CaII also contain significant emission, which can be formed in the circumstellar disk or in the chromosphere of the star. This line profile of the H, K CaII doublet differs significantly from the line profiles of hydrogen, helium and other elements, which significantly complicates the understanding of their origin, and, as noted above, is one of the controversial issues. To correctly interpret the structure of these lines, it is important to separate the contribution of the radiation from the purely emission component. To clear the contribution of the stellar photosphere in these lines, it is necessary to subtract the line profile of the standard star from the observed line profile. To do this, you need to correctly establish a model of the synthetic spectrum, which is more suitable for the spectrum of the star HD 190073. Since weak lines of metals can often contain additional line or continuous emission, such lines are not suitable for selecting a synthetic spectrum. For this we decided to use the wide wings of the Balmer

series hydrogen lines.

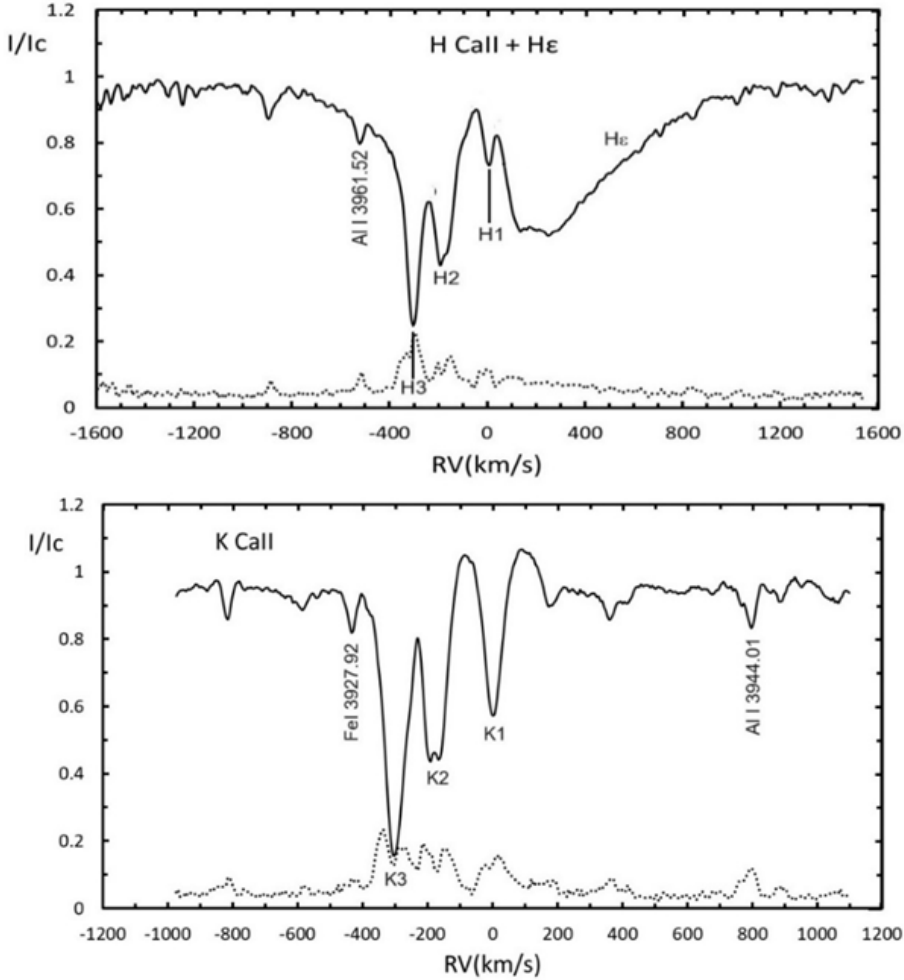


Fig. 1. Average H and K line profiles Call obtained in 2016-2023. Solid lines show H line profiles Call + H_ϵ (top), and K Call (bottom). The dotted lines show the level of standard deviation from the average intensity. The individual components of the doublet are designated, respectively, H1, H2, H3 and K1, K2, K3.

3. HYDROGEN LINE PROFILES

Since many photospheric lines in a star's spectrum contain emission components, comparing synthetic and observed spectra based on metal lines can lead to erroneous results. Therefore, to clarify which synthetic model of the spectrum

corresponds to the observed spectrum of the star, we used hydrogen line profiles. Despite the fact that the hydrogen lines of the Balmer series also contain emission in the center, the photospheric Stark wings of these lines are very wide and for the $H\beta$, $H\gamma$ and $H\delta$ lines they are practically not distorted by emission. Therefore, we combined the wings of the hydrogen lines with model profiles in the synthetic spectrum. To select the model, we used the database of synthetic spectra from the PH δ ENIX archive. Since the literature gives different values for the temperature and gravitational acceleration of a star (see, for example, $8750 \sim K$, $\log g = 3.0$, [8], $9250 \sim K$, $\lg g = 3.5$ [2, 7] $9750 \sim K$, $\lg g = 3.5$ [40]), we checked all possible values of temperature and gravity acceleration. Synthetic spectra were selected in the range of effective temperatures 8750, 9000, 9250 and 9500 , at $\log g = 3.0, 3.5, 4.0$ and with chemical composition $[\text{Fe}/\text{H}]$, 0.0, 0.5, 1.0. Since radial velocities along photospheric lines are close to zero, and the rotation velocity is ~ 3.2 km/s [1], no additional corrections were applied to the broad hydrogen line profiles in the synthetic spectra. After some tests, it became clear that for our spectral resolution, when combining the wings of the $H\beta$, $H\gamma$ and $H\delta$ lines, it is practically impossible to distinguish between models of synthetic spectra with effective temperatures of 9250, 9000 K and 8750 K at $\lg g = 3.0$. We chose the most suitable model with parameters $T_{\text{eff}} = 9000 \pm 250$ K, $\log g = 3.0 \pm 0.1$, $[\text{Fe}/\text{H}] = 1.0$. These parameters correspond to the A2III spectral type [31], and are in satisfactory agreement with the data of [8]. After the best alignment of the wings of the hydrogen lines, we subtracted the synthetic normalized profiles from the observed ones. The extracted spectrum profile represents an emission spectrum of nonphotospheric origin.

Figure 2 shows the average profiles for individual $H\alpha$ - $H\delta$ lines. In Fig. 2, the solid line is the observed normalized profile, the small broken line is the synthetic normalized profile, the broken line indicates the star-model difference profile, and the dotted line shows the standard deviation from the average for the difference profile. One of the intensive emission lines of FeII 4351 observed on the red wing of the $H\gamma$ line, which apparently significantly distorts the true intensity level of the red wing of the $H\delta$ line. The best agreement was obtained for the $H\beta$ and $H\delta$ lines. As can be seen from Fig. 2, all dotted lines indicating the standard deviation from the average have two peaks, which are symmetrically located relative to the center of the line. These peaks indicate at what wavelength the intensities change the most. Consequently, we observe the greatest change in the blue and red wings of the lines. This means that, apparently, the variability of the line intensity changes due to the ejection and fall of matter on the surface of the star.

As can be seen from Fig. 2, all difference profiles, without exception, have a single emission peak, for which the ratio of residual intensities $H_\alpha : H_\beta : H_\gamma : H_\delta$ is equal to 6.17:1.04:0.65:0.42.

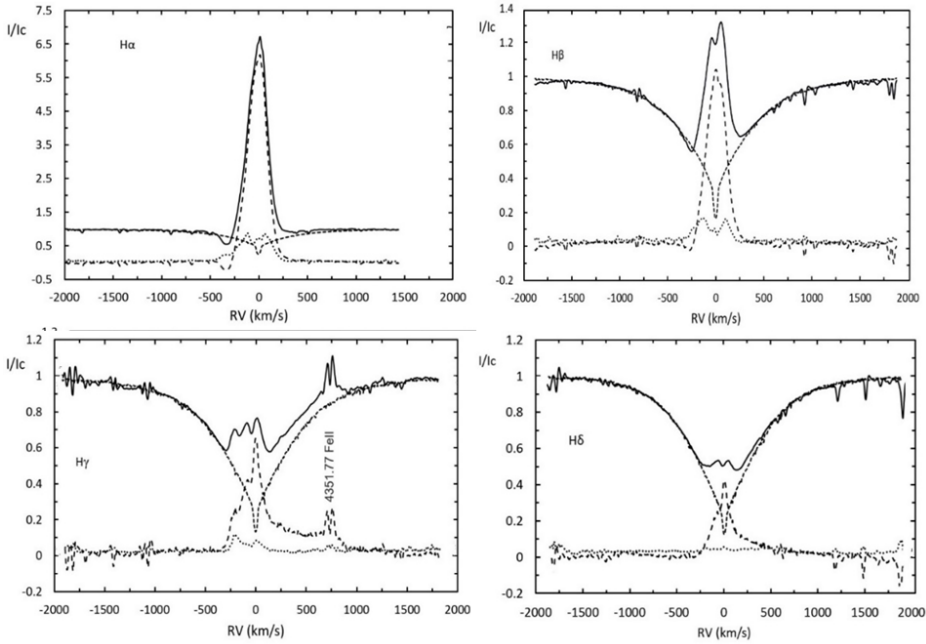


Fig. 2. H α - H δ line profiles. Solid line, normalized observed profile, small dotted line, synthetic normalized profile, large dotted line, star - model extracted difference profile ($T_{eff} = 9000K$, $\log g = 3.0$, $[Fe/H]=1.0$), dotted line - standard deviation of intensity along the extracted profile.

4. EXTRACTED PROFILES OF H, K CaII LINES

On the obtained parameters of the star's photosphere, we constructed a difference (extracted) spectrum also for the profiles of the H and K CaII lines. Figure 3 shows the profiles of these lines in two different panels. The figured line designations are the same as in Fig.2. As can be seen, the extracted profile consists mainly of three components. In fig.3, the extracted profile of the K CaII line shows the velocities of individual details. One of them, the purely emission component, is more intense and symmetrical relative to the velocity of the star's center of mass and is divided into two peaks. The displacements of these emission peaks are -58 and +63 km/s, respectively. The second component has two absorption detail with displacements of -196 and -161 km/s. Finally, the third absorption component is shifted by approximately -300 km/s. This component also observed in the ordinary observational profile. We believe that it is formed in a strong accretion zone from the disk. Similar components are observed also in the H CaII line.

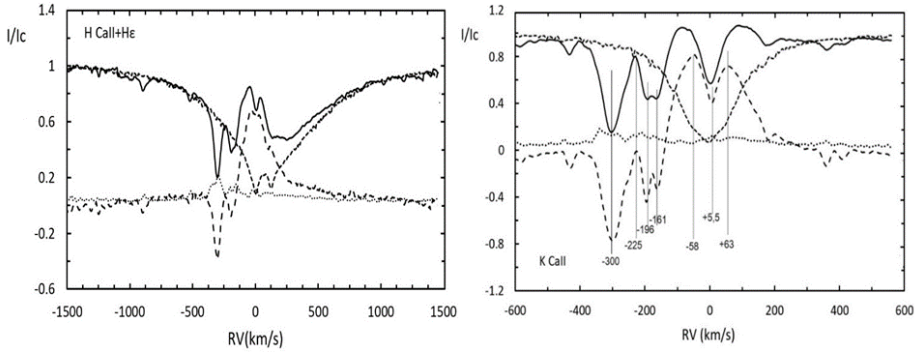


Fig. 3. H and K line profiles of CaII. Designations are the same as in Fig. 2. The second panel shows the radial velocities of individual features in km/s.

5. LONG TIME SPECTRAL VARIABILITY

In the Figure 4 shown the time variability of individual spectrophotometric parameters of the $H\alpha$ and $H\beta$ lines. The upper panels, from left to right, shows the equivalent widths of the emission components EW_e of the $H\alpha$ and $H\beta$ lines. The lower panels show the bisector radial velocities of the RV_{bis} emission components, as well as the FWHM of these lines. As can be seen from Fig. 4, from 2015 to 2023, all parameters shows a slow and smooth variability from year to year. The presented cycle covers 9 years of observation, and apparently the full cycle of slow variations should be at 38 years. At the same time, the spread of data over individual years indicates the existence of rapid variability, from several days to months.

As can be seen from Fig.4, the total range of variations in the radial velocities of the emission components for both lines is about 50 km/s. When the lines shift to the red part, a decrease in the total of the FWHM lines is observed, and the equivalent widths gradually decreased. This is especially clearly seen from the $H\beta$ line data. The average value of the FWHM parameter for the $H\alpha$ line is $4.6 \pm 0.3 \text{ \AA}$, and for the $H\beta$ line, it is about $2.99 \pm 0.5 \text{ \AA}$, which corresponds to an expansion of $210 \pm 13 \text{ km/s}$ and $186 \pm 20 \text{ km/s}$, respectively. At 10% of the total residual intensity, the $H\alpha$ and $H\beta$ line widths reach $9 \pm 1 \text{ \AA}$ and $7 \pm 1 \text{ \AA}$, which is approximately twice larger, -420 and 370 km/s.

Figure 5 shows the temporal variability in the parameters EW_e , RV_{bis} and FWHM for the HeI 5876 line. As can be seen, there is variability that is similar to that observed in the hydrogen lines. As shown in our paper I, hydrogen lines have P Cyg type profiles, where the emission peaks on the blue and red wings have absorption. Let us recall that we denoted the absorption equivalent width on the blue wing of the emission component as EW_{a1} , on the red wing as EW_{a2} , and

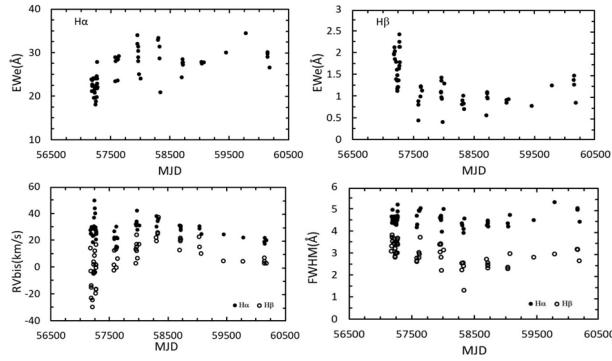


Fig. 4. Time variability in the spectrophotometric parameters of the $H\alpha$ and $H\beta$ lines.

the equivalent width of the emission component as EW_e . As was shown in article I, with an increase in the intensity of the absorption component on the blue wing of the emission, a synchronous variation in the spectrophotometric parameters of the hydrogen lines was observed.

Figure 6 shows the dependence of some parameters on the equivalent width of the blue absorption component EW_{a1} for the $H\beta$ line. As can be seen, the EW_{a2} and RV_{bis} parameters have a direct correlation, and the EW_2 and FWHM parameters have an inverse correlation with the equivalent width of the blue component EW_{a1} . The value of the Spearman correlation coefficient and its error of determination are shown in each panel of the figures. For the $H\alpha$ line, the correlation between similar parameters is close to zero. This indicates that the $H\alpha$ line is formed under more complex conditions.

The observed relationships can be explained as follows. When EW_{a1} increases, it is because the emission, often seen as a separate weak component of the main emission peak, is red-shifted and appears to enhance the emission in the main emission. This should lead to a decrease at the half-width of the emission line, which could create a visible red shift in radial velocity. This all means that we often see a release, or outflow of matter, which is observed in the form of a weak emission. At the very beginning of its appearance, this peak has a high negative RV, about 450 km/s. Then gradually its RV drops down to a small redshift, which is observed at the main constant emission. Figure 7 shows emission profiles cleared from the photospheric spectrum for different dates in the $H\alpha$ and $H\beta$ lines. As can be seen, the emerging emission peak on the blue wing of the $H\alpha$ line gradually merges with the main, more stable red emission peak. $H\alpha$ line profiles obtained sequentially on close dates show a gradual merging of the blue emission peak with the red one over approximately 20 days, and on July 17, 2017, we already observe a single enhanced emission peak. $H\alpha$ line profiles do not show

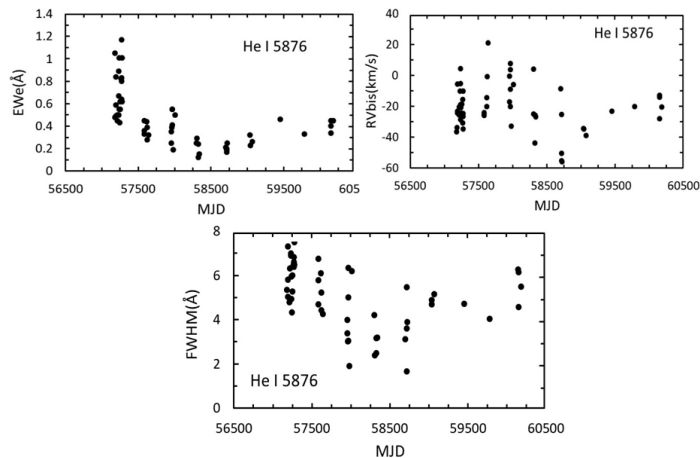


Fig. 5. Time variability in parameters EW_e , RV_{bis} and FWHM for the He I 5876 line.

rapid variability over several hours, or even days. A similar characteristic time of variability is also observed in the $H\beta$ line profiles. The shortest time of variations is observed between the $H\beta$ line profiles obtained on July 26, 2018 and July 28, 2018, about 2 days.

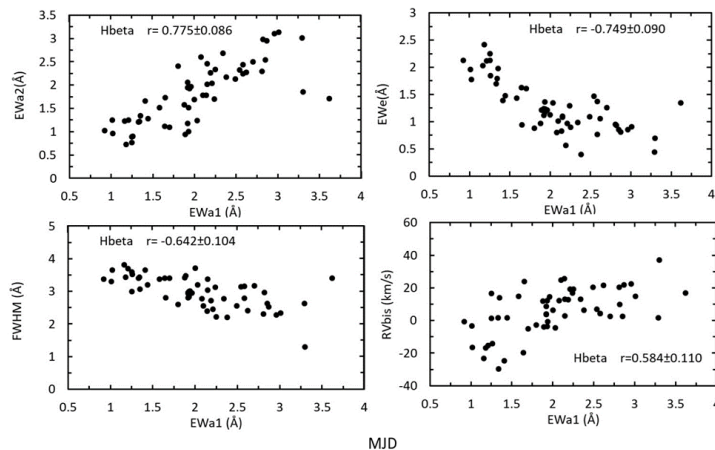


Fig. 6. The spectrophotometric parameters of the $H\beta$ line versus of blue absorption equivalent widths EW_{a1} . The values of the correlation coefficient r and its error for each relations are given on the panels.

6. PHOTOMETRICAL VARIABILITY

The published long time series of photometric data of the star HD 190073 are very small. [38] giving 24 nightly average photoelectric brightness estimates relative to the standard star HD 189851 obtained in JD 2439291-2439399 (108 days). The author showed that the star's brightness is variable, and if it is periodic, then the period should be more than 100 days.

Another work on star photometry was published in [10]. The star was observed in the interval JD 2443259-2443389 (130 days), provided 20 nights of observations. Since these works were carried out in different years and different standard stars were used, the magnitudes are given in relative values, it is impossible to combine these data into one series with the previous data of [38] to find the period. Therefore, we used each array separately for this purpose. To search for the period, the program Period 04 [20] was used, which applied Fourier analysis using the method of [30].

In Figure 8 shows, the power spectrum obtained from data [38]. As can be seen, only three significant peaks stand out, with frequencies $\nu_1 = 0.34341/d$, $\nu_2 = 0.26911/d$ and $\nu_3 = 0.01021/d$, which corresponds to the periods $P_1 = 2.9388$ days, $P_2 = 3.716$ days and $P_3 = 97.9432$ days, respectively.

Period P_2 is less powerful than the other two peaks, and perhaps is the last of the probable periods that can be real. To clarify which of these periods is more realistic, we also used spectral data for analysis.

To analyze periodic changes in the spectrum of the star, we used different values of spectrophotometric parameters, such as the equivalent widths of the absorption and emission components, half-widths, residual intensities, and radial velocities of the emission and absorption components of the $H\alpha$ and $H\beta$ lines. Figure 9 shows an example of the power spectrum for $H\beta$ lines for different parameters. Almost for most parameters in the power spectrum, we found a frequency $\nu_2 = 0.2462 \pm 0.0021/d$, which is close to the frequency we discovered from photometric data. In addition, the frequency $\nu_4 = 0.25781/d$ is also observed in a weaker form, which is repeated in most arrays. These frequencies are shown in Fig. 9 by vertical lines. The periods at these frequencies are respectively equal to $P_2 = 4.061 \pm 0.036$ d, $P_4 = 3.8789 \pm 0.767$ d. The frequency ν_3 observed from photometric data (Fig. 8) in different spectral parameters is detected in close but divergent frequencies, corresponding to periods of 92-105 days.

In addition, according to the parameters EW_a and EW_e , the strongest peak $\nu_5 = 0.0108 \pm 0.0002$ is revealed in frequency, which corresponds to the period $P_5 = 92.1 \pm 0.1$ days. Figure 10 shows the phase curves collapsed over this period. As can be seen, for individual parameters there is a satisfactory picture of periodicity.

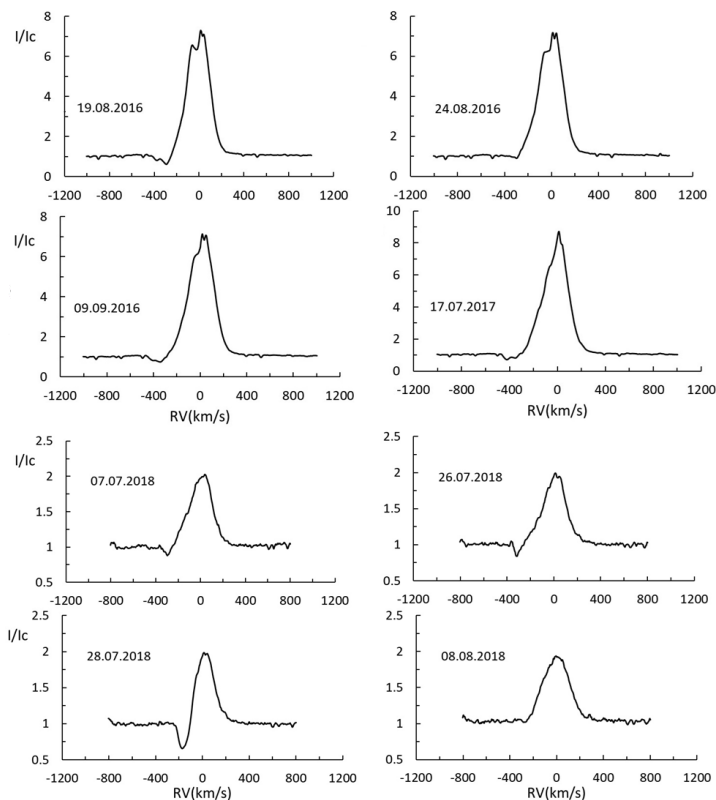


Fig. 7. $H\alpha$ (above) and $H\beta$ (below) line profiles, presented for different dates, extracted from photospheric radiation.

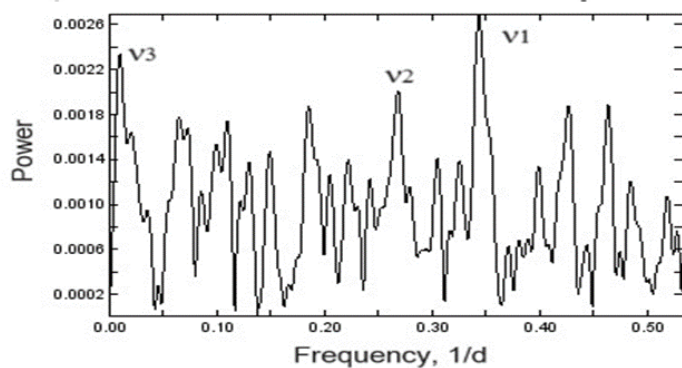


Fig. 8. Power spectrum according to photometric data [38].

Thus, statistical Fourier analysis carried out on photometric and spectral data showed that it is possible that there are several periodic components, which to-

gether give an overall complex picture of the variability of both the spectrum and the brightness of the star. The most probable periods are $P_2 = 4.06 \pm 0.2$ days and $P_5 = 92.1 \pm 0.5$ days.

7. SPECTRAL ENERGY DISTRIBUTION

For analysis of the spectral energy distribution (SED) of the star, we constructed a SED curve of the star in the wavelength interval $0.36\text{--}100\ \mu\text{m}$. The starting material for constructing the SED curves was multicolor broadband photometry data in the standard UBVRIJHKLM system; for the region of longer waves we used data from the WISE W1-W4 infrared (IR) satellite [17], as well as IRAS data [24], respectively, in the bands of 12, 25, 60, $100\ \mu\text{m}$. The principle of constructing SED for different objects based on stellar magnitudes obtained in different bands of broadband photometry is to convert the magnitudes m_λ into absolute fluxes F_λ according to the famous expression

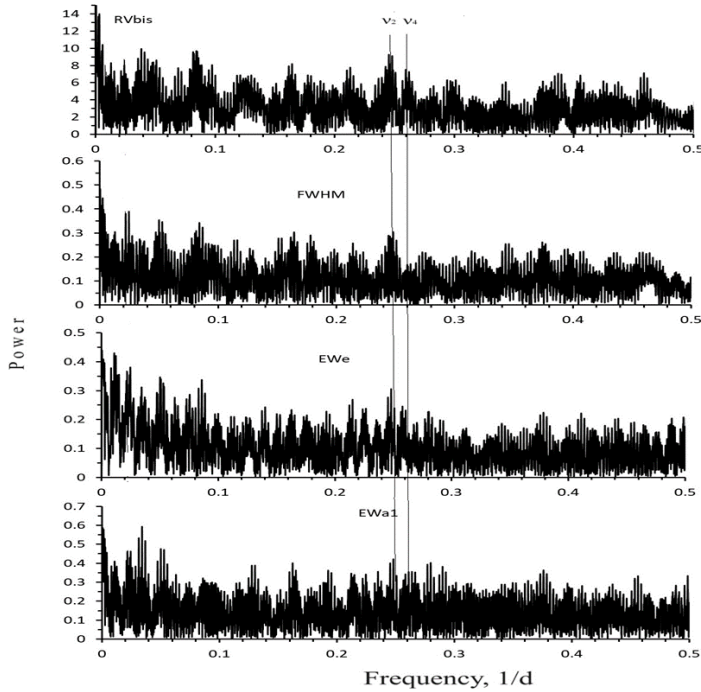


Fig. 9. Examples of power spectrum diagrams for different spectral parameters of the H_β line. Vertical lines show the positions of frequencies ν_2 and ν_4 .

$$F_\lambda = F_0 \cdot 10^{-0.4(m_\lambda - m_0)} \quad (1)$$

Here F_0 is the adapted radiation flux for the zero point of the system when m_0 is taken equal to zero. The reference is usually made to the adapted absolute radiative flux of a standard star of zero magnitude A0V in all emission bands. We described the detailed methodology for constructing the SED curve in the work of Ismailov et al. [15,16].

As can be seen from Fig.11 , the SED curve agrees well with observations only in the visible and near IR region up to the K band ($2.2\mu\text{ m}$). Excess emission from the gas component of the disk mainly begins from this band.

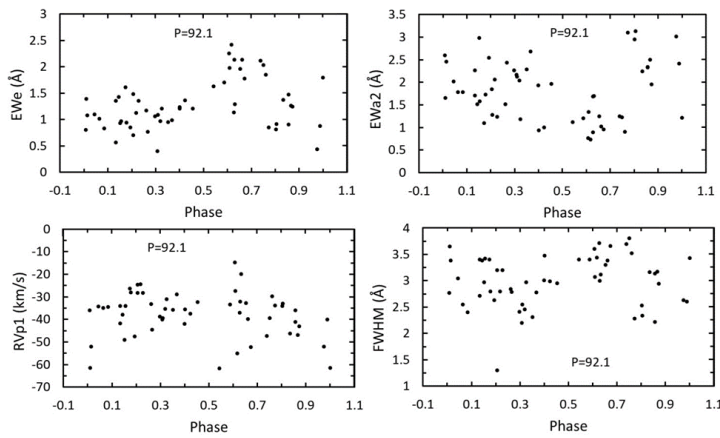


Fig. 10. Examples of phase curves collapsed by phases of the period $P_5 = 92.1$ days.

We have collected in Table 1 some physical parameters of the star, including the values we determined for T_{eff} and $\log g$. Using the magnitude V cleared of interstellar reddening, the distance to the star, and the bolometric correction taken from [26], the absolute bolometric magnitude M_{vb} was calculated (Table 1). Knowing the solar absolute luminosity $M_{\text{vb}\odot} = 4.83\text{ mag}$, we calculated the absolute luminosity of the star in units of $L/L_{\odot}$. Next, knowing the effective temperature and luminosity, we calculated the radius of the star $R = 10.4 \pm 0.6 R_{\odot}$. The solar effective temperature $T_{\text{eff}\odot}$ was taken equal to 5800 K .

Using theoretical evolutionary tracks [6,21] the mass and age of the star were also determined. Figure 12 shows the evolutionary diagram of HR where the position of the star HD 190073 is marked with a circle. The mass and age determined from this diagram are given in Table 1.

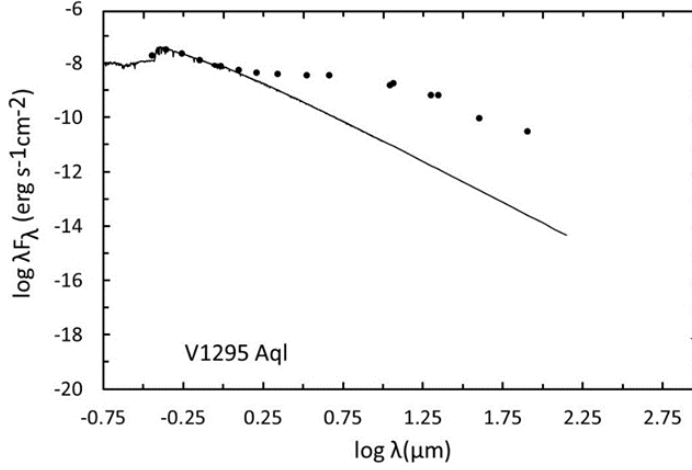


Fig. 11. . Spectral energy distribution for HD190073. Solid curve-Kurucz model with $T_{eff} = 9000$ K , $\log g = 3.0$. Points are observational data.

Table 1. Main physical parameters of the HD 190073.

T_{eff}	$\log g$	V	A_v	D,pc	Mb	Mvb	$\log L/L_{\odot}$	$M/M_{\odot}$	t,Myr
9000	3.0	7.73	0.40	847	-0.15	-2.16	2.79	4.2	0.9
± 250	± 0.3		$+0.12$	± 22		± 0.15	± 0.12	± 0.25	± 0.2
			-0.26						
		[22]	[39]	[11]	[26]				

8. DISCUSSION AND CONCLUSIONS

Summarizing the results obtained in the 2 nd article, in conclusion we will highlight the most important conclusions of this work. Complementing the studied spectral material with a resolution of 28000, which were obtained for 2016-2023. We managed to find the answer to some questions observed in the spectrum of the star.

By using the Balmer line profiles we were able to select a synthetic spectrum corresponding to the effective temperature and gravitational acceleration $T_{eff} = 9000 \pm 250$ K, $\log g = 3.0 \pm 0.1$, at $[\text{Fe}/\text{H}] = 1.0$. After selecting such a model, we determined the extracted profile (star minus standard) in the H and K CaII lines. We have shown that the extracted profile of ionized calcium lines has a typical of the P Cyg type profile, and in general does not differ much from the profiles of hydrogen lines. The structure of these lines showed that there is a strong outflow of matter with a velocity of over 300 km/s. Analysis of the difference profiles of hydrogen lines showed that a dense mass of matter ejected

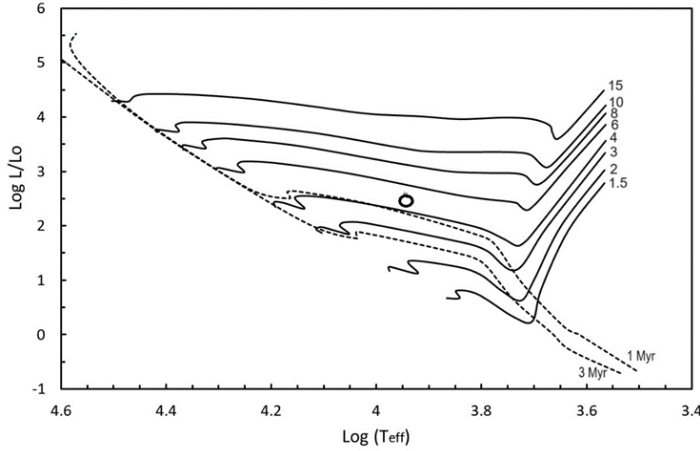


Fig. 12. Position of the star on the HR diagram, with evolutionary tracks, constructed in the works of . [6, 12] Solid lines indicate masses, dotted lines indicate ages.

and directed along the magnetic field lines forms a deep absorption component. Over time, the ejected mass at high latitudes becomes rarefied and accretes to the surface of the star, forming weak emission components on the blue wing of the profile. These components are unstable and gradually merge with the main emission, which is formed from the radiation of the disk. We were able to determine the intensity ratio of the hydrogen lines $H\alpha : H\beta : H\gamma : H\delta$ as 6.17:1.04:0.65:0.42. This shows that the Balmer decrement is too steep, apparently caused by valuable interstellar and/or circumstellar reddening.

Long-term variability of spectrophotometric parameters is detected for the lines of hydrogen, helium and other elements. On the character of the long-term variability over time, there is a general cycle of about 38-12 years. A stellar companion or massive planets may cause the reasons for such variations.

A correlation was found in certain parameters with the intensity of the blue absorption component. This indicates that the main mechanism of activity is the accretion process.

We were able to conduct a Fourier analysis of the star's brightness and spectrum. Based on the variations in brightness, three most probable periods of variability have detected. Analysis of the Fourier spectrum showed a complex nature of variability. Some periods found in the spectrum and brightness are close and determined with high reliability. From short periods $P_2 = 4 \pm 0.5$ days, and from relatively long periods $P_3 = 97 \pm 3$ days are reliably established.

We plotted a star SED curve in the wavelength range $0.36 - 100\mu\text{ m}$. It is shown that there is excess radiation characteristic of cold dust in the far IR part of the spectrum. In addition, an excess of radiation in the spectrum is also observed

in the near-IR part of the spectrum, which is characteristic of gas radiation. Using updated literature data and our results, all the fundamental parameters of the star and its evolutionary status were determined.

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WOLF-RAYET STARS – WHAT WE KNOW AND WHAT WE DON'T

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Today, we have a sufficiently complete picture of what the Wolf-Rayet (WR) stars are. Predictions of stellar evolution theory are in a good agreement with their parameters, estimated from observational data using stellar atmospheres codes; predictions of population synthesis also agree well with number of known WR stars. This article provides an overview of the main historical milestones in the studies of WR stars, showing how we came to this understanding, and what questions are still unanswered.

Keywords: Stars: Wolf-Rayet – Stars: evolution – Stars: atmospheres – General: history and philosophy of astronomy

1. INTRODUCTION

Wolf-Rayet (WR) stars are a class of objects identified on the basis of their spectral features. WR spectra show strong emission lines of helium, nitrogen, carbon and oxygen in different stages of ionization. The width of these lines reaches tens of angstroms, the central intensities are sometimes 10-20 times the intensity of the continuum spectrum. A prominent feature of WRs are two bumps at 5808 and 4650 Å, which are groups of closely located lines of N II, N III, C III and C IV, which are visible even in low-resolution spectra. The lines are formed in an extended atmosphere – in the stellar wind, expelling at velocities of $10^2 - 10^3 \text{ km s}^{-1}$. WR stars are characterized by a high mass-loss rate of several $10^{-5} M_{\odot} \text{ yr}^{-1}$ and by high temperatures ($T_{\text{eff}} \gtrsim 30000 \text{ K}$). WR are the final stage in the evolution of massive stars (stars with an initial mass $\gtrsim 25 M_{\odot}$) before the core-collapse supernova explosion.

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With accumulation of observational data it became clear that emission spectra and WR bumps are intrinsic to objects of different natures. Therefore nowadays there is a clear distinction between WR stars and *WR phenomenon*, which occurs when fast-moving, hot plasma is expanding around a hot star [1, 2]. WR phenomenon may occur in the low mass stars after ejecting their outer layers in the planetary nebula phase and exposing their hot cores prior to the white-dwarf phase [3–5]. Central stars of planetary nebulae showing WR phenomenon in their spectra are denoted as [WR] [3]. Rare and still unique case of low mass object with WR phenomenon and the absence of a clearly detected circumstellar nebula is LAMOST J040901.83+323955.6 [6]. It was selected as a WR star by Škoda et al. 2020 [7], but [6] showed that this object is $0.9 M_{\odot}$ star caught in a rare transitional phase from post-AGB to CSPN. Another unique object with WR phenomenon is IRAS 00500+6713, formed as a result of a merger of two white dwarfs [8]. The WR phenomenon is also observed in young supernovae [9].

As we know now, massive stars showing WR spectra are also not a homogeneous class. They are split into two groups: *very massive stars* and *classical WR stars*. *Very massive stars* ($M_{\text{ini}} \geq 100M_{\odot}$) experience strong stellar winds and show WR spectra already during core H-burning phase, when they are located on main sequence. All of them show signs of hydrogen on their surface and are classified as WNh objects [10–12]. *Classical WR stars* (usually just named *WR stars*) stars are hydrogen-depleted objects that have evolved off the main sequence and suffered intense mass loss [13, 14]. *Classical WR stars* will be the subject of this review article.

The field of contemporary studies of WR stars is enormous and cannot be fully covered in a single small review like this one, so I'd like to recommend two other detailed reviews [13] and [14] for better understanding what WR stars are. On the other hand, here I will concentrate more on the historical aspects of WR studies, on how we have arrived to our present day understanding of them. Therefore Section 2 will cover the history of studies of WR stars, while Section 3 will highlight several topical problems and open questions about them.

2. FROM DISCOVERY TO UNDERSTANDING

In 1867 year astronomers from Paris observatory Charles Wolf and Georges Rayet discovered three stars in Cygnus constellation those spectra significantly differ from other stars. In contrast with other stars, where usually absorption lines are dominant in spectra, discovered objects showed strong emission lines [15]. The class of objects received its name in honor of the discoverers and gradually began to be replenished with new members. One hundred years after the discovery of WRs, by the end of 1960-s the number of known WRs in the Galaxy

had reached over a hundred, totalling 127 [16, 17], while now is ~ 700 [18]. At the same time, in the late 1950-s middle 1960-s, work began to search for WR in the Large Magellanic Cloud [19, 20].

Significant contribution to the understanding of the physics of WR stars was given by [21]. Beals found that some lines in the spectra of WR stars have a P Cygni profile and based on comparison with P Cygni profile lines in spectra of novae he suggested that WRs are surrounded by expanding envelopes [21]. Beals also found a difference between WR stars and novae: the P Cygni profiles in the WR stars do not change over time. This allowed to propose that an outflow from WR stars occurs continuously [21]. This was confirmed by [22], who developed a solid footing for interpreting P Cygni profiles as arising in expanding atmospheres. In [23] used the diagnostics developed by Chandrasekhar to estimate the mass loss and maximum outflow velocity of a WR star and found, respectively, $\sim 10^{-5} M_{\odot} yr^{-1}$ and $\sim 1000 km s^{-1}$.

At the beginning of the 20th century, stellar spectroscopy developed in close cooperation with atomic physics. Investigating spectra of the star ζ Puppis Edward Pickering (1896) paid his attention to previously unknown lines 5411, 4541, 4200, 4100, 4026, 3924, 3858, 3813, 3782 Å [24]. He interpreted them as another series of hydrogen (besides Balmer) [25]. Line 4686 Å, first discovered during a solar eclipse and often found in WR spectra, was also considered to be a hydrogen line [26]. Although Fowler [26] was able to obtain these spectral lines in the laboratory in 1912, during an experiment with a helium-filled tube, he considered their appearance to be a contribution from hydrogen impurity. It was not until 1913 that Niels Bohr's work [27] explained the nature of these lines as ionized helium He II, confirming the atomic model (see historical review [28]).

In 1890 Pickering drew attention to the similarity of the spectra of WR stars and planetary nebula [29]. Due to this, in papers devoted to emission spectra of nebulae it is possible to find descriptions of spectra of WR stars. The lines at 4647, 4650, 5696, 5801 and 5812 Å were identified with the carbon by [30]. Ira S. Bowen, who found an interpretation of the "nebulium" lines as [O III], gave a detailed list of emission lines observed in nebulae, which includes an identification of almost all lines visible in the WRs [31]. In a 1934 paper Bowen [32] suggests a significant role of the fluorescence for formation of the N III 4634, 46340 lines belonging to the WR bump.

Already the spectra of the first discovered WR stars showed a difference: the broad emission bands are located in different places [15, 33]. After the identification of all the main spectral lines, [34] proposed the splitting of WR into two groups. This classification was approved in 1938, the International Astronomical Union divided the spectra of WR stars into types WN and WC, depending on whether the spectrum was dominated by lines of nitrogen or carbon-oxygen

respectively [34,35]. WN stars are believed to show the hydrogen burning products via the CNO cycle, while WC stars reveal the helium burning products via the triple- α cycle. Based on the strength of the emission lines and line ratios, WN stars can be further classified into the spectral subtypes WN2 to WN11, and WC stars into the spectral subtypes WC4 to WC9 [10,17,36–38]. Also, there are transition types from WN to WC, which are called WN/C, whose spectra show strong emission lines of carbon and nitrogen simultaneously [39].

In 1933 [40] estimated He/H ratio for WR stars using intensities of H β and He II 4686 lines and found $\text{He}/\text{H} \gtrsim 1.8$. Subsequent studies [41] and references therein) confirmed excess of helium. [42] suggested that the anomalous composition of WR stars was the result of nuclear processed material being visible on their surfaces. Despite these arguments in favor of far evolved status of WR stars, debates about it continued until the mid-1970s. There was alternative hypothesis, that WR are young and more massive than T Tau objects, before main sequence [43,44]. It is important to mention the studies of Sergej V. Rublev, in which he developed methods for determining the temperatures and luminosities of WR stars and estimated the hydrogen abundances [45–48]. These works played a significant role in the formation of the modern understanding of WR stars as far evolved massive objects.

2.1. Development of numerical methods

Contemporary progress in our understanding of hot stars and especially WR stars has been significantly defined by the progress of numerical modelling of stellar atmospheres, in turn enabled by the development of both physical approximations and numerical methods.

Victor V. Sobolev developed the theory of radiative transfer in moving media and applied it to the determination of physical conditions in the envelopes of WR, Be, novae, etc. type stars [49,50]. He showed that due to the presence of a velocity gradient, photons of spectral lines are able to leave the deep layers of the atmosphere directly, avoiding the usual diffusion process; this significantly simplifies the study of the radiative equilibrium of moving atmospheres. This theory became the basis for the transition to modern quantitative calculations of the stellar wind.

WR stars are essentially hot stellar cores surrounded by extended, low-density atmospheres. Due to their high luminosity the radiation in the stellar wind dominates over collisional processes, and the models of WR's atmospheres should be calculated taking into account the deviations from local thermodynamic equilibrium (non-LTE). Straightforward iterative procedure for the solution of radiative transfer equations – Λ iteration – fails to converge in typical non-LTE conditions,

as in scattering dominated media of large optical thickness, its convergence is extremely slow [51] and references therein.

Several approaches have been proposed in early 1970-s as a way to numerically solve radiative transfer (RT) problems in non-LTE case. The first fully self-consistent solution of RT problems for non-LTE case was achieved by [52] who developed the complete linearization method based on the Newton–Raphson scheme to solve the set of discretized structural equations in a robust manner that opened a way for significant progress in the modelling of stellar atmospheres.

A different approach is the “core saturation method”, introduced [53] who implemented a modification of the Λ iteration method that made it practically usable for solving the RT and statistical equilibrium equations. In order to eliminate the cause of the slow convergence of simple Λ iteration (poor conditioning of the equations arising from a large number of scatterings), Rybicki proposed the elimination of scattering events in the line core as they do not contribute much to the transfer process.

Another approach is “perturbation technique” proposed by [54, 55] who was the first to use the idea of ‘operator splitting’ in radiative transfer computations. He replaced the full (exact) Λ operator by a simplified one (so called approximate Lambda operator, or ALO) and computed a small error term made by this approximation by using a perturbation technique. Cannon’s operator perturbation technique was an efficient way to combine computational advantages of approximate solutions with the accuracy of exact methods.

In 1980-s computational approximations to accelerate the Λ iteration started to be used together with the operator perturbation technique introduced [54, 55] to simplify the direct solution, making the basis for the class of methods known as Accelerated Lambda Iteration. [56, 57] adopted perturbation technique to approximate lambda operator, based on idea of “core saturation” and presented test calculations for a typical WR star atmosphere. This effort became the foundation for the PoWR code [58] that is still being actively developed and successfully applied for numerical modelling of various types of astrophysical objects. Independently, [59] presented a method based on tridiagonal Newton-Raphson operator, complete linearization scheme and perturbation technique for calculations of WN and WC atmosphere models. Over time, this method has grown into CMFGEN code [60].

Since the mid-1990s, CMFGEN and PoWR have become a reliable instruments for studying hot stars with high mass-loss rates. The study of Galactic WR stars systematically started with a series of works by Paul Crowther titled “Fundamental parameters of WR stars” and devoted to the analysis of properties of nitrogen-rich WR stars (WN) based on optical and ultraviolet UV data and numerical modelling using CMFGEN code [61–65]. Advances in infrared (IR)

spectroscopy also enabled studies of WR stars near the Galactic center [66, 67]. Modeling of large sample of Galactic WN [68] and WC [69] stars (≈ 126 objects in total) allowed to obtain a homogeneous set of stellar and atmospheric parameters for them, to determine the correct location of WR stars in the Hertzsprung–Russell (HR) diagram.

PoWR code was widely used for studying extragalactic objects. Among WR stars in nearby galaxies, the ones in Magellanic Clouds are most studied [70–72]. Sample of 74 WR stars belonged to M33 galaxy was analysed by [73] investigated late-type WN stars in M31 galaxy [74]. These studies extended our understanding of properties of WR stars in different galactic environments and metallicity-dependence of massive star winds.

2.2. Evolution

Modern view on WRs as products of evolution of massive stars was finally formed only in 1980s. Although by the 1980s WR stars were already recognised as descendants of massive OB stars, their exact evolutionary status with respect to the main sequence and other evolved massive stars was still an open question. WR stars were being proposed as possible progenitors of supernovae, and particularly the newly-discovered type Ib supernovae that lack hydrogen but are apparently associated with young massive stars.

The start of systematic X-ray observations with space-borne X-ray telescopes in 1960s significantly advanced the theory of close binary stars and their interactions, and it led [75] to the suggestion that WR stars are the products of binary evolution – namely, mass exchange in a binary system. In his scenario, a more massive star in binary system evolves faster and, upon exhaustion of hydrogen in the core, fills the Roche lobe and rapidly loses its hydrogen envelope that outflows towards the companion. As a result, when the envelope is fully transferred, its hot helium core remains as a WR star with little hydrogen in the outermost layers [76].

The hypothesis of Paczyński was well accepted and it naturally explained the anomalous chemical composition of WR stars as naked stellar cores enriched with products of nuclear reactions. On the other hand, based on the similarity of Of and WN stars (Figure 1) and on the first estimates of the mass loss rate for hot massive stars based on UV observations [77] suggested that the stellar wind of O stars is strong enough to remove the outer layers and uncover the stellar core, thus proposing a single star mass loss channel to form WR stars. In addition, brightest WR star, γ Vel, was inconsistent with Paczyński's hypothesis as, while being a binary, its orbit was clearly elliptical and its second component lacks any

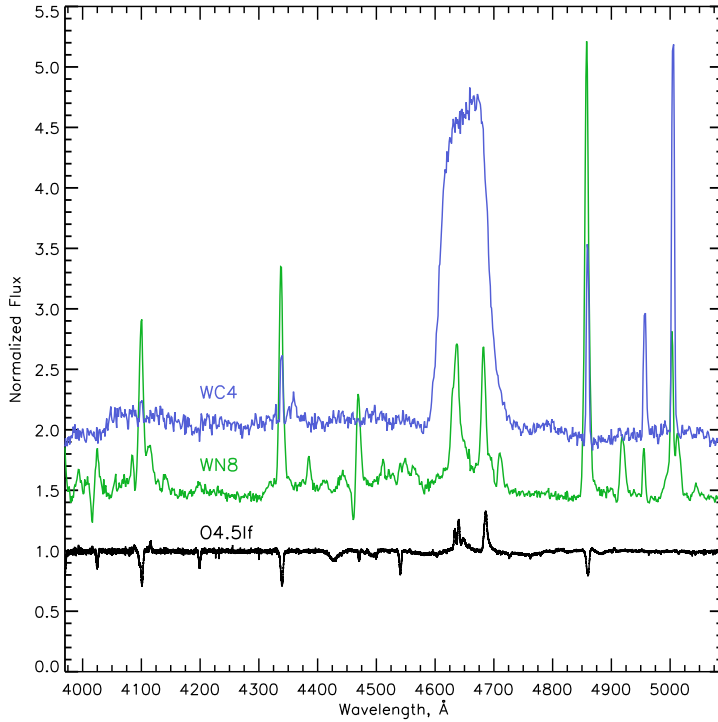


Fig. 1. Comparison of spectra of $J013340.19+303134.5(WC4)$, $J013352.43+304351.7(WN8)$ and HD 14947 (O4.5lf) as illustration of significant differences in intensities of spectral lines for O stars and different sub-types of WR stars.

signs of previous mass exchange, both suggesting that there was no interaction between the components [79].

In 1984 [78] introduced a new class of objects. In his talk at the international astronomical union (IAU) symposium, Peter Conti grouped S Doradus variables, Hubble–Sandage variables, η Carinae, P Cygni, and other similar stars together under the term “luminous blue variables” (LBV). LBV are characterized by strong mass loss (around $10^{-5} M_{\odot} yr^{-1}$) and occasional giant eruptive events [80]. Conti suggested that massive O stars transit to WR stars through this short-duration LBV phase. This idea is consolidated as the “Conti scenario” and becomes the main channel for WR star formation. Modern stellar evolution calculations are consistent with the “Conti scenario” [81, 82]. According to numerical calculations the stars with initial mass of $60 M_{\odot}$ spend 2×10^5 yr in the LBV phase — only 5% of their lifetime [81]. Recently observed transition from LBV to WN8 spectral type in Romano’ star is also a direct confirmation of “Conti scenario” [83, 84].

Similar scenario for WR formation was also proposed by [85], with significant mass loss on the red supergiant phase. They show that large inverse density gra-

dient appears in the outer layers of a $30 M_{\odot}$ star in this phase due to supercritical luminosity, resulting in powerful and rapid mass loss and formation of a stripped helium core.

In the last decade, Paczyński's hypothesis has again been discussed as a mechanism for the formation of WR stars. Analysing the spatial positions of LBV and WR stars, [86–88] concluded that both LBVs and WRs could be the products of binary evolution, LBVs being mass-gainers, and WRs – mass-donors, or stripped components. This idea was critically discussed by [89] and [90]. Now we may confidently conclude only that we do not have enough data for statistical analysis. Modern evolutionary codes allow detailed calculations of binary system evolution [91, 92], thus making it possible to compare theoretical predictions for stripped stars with properties of real WR stars [91]. Our current understanding is that binary interaction scenario cannot properly describe all observed WR stars, but most probably takes place in a part of them [14] and references therein.

Improving the statistics of binarity among WR stars is a crucial task. Among the first researchers who started to work on it was Virpi S. Niemelä, who determined the stellar masses in binary systems and discovered and analyzed the spectroscopic orbits of many binary systems with WR components for example her works [93, 94]. Nowadays this work is being continued, both through spectroscopy [95] and using high-resolution imaging [96].

3. CURRENT PROBLEMS

3.1. Search for new WR stars

In our Galaxy there are 679 WR stars currently discovered [18], while the theory based on current Milky Way star formation rate and duration of WR phase predicts the numbers of WR stars ~ 1200 [18]. It means that significant part of WR stars are still not discovered. WR stars in the Galaxy align with spiral arms and the regions of star formation. Thus, the discovery of new WR stars through optical observations has been significantly limited due to the presence of dust extinction. Although the probability of finding a WR star during optical spectroscopic surveys remains [97, 98], the majority of discoveries of new WR stars now happens through the observations in IR range. [99] identified 60 Galactic WR stars: candidates were selected using the photometry from *Spitzer* and Two Micron All Sky Survey (2MASS) surveys and confirmed by near-IR spectroscopy. [100] expanded the list by adding 71 more stars, also preliminary selected from *J* and *K* band 2MASS photometry.

Moreover, the search for new WR stars is complicated by the effect of spectral mimicry – low mass [WR] objects masquerading as classical WR stars. Thanks

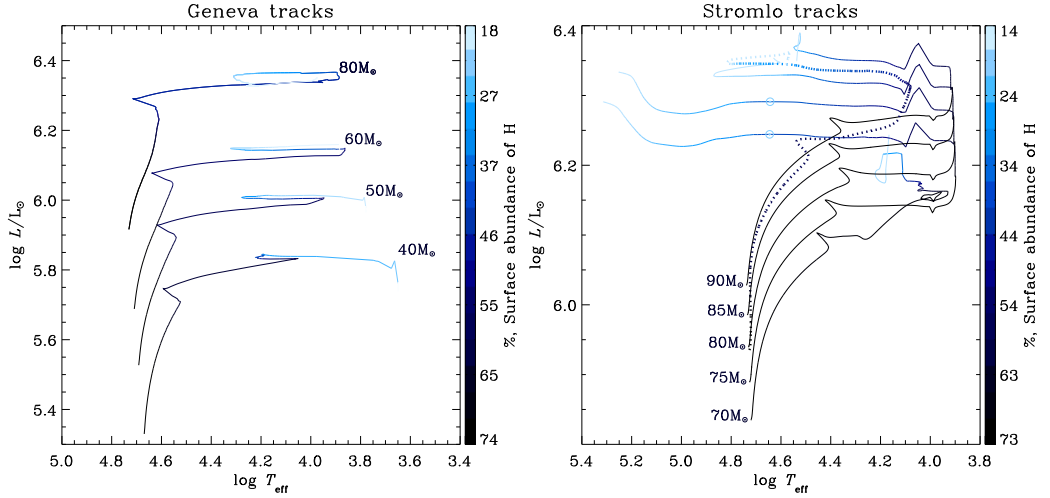


Fig. 2. HR diagram and evolutionary tracks for the low metallicity massive stars ($Z = 0.002$) from [110] (left panel) and [111] (right panel) evolutionary models. Geneva tracks do not produce massive WR stars at such low metallicities, while Stromlo tracks show rather different evolutionary path and produce WR stars with $M_{*} > 70M_{\odot}$.

to the results of *Gaia* mission [101] we now have reliable estimations of distances, and it helps to quickly understand the nature of individual objects and separate low-mass evolved stars from massive stars, and, moreover, to find the objects of unusual origin among low mass stars. For example, based on *Gaia* distance estimation [8] demonstrated that IRAS 00500+6713 is a product of merging of two white dwarfs, while the star has WO-type spectrum. Counterexample is PMR 5 star classified as [WN6] by [102] that was recently reclassified as a classical WN.

Systematic search for WR stars in nearby galaxies is ongoing since 1970-s. In 1972 Wray & Corso [103] published first catalog of WR candidate stars located in M33 galaxy. Twenty-five objects were selected based on photometry in three narrow-band filters (one filter is centered on He II 4686 – the strongest emission line in WN-type WRs, one is centered on C III-IV ≈ 4650 – the strongest line in WC-type WRs, and one is centered on continuum). This technique of selection of WR candidates for following spectroscopy has proven itself successfully and is still widely used [104–107]. As of today, 211 WR are known in M33 galaxy (Massey et al. 2016, [108]) and 173 are in M31 [109]). Search for new WR and their following investigations are important for understanding the impact of metallicity on mass-loss rate.

3.2. Wolf-Rayet stars in low metallicity environment

As the opacity of stellar wind depends on the metallicity, mass-loss rates of massive stars decrease with Z . It means that in low metallicity environment single massive stars are unable to lose enough material through the stellar wind to become WR star. Thus, the mass loss on pre-WR stages is of fundamental importance for the final fate of massive stars, and may influence e.g. the formation of long-duration Gamma Ray Bursts (GRBs) or the yields from early stellar generations.

Metallicity impacts overall evolutionary behaviour of massive stars in a complicated way. [110] calculated evolutionary tracks for stars in a wide range of initial masses at low metallicity. According to their calculations, metal-poor stars become colder after the end of hydrogen burning in the core and move along the track to the right side of the diagram. Unlike solar metallicity stars, metal-poor ones no longer return to the left side of the diagram (Figure 2), even when the effects of stellar rotation are taken into account in the models. On the other hand, evolutionary tracks behave differently if the models implement Galactic Concordance abundances instead of solar, scaled-solar, or alpha-element enhanced abundances [111] – the stars with the initial mass of $M_* > 70M_\odot$ with rotation $V/V_{crit} = 0.2$ after the main sequence move to the right and then return to the left to the WR stars region, in contrast to predictions of [110].

[112] used evolutionary tracks from [110] and [111] for the study of emission-line stellar-like object in the nearby low-metallicity ($Z \sim 0.1Z_\odot$) dwarf galaxy NGC 4068. They found the best agreement between the modelled and observed spectra for the model assuming ionization by low-metallicity WR star of $M_* \approx 80M_\odot$ mass, ionizing the nebula through the strong wind and enriching the interstellar medium with nitrogen. Thus, parameters of the object favor [111] predictions. Therefore, understanding of mass loss rate requires complex approach that includes both studies of massive stars in different metallicities, and studies of present-day chemical abundances.

3.3. Wolf-Rayet stars and red supergiants

Isolated massive stars with initial masses in $8 M_\odot < M_* \lesssim 20 M_\odot$ interval undergo the transition to Red Supergiants (RSG) after hydrogen in the core is exhausted. For them RSG is the final stage before Type-II supernova (SNII) explosion. More massive stars ($40 M_\odot \lesssim M_* < 90 M_\odot$) evolve through LBV phase before reaching WR phase, and finally explode as SN Type Ib/c. The evolution of stars with $25 M_\odot \lesssim M_* \lesssim 35 M_\odot$ initial masses is more complicated. Observed population of supernovae Type II progenitors in the local Universe shows that they are produced by the stars with initial masses $M_* \lesssim 18M_\odot$ [113], and it

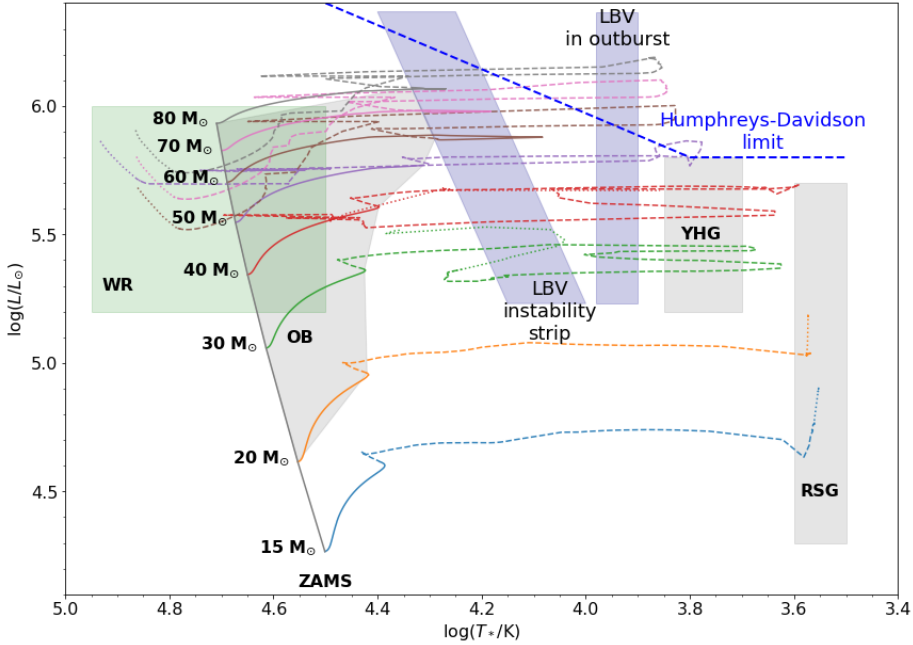


Fig. 3. Hertzsprung-Russell (HR) diagram (luminosities versus effective temperatures). Color horizontal lines show evolutionary tracks, with solid parts showing the phase when hydrogen burns in the stellar core. The tracks are taken from [114]. ZAMS is zero age Main Sequence.

suggests that more massive stars should either directly collapse to black holes, or evolve leftwards in HR diagram, thus becoming Wolf-Rayet stars. It is supported by the luminosity distributions of cool supergiants in Large and Small Magellanic Clouds [115] that overlaps with those of apparently-single WR stars in both galaxies, thus suggesting a changing evolutionary sequence of massive stars with increasing initial mass. At the same time, between the RSG and WR regions in HR diagram lies the region of *low luminosity LBVs* and yellow hypergiants (YHGs) (Figure 3). Therefore, the evolution of $25 M_{\odot} \lesssim M_{*} \lesssim 35 M_{\odot}$ initial mass may look like that:

$$O \rightarrow RSG \rightarrow YHG(?) \rightarrow \text{low LBV} \rightarrow WR \quad (\text{for } M_{*} \approx 25 - 35 M_{\odot})$$

It means that the star with initial mass about $30 M_{\odot}$ should pass through all four stages – do such objects really exist?

[116] demonstrated that the stars with $20 - 25 M_{\odot}$ initial masses are unstable on *low luminosity LBV* stage, and explode as core-collapse supernovae (SN Type IIL/b). Prior to the explosion they show the spectrum similar to S Dor during its minimum of brightness (WN11h spectral type). [117] have recently found

a Galactic object, Wray 15-906, with characteristics typical of a low luminosity LBV and the spectrum looking like WN11h. It was identified via the detection of its infrared circumstellar shell (of ≈ 2 pc in diameter) with the Wide-field Infrared Survey Explorer (WISE) and the Herschel Space Observatory. [117] found that Wray 15-906 is a relatively low-luminosity, $\log(L^*/L_\odot) \approx 5.4$, star with a temperature of 25 ± 2 kK, with position in HR diagram corresponding to post-red supergiant with initial mass of $\approx 25M_\odot$. Its spectrum and properties are consistent with theoretical predictions of [116]. Thus, the monitoring of this object, and the search for similar ones, may improve our understanding of the link between WR and RSG.

4. CONCLUSION

Wolf-Rayet stars were discovered more than 150 years ago, and since then they were targets of numerous studies that combined astrophysical insights with advancements in atomic physics, development of numerical methods, and instrumental progress. Nowadays we understand quite well what Wolf-Rayet stars are, and they are no longer a hot topic in astrophysics. However they still are keystones for many directions of research, from theory of stellar atmospheres up to stellar populations in other galaxies and gravitational waves. Through the existence of the Wolf-Rayet phenomenon WR stars are linked, besides massive stars, with low mass evolved stars.

We expect new progress in understanding the Wolf-Rayet stars and mass-loss of massive stars in general from the upcoming advances in the instrumentation. For example, SITELE imaging Fourier transform spectrometer at Canada-France-Hawaii telescope [118] may provide spatially resolved line ratios and kinematics of WR nebulae thus hinting us on ionizing flux from the stars, and their mass loss history. James Webb Space Telescope will allow studying dust shells around WR stars [119], and to assess their role in enrichment of interstellar medium with organic compounds and carbonaceous dust. Spectropolarimetric surveys of WR and monitoring of variability of linear polarization are also still topical.

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NATURE OF THE DISTANT COMPONENT IN THE TRIPLE SYSTEM DV CAM

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DV Cam (HD 34233) is a relatively bright spectroscopic binary system exhibiting complex variability. This study presents an extensive analysis of its orbital dynamics and pulsational behavior using multi-source photometric data, including the Hipparcos, ground-based, and TESS satellite observations. The O–C residuals analysis reveals a sinusoidal variation indicative of the light-time effect (LITE), leading to the identification of a third component with an orbital period of 35.8 years. TESS data further unveil cyclic out-of-eclipse variations, which are characteristic of pulsational behavior. Using the Period04 software, two main pulsation frequencies, $f_1 = 0.91789$ cy/day and $f_2 = 0.70165$ cy/day, were identified, which are consistent with the behavior of Slowly Pulsating B (SPB) stars. This suggests a potential connection between the pulsational modes of DV Cam and SPB stars. The study also applies a light-curve fitting technique to isolate out-of-eclipse variations, enhancing the characterization of the system's pulsational properties. The results provide valuable insights into the dynamics of this triple star system and its connection to SPB-like pulsations. Future work will focus on further refining the orbital and pulsational models with additional data and investigating the system's long-term behavior.

Keywords: Stars: Individual: DV Cam – Stars: SPB – Stars: Eclipsing Binaries

1. INTRODUCTION

DV Cam (HD 34233) is a relatively bright ($V = 6^m.1$) spectroscopic binary, first identified by [1]. Its radial velocity (RV) variability was confirmed by [2]

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and later classified as a single-lined spectroscopic binary (SB1) by [3]. Using high-resolution spectra, [4] established the triple nature of the system, identifying spectral lines from all three components. Their study revealed that the system comprises a slowly rotating helium-weak star and a rapidly rotating mid-B star in a close binary configuration, with a third component—a slowly pulsating B (SPB) star—in a wide orbit. [4] provided the system's spectroscopic orbital parameters as $K_1 = 101.2$ km/s, $K_2 = 163.5$ km/s, $e = 0.493$, $\omega = 78^\circ.1$, $T_{\text{peri}} = 2455617.375$, and $P_{\text{orb}} = 6.678514$ days. Additionally, they reported Doppler shifts in the third component's lines of approximately 8 km/s, with a frequency of 0.91550 cy/day (1.0923 days).

The Hipparcos satellite [5] identified DV Cam as a photometrically variable eclipsing binary with a light variation amplitude of approximately 0.2 mag. The catalogue listed an orbital period of 1.5295 days, with only one minimum observed in the light curve. Subsequently, [6] determined the orbital period of the system to be $P_{\text{orb}} = 6.678514$ days based on spectral line variations. Hipparcos astrometry also reported an "acceleration solution," indicating that the star's proper motion changes over time. This non-linear motion suggests evidence of acceleration, which can arise from the gravitational influence of an unseen companion (such as a binary star or exoplanet) or from dynamical interactions in a cluster or galactic environment.

2. PHOTOMETRIC DATA

There are three sources of photometric observations for DV Cam: (a) Hipparcos photometry, (b) ground-based photometry, and (c) TESS photometry. The Hipparcos dataset includes 112 observations taken over 21 epochs, with 4 observations capturing eclipse data. Here, "epochs" refer to groups of observations separated by intervals not significantly exceeding 0.1 days. The longest "continuous" observation spans 1.95 days (24 data points), including 4 consecutive measurements within an eclipse, two on either side of the mid-eclipse. This dataset establishes the duration of one eclipse as approximately 0.15–0.2 days and determines a mid-eclipse time of $\text{HJD } 2448751.926 \pm 0.002$. The remaining 3 eclipse observations are isolated, each occurring at the beginning or end of a short observation series, with the second measurement (taken 20 minutes later) excluded in all three cases.

The ground-based photometric data consists of observations in the R-band (see Fig. 1) was collected over 22 nights during an 81-day period from January to March 2011. These observations were conducted using different telescopes and comparison stars due to varying fields of view of the optical systems. The data were acquired with the T122 (122-cm) and T40 (40-cm) Cassegrain-Schmidt tele-

scopes at the Ulupınar Observatory of Çanakkale Onsekiz Mart University, using HD 38831 (A0) and HD 35607 (A0) as comparison and check stars, respectively. Additionally, observations were made with the T5 (5-cm) telescope, using HD 34787 (A0) and HD 34361 (A2) as comparison and check stars.

An observing log with details about the photometric accuracy is provided in Table 1. Ideally, the accuracy of individual measurements ranges between 5 and 10 millimag, but on several nights, the accuracy was significantly lower. This was due to observations being conducted under suboptimal atmospheric conditions, with the primary goal of confirming the presence or absence of an eclipse rather than obtaining high-precision data. The TESS satellite [7, 8] observed DV Cam during Sectors 19, 59, and 73, spanning the period from November 26, 2019, to December 22, 2019 (see Fig. 1). The TESS photometric data reveal clear cyclic out-of-eclipse variations, strongly suggesting pulsational behaviour in the system.

Table 1. Log of ground-based photometric observations.

HJD	fracHJD	tel.	qual.	HJD	fracHJD	tel.	qual.
2455571	0.199–0.270	T122	0.007	2455626	0.368–0.683	T5	0.006
2455576	0.350–0.537	T122	0.020	2455627	0.232–0.686	T5	0.006
2455579	0.370–0.388	T122	0.016	2455629	0.236–0.450	T5	0.004
2455580	0.242–0.542	T122	0.007		0.450–0.672	T5	0.007
2455581	0.208–0.480	T122	0.008	2455632	0.360–0.484	T20	0.017
2455589	0.238–0.253	T122	0.011	2455633	0.312–0.400	T20	0.009
2455592	0.313–0.427	T122	0.013		0.400–0.495	T20	0.018
	0.464–0.506	T122	0.023	2455634	0.296–0.420	T20	0.011
2455604	0.307–0.492	T122	0.021		0.420–0.473	T20	0.028
2455606	0.280–0.433	T122	0.015	2455637	0.264–0.303	T122	0.026
2455621	0.277–0.501	T5	0.006		0.404–0.441	T122	0.039
2455622	0.241–0.450	T5	0.007	2455650	0.253–0.614	T5	0.004
	0.450–0.689	T5	0.014	2455651	0.254–0.430	T5	0.005
2455624	0.335–0.635	T5	0.009		0.430–0.571	T5	0.009
2455625	0.242–0.684	T5	0.008				

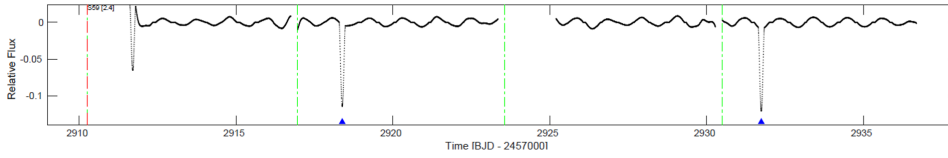


Fig. 1. The photometric data obtained by the Hipparcos and TESS satellites and ground-based telescopes.

3. ORBITAL PERIOD ANALYSIS

The orbital period analysis was conducted by examining the O–C residuals, which represent the difference between the observed times of minimum (ToM) and the calculated ToM based on a linear ephemeris. The O–C data set includes 9 ToM measurements (1 from Hipparcos, 2 from TESS, and 6 from ground-based observations) spanning approximately 27 years. The O–C diagram reveals a sinusoidal-like variation (see Fig. 2), indicating the presence of the light-time effect (LITE) caused by the gravitational influence of the known third component in the system.

The LITE equation of [10] was applied to model this variation. The fitting process was executed using the `curve_fit` function from the `scipy.optimize` package, which employs non-linear least-squares optimization to align the model with the O–C data. To ensure robust error estimation, the analysis was supplemented by a Markov Chain Monte Carlo (MCMC) method, utilizing 500 walkers and 1000 steps. The resulting corner plot (Fig. 3) illustrates the best-fit parameter values along with their statistical uncertainties. The LITE analysis provides

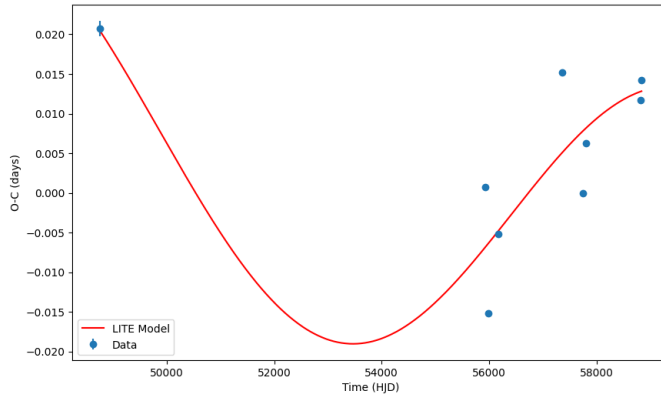


Fig. 2. The O-C data (blue dots) and best fitting LITE model (red solid line).

insights into the orbital parameters of the wide orbit of DV Cam caused by the gravitational influence of the third component. The orbital period of the third

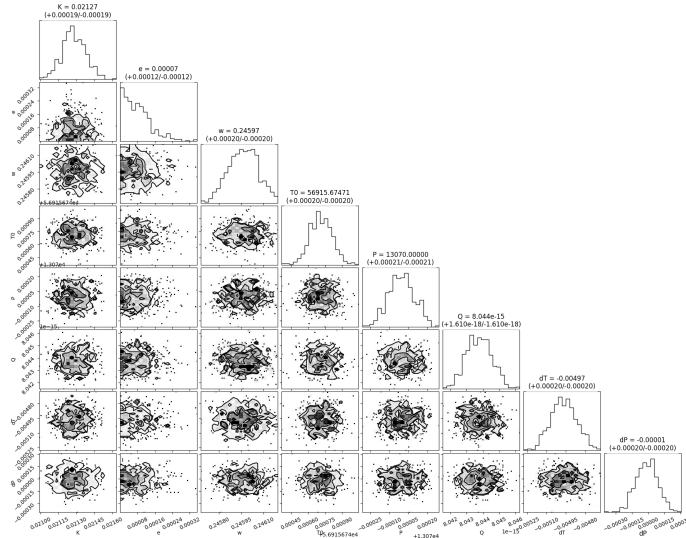


Fig. 3. The corner plot derived by the Monte-Carlo Markov-Chain (MCMC) error analysis for the orbital period analysis.

component is determined to be $P_3=35.8$ years, indicating a nearly circular orbit. This result highlights the long-term dynamical interaction within the triple system and confirms the presence of the tertiary companion.

4. PULSATIONS

The TESS satellite provides a significant advantage with its continuous, high-precision photometric measurements of sources within its observational sectors. This capability confirmed that the scatter observed in Hipparcos and ground-based data corresponds to genuine periodic variations in the light curve. To analyze these periodic variations, it was necessary to first isolate and remove the variations caused by eclipses. This was achieved through light-curve modeling applied to the TESS data, after which the eclipse contribution was subtracted from the entire dataset, leaving only the out-of-eclipse variations.

The light-curve modeling was performed using the PHOEBE (Physics Of Eclipsing Binaries) analysis package [9]. The resulting model light curve, along with the residuals, is presented in Fig. 4, demonstrating the accuracy of the model and the effectiveness of the subtraction process in isolating the periodic variations.

The out-of-eclipse variations were characterized using the Period 04 software package. Two main frequencies were identified: $f_1=0.91789$ cy/day with amplitude $A_1=0.00813$ mag, and $f_2=0.70165$ cy/day with amplitude $A_2=0.00169$ mag. These frequencies are in the typical range observed for slowly pulsating B stars

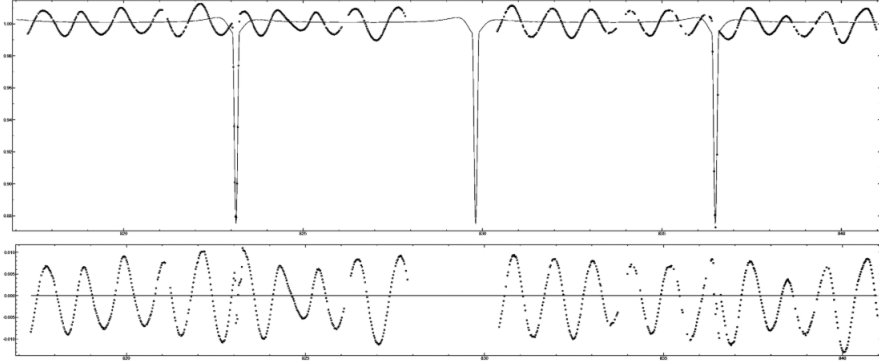


Fig. 4. *Top:* The TESS light curve of DV Cam and eclipsing-binary model. *Bottom:* The residuals between the data and model.

(SPBs), characterized by low-amplitude, low-frequency pulsations. The superimposed variation corresponding to these frequencies is shown in Fig. 5, along with the observational data.

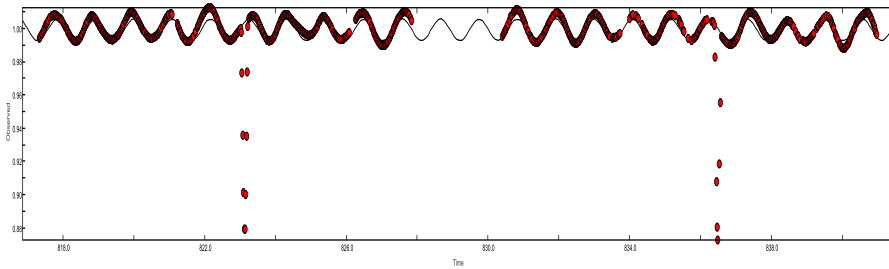


Fig. 5. The out-of-eclipse model was generated using Period04. The red points represent the observational data, while the black solid line shows the pulsation model with two frequencies.

These pulsation modes are likely linked to the stellar properties of DV Cam, possibly indicating that the system contains an SPB-type component. The second identified frequency may correspond to a harmonic or secondary pulsation mode. The pulsational characteristics of this system suggest that it could serve as a valuable case study for understanding the interplay between pulsations and eclipsing binary dynamics.

5. CONCLUSIONS AND FUTURE WORK

In this study, we have analyzed the complex variability of DV Cam, a spectroscopic binary system, using data from multiple sources including the Hipparcos, ground-based, and TESS satellite observations. Our analysis revealed key insights into the orbital dynamics and pulsational behavior of the system. The O–C residuals showed a clear sinusoidal variation, indicating the presence of a third component, and the light-time effect (LITE) was modeled using the equation of [10], yielding an orbital period for the third component of $P_3 = 35.8$ years in a nearly circular orbit. The TESS data confirmed the pulsational behavior of the system, showing periodic out-of-eclipse variations, which were well-characterized using the Period 04 software package. The two main frequencies identified, $f_1 = 0.91789$ cy/day and $f_2 = 0.70165$ cy/day, provide important information about the pulsations of the system’s primary star.

The out-of-eclipse variations in the light curve of DV Cam closely resemble the characteristics of Slowly Pulsating B (SPB) stars, which are known to exhibit low-frequency pulsations typically on the order of a few hours to days. The frequency $f_1 = 0.91789$ cy/day is particularly noteworthy, as it falls within the typical range of SPB pulsations. These stars are often characterized by g-mode pulsations, which arise due to the internal structure of the star, and the identification of such frequencies in DV Cam suggests that its tertiary component may be an SPB star or influenced by similar pulsation mechanisms. This connection adds a significant layer to our understanding of the star’s pulsational behavior, providing a potential link between the binary nature of DV Cam and the pulsational characteristics of SPB stars.

The use of high-precision, continuous photometric data from TESS allowed for the removal of eclipse-related variations and the accurate characterization of out-of-eclipse pulsations. The light-curve fitting and residual analysis further confirmed the presence of these pulsational modes. This work demonstrates the power of multi-wavelength data, combining Hipparcos astrometry, ground-based photometry, and space-based TESS observations, to study complex stellar systems.

Future work will focus on refining the model of DV Cam’s light-curve variations by incorporating more data points, particularly from subsequent TESS sectors, to improve the precision of the pulsation analysis. Additionally, we aim to expand the study of the third component’s influence on the binary system by continuing the O–C analysis and investigating its impact on the system’s long-term behavior. Further spectroscopic observations could provide a better understanding of the system’s dynamics, including the interaction between the components and the potential for additional companions. Ultimately, a more comprehensive

analysis of the system's orbital and pulsational parameters will contribute to a deeper understanding of the physical processes governing such complex stellar systems and their connection to the pulsational properties of SPB stars.

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