

AZƏRBAYCAN MİLLİ ELMLƏR AKADEMİYASI

AZƏRBAYCAN
ASTRONOMİYA
JURNALI

2025, Cild 20, № 2

AZERBAIJAN NATIONAL ACADEMY OF SCIENCES

AZERBAIJANI
ASTRONOMICAL
JOURNAL

2025, Vol. 20, № 2

Bakı-2025 / Baku-2025
<https://doi.org/10.59849/2078-4163.2025.2>

AZERBAIJANI ASTRONOMICAL JOURNAL

Founded in 2006 by the Azerbaijan National Academy of Sciences (ANAS)
Published in the Shamakhy Astrophysical Observatory (ShAO) named after
N. Tusi, ANAS
ISSN: 2078-4163 (Print), 2078-4171 (Online)

Editorial board

Editor-in-Chief:	Dzhalilov N.S.
Associate Editor-in-Chief:	Ismailov N.Z.
Secretary:	Adigozalzade H.N. <i>Shamakhy Astrophysical Observatory</i>
	Guliyev A.S. <i>Shamakhy Astrophysical Observatory</i>
	Babayev E.S. <i>Baku State University</i>
	Andrievsky S.M. <i>Odessa I.I.Mechnikov National University, Ukraine</i>
	Hubrig S. <i>The Leibniz Institute for Astrophysics Potsdam, Germany</i>
	Kubatova B. <i>Astronomical Institute of the Czech Academy of Sciences, Czech Republic</i>
	Pogodin M.A. <i>Main Astronomical Observatory of the Russian Academy of Sciences at Pulkovo, Russian Federation</i>
	Romanyuk I.I. <i>Special Astrophysical Observatory of the Russian Academy of Science, Russian Federation</i>
	Aret A. <i>Tartu Observatory of the University of Tartu, Estonia</i>

Kuznetsov V.D.

*Pushkov Institute of Terrestrial Magnetism,
Ionosphere and Radio Wave Propagation of Russian
Academy of Sciences, Russian Federation*

Cherepaschuk A.M.

*Lomonosov Moscow State University,
Russian Federation*

Bakış V.

Akdeniz University, Turkey

Samadov Z.A.

Baku State University Department of Astrophysics

Huseynov N.A.

Shamakhy Astrophysical Observatory

Alisheva K.I.

Baku State University Department of Astrophysics

Rustamov J.N.

Shamakhy Astrophysical Observatory

Gasimov H.A.

Baku Engineering University

Technical Editors:

Tagiyeva J.J., Salehli O.M.

Editorial Office address:

ANAS, 30, Istiglaliyyat Street, Baku, AZ-1001,
the Republic of Azerbaijan

Address for letters:

ShAO, P.O.Box №153, Central Post Office,
Baku, AZ-1000, Azerbaijan

E-mail:

azaj@shao.science.az

Phone:

(+994 12) 510 82 91

Fax:

(+994 12) 497 52 68

Online version:

<http://www.aaj.shao.az>

AZERBAIJANI ASTRONOMICAL JOURNAL

2025, Vol. 20, № 2

Contents

NEW OPPORTUNITIES FOR SEARCHING FOR MAGNETIC STAR CANDIDATES	6
<i>I.I. Romanyuk, I.A. Yakunin, E.P. Korchagina, A.V. Moiseeva, V.N. Aitov</i>	
BINARIES CAS ANALOGS: OPTICAL AND X-RAY VARIABILITY	10
<i>A.F. Kholtygin, E.B. Ryspaeva A.V. Dodinc, O.A. Tsiopa</i>	
THE ORIGIN OF COPPER IN COSMOS	15
<i>S.M. Andrievsky, S.A. Korotin</i>	
DESCRIPTION OF THE HELIO-GEOPHYSICAL CONDITIONS DURING THE MAGNETICALLY DISTURBED PERIOD OF JUNE 21–26, 2015	21
<i>S.N. Mukasheva, A.B. Andreyev, V.I. Kapytin, O.I. Sokolova, G.B. Tileua</i>	
TWO NEUTRON STAR-BLACK HOLE MERGERS OBSERVED BY THE LIGO-VIRGO COLLABORATION	25
<i>Z.Vidadi, N.Kochiashvili, N.Z. Ismailov</i>	
SPECTRAL AND PHOTOMETRICAL PROPERTIES OF SELECTED MASSIVE HERBIG AE/BE STARS	28
<i>F.S. Huseynova, N.Z. Ismailov, U.S. Veliyev</i>	

**RESEARCH OF THE RELIEF FACTORS OF THE PIRGULU
RESERVE BASED ON SATELLITE IMAGES**

36

F.I. Ismailov, N.S. Dzhililov, A.E. Humatova

**DETERMINATION OF EFFECTIVE TEMPERATURES AND SURFACE
GRAVITY OF A NUMBER F-SPECTRAL CLASS STARS BASED ON
OBSERVED PHOTOMETRIC INDICES**

39

Z.A. Samedov, U.R. Rustam, Z.F. Alieva, S.Sh. Racabova, A.A. Ganbarov

NEW OPPORTUNITIES FOR SEARCHING FOR MAGNETIC STAR CANDIDATES

I. I. Romanyuk,^{*} A. Yakunin, E. P. Korchagina, A. V. Moiseeva, V. N. Aitov

¹ *Special Astrophysical Observatory, Russian Academy of Sciences, Nizhnii Arkhyz, 369167 Russia*

Last updated 2025 September 19; in original form 2025 October 25

ABSTRACT

Spectropolarimetric observations required for direct measurement of stellar magnetic fields are technically complex and require a large amount of observation time. This fact is an obstacle to a large-scale search for new magnetic chemically peculiar stars. To improve the efficiency of the search for such objects, a reliable preliminary selection of candidates is necessary, which is traditionally based on the identification of characteristic photometric patterns and anomalies in the chemical composition. Recently, a new approach was proposed — selection by features of line splitting in unpolarized infrared spectra associated with the Zeeman effect. In this work, observations of 18 stars selected by these features were carried out using the Main Stellar Spectrograph on the 6-m telescope. As a result, the presence of a magnetic field was reliably confirmed for 15 objects, which demonstrates the high efficiency of the proposed selection criterion and opens up new opportunities for searching for magnetic star candidates.

Key words: stars: magnetic field – stars: chemically peculiar

1 INTRODUCTION

Despite numerous attempts to explain the phenomenon of large-scale magnetic fields of upper main sequence stars, their nature and the extent of their influence on evolution have not been fully described. Various theoretical models have been proposed to explain the origin and evolution of magnetic fields, but none of them can account for the full range of observed manifestations of stellar magnetism (Moss 1989; Mestel 2003; Schneider et al. 2019).

Magnetic fields have the most noticeable effect on some subclasses of chemically peculiar (CP) stars. The so-called Ap/Bp- and He-rich/weak stars (subclass CP2/CP4 according to Preston (1974)) show significant strengthening and variability of lines of various chemical elements. In particular, Ap stars are characterized by anomalously strengthened lines of silicon, strontium, chromium, and rare earth elements, whereas He-rich and He-weak stars of early B-classes exhibit anomalously strengthened or weakened helium lines. The observed anomalies in these objects are not associated with changes in atmospheric temperature but rather reflect the uneven distribution of chemical elements in the stellar atmosphere (Preston 1974).

These elements are concentrated in spots distributed non-uniformly across the stellar surface, causing strong photometric and spectral variability. As the star rotates, the observer

sees different portions of its surface, leading to changes in both spectral and photometric characteristics. At the same time, the spots generally remain stable over long periods (Bohlender et al. 1993).

The most complete compiled catalog of CP stars contains 8205 objects. Since then, advances in large-scale photometric surveys (Kepler, TESS, ASAS-SN, ZTF) and spectroscopic surveys (LAMOST, Gaia-ESO, APOGEE) have enabled identification of CP stars based on homogeneous, high-quality data covering large samples. This has significantly expanded CP star catalogs, both in terms of photometric features (Hümmerich et al. 2018; Bernhard et al. 2020; Bauer-Fasching et al. 2024) and spectroscopic characteristics (Petravnov et al. 2024; Hümmerich et al. 2020, 2024).

2 MAGNETIC FIELD OF CHEMICALLY PECULIAR STARS

Ap/Bp stars have stable global magnetic fields with slow dissipation, the structure of which does not change over long periods of time (Romanyuk et al. 2024). In addition, they cover a wide range of ages and spatial distributions in the Galaxy (Kochukhov & Bagnulo 2006; Kudryavtsev et al. 2006), which allows us to study the evolutionary and kinematic aspects of stellar magnetism.

Babcock first detected a magnetic field in the CP star 78 Vir of spectral type A (Babcock 1947). This was the first reliable confirmation of the existence of a magnetic field in a star

^{*} Contact e-mail: roman@sao.ru

other than the Sun, marking the beginning of observational stellar magnetometry.

Since then, a large sample of known objects with confirmed magnetic fields has been accumulated to study the nature of CP star magnetism. The most noteworthy are large-scale observational programs using medium- and high-resolution spectropolarimetry (e.g., BOB (Morel et al. 2014), MiMeS (Alecian et al. 2015), BinaMiCS (David-Uraz et al. 2021), MOBSTER (Shultz et al. 2020)), as well as some statistical surveys (Kochukhov & Bagnulo 2006; Kudryavtsev et al. 2006; Mathys 1995; Wade et al. 2000, 2016; Sikora et al. 2019).

To estimate the magnetic field magnitude using the spectropolarimetric method, a differential circular polarization analyzer is employed, which measures the relative shifts of circularly polarized components of spectral lines split due to the Zeeman effect (Babcock 1958). In this case, only the effective longitudinal field (the projection of the magnetic field vector onto the line of sight, weighted average over the stellar disk) is recorded; its magnitude varies as the star rotates. To explain the periodic magnetic variability, a model of an inclined rotator was proposed (Stibbs 1950), in which the magnetic axis is inclined relative to the rotation axis. Such a configuration leads to cyclic changes in the observed magnetic projection, typically producing a sinusoidal curve.

The above surveys are limited by both the number of telescopes equipped with polarimetric instruments and the high cost of observing time, making effective preliminary selection especially relevant. Although large-scale photometric (TESS, Kepler) and spectroscopic (LAMOST) surveys have significantly expanded the list of candidates, analysis of light curves or unpolarized spectra alone is insufficient to estimate the magnetic field strength. Modern works (Romanyuk et al. 2023; Yakunin et al. 2023; Chojnowski et al. 2019) demonstrate the high efficiency of combining large surveys with targeted spectropolarimetry to detect and confirm magnetic CP stars.

Increasing the sample of known magnetic CP stars will allow us to study possible connections between the magnetic fields of individual objects and the magnetic field of the Galaxy. Currently, magnetic fields of stars fainter than 11–12 mag are registered extremely rarely, which significantly limits the depth and volume of the sample. As a result, most known magnetic CP stars are concentrated within a radius of about 1 kpc from the Sun.

The relative scale of magnetic line splitting increases with wavelength, which significantly enhances the sensitivity of the technique in the infrared region of the spectrum (Leone et al. 2003). Therefore, the transition to infrared unpolarized spectra, where the Zeeman effect is more pronounced, opens new possibilities for detecting and analyzing magnetic fields, including those with complex structures. A large-scale search for magnetic stars based on Zeeman splitting in the IR region was first carried out by Chojnowski et al. (2019). Analysis of a large array of IR spectra from the APOGEE survey allowed classification of about 1000 CP stars. The authors identified 157 objects with signs of magnetic line splitting, from which

they estimated the magnitude of the surface magnetic field, B_s . However, further spectropolarimetric observations in the optical range are required to unambiguously confirm the magnetic nature of the splitting.

3 MAGNETIC STAR CANDIDATES

As a first step in this work, we selected 33 stars from the catalogue (Chojnowski et al. 2019). For 18 of them, we carried out observations with the Main Stellar Spectrograph (MSS) (Panchuk et al. 2014) using the circular polarization analyzer (Chountonov 2016) during the period 2024–2025. Spectral data processing was performed following a standard method using the ZEEMAN context (Kudryavtsev 1999) of the ESO-MIDAS system.

On each observing night we measured standard stars with known longitudinal magnetic field variability curves, such as 53 Cam, α^2 CVn, and β CrB. We also regularly measured stars with magnetic fields clearly below the detection limit (“zero” field standards), such as β Gem and UMa. The level of the false instrumental magnetic field B_e does not exceed 100 G (Romanyuk et al. 2024).

We determined the longitudinal magnetic field B_e using a modified classical method (Babcock 1958). Since the rotation periods are unknown for many stars from the catalog (Chojnowski et al. 2019), we used the root-mean-square value of the field B_{rms} , the corresponding error σ_{rms} , and the normalized goodness-of-fit criterion χ^2/n (Bohlender et al. 1993) to analyze the magnetic nature of the objects.

$$B_{\text{rms}} = \left(\frac{1}{n} \sum_{i=1}^n B_{ei}^2 \right)^{1/2} \quad (1)$$

$$\sigma_{\text{rms}} = \left(\frac{1}{n} \sum_{i=1}^n \sigma_i^2 \right)^{1/2} \quad (2)$$

$$\chi^2/n = \frac{1}{n} \sum_{i=1}^n \left(\frac{B_{ei}}{\sigma_i} \right)^2 \quad (3)$$

The first results of the magnetic field measurements are presented in Table 1. The columns of the table include: the name of the star in the HD, BD, and TYC catalogues; the apparent stellar magnitude from SIMBAD; the peculiarity type from the catalogue (Renson & Manfroid 2009); surface magnetic field measurements from Chojnowski et al. (2019); our measurements of the root-mean-square magnetic field B_{rms} and the χ^2/n criterion; and the number of spectra obtained.

4 CONCLUSION

This paper presents the first intermediate results of spectropolarimetric observations of 18 stars selected from a sample of 33 objects in the catalogue (Chojnowski et al. 2019).

Table 1. Results of magnetic field assessment of 18 stars from the list of (Chojnowski et al. 2019).

Star	m_V (mag)	Sp. pec	$B_s \pm \sigma$ (kG)	$B_{rms} \pm \sigma$ (kG)	χ^2/n	n
HD2887	8.4	B9 Si	4.95 ± 0.24	0.44 ± 0.25	8.1	6
HD13404	8.8	A0 SrCrEu	21.89 ± 0.52	3.68 ± 0.38	92.8	19
HD14873	9.1	B9 Si	5.63 ± 0.34	0.82 ± 0.14	42.2	4
HD18410	9.2	B9 Si	5.01 ± 0.40	2.41 ± 0.32	110.8	4
HD36644	9.6	A0 SrCrEu	18.48 ± 0.27	2.09 ± 0.15	408.4	14
HD38586	9.3	B9 Si?	6.73 ± 0.66	0.85 ± 0.50	2.9	2
HD46297	9.0	B9 Si?	6.06 ± 0.23	1.05 ± 0.52	483.6	4
HD47074	9.4	B9 Si	11.85 ± 0.15	2.40 ± 0.13	336.8	2
HD188103	8.0	B9 Si	10.10 ± 0.62	0.29 ± 0.19	5.3	4
HD225114	8.1	A0 Si	7.46 ± 0.53	0.97 ± 0.22	30.6	10
BD+57°764	10.0	B9 Si	5.60 ± 0.98	0.56 ± 0.26	4.8	2
BD+60°562	10.1	A0 SrCrEu	9.88 ± 0.34	3.83 ± 0.18	–	1
BD+62°352	10.2	B9 Si	7.34 ± 1.16	0.43 ± 0.49	–	1
BD+64°352	9.5	A0 SrCrEu	10.98 ± 0.55	4.24 ± 0.39	448.2	15
TYC3676-505-1	11.2	A0 SrCrEu	18.49 ± 0.76	0.76 ± 0.08	–	1
TYC3681-1528-1	10.5	A0 SrCrEu	9.67 ± 0.50	1.51 ± 0.08	–	1
TYC4299-696-1	10.6	A0 SrCrEu	7.92 ± 0.89	1.45 ± 0.35	–	1
TYC4306-1062-1	10.8	A0 SrCrEu	4.17 ± 0.28	1.80 ± 0.07	–	1

The observations were carried out during 2024–2025 at the 6-m BTA telescope using the MSS spectropolarimeter equipped with a circular polarization analyser.

More than 80 per cent of the observed stars exhibit magnetic fields exceeding 300 G, highlighting the high efficiency of the selection method employed. Several objects, including HD 38586, BD+57°764, and BD+62°352, require further observations but can already be regarded as promising candidates for magnetic CP stars.

These results demonstrate that the preliminary selection of magnetic CP stars based on unpolarized infrared spectra can serve as a highly effective complement to spectropolarimetric techniques. This approach enables the expansion of the candidate sample for targeted follow-up observations, which remain essential for the accurate confirmation and quantitative determination of stellar magnetic fields.

FUNDING

The work was performed as part of the SAO RAS government contract approved by the Ministry of Science and Higher Education of the Russian Federation.

REFERENCES

Alecian E., Neiner C., Wade G. A., et al., 2015, *Proc. IAU Symp.*, 307, 335
 Babcock H. W., 1947, *Astrophys. J.*, 105, 105
 Babcock H. W., 1958, *Astrophys. J. Suppl. Ser.*, 3, 141
 Bauer-Fasching B., Bernhard K., Brändli E., et al., 2024, *A&A*, 687, A211
 Bernhard K., Hümmerich S., Paunzen E., 2020, *MNRAS*, 3330
 Bohlender D. A., Landstreet J. D., Thompson I. B., 1993, *A&A*, 269, 376
 Chojnowski S. D., Hubrig S., Hasselquist S., et al., 2019, *ApJ Lett.*, 873, L5
 Chountonov G. A., 2016, *Astrophys. Bull.*, 71, 495

David-Uraz A., Shultz M. E., Petit V., et al., 2021, *MNRAS*, 504, 4849
 Hümmerich S., Mikulášek Z., Paunzen E., et al., 2018, *A&A*, 619, A98
 Hümmerich S., Paunzen E., Bernhard K., 2020, *A&A*, 640, A40
 Hümmerich S., Bernhard K., Paunzen E., 2024, *A&A*, 692, A231
 Kochukhov O., Bagnulo S., 2006, *A&A*, 450, 763
 Kudryavtsev D. O., 1999, in *Proc. Intern. Meeting on Magnetic Fields of Chemically Peculiar and Related Stars*, SAO RAS, Nizhnij Arkhyz, Russia, Ed. by Y. V. Glagolevskij and I. I. Romanyuk, 84
 Kudryavtsev D. O., Romanyuk I. I., Elkin V. G., Paunzen E., 2006, *MNRAS*, 372, 1828
 Labadie-Bartz J., Hümmerich S., Bernhard K., et al., 2023, *A&A*, 676, 55
 Leone F., Vacca W. D., Stift M. J., 2003, *A&A*, 409, 1055
 Mathys G., 1995, *A&A*, 293, 746
 Mestel L., 2003, *ASP Conf. Ser.*, 305, 3
 Morel T., Castro N., Fossati L., et al., 2014, *Messenger*, 157, 27
 Moss D., 1989, *MNRAS*, 236, 629
 Panchuk V. E., Chuntunov G. A., Naidenov I. D., 2014, *Astrophys. Bull.*, 69, 339
 Paunzen E., Prišegen M., Hümmerich S., et al., 2024, *Contrib. Astron. Obs. Skalnaté Pleso*, 54, 5
 Potravnov I., Piskunov N., Ryabchikova T., 2024, *A&A*, 689, A111
 Preston G. W., 1974, *ARA&A*, 12, 257
 Renson P., Manfroid J., 2009, *A&A*, 498, 961
 Romanyuk I. I., Moiseeva A. V., Kudryavtsev D. O., et al., 2023, *Astrophys. Bull.*, 78, 49
 Romanyuk I. I., Kudryavtsev D. O., 2008, *Astrophys. Bull.*, 63, 139
 Romanyuk I. I., Moiseeva A. V., Yakunin I. A., Kudryavtsev D. O., 2024, *Astrophys. Bull.*, 79, 644
 Schneider F. R. N., Ohlmann S. T., Podsiadlowski P., et al., 2019, *Nature*, 574, 211
 Semenko E., Romanyuk I., Yakunin I., et al., 2022, *MNRAS*, 515, 998
 Shultz M. E., Owocki S., Rivinius T., et al., 2020, *MNRAS*, 499, 5379
 Sikora J., Wade G. A., Power J., Neiner C., 2019, *MNRAS*, 483, 2300
 Stibbs D. W. N., 1950, *MNRAS*, 110, 395
 Thomson-Paressant K., Neiner C., Labadie-Bartz J., 2024, *A&A*, 689, 208

- Wade G. A., Donati J.-F., Landstreet J. D., Shorlin S. L. S., 2000, MNRAS, 313, 851
Wade G. A., Neiner C., Alecian E., et al., 2016, MNRAS, 456, 2
Yakunin I. A., Semenko E. A., Romanyuk I. I., et al., 2023, Astrophys. Bull., 78, 141

BINARIES γ CAS ANALOGS: OPTICAL AND X-RAY VARIABILITY

A. F. Kholtygin^{1*}, E. B. Ryspaeva², A. V. Dodin³, O. A. Tsiopa⁴

¹*St. Petersburg State University, St. Petersburg, 198504, Russia*

²*Crimean Astrophysical Observatory RAS, Nauchnyi, 298409, Crimea, Russia*

³*Sternberg Astronomical Institute, Moscow University, Moscow, 119234, Russia*

⁴*Main (Pulkovo) Observatory, St. Petersburg, 196140, Russia*

Last updated 2025 October 19; in original form 2025 November 28

ABSTRACT

γ Cas analogs constitute a small group of Be stars characterized by unusual X-ray spectra and high X-ray luminosities, $L_X \sim 10^{31}–10^{33}$ erg s^{−1}. This is 2–3 orders of magnitude higher than for typical Be stars, yet lower than that observed in massive X-ray binaries with Be components. Compared to classical Be stars, these objects exhibit unusually hard X-ray spectra.

In the present paper, we present results from the analysis of the spectral and photometric variability of binary γ Cas analogs in both optical and X-ray bands. Notably, the periods of regular optical and X-ray variability appear to be similar. This suggests that at least part of the X-ray emission arises from interactions between local magnetic fields of the Be stars and the magnetic fields of their decretion disks.

X-ray flares are expected to result from the reconnection of magnetic field lines. For the stars BZ Cru and π Aqr, several thousand flare events were identified in the X-ray light curves obtained with the *XMM-Newton* satellite. Moreover, regular variations in X-ray brightness with periods of 50–90 seconds have been detected for the γ Cas analogs HD 45314, HD 45995, NGC 6649 9, and V558 Lyr. These periods may correspond to the rotation periods of white dwarfs in binary Be+WD systems.

We propose that the hard component of X-ray emission from γ Cas stars is generated via the accretion of disk material onto a rapidly rotating white dwarf.

Key words: stars: emission-line, Be – stars: binaries: individual: γ Cas – stars

1 INTRODUCTION

The γ Cas analogs constitute a small group of Be stars exhibiting X-ray luminosities 1–2 orders of magnitude higher than those of ordinary Be stars, along with anomalously high plasma temperatures ($kT \sim 10–20$ keV or more) in their X-ray emitting regions. Despite these extreme X-ray properties, the optical spectra of γ Cas analogs do not differ significantly from those of other Be stars. These stars possess Keplerian decretion disks, which give rise to strong emission lines in their optical spectra (Naze et al. 2020a).

The hardness of the X-ray spectra of γ Cas analogs—defined as the ratio of hard (2–8 keV) to soft (0.2–2 keV) X-ray flux—exceeds 1.6. Long-term X-ray observations show significant variability in the stellar X-ray fluxes, which has been attributed to changes in the mass and density of the circumstellar disks (Rauw et al. 2018; Naze et al. 2022a).

The origin of X-ray emission in γ Cas analogs remains uncertain. Recent modeling of Be star outflows by Bogovalov et al. (2021) and (Bogovalov & Petrov 2022) reproduces the formation of a fast polar wind and a slow, highly turbulent equatorial outflow. At rotational velocities 0.5–1% above critical, a quasi-Keplerian disk with a size of 10–15 stellar radii forms at the equator.

Several mechanisms have been proposed to explain the X-ray emission. Postnov et al. (2017) suggested accretion of Be star material onto a neutron star in the propeller mode, while Hamaguchi et al. (2016) considered accretion onto a magnetic white dwarf. Ryspaeva & Kholtygin (2021) proposed contributions from non-thermal X-ray radiation. Another hypothesis is that X-rays are generated by interactions between the Be star's local magnetic fields and the disk magnetic field (Robinson et al. 2002), a mechanism considered the dominant process by Smith et al. (2016).

A large fraction of γ Cas analogs are found in binary systems (Naze et al. 2022b). More recently, Gies et al. (2023) proposed that the bright and hard X-ray flux in this subgroup

* Contact e-mail: afkholtygin@gmail.com

may result from gas accretion onto an orbiting white dwarf (WD) companion, a scenario further supported by Gunderson et al. (2025). In the present paper, we compare the variability of the optical and X-ray spectra for several known binary γ Cas analogs to investigate how rapid optical and X-ray variations can provide insights into the origin of their X-ray emission.

The present paper is organized in the following manner. The properties of known binary γ Cas analogs are summarized in Section 2. In Section 3, we analyze the variability of spectral line profiles in these stars. Section 4 is devoted to the study of X-ray light curve variability. Finally, in Section 5, we discuss the impact of binarity on the mechanisms of X-ray formation.

2 BINARY γ CAS ANALOGS

To date, 26 stars have been identified as γ Cas analogs, along with 2 candidate objects. A list of 24 confirmed γ Cas analogs and the candidate stars is provided by Kholtygin et al. (2022a). The star 2XMMJ 180816.6–191939 (Naze et al. 2020a) and the bright star ζ Tau (Naze et al. 2020b) should also be added to this list. In Table 1, we present the known binary γ Cas analogs with established orbital parameters.

In Table 1, the orbital period P_{orb} in days, the masses of the Be stars (M_1) and their low-mass companions (M_2) in solar masses, the orbital inclination i , and the semi-major axes a (calculated using Kepler’s third law) are presented. Additionally, five other γ Cas analogs (FR CMa, BZ Cru, V771 Sgr, HD 119682, and HD 161103) are likely binaries, although their orbital parameters are unknown. Thus, more than half of the γ Cas analogs are either confirmed or probable binary systems.

The masses of the Be components in these binaries range from 8 to 13 $M_{\odot}$, while the masses of their companions, excluding π Aqr, do not exceed the mass limit for white dwarfs (WDs). According to Bjorkman et al. (2002), the secondary mass in π Aqr is $M_2 = 1.8 \pm 0.2 M_{\odot}$, whereas Tsujimoto et al. (2023) report a mass below 1.4 $M_{\odot}$. This indicates that the companion in π Aqr may also be a WD.

The nature of the secondary stars in γ Cas analogs remains uncertain. They could be low-mass main-sequence (MS) stars, subdwarf O or B stars (sdOB), WDs, or neutron stars (NS). Low-mass MS stars may have been formed before the first mass-transfer stage in the close binary, but forming a Be star at this stage is highly unlikely. Be+sdO binaries can form through Case B mass transfer, where the donor fills its Roche lobe during H-shell burning expansion (Shao & Li 2021). During the second mass-transfer stage, the sdO star (with mass $< 1.4 M_{\odot}$) loses about 12% of its mass to the Be star and becomes a WD. The resulting post-mass-transfer binary typically has a longer orbital period. Willems & Kolb (2004) show that WD remnants in such systems have masses in the range 0.7–1.4 $M_{\odot}$, with orbital periods peaking near 200 days. The Be stars in these systems acquire masses of 7–

17 $M_{\odot}$, consistent with the properties of known Be binaries (see Table 1).

To investigate the nature of low-mass companions in Be binaries, Klement et al. (2024) used optical/near-infrared interferometry with the Center for High Angular Resolution Astronomy (CHARA) on 37 Be stars suspected of hosting low-mass spectroscopic companions. Their targets included six γ Cas analogs: γ Cas, FR CMa, HD 45995, V558 Lyr, V782 Cas, and π Aqr. No sdOB or MS companions of the expected spectroscopic mass were detected, leaving elusive WDs as the most likely companions. In contrast, sdOB companions have been detected in other Be binaries.

The flux difference between a Be star and a WD in the H -band (1.63 μm) exceeds 11.5 magnitudes (Gies et al. 2023), making current interferometers unable to detect WDs in Be+WD binaries. Neutron star companions are also excluded for the secondary masses listed in Table 1. Therefore, generalizing the results of Gies et al. (2023), we conclude that all γ Cas analogs are wide (~ 1 au) Be+WD binaries.

3 VARIABILITY OF LINE PROFILES IN SPECTRA OF BINARY γ CAS ANALOGS

Sixteen γ Cas analogs with declinations $\delta > -12^\circ$ can be observed from Russia. We obtained spectra for nine of these stars using the 6-m BTA telescope (Russia), the 1.25-m ZTE telescope at the Crimean station of the Sternberg Astronomical Institute (SAI), Moscow State University, and the 2.5-m SAI25 telescope at the Caucasian Mountain Observatory of SAI. A summary of our observations is provided in Table 1 of Kholtygin et al. (2024a).

The line profiles variations of Balmer lines for all observed Be binaries appear to be typical for γ Cas analogs too, as illustrated in Fig. 1 (two left panels) for the binary star V558 Lyr. Spectra of V558 Lyr were obtained on 18 April 2024 and 14 December 2024 using the 2.5-m SAI25 telescope at the Caucasian Mountain Observatory of the Sternberg Astronomical Institute, Moscow State University, equipped with the low-resolution TDS spectrograph (Potanin et al. 2020).

To study the line profile variations (LPVs) in the stellar spectra, we use the difference line profiles (residuals):

$$d_i(V) = F_i(V) - \langle F(V) \rangle, \quad (1)$$

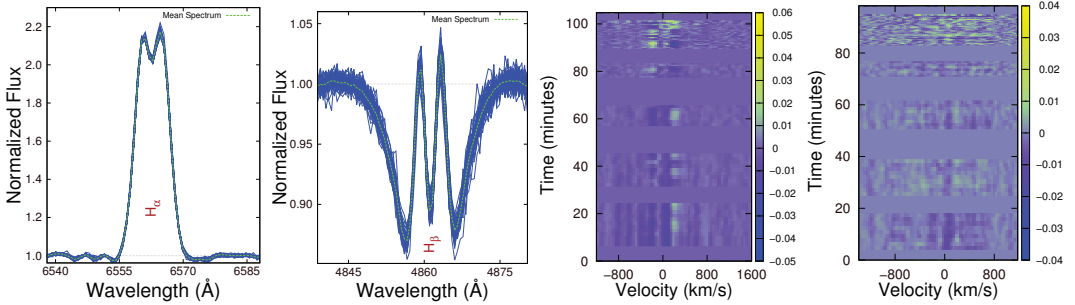
where $F_i(V)$ is the flux in the spectral line corresponding to the Doppler shift V , normalized to the continuum in spectrum i , and $\langle F(V) \rangle$ is the flux averaged over all observations. The collection of difference spectra (dynamic spectrum) for the $H\alpha$ and $H\beta$ lines is presented in Fig. 1 (two right panels).

We applied the CLEAN Fourier analysis method (Roberts et al. 1987) to the time series of difference line profiles $d(V, t_i)$ in the spectra of binary γ Cas analogs, corresponding to all observation times t_i . In Table 2, we list the periods P of the revealed regular components in the LPVs for the binary γ Cas analog V558 Lyr. The corresponding false-alarm probability (FAP) levels α are given in the last row of the table.

Similar regular components of LPVs with periods ranging

Table 1. Parameters of binary γ Cas analogs

Star Name	P_{orb} (d)	M_1 ($M_{\odot}$)	M_2 ($M_{\odot}$)	i (deg)	a (au)	Reference
γ Cas	203.36	13	0.98	45	1.63	Naze et al. (2022b), Nemravova et al. (2012)
V782 Cas	122.0	9	0.6–0.7	60–90	1.02	Naze et al. (2022b)
ζ Tau	133.0	11	0.87–1.02	60–90	1.17	Ruzdjak et al. (2009)
HD 45995	103.1	10	1.0 ± 0.1	46.8	0.96	Naze et al. (2022b)
V558 Lyr	83.3	8	0.7–0.8	60–90	0.77	Naze et al. (2022b)
SAO 49725	137.0	13	0.5–0.7	30–90	1.24	Naze et al. (2022b)
V2156 Cyg	126.6	11	0.7–0.8	60–90	1.12	Naze et al. (2022b)
π Aqr	84.1	15	<1.4	70	0.95	Bjorkman et al. (2002), Tsujimoto et al. (2023)
V810 Cas	75.8	12.5	0.7–0.8	60–90	0.83	Naze et al. (2022b)

**Figure 1.** Line profile variations and dynamical spectra of V558 Lyr. Panels (a) and (b) show the H α and H β line profile variations, respectively. Panels (c) and (d) show the corresponding dynamical spectra.**Table 2.** Regular components of line profile variations in the spectrum of V558 Lyr

Component number	1	2	3	4
P (min)	1.22 ± 0.02	1.77 ± 0.03	5.00 ± 0.25	21.2 ± 4.6
FAP (α)	10^{-2}	10^{-3}	10^{-2}	10^{-4}

from 1 to 150 minutes and amplitudes of 0.5–2% of the continuum level were also detected in other γ Cas analogs: γ Cas itself (Kholtygin et al. 2021), π Aqr (Kholtygin et al. 2022b), HD 45995 (Kholtygin et al. 2023), and SAO 49725 (Kholtygin et al. 2024b).

The detected periods of LPVs could correspond to high-order non-radial pulsations (NRPs; e.g., Kholtygin & Ryspaeva 2024). However, very short regular components with periods less than 5 minutes were observed for γ Cas (4.02 ± 0.13 min), SAO 49725 (0.89 ± 0.01 min), and π Aqr (4.10 ± 0.10 min). Such short LPV periods are difficult to explain even by high-order NRPs.

By contrast, the rotation periods of isolated white dwarfs can reach ~ 70 s (Kilic et al. 2021), while for the white dwarf in the binary system HD 49798 with an O-type donor, the period is as short as 13.2 s (Mereghetti et al. 2021). We therefore propose that the shortest LPV periods may correspond to, or be multiples of, the rotation periods of white dwarfs in Be+WD binary systems. The existence of these very short periods in binary Be stars provides additional evidence that the companions in these systems are white dwarfs. While the rotation periods of white dwarfs in Be+WD systems can sometimes exceed 5 minutes, identifying such periods among the bulk of NRP periods remains challenging.

4 X-RAY LIGHT CURVES VARIABILITY

A comparison of the X-ray and optical variability can provide insights into the origin of the extremely hard X-rays in γ Cas analogs. We reanalyzed archival X-ray light curves of known γ Cas analogs obtained with the *XMM-Newton* satellite. Currently, X-ray observations are available for 15 γ Cas analogs for which optical spectral observations have also been obtained.

Particularly interesting results were obtained for the bright star π Aqr. The CLEAN spectrum of the X-ray light curves of π Aqr, observed with *XMM-Newton* on 21 January 2020, is presented by Kholtygin & Ryspaeva (2024) (their Fig. 3, left panel). Four regular components with periods ranging from 35 minutes to 8 hours 37 minutes were revealed.

The most intriguing result is the correspondence between the periods of optical and X-ray variations. In the CLEAN spectrum of the X-ray light curve of γ Cas obtained with *XMM-Newton* on 5 February 2004 (ObsID 201220101), we detected 10 regular components with periods ranging from 29.6 min to 10 h 4 min across different energy bands. These components are plotted in Fig. 2.

The ninth period of the X-ray light curve, $P_9 = 36.69 \pm 1.24$ min, is very close to the period of the optical LPVs in γ Cas, $P = 37.11 \pm 3.59$ min. It is also notable that the periods

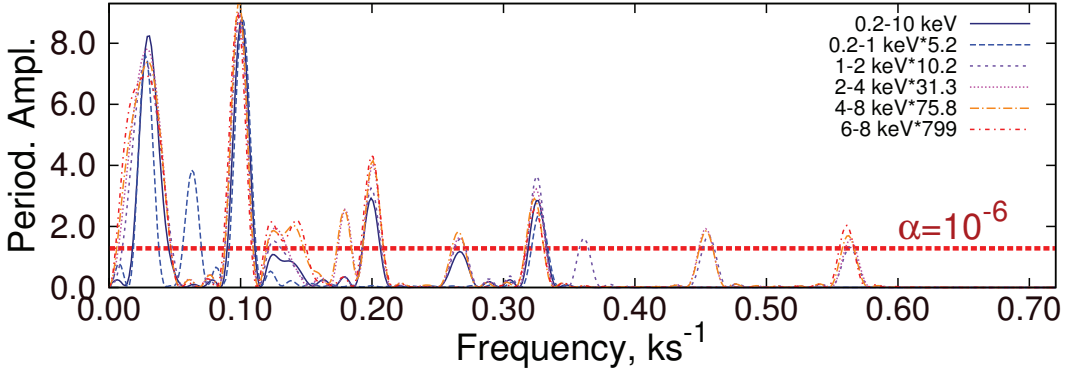


Figure 2. Amplitude of the CLEAN periodogram of the γ Cas X-ray light curve obtained with the *XMM-Newton* satellite on 5 February 2004 for different energy bands. The dashed line marks the false-alarm probability (FAP) level of 10^{-6} .

of the components corresponding to different energy bands are nearly identical, as seen in Fig. 2.

For HD 45995 and V558 Lyr, very short X-ray variation periods were detected: 48.5 ± 0.5 s and 1.16 ± 0.02 min, respectively. The latter is very close to the period of 1.22 ± 0.02 min of the optical LPVs given in Table 2. The similar fast X-ray variations were detected for HD 45314 and NGC 6649 9. This closeness of periods supports the hypothesis that these periods correspond to the rotation period of the white dwarf in the V558 Lyr binary system.

5 A NATURE OF THE X-RAY EMISSION IN THE BINARY γ CAS ANALOGS

Our analysis shows that the X-ray fluxes of all analysed γ Cas analogs exhibit regular components with periods up to 5–8 hours, corresponding to the characteristic timescales of variability in the optical spectra. The periods of optical and X-ray variations in γ Cas analogs are also similar to the typical periods of non-radial pulsations (NRPs) in Be stars (Rivinius et al. 2003). This correspondence indicates that the X-ray and optical radiation are, at least in part, generated in spatially close regions.

Since the optical radiation in these stars is formed either in the Be star itself or in the circumstellar decretion disk, the regular component of their X-rays may originate in the same regions or in the interface between the disk and the stellar photosphere. From a comparison of the periods of optical and X-ray variability, it is possible to conclude that the mechanism proposed by Smith et al. (2016), in which X-rays are generated by the interaction of local magnetic fields of the Be star with the decretion disk, significantly contributes to the total X-ray emission of these stars.

On the other hand, the presence of regular components in both optical and X-ray variations that are close to, or multiples of, the rotation periods of white dwarfs in binary γ Cas analogs supports the hypothesis that part of the X-ray emission arises from accretion of matter from the decretion disk

onto a rapidly rotating white dwarf. One of the most intriguing and still unresolved questions is whether the white dwarfs in these binaries are magnetic. Addressing this question requires high-resolution polarimetric observations, which could also help to determine whether the less massive component in a γ Cas binary could be a neutron star.

FUNDING

AFK and EBR thanks RSF grant 23-22-00090 for the support.

ACKNOWLEDGMENTS

Observations with the SAO RAS telescopes are carried out with the support of the Ministry of Science and Higher Education of the Russian Federation (including agreement no. 05.619.21.0016, unique project identifier RFMEFI61919X0016).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

- Afraimovich E. L., Demyanov V. V., Kondakova T. N., 2003, PS Solut., **7**, 109
- Bjorkman K. S., Miroshnichenko A. S., McDavid D., Pogrosheva T. M., 2002, ApJ, **573**, 812
- Bogovalov S. V., Petrov M. A., Timofeev V. A., 2021, MNRAS, **502**, 2409
- Bogovalov S., Petrov M., 2022, Universe, **8**, 591
- Gies D. R., Wang L., Klement R., 2023, ApJL, **942**, L6
- Gunderson S. J., Huenemoerder D. P., Torrejon J. M., et al., 2025, ApJ, **978**, 105
- Hamaguchi K., Oskoinova L., Russell C. M. P., et al., 2016, ApJ, **832**, 140

- Kilic M., Kosakowski A., Moss A. G., 2021, *ApJL*, 923, L6
- Kholtygin A. F., Burlak M. A., Tsiopa O. A., 2021, *Astron. Tsirk.*, 1649
- Kholtygin A. F., Ryspaeva E. B., Moiseeva A. V., 2022a, in *The Multifaceted Universe: Theory and Observations*, SAO RAS, id. 44
- Kholtygin A. F., Burlak M. A., Milanova Y. V., et al., 2022b, *Astron. Tsirk.*, 1652
- Kholtygin A. F., Yakunin I. A., Burlak M. A., Ryspaeva E. B., 2023, *Astrophys. Bull.*, 78, 557
- Kholtygin A. F., Yakunin I. A., Ryspaeva E. B., Mokshin D. N., 2024a, in *Proc. VAK-2024, Modern Astronomy*, in press
- Kholtygin A. F., Yakunin I. A., Bukharinov et al., 2024b, *Astrophys. Bull.*, 79, 437
- Kholtygin A. F., Ryspaeva E. B., 2024, *Geomagnetism and Aeronomy*, 64, 1267
- Klement R., Rivinius T., Gies D. R., et al., 2024, *ApJ*, 962, 70
- Mereghetti S., Pintore F., Rauch T., et al., 2021, *MNRAS*, 504, 920
- Naze Y., Motch C., Rauw G., et al., 2020a, *MNRAS*, 493, 2511
- Naze Y., Pigulski A., Rauw G., Smith M. A., 2020b, *MNRAS*, 494, 958
- Naze Y., Rauw G., Bohlens T., et al., 2022a, *MNRAS*, 512, 1648
- Naze Y., Rauw G., Smith M. A., Motch C., 2022b, *MNRAS*, 516, 3366
- Nemravova J., Harmanec P., Koubsky P., et al., 2012, *A&A*, 537, A59
- Potantin S. A., Belinski A. A., Dodin A. V., et al., 2020, *Astron. Lett.*, 46, 836
- Postnov K., Oskinova L., Torrejon J. M., 2017, *MNRAS*, 465, L119
- Rauw G., Naze Y., Smith M. A., et al., 2018, *A&A*, 615, A44
- Rivinius Th., Baade D., Stefl S., 2003, *A&A*, 411, 229
- Robinson R. D., Smith M. A., Henry G. W., 2002, *ApJ*, 575, 435
- Roberts D. H., Lehar J., Dreher J. W., 1987, *AJ*, 93, 968
- Ruzdjak D., Bozic H., Harmanec P., et al., 2009, *A&A*, 506, 1319
- Ryspaeva E., Kholtygin A., 2021, *Open Astronomy*, 30, 132
- Shao Y., Li X.-D., 2021, *ApJ*, 908, 67
- Smith M. A., Lopes de Oliveira R., Motch C., 2016, *Adv. Space Res.*, 58, 782
- Tsujimoto M., Hayashi T., Morihana K., Moritani Y., 2023, *PASJ*, 75, 177
- Willems, B., Kolb, U., 2004, *A&A*, 419, 1057

THE ORIGIN OF COPPER IN COSMOS

S. M. Andrievsky^{1*}, S. A. Korotin²

¹*Astronomical Observatory, I.I. Mechnikov Odessa National University, Odessa, Ukraine*

²*Crimean Astrophysical Observatory, Nauchny 298409, Republic of Crimea*

Last updated 2025 October 17; in original form 2025 November 23

ABSTRACT

Copper appears to be the most problematic element in the context of the Galactic chemodynamics. The dependence of the relative-to-iron copper abundance $[\text{Cu}/\text{Fe}]$ as a function of the metallicity remains a subject of debate. At very low metallicity, the observed copper abundance is also quite low. Several sources of the copper nuclei production have been proposed. Unfortunately, none of them provides an adequate explanation of such a low abundance. It is discussed here that this problem may be related to the LTE assumption used in spectroscopic studies of copper lines. Andrievsky et al. (2018) and Korotin et al. (2018) have shown that copper lines are strongly influenced by NLTE effects. Overionization of the copper neutral atoms leads to a decrease in the overall absorption in Cu I spectral lines, and as a result, LTE analysis yields a copper underabundance (i.e., NLTE corrections are positive). Correct determination of the copper abundance using the NLTE approximation eliminates this problem. Thus, in the low-metallicity regime, copper does not exhibit a significant deficiency and behaves essentially as a primary chemical element. Its cosmic production in the earliest stages of the Galaxy evolution may be associated with explosions of massive stars, such as type II supernovae (core-collapse supernovae) and hypernovae. The main source in this case may be the α -rich freeze-out process during the explosive silicon burning.

Key words: stars: abundances – nuclear reactions, nucleosynthesis, abundances

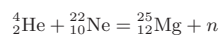
1 INTRODUCTION

Copper ($Z = 29$) has two stable isotopes: ^{63}Cu and ^{65}Cu . From the perspective of the Galactic chemical evolution, copper is a highly problematic element. Numerous spectroscopic studies aimed at the copper abundance determination in stars of various metallicities have revealed a very consistent pattern. According to this pattern, as the metallicity of stars decreases, the relative-to-iron ratio $[\text{Cu}/\text{Fe}]$ also decreases. It should be noted that in these cases, the analysis was based on the assumption of the validity of the local thermodynamic equilibrium (LTE) condition in stellar atmospheres. In the next Section we briefly review some relevant studies.

The above behavior of the $[\text{Element}/\text{Fe}]$ ratio as a function of $[\text{Fe}/\text{H}]$ is characteristic of secondary chemical elements, whose nuclei formation depends on the metallicity of the environment. The abundances of primary elements do not exhibit the same dependence as the copper abundance. A number of processes responsible for the production of both secondary and primary elements (e.g., α -elements – neon, magnesium, silicon, sulfur, and others) are discussed in the literature. In particular, the following sources of copper nuclei production have been considered: explosive nucleosynthesis in supernovae (SNe) of type II and hypernovae (HNe),

nucleosynthesis in type Ia supernovae, the weak s -process in massive stars, the main s -process in asymptotic giant branch stars (low-mass, intermediate-mass and more massive), and the r -process in massive stars (s -process is a slow neutron capture process in which a seed nucleus captures free neutron and undergoes β^- -decay before capturing another neutron; r -process – the rapid capture of several neutrons by the seed nucleus, followed by β^- -decays). It should be noted that the certain processes listed here operate effectively at different stages of the Galaxy evolution. In the early stages (corresponding to low metallicity), massive stars should be the main cosmic suppliers of copper.

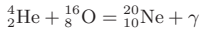
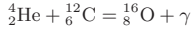
Helium burning may be responsible for the formation of the most abundant stable isotope ^{63}Cu . Reactions between the nuclei of ^{14}N and α -particles form nuclei of fluorine isotope ^{18}F . After their β^+ -decay nuclei of the oxygen isotope ^{18}O are formed. Reactions between ^{18}O and α -particles produce ^{22}Ne nuclei. Subsequent reactions with α -particles lead to the formation of free neutrons in the well known reaction:



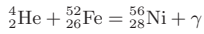
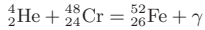
Newly formed free neutrons can be captured by seed nuclei (e.g., nuclei of iron-peak elements such as iron, nickel). In the sequence of these reactions, accompanied by β^- decays, progressively heavier nuclei are formed, including those of copper

* Contact e-mail: andrievskii@ukr.net

and others (e.g., Zn, and heavier nuclei, if the neutron concentration is sufficient). In this scenario, copper will behave as a secondary element. Thus, copper can be produced by n -capture in the process of He burning in hydrostatic equilibrium (Woosley & Weaver 1995). The pure α -process (consecutive captures of the He nuclei) has the following form:



...



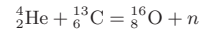
Romano & Matteucci (2007) and Romano et al. (2010) have also concluded that copper is mainly produced in massive stars during the helium burning and carbon burning in the hydrostatic regime. The presence of free neutrons and their high flux ensure that the conditions for the s -process are met. According to Woosley & Weaver (1995) and Limongi & Chieffi (2003) this is also possible in the explosive neon burning.

Explosive burning in the silicon shell of a type II SN (at the final stages of the massive star evolution), is accompanied by a high temperature of the environment through which the shock wave propagates (conditions: temperature above 5×10^9 K, density is about $10^6 - 10^7$ g cm $^{-3}$). Under these conditions, the high-energy γ -quanta are produced. They can cause the photo-disintegration of silicon nuclei converting them into protons, neutrons, and α -particles. The subsequent expansion of the shell and plasma cooling create favorable conditions for the reassembly of α -particles, forming increasingly heavier nuclei, as shown by the formulas above. This process is described by the α -rich freeze-out phenomenon (Truran & Arnett 1971, Woosley & Hoffman 1992, Howard et al. 1993). Due to the very high concentration of the α -particles, and high temperature, the nuclei lying slightly outside the region of the most stable nuclei with the highest binding energy per nucleon (Fe, Ni) can also be formed, for example, zinc nuclei, ${}^{60}_{30}\text{Zn}$. In the explosive silicon burning shell the concentration of neutrons is high. The captures of free neutrons by seed nuclei and β -decays lead, in particular, to the formation of copper nuclei.

In the case of a gradual decrease of the fraction of unassembled α -particles and a large excess of neutrons, α -rich freeze-out undergoes in the r -process (Woosley & Hoffman 1992, Woosley & Weaver 1995, Umeda & Nomoto 2002). This is another option of the copper nuclei production in massive stars that explode as supernovae.

Massive stars (hypernovae and supernovae) should be the only source of copper production in the early Galaxy. Over time, the less massive and long-lived stars begin to play a role in the chemical evolution of the Galaxy. Among them there are the stars which explode as supernovae of type Ia

(Iwamoto et al. 1999), and intermediate- and low-mass stars that become the asymptotic giant branch objects at the advanced stages of their evolution (Gallino et al. 1998). The latter sources make a minor contribution to the formation of copper nuclei through the s -process (Bisterzo et al. 2004). The s -process operates at a neutron concentration significantly lower than in the r -process. In lower-mass stars, the main source of free neutrons is the reaction:



${}^{13}_6\text{C}$ nuclei originate in the intermediate zone of low-mass stars during the asymptotic giant branch phase, where the hydrogen burning (CNO cycle) zone interacts with a zone enriched in helium nuclei. In massive stars and intermediate-mass stars, the internal temperature is higher, and the reactions between helium and neon nuclei lead to the production of the free neutrons, as shown above, in reactions between ${}^4_2\text{He}$ and ${}^{22}_{10}\text{Ne}$ nuclei.

Since the primary source of copper in the very early Galaxy was very massive stars exploding as supernovae and hypernovae, when the metallicity [Fe/H] was less than -3 dex, then the following question arises: why is the copper abundance (namely, [Cu/Fe]) so low in the old, low-metallicity stars, which have survived to the present day due to their low masses? Let us consider the observational data on the copper abundance in old (low-mass and metal-deficient) stars of our Galaxy.

2 LTE COPPER ABUNDANCE RESULTS

A good overview of copper abundance determinations in stars of different types and populations published before 2004 is presented in Bisterzo et al. (2004). Here we will mention only a few papers from that period and briefly touch on more recent ones. Halo and disk stars were studied by Sneden et al. (1991). It was found that the relative copper abundance [Cu/Fe] varies linearly with metallicity: the lower the metallicity, the lower the copper abundance. A fairly large sample of metal-poor stars in the metallicity range $[-3; -0.5]$ dex was studied by Mishenina et al. (2002). As in the above-mentioned work, the authors focused, in particular, on the copper abundance determination. As a result, a clear tendency of the relative copper abundance decrease with metallicity decreasing (in the range of [Cu/Fe] from zero to ≈ -1 dex) was found. To explain this dependence, the authors proposed that massive stars (which are considered the most efficient suppliers of many chemical elements in the early stages of the chemical evolutions of galaxies) produce only a small amount of the copper nuclei. A similar observational conclusion was reached by Simmerer et al. (2003), where the copper abundance in the giants from ten globular clusters and the halo field were compared. The relative copper abundance [Cu/Fe] shows similar trends for cluster and halo stars. Reference should also be made to Bihain et al. (2004), where the copper abundance was determined for a sample

of FGK stars with $[\text{Fe}/\text{H}]$ values ranging from -3 dex to approximately solar value. The result was expected, the copper abundance $[\text{Cu}/\text{Fe}]$ gradually decreases from about solar value to -1 dex when the metallicity reaches $[\text{Fe}/\text{H}] \approx -3$ dex. Cohen et al. (2008) determined LTE abundance of copper in several extremely metal-poor giant stars. For this purpose, the near-UV resonance lines of Cu I near $3250 \text{ \AA}$ were used. Combining these new data on abundances with the results of Mishenina et al. (2002) and Simmerer et al. (2003), cited above, the authors concluded that starting from the solar $[\text{Cu}/\text{Fe}]$ ratio, the relative copper abundance gradually decreases to $[\text{Fe}/\text{H}] \approx -1.5$ dex, reaching $[\text{Cu}/\text{Fe}] \approx -0.7$ dex (but with a large scatter), and then this ratio reaches (very) roughly a plateau value in the range ≈ -0.9 to -0.6 dex.

A very interesting paper was published by Roederer & Barklem (2018). The authors analyzed the lines of neutral and ionized copper in a sample of six metal-poor stars (iron abundance ranges from about -2.5 to -1 dex). The temperatures and gravities of the studied stars are in the ranges ($\approx 5770 - 6500$) K and ($\approx 3.6 - 4.5$) dex, respectively. Since the program stars are metal-deficient, some of the copper lines in the visual part of the spectra are very weak. The authors used the spectra in ultraviolet and visible ranges obtained with the help of space and ground-based telescopes. The following copper lines were used: Cu I (5218.20, 5105.54, 3273.96, 3247.54) $\text{\AA}$, Cu II (2126.04, 2104.80, 2054.98, 2037.13) $\text{\AA}$. The main result for the copper abundance was the following: for stars with metallicity less than -1.8 dex, the difference in the copper abundance inferred from the Cu II lines was 0.36 ± 0.06 dex greater than the abundance derived from the Cu I lines. This is clear evidence that the Cu I lines are very strongly influenced by NLTE effects in the low-metallicity regime. Recently Sneden et al. (2023) published LTE results on the copper abundance in 37 main-sequence (turn-off) very metal-poor stars ($[\text{Fe}/\text{H}]$ less than -2 dex). The authors showed that in this metallicity range $[\text{Cu}/\text{Fe}]$ values are scattered within the range from -0.5 to -0.9 dex.

Timmes et al. (1995) performed a numerical analysis of the chemical evolution of the seventy-six stable isotopes of elements from hydrogen to zinc, using the SNe of type II models with various masses ranging from 11 to $40 M_{\odot}$ and five fixed values of metallicities. The results were compared with the stellar LTE abundances inferred from observations (metallicity from -3 to 0 dex). In particular, for copper, these authors failed to reproduce the LTE elemental abundance results in their calculations. To achieve reasonable agreement with observations they had to reduce the iron yield from type II SNe by a factor of two, which was, in fact, not sufficiently justified. Apparently, the LTE results once again emphasize that for some unknown reason copper is underproduced in the early Galaxy.

3 NLTE COPPER ABUNDANCE RESULTS

A new approach to solving the copper abundance problem arose from the analysis of copper lines within the NLTE approximation. Here, we will mention two relevant papers devoted to the NLTE copper abundance in a sample of the metal-poor stars. Andrievsky et al. (2018) developed the copper atomic model for the NLTE analysis. The sample of stars used by these authors included dwarfs and giants. Eleven program stars have metallicities $[\text{Fe}/\text{H}]$ from -4.2 to -1.4 dex. The authors used a large number of neutral copper lines. Copper lines have been shown to be susceptible to strong NLTE effects. As an example, this is demonstrated in Fig. 1 for several lines located in the ultraviolet region of the spectrum of the metal-deficient star HD 84937 ($[\text{Fe}/\text{H}] = -2.25$ dex), which show an agreement between the observed and calculated NLTE synthetic profiles. In contrast to the LTE result, which yields a strongly underestimated copper abundance: $[\text{Cu}/\text{Fe}] = -0.83$ (Sneden et al. 2016), our NLTE abundance result is $[\text{Cu}/\text{Fe}] = -0.2$. Since NLTE effects cause overionization of neutral copper atoms, absorption in the lines is reduced, and, accordingly, the Cu I lines become weaker. As a result, in this case, NLTE abundance corrections to the LTE abundances are positive, i.e., NLTE correction = abundance(NLTE) – abundance(LTE). Fig. 2 shows the obtained NLTE copper abundance in the program stars. For each star, the LTE abundance was also calculated. As can be seen from this Figure, the difference in copper abundances between NLTE and LTE cases is striking. Thus, direct LTE analysis of the equivalent widths of neutral copper lines or fitting their profiles with synthetic spectrum lead to an artificial underestimation of the copper abundance, and this effect becomes increasingly pronounced as the metallicity decreases. At the same time, a detailed analysis using the NLTE approximation yields a radically different result: the relative copper abundance $[\text{Cu}/\text{Fe}]$ is practically independent of metallicity (namely, $[\text{Fe}/\text{H}]$), and the average copper abundance $[\text{Cu}/\text{Fe}]$ is ≈ -0.2 in the low-metallicity regime.

A similar conclusion was also reached by Korotin et al. (2018). These authors have also analyzed copper lines in a sample of dwarfs with temperatures of $5800 - 6100$ K. In addition to neutral copper lines, these authors studied eight ultraviolet lines of ionized copper. The first ionization potential of copper is about 7.73 eV. For effective temperature of about 6000 K, in the atmosphere levels where the weak lines of ionized copper are formed, the dominant ionization stage should be Cu II. Therefore, it can be assumed that the Cu II energy levels will be populated according to the Boltzmann distribution, i.e., the analysis in the LTE approximation can be applied to the lines of this ionization stage. Fig. 3 shows examples of the Cu II lines in the spectra of two program stars HD 94028 and HD 140283. In paper by Korotin et al. (2018), excellent agreement between the abundances derived from the lines of two ionization stages was obtained (the difference is less than 0.1 dex for five of the six stars studied). Fig. 4. shows the overall distribution of the relative copper abundance $[\text{Cu}/\text{Fe}]$ as a function of $[\text{Fe}/\text{H}]$ from

the aforementioned two papers. Interestingly, in this nearly flat distribution of the relative copper abundance, a shallow dip can be noted in the metallicity region around -2 dex. This feature can be associated with the onset of the enrichment of the Galactic gas with iron-peak elements. These elements are produced by relatively long-lived stars that explode as SNe of type Ia. This process occurs approximately after a few Gyrs of the Galaxy evolution.

Thus, taking into account the discussion above, it can be argued that from an astrophysical perspective, copper behaves as a primary-like chemical element. Its production in the early Galaxy is controlled by massive stars exploding as SNe and HNe. There is no need to invoke any artificial mechanisms in order to explain the low LTE abundance of this element in the low-metallicity regime. Nevertheless, LTE copper abundance in metal-poor stars is still used in the literature when comparing this value with the predictions of theoretical models of copper yield in the early Galaxy. For example, Kobayashi et al. (2020) recently performed a fit of the modeled $[\text{Cu}/\text{Fe}]$ behavior to the LTE copper abundance distribution in the metallicity range from -3 to zero dex, but without due consideration of the latest NLTE results.

4 DISCUSSION

As seen in previous discussion, the LTE copper abundance in the low-metallicity stars may provide an incorrect evidence that copper behaves as a secondary element. Sneden et al. (2016) presented the LTE abundances in metal-poor star HD 84937. The most noticeable deviation from the solar $[\text{Element}/\text{Fe}]$ ratio is observed only for copper. The resulting copper abundance (relative to iron abundance) $[\text{Cu}/\text{Fe}] = -0.83$ dex, which is a very low value. Other chemical elements, whose abundances were determined in this star, do not show such a remarkable underabundance. It should be noted that Andrievsky et al. (2018) analyzed several metal-deficient stars using the NLTE approximation. This star was among the sample stars. Due to the very low metallicity of this star, the copper lines in the visual region of the spectrum are very weak. The only option is to use the near-UV doublet lines of Cu I. The authors showed that these lines suffer from strong NLTE effects. Moreover, the far-UV lines are also strongly affected by the NLTE effects. The NLTE corrections are large and positive. This means that the LTE copper abundance inferred from Cu I lines is significantly underestimated. This is demonstrated by Fig. 2 for all stars of the sample. At the same time, as shown by Korotin et al. (2018), the ultraviolet line profiles of the ionized copper are well reproduced in LTE. The NLTE copper abundance inferred from Cu I UV lines in metal-poor stars agrees very well with LTE abundance derived from Cu II lines. This result was confirmed by Xu et al. (2022). These authors used their own NLTE model of copper atom for analysis of six metal-poor stars ($[\text{Fe}/\text{H}]$ ranges from -2.59 to -0.95).

The nearly flat distribution of the relative copper abundance presented by Korotin et al. (2018) and Caliskan et al.

(2025) exhibits a shallow dip, visible in the metallicity region around $[\text{Fe}/\text{H}] \approx -2$ dex. This feature may be related to the onset of enrichment of the Galactic gas with iron-peak elements. These elements are produced by relatively long-lived stars that explode as type Ia SNe. This process occurs after approximately a few Gyrs of the Galaxy evolution. The gradual increase in the relative copper abundance up to the solar ratio $[\text{Cu}/\text{Fe}]$ toward solar metallicity ($[\text{Fe}/\text{H}] \approx 0$ dex) may be due to the increasing efficiency of the weak s -process in massive stars, the progenitors of type II SNe. At this stage of the Galaxy evolution, the abundance of iron-peak elements in the interstellar medium is gradually increases due to type I SNe activity. The greater the proportion of iron-peak elements in massive stars, progenitors of type II SNe, the greater the number of seed nuclei, which is necessary for more efficient neutron capture processes and, in particular, copper production.

Farouqi et al. (2025) discussed the origin of the chemical elements through the lens of the Galactic archaeology. They gathered data on the elemental abundances in stars with metallicity $[\text{Fe}/\text{H}]$ lower than -2 dex, as these stars are bearing the imprints of primordial nucleosynthesis in the Galaxy. The abundances of 34 chemical elements from lithium to lead were considered. Although copper was mentioned in this interesting study, its abundance in the first Galactic low-mass stars was not discussed because the LTE abundance of this element was found to be too low for the metallicity considered. In fact, the theoretical models failed to predict such a low ratio $[\text{Cu}/\text{Fe}]$ (see, Fig. 3 of this paper). However, it should be emphasized that theoretical models of Woosley & Heger (2007), after analyzing the evolution of the stars in the mass range from 12 to 120 $M_{\odot}$, showed that the expected $[\text{Cu}/\text{Fe}]$ ratio should be in the range from -0.4 to $+0.6$ dex, with a maximum probability of production of about $+0.4$ dex. This expectation appears to significantly exceed the abundance obtained from LTE analysis ($[\text{Cu}/\text{Fe}] = -0.83$ for metallicity -2.25 ; star HD 84937, see discussion above).

5 CONCLUSION

This brief note was intended to attract the attention of specialists working in the field of chemodynamic models of the early Galaxy, when massive SNe of type II and HNe contaminated their environment with certain chemical elements, to the copper problem. Copper is the most problematic element from the perspective of the Galactic chemodynamics. Currently, the dependence of the relative-to-iron copper abundance $[\text{Cu}/\text{Fe}]$ as a function of the metallicity (namely, $[\text{Fe}/\text{H}]$) is still a subject of debate. The observed copper abundance at the very low metallicity is quite low. None of the proposed sources of the copper nuclei production can explain such a low abundance. The problem is apparently related to the LTE assumption used in the spectroscopic analysis of Cu I lines. Studies by Andrievsky et al. (2018) and Korotin et al. (2018) have shown that copper lines are strongly influenced by NLTE effects. Overionization of the copper neutral atoms

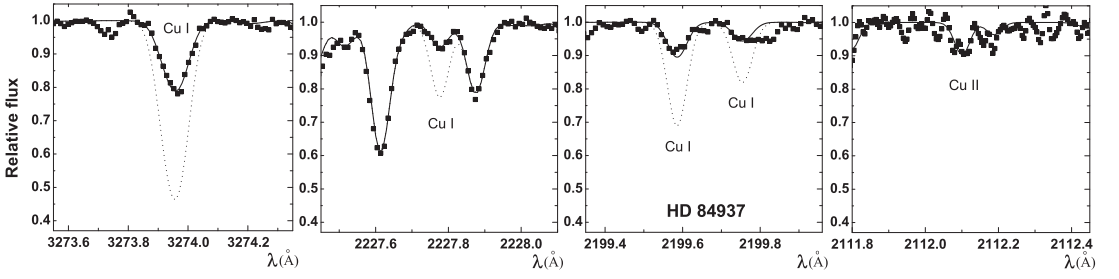


Figure 1. Copper (Cu I and Cu II) line profiles in the spectrum of HD 84937. Observed spectrum – filled squares, NLTE spectrum – continuous line, LTE spectrum calculated with the same abundance that was used for NLTE spectrum generation – dotted line. According to Andrievsky et al. (2018).

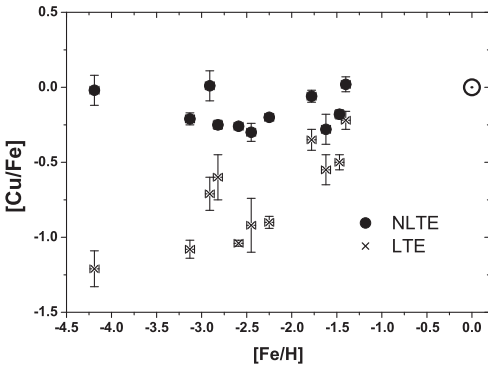


Figure 2. NLTE and LTE copper abundances as a function of $[\text{Fe}/\text{H}]$ in a sample of stars from Andrievsky et al. (2018). Copper abundance in the Sun is denoted $\odot$.

leads to a decrease in the total absorption in the spectral lines (the NLTE corrections are positive), resulting in a copper deficiency in the LTE analysis. A correctly determined copper abundance with the help of the NLTE approximation eliminates this artificial underabundance. Thus, in the low-metallicity regime, copper behaves mainly as the primary chemical element. Its production may be associated with massive stars exploding as the core-collapse supernovae or hypernovae. The primary source in this case may be the α -rich freeze-out process during the explosive silicon burning. The reassembly of α -particles, the sequential formation of increasingly heavier nuclei, and their interaction with a neutron-rich environment create favorable conditions for the production of copper nuclei.

ACKNOWLEDGEMENTS

Special thanks to Prof. F-K. Thielemann for helpful advice.

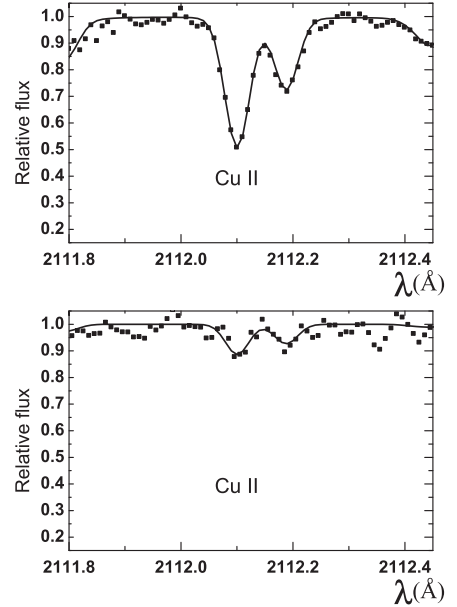


Figure 3. Cu II line profiles in the spectra of HD 94028 (top) and HD 140283 (bottom). Observed spectrum – filled squares, NLTE spectrum – continuous line. According to Korotin et al. (2018).

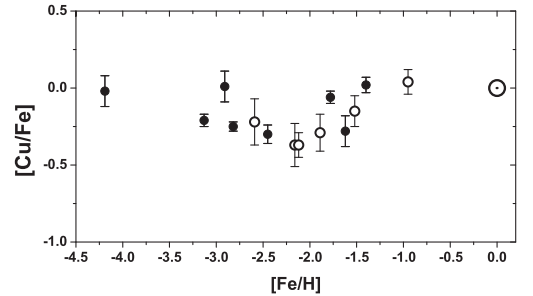


Figure 4. NLTE copper abundance as a function of $[\text{Fe}/\text{H}]$ in a sample of stars from Andrievsky et al. (2018) and Korotin et al. (2018). Filled circles – abundances in stars obtained in Andrievsky et al. (2018), open circles – abundances obtained in Korotin et al. (2018). Copper abundance in the Sun is denoted $\odot$.

REFERENCES

- Andrievsky, S., Bonifacio, P., Caffau, E., et al., 2018, MNRAS, **473**, 3377
- Bihain, G., Israelian, G., Rebolo, R., et al., 2004, A&A, **423**, 777
- Bisterzo, S., Gallino, R., Pignatari, M., et al., 2004, MmSAI, **75**, 741
- Caliskan, S., Amarsi, A. M., Racca, M., et al., 2025, A&A, **696**, A210
- Cohen, J., Christlieb, N., McWilliam, A., et al., 2008, ApJ, **672**, 320
- Faroqui, H., Frebel, A., Thielemann, K.-F., 2025, Eur. Phys. J. A, **61**, 207
- Gallino, R., Arlandini, C., Busso, M., et al., 1998, ApJ, **497**, 388
- Howard, W. M., Goriely, S., Rayet, M., Arnould, M., 1993, ApJ, **417**, 713
- Iwamoto, K., Brachwitz, F., Nomoto, K., et al., 1999, ApJS, **125**, 439
- Kobayashi, Ch., Karakas, A. I., Lugaro, M., 2020, ApJ, **900**, 179
- Korotin, S. A., Andrievsky, S. M., Zhukova, A. V., 2018, MNRAS, **480**, 965
- Limongi, M., Chieffi, A., 2003, ApJ, **592**, 404
- Mishenina T.V., Kovtyukh V.V., Soubiran C. et al., 2002, A&A, **396**, 189
- Roederer, I. U., Barklem, P. S., 2018, ApJ, **857**, 2
- Romano, D., Matteucci, F., 2007, MNRAS, **378**, 59
- Romano, D., Karakas, A. I., Tosi, M., Matteucci, F., 2010, A&A, **522**, A32
- Simmerer, J., Sneden, C., Ivans, I., et al., 2003, AJ, **125**, 2018
- Sneden, C., Gratton, R. G., Crocker, D. A., 1991, A&A, **246**, 354
- Sneden, C., Cowan, J. J., Kobayashi, Ch., et al., 2016, ApJ, **817**, 53
- Sneden, C., Boesgaard, A.M., Cowan, J.J., et al., 2023, ApJ, **953**, 31
- Timmes, F. X., Woosley, S. E., Weaver, T. A., 1995, ApJS, **98**, 617
- Truran, J. W., Arnett, W. D., 1971, ApSS, **11**, 430
- Umeda, H., Nomoto, K., 2002, ApJ, **565**, 385
- Woosley, S. E., Heger, A., 2007, Phys. Rep., **442**, 269
- Woosley, S. E., Hoffman, R. D., 1992, ApJ, **395**, 202
- Woosley, S. E., Weaver, T. A., 1995, ApJS, **101**, 181
- Xu, X., Shi, J., Wang, X., 2022, ApJ, **936**, 4

Description of the helio-geophysical conditions during the magnetically disturbed period of june 21–26, 2015

S. N. Mukasheva^{1*}, A. B. Andreyev², V. I. Kapytin², O. I. Sokolova², G. B. Tileu¹

¹*Al-Farabi Kazakh National University, Faculty of Physics and Technology, Almaty, Kazakhstan*

²*Ionosphere Institute, Almaty, Kazakhstan*

Last updated 2025 October 23; in original form 2025 November 25

ABSTRACT

Extreme solar events, such as flares accompanied by coronal mass ejections (CMEs), perturb the Earth's magnetic field and generate fluctuating currents in the ionosphere and magnetosphere. In this study, we describe the helio-geophysical conditions during the magnetically disturbed period of 21–26 June 2015 on the basis of satellite and ground-based observations. Variations in the solar wind, interplanetary magnetic and electric fields, the planetary Kp index, and geomagnetic field components measured at a mid-latitude observatory are analysed. The storm of 22–24 June 2015 represents one of the strongest geomagnetic disturbances of Solar Cycle 24 and provides an important example of a geoeffective CME.

Key words: stars: coronal mass ejections – magnetic field – magnetic storm

1 INTRODUCTION

Extreme solar events, such as flares accompanied by powerful coronal mass ejections (CMEs), perturb the terrestrial magnetic field and generate highly variable currents in the ionosphere and magnetosphere. Geoeffective CMEs influence the entire Sun–interplanetary medium–magnetosphere–ionosphere–atmosphere–Earth system (e.g. Chernogor & Rozumenko 2008; Chernogor 2011).

The scientific interest in such events is driven by their impact on satellite navigation, communication systems, and spacecraft operating in low and medium Earth orbits. A CME directed toward Earth can disrupt both ground-based and space-based technological systems (Afraimovich et al. 2003; Andreyev et al. 2023). Multiple studies have investigated extreme space-weather events of recent solar cycles (e.g. Polekh et al. 2017; Singh & Sripathi 2017; Shpynev et al. 2018; Paul et al. 2020; Chernogor et al. 2020, 2021; Tulası Ram et al. 2024; Paul et al. 2025; Gordiyenko et al. 2025).

Here, we perform a detailed analysis of helio-geophysical parameters during a very large geomagnetic storm with a sudden commencement that occurred on 22–24 June 2015.

2 MATERIAL AND METHODS

We used 5-min resolution solar wind and interplanetary data provided by OmniWeb (NASA/GSFC; omni-

web.gsfc.nasa.gov), as well as planetary geomagnetic indices (Kp) from WDC Kyoto (wdc.kugi.kyoto-u.ac.jp). Local geomagnetic field measurements were obtained from the Alma-Ata Observatory (code AAA; 43.25°N, 76.92°E), part of the INTERMAGNET network.

3 OBSERVATIONAL RESULTS

Using the example of a very large geomagnetic storm with a sudden onset on 22–24 June 2015, we describe the helio-geophysical conditions that led to the occurrence of geomagnetically induced currents at mid-latitudes. Previous studies have carried out a comprehensive analysis of this unique event using measurements from orbiting satellites and ground-based observatories (e.g. Singh & Sripathi 2017; Astafyeva et al. 2016; Baker et al. 2016; Reiff et al. 2016; Piersanti et al. 2017; Zhao et al. 2017; Gopalswamy et al. 2018; Augusto et al. 2018). The novelty of the present work is that we examine this storm from the viewpoint of the variability of solar-wind parameters and interplanetary electric and magnetic fields, and we also present the corresponding variations of geomagnetic-field parameters based on observations from a mid-latitude geomagnetic station.

Figure 1 presents the variations of helio-geophysical parameters from 21 to 25 June 2015. Panel (a) shows the solar-wind dynamic pressure, P (nPa); panel (b) shows the solar-wind speed, SW (km s^{−1}); panel (c) shows the B_z component of the interplanetary magnetic field (IMF B_z , nT); panel (d) shows the E_y component of the interplanetary electric field

* Contact e-mail: snmukasheva@gmail.com

(IEF E_y , $\text{mV}\cdot\text{m}^{-1}$); panel (e) shows the auroral electrojet index, AE (nT); panel (f) shows the eastern electrojet AU (nT, purple) and western electrojet AL (nT, dark green); panel (g) shows the Sym-H index (nT); and panel (h) shows the planetary Kp index.

The AU index (auroral upper) represents the maximum positive deviation of the H component of the geomagnetic field from the quiet-time average across all auroral-zone observatories. The AL index (auroral lower) corresponds to the maximum negative deviation at the same stations. The AT index is defined as the sum of the absolute values of AU and AL, representing the total magnitude of magnetic fluctuations in the H component. The AE index provides a measure of the overall magnetic disturbance in the auroral zone (?). The Sym-H index characterizes the symmetric component of the ring current and is commonly used to quantify geomagnetic disturbances at mid-latitudes.

Two solar flares, classified as M2.0 and M2.6, were accompanied by coronal mass ejections (CMEs) directed towards the Earth. The first CME arrived at the Earth's magnetosphere at 05:45 UT on 22 June 2015, causing a modest increase in the Sym-H index of approximately 35 nT. The second CME reached the magnetosphere at 18:30 UT, coinciding with an increase in solar-wind dynamic pressure from 5 to 58 nPa (Fig. 1a) and an increase in solar-wind speed from 350 to 745 $\text{km}\cdot\text{s}^{-1}$ (Fig. 1b). The onset of the geomagnetic storm is marked by a sudden rise in the Sym-H index of 77 nT at 18:35 UT on 22 June, followed by a sharp decrease to a minimum of 207 nT at 04:25 UT on 23 June. The interval from 18:35 UT on 22 June to 04:25 UT on 23 June corresponds to the main phase of the storm, followed by a slower recovery phase, with Sym-H reaching approximately -60 nT by 00:00 UT on 25 June 2015.

The B_z component of the interplanetary magnetic field (IMF) turned sharply southward, reaching a minimum of -37 nT at 19:20 UT, before returning northward at 19:50 UT (Fig. 1c). The IMF B_z remained predominantly northward, except for a brief interval near 21:00 UT when it turned negative for approximately 20 min (Astafyeva et al. 2016). Under quiet conditions, variations of the interplanetary electric field (IEF) E_y component are typically within $0 \pm 0.28 \text{ mV}\cdot\text{m}^{-1}$. Following the arrival of the second CME at the Earth's magnetosphere, E_y increased sharply to $25.79 \text{ mV}\cdot\text{m}^{-1}$ and subsequently varied in antiphase with IMF B_z (Fig. 1d).

After 00:00 UT on 24 June 2015, the IMF B_z and IEF E_y returned to quiet levels. Variations in the AE auroral electrojet index indicate that the storm was accompanied by intense auroral activity, with AE exceeding 2000 nT at 18:30–18:40 UT and again at 20:00–20:30 UT. During the initial phase of the geomagnetic storm associated with the second CME, the AU and AL indices reached maxima of 1265 nT and -1370 nT, respectively, and varied in antiphase throughout the main phase of the storm (Fig. 1f). The Kp index reached a value of 8, identifying the geomagnetic disturbance of 22–23 June as a major solstice storm of Solar Cycle 24 Augusto et al. (2018). Figure 2 shows the variations of the X-, Y-, and Z-components, as well as the total vector

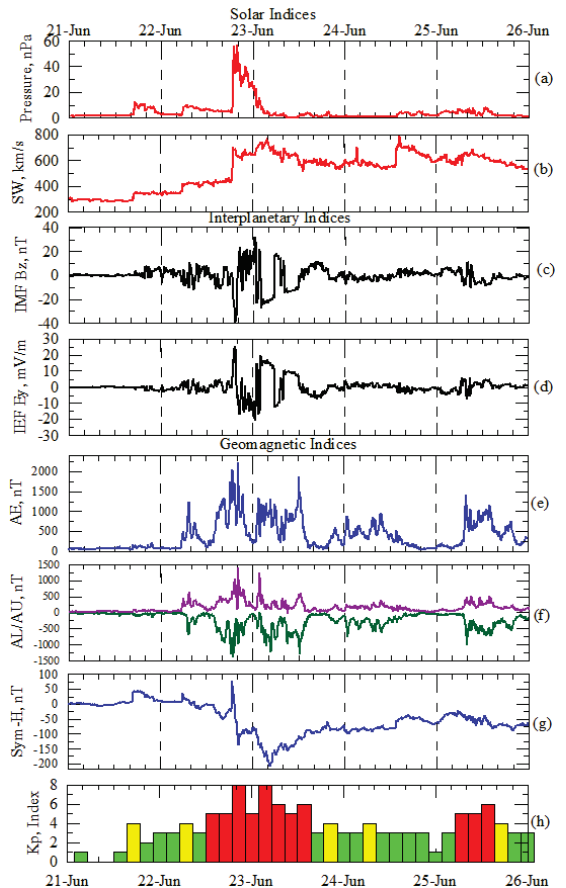


Figure 1. Variation of solar, interplanetary & geomagnetic indices during 21–26 June 2015.

F of the geomagnetic field, based on data from the Alma-Ata Geomagnetic Observatory (code AAA).

The Alma-Ata Geomagnetic Observatory is situated at an altitude of 1300 m in the foothills of the Tien Shan Mountains, approximately 10 km from Almaty, Kazakhstan, with geographic coordinates 43.10°N , 76.57°E , and geomagnetic coordinates 34.3°N , 152.7°E . Geomagnetic measurements are performed using a fluxgate magnetometer (LEMI-008), a portable single-component magnetometer (LEMI-203), and a processor-based Overhauser sensor (POS-1), all conforming to modern international standards. In 2005, the observatory was awarded a quality certificate by the International INTERMAGNET organization.

The observatory measures the X (north), Y (east), and Z (vertical) components of the geomagnetic field vector, as well as the total field F , all in nT. Variations in the XYZ components are recorded at 1 s intervals, while F is sampled every 5 s. Minute-averaged XYZF files are generated from real-time

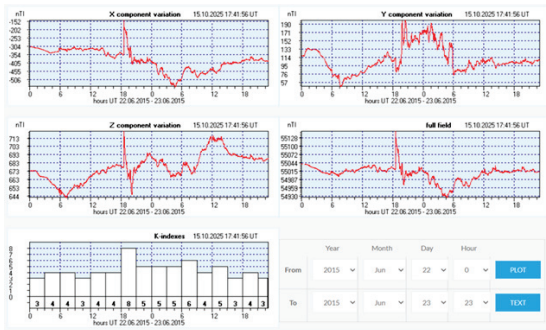


Figure 2. Variations of the X-, Y-, and Z-components of the total geomagnetic field vector, based on data from the Alma-Ata Geomagnetic Observatory, Kazakhstan (observatory code: AAA; coordinates: 43.25°N, 76.92°E). <https://ionos.kz/geomagnetic-observatory/>

data, and absolute measurements are performed two to three times per week.

Data from 2004 to the present are available through the INTERMAGNET website¹. Historical local data from 1964–2003 (hourly HDZF) and 2003–present (second- and minute-resolution XYZF) can be provided upon request. The Institute of Ionosphere offers open access to minute- and hourly-averaged XYZF data and K-index values from 2003 onwards.

The mid-latitude geomagnetic observatory AAA recorded a very large geomagnetic storm with a sudden commencement (SC) during the period from 17:40 UT on June 21, 2015, to 21:00 UT on June 25, 2015, lasting 101 hours and 20 minutes. The maximum local K-index reached 8, and the minimum value of the X-component, -544.8 nT, was observed at 04:51:00 UT on June 23, 2015 (Fig. ??).

4 CONCLUSION

Based on satellite and ground-based observations, we have described the helio-geophysical conditions during the magnetically disturbed period of 21–26 June 2015. Accounting for these conditions is essential for modelling variations of electromagnetic fields in near-Earth space. The variability of parameters during geoeffective coronal mass ejections must be considered in space weather forecasting to mitigate the adverse effects of the radiation environment on both spacecraft instrumentation and ground-based technological systems.

During geomagnetic storms, corpuscular eruptions occur, predominantly involving electrons and protons from the Earth's radiation belts. Eruptions of energetic charged particles from the magnetosphere and radiation belts can contribute to longitudinal currents, but the principal effect of these eruptions on geomagnetically induced currents (GICs)

follows a well-understood mechanism. Particles with kiloelectronvolt energies precipitating into the ionosphere enhance ionization at altitudes of 90–120 km, increasing conductivity in affected regions. According to Ohm's law, this leads to amplified horizontal ionospheric currents and associated magnetic fields. Temporal variations of these fields, particularly during storms and sub-storms, induce GICs in pipelines and power systems via Faraday's law (Andreyev et al. 2023). Future work will focus on the effects of extreme solar events in the upper layers of the Earth's atmosphere.

This study provides a useful reference for researchers in solar–terrestrial physics and offers methodological guidance for undergraduate, master's, and doctoral students analysing helio-geophysical data.

AUTHOR CONTRIBUTIONS

All authors contributed to the conception and design of the study. Material preparation, data collection, and analysis were performed by S. N. Mukasheva, A. B. Andreyev, V. I. Kapytin, O. I. Sokolova, and G. B. Tileu. The first draft of the manuscript was written by S. N. Mukasheva, and all authors provided critical revisions. All authors have read and approved the final version of the manuscript.

CONFLICT OF INTEREST

The authors state that they have no conflict of interest.

FUNDING

This research has been funded by the Science Committee of the Ministry of Science and Higher Education of the Republic of Kazakhstan (Grant No. AP26103851).

REFERENCES

- Afraimovich, E. L., Demyanov, V. V., & Kondakova, T. N., 2003, PS Solut., **7**, 109
- Andreyev, A. B., Mukasheva, S. N., Kapytin, V. I., & Sokolova, O. I., 2023, Space Weather, **21**, e2023SW003639
- Astafeyeva, E., Zakharenkova, I., & Alken, P., 2016, Earth Planet. Space, **68**, 152
- Augusto, C. R. A., Navia, C. E., & de Oliveira, M. N., 2018, Sol. Phys., **293**, 5
- Bailey, R. L., Leonhardt, R., Möstl, C., Beggan, C., Reiss, M. A., Bhaskar, A., & Weiss, A. J., 2022, Space Weather, **20**, e2021SW002907
- Baker, D. N., Jaynes, A. N., Kanekal, S. G., et al., 2016, JGR Space Physics, **121**, 6647
- Chernogor, L. F., & Rozumenko, V. T., 2008, Radio Phys. Radio Astron., **13**, 120
- Chernogor, L. F., 2011, Int. J. Rem. Sens., **32**, 3199
- Chernogor, L. F., Garmash, K. P., et al., 2020, Adv. Space Res., **66**, 226
- Chernogor, L. F., Garmash, K. P., Guo, Q., et al., 2021, Geomagn. Aeron., **61**, 73

¹ www.intermagnet.org

- Ebihara, Y., Watari, S., & Kumar, S., 2021, *Earth Planets Space*, **73**, 163
- Gopalswamy, N., Mkel, P., et al., 2018, *J. Atmos. Sol. Terr. Phys.*, **179**, 225
- Gordiyenko, G., Arian, F., Litvinov, Y., & Zhiganbaev, M., 2025, *Atmosphere*, **16**, 854
- Kane, R. P., 2005, *Adv. Space Res.*, **35**, 866
- Paul, B., Gordiyenko, G., & Galav, P., 2020, *Astrophys. Space Sci.*, **365**, 174
- Paul, K. S., Haralambous, H., Moses, M., & Tripathi, S. C., 2025, *Remote Sens.*, **17**, 2329
- Piersanti, M., Alberti, T., Bemporad, A., et al., 2017, *Sol. Phys.*, **292**, 169
- Polekh, N., Zolotukhina, N., Kurkin, V., Zhrebtsov, G., Shi, J., Wang, G., & Wang, Z., 2017, *Adv. Space Res.*, **60**, 2464
- Reiff, P. H., Daou, A. G., & K. J., 2016, *Geophys. Res. Lett.*, **43**, 7311
- Sibeck, D. G., Lopez, R. E., & Roleof, E. C., 1991, *J. Geophys. Res.*, **96**, 5489
- Singh, R., & Sripathi, S., 2017, *J. Geophys. Res. Space Phys.*, **122**, 11645
- Shpynev, B. G., Zolotukhina, N. A., et al., 2018, *J. Atmos. Sol.-Terr. Phys.*, **180**, 93
- Tulasi Ram, S., Veenadhari, B., et al., 2024, *Space Weather*, **22**, e2024SW004126
- Zhao, X., Liu, Y. D., Hu, H., & Wang, R., 2017, *Astrophys. J.*, **837**, 10

TWO NEUTRON STAR-BLACK HOLE MERGERS OBSERVED BY THE LIGO-VIRGO COLLABORATION

Z. Vidadi^{1*}, N. Kochiashvili², N. Z. Ismailov¹

¹*Shamakhy Astrophysical Observatory named after N. Tusi, AZ5626 Shamakhy, Y. Mammadaliyev settlement, Azerbaijan*

²*E.Kharadze Georgian National Astrophysical Observatory; Mt. Kanobili, Abastumani, 0301, Adigeni, Georgia*

Last updated 2025 June 26; in original form 2025 November 18

ABSTRACT

Neutron star–black hole (NSBH) mergers are still very rare among gravitational-wave sources. However, together with binary neutron star (BNS) mergers, they play a crucial role in gravitational-wave astronomy, producing not only gravitational waves but also electromagnetic (EM) radiation, as well as neutrinos and high-energy particles (cosmic rays). In the Fourth Open Gravitational-wave Catalog (4-OGC), out of 94 recorded events, 90 are binary black holes (BBHs), 2 are NSBH mergers, and 2 are BNS mergers. Therefore, despite the limited number of NSBH and BNS mergers, their study remains a highly significant area of research.

In this article, we review existing observational data for the events GW200115 (S200115j) and GW200105 (S200105ae), which are confirmed NSBH mergers. Powerful networks have been developed globally to observe EM counterparts of gravitational waves, including the GRANDMA collaboration. The GRANDMA project, in which the Shamakhi Astrophysical Observatory named after N. Tusi participates, has been important for coordinating observations across multiple countries and implementing advanced tracking strategies via joint telescope monitoring.

No optical counterparts have been found, but the observational data obtained are useful for establishing constraints on the properties and observational capabilities of NSBHs.

Key words: stars: neutron stars, black holes, gravitational waves, kilonova.

1 INTRODUCTION

In 1916, Albert Einstein proposed the General Theory of Relativity and introduced the concept of gravitational waves, laying the theoretical foundation for gravitational-wave (GW) astronomy. For a century, the detection of gravitational waves remained impossible due to technological limitations. However, in 2015, the first GW signal (GW150914) detected by LIGO (Abbott et al. 2021) revived interest in this field. This event marked the first practical confirmation of GWs produced by the merger of two black holes, validating Einstein's predictions. Later, joint observations of Advanced LIGO and Virgo led to the discovery of the binary neutron star merger GW170817 (Bartos et al. 2017). These breakthroughs enabled GW astronomy to develop into an entirely new observational discipline.

The study of the late stages of stellar evolution has become one of the key areas of astrophysics involving GW messengers. The remnants of GW sources include neutron stars and black holes formed through several processes: neutron

star–black hole (NSBH) mergers, binary neutron star (BNS) mergers, binary black hole (BBH) mergers, supernova explosions of massive stars, and direct collapse of massive stars. These events emit not only GWs but also electromagnetic (EM) radiation and neutrinos. Cosmic rays are also produced in NSBH and BNS mergers, but they cannot be detected due to their slow propagation—taking hundreds to thousands of years to reach Earth (Metzger 2019). The presence of multiple messengers allows multi-messenger astronomy to provide a more complete understanding of compact object mergers by combining GW, EM, and neutrino observations (Anand et al. 2021). Rapid development in this field is closely tied to advances in multi-messenger infrastructure.

Large-scale collaborations such as LIGO, Virgo, and KAGRA, together with EM telescopes and neutrino detectors, form a strong global infrastructure for observing transient events. Networks such as GRANDMA (Global Rapid Advanced Network Devoted to the Multi-messenger Addicts) and wide-field facilities like ZTF (Zwicky Transient Facility) play key roles in follow-up observations of GW alerts (Graham et al. 2021). The GRANDMA project, which includes the Shamakhi Astrophysical Observatory named after

* Contact e-mail: zumrudvidadiqizi@gmail.com

N. Tusi, improves coordination between telescopes around the world and enhances follow-up strategies (Antier et al. 2020; Noysena et al. 2020). These efforts enable fast alert dissemination, rapid organization of real-time observations, and detailed study of remnants and their environments. Such follow-up observations aim to confirm or constrain the presence of kilonovae (Kasen et al. 2017) and relativistic jets, thus expanding our ability to detect these transients.

One of the main scientific targets is BNS mergers, which generate both gravitational waves and electromagnetic signals, including short gamma-ray bursts and kilonovae (Kasen et al. 2017). Another important field concerns the formation of black holes through failed supernovae, which emit GWs and neutrinos without a bright optical transient.

NSBH mergers have also become a crucial area of study in GW astrophysics. These mergers can produce a range of EM counterparts such as kilonovae, accretion-powered emission, and relativistic jets (Turpin et al. 2020). The outcome of an NSBH merger depends on multiple factors: total system mass, black-hole spin, and the equation of state of neutron star matter. These mergers typically lead to the formation of a more massive black hole, often surrounded by an accretion disc emitting EM radiation (Foucart 2018; Kawaguchi et al. 2020).

All confirmed BBH, BNS, and NSBH mergers are compiled in the Fourth Open Gravitational-wave Catalog (4-OGC) (Nitz et al. 2023). The 4-OGC catalog includes all observations from 2015 to 2020, covering the O1, O2, O3a, and O3b runs of Advanced LIGO and Virgo. This updated catalog includes seven previously unclassified BBH mergers from O3b. In total, 94 events have been reported: 90 BBHs, 2 NSBHs, and 2 BNS mergers. Thus, despite their rarity, NSBH mergers represent a highly important and rapidly developing direction in modern GW astrophysics.

2 PROPERTIES OF GW 200115 AND GW 200105 EVENTS

In this paper, we examine the events GW200115 and GW200105, which are confirmed to be NSBH mergers based on their mass and spin characteristics (LIGO Scientific Collaboration & Virgo Collaboration 2020a). Unlike binary neutron star mergers, NSBH mergers are less likely to produce an observable kilonova because the neutron star may be completely consumed by the black hole without forming a significant accretion disk (Foucart 2018). However, if the neutron star is disrupted before being fully swallowed, a kilonova might still be detected.

The detection of GW200115 and GW200105 has prompted extensive follow-up observations to search for electromagnetic counterparts. Collaborations like GRANDMA have played a significant role in coordinating optical follow-ups of these GW events (Graham et al. 2021; Kawaguchi et al. 2020; Noysena et al. 2020). By analyzing data from various telescopes around the world, researchers are looking for kilonova signatures or afterglows associated with these mergers. The study

of the remnants of mergers like GW200115 and GW200105 is crucial for understanding the late stages of stellar evolution. These events, detected by the LIGO and Virgo collaborations (LIGO Scientific Collaboration & Virgo Collaboration 2022), are thought to result from NSBH mergers. By combining GW data with EM and neutrino observations, scientists can gain a more complete understanding of these powerful cosmic events (Bartos et al. 2017).

Optical follow-up observations were also conducted by various networks and telescopes, including the Zwicky Transient Facility (ZTF), which covered a significant fraction of the localization regions. However, no EM counterparts were detected. Despite this, the observations provided constraints on the ejecta mass, mass ratios, and spin properties of black holes (Foucart 2018; Kawaguchi et al. 2020; Metzger 2019). Observations in the *i*- and *z*-bands are considered particularly important for detecting NSBH kilonovae, due to their sensitivity to these events.

S200105ae was detected on 5 January 2020 at 16:24:26.057 UTC. Although observed by both LIGO detectors, it was recorded only by the Livingston detector, as Hanford was temporarily offline. Initial analyses indicated it was an NSBH merger (LIGO Scientific Collaboration & Virgo Collaboration 2020b). S200105ae was initially classified as a 97% probability terrestrial signal, but its significance was later reassessed as high. Its chirp-like structure in the spectrograms indicated a real astrophysical event. Finally, it was classified as an NSBH merger with $> 98\%$ probability that one component had a mass $< 3 M_{\odot}$, making it a neutron star. The initial analysis estimated that the probability of remnant material being left after the merger was $< 1\%$. Its 90% confidence localization covered 7373 deg^2 , and its median distance was $283 \pm 74 \text{ Mpc}$. Optical follow-up observations by ZTF covered 48% of the localization region. Over three nights, 3300 deg^2 were observed. GRANDMA performed tiled observations with the FRAM-Auger, FRAM-CTA-N, TAROT-Calern (TCA), and TAROT-Chili (TCH) telescopes, covering $\sim 8.5\%$ of the GW skymap (Noysena et al. 2020). Observations were sensitive enough to detect kilonovae brighter than -17.5 mag fading slower than 0.5 mag/day , but no counterpart was detected. Observations were compared with kilonova model simulations, suggesting that ejecta masses $M_{\text{ej,dyn}} \leq 0.02 M_{\odot}$ and $M_{\text{ej,pm}} \leq 0.04 M_{\odot}$ would have been detectable at 283 Mpc in a polar direction (Perkins et al. 2024; LIGO Scientific Collaboration & Virgo Collaboration 2020c).

3 CONCLUSION AND DISCUSSION

It has been determined that NSBH mergers generally produce more massive ejecta compared to binary neutron star mergers. Consequently, this results in a slower evolution of kilonova brightness after reaching its peak. In future observations, it is crucial to aim for consistent and deep coverage across all wavelengths, particularly in the *i*- and *z*-bands, as these bands are more suitable for detecting NSBH kilonovae. Although no optical counterpart was detected during the

study of S200105ae, this event remains an important case for understanding NSBH mergers (LIGO Scientific Collaboration & Virgo Collaboration 2020a,b,c; Foucart 2018; Kawaguchi et al. 2020; Noysena et al. 2020).

Due to the large distance of the S200115j event and limited sky coverage, constraints on kilonova properties have been weaker. Deeper observations in the *i*- and *z*-bands could improve the study of optical counterparts of NSBH kilonovae. The high probability of remnant material remaining after the merger makes S200115j an important candidate for understanding NSBH mergers and their electromagnetic signatures (LIGO Scientific Collaboration & Virgo Collaboration 2020a,b,c; Foucart 2018; Kawaguchi et al. 2020; Noysena et al. 2020).

Observing the remnants of gravitational-wave sources is crucial for understanding the complex interactions following compact object mergers. Although observations of GW200115 and GW200105 have not revealed confirmed electromagnetic counterparts, ongoing and future studies, including contributions from the GRANDMA collaboration, will enhance our ability to detect and study such phenomena. The next generation of gravitational-wave observatories, such as the Einstein Telescope and Cosmic Explorer, will provide deeper insights into the late stages of stellar evolution, through observations of compact object mergers and other gravitational-wave sources (Punturo et al. 2010).

REFERENCES

- Abbott B. P., et al., 2021, *Phys. Rev. X*, 11, 2
 Anand S., Coughlin M. W., et al., 2021, *Nat. Astron.*, 5, 46
 Antier S., et al., 2020, *MNRAS*, 497, 5518
 Antier S., Agayeva S., Almualla M., Awiphan S., Baransky A., Barynova K., Beradze S., Blažek M., Boër M., Burkhonov O., Noysena K., de Ugarte Postigo A., Vasylenko V., et al., 2020, *MNRAS*, 497, 5518
 Bartos I., et al., 2017, *Nat. Commun.*, 8, 831
 Foucart F., 2018, *Phys. Rev. D*, 98, 081501
 Graham M. J., et al., 2021, *PASP*, 133, 094503
 Kasen D., et al., 2017, *Nature*, 551, 2
 Kawaguchi K., et al., 2020, *MNRAS*, 497, 246
 LIGO Scientific Collaboration & Virgo Collaboration, 2020a, GRB Coord. Network, 26640
 LIGO Scientific Collaboration & Virgo Collaboration, 2020b, GRB Coord. Network, 26657
 LIGO Scientific Collaboration & Virgo Collaboration, 2020c, GRB Coord. Network, 26759
 LIGO Scientific Collaboration & Virgo Collaboration, 2020d, GRB Coord. Network, 26807
 LIGO Scientific Collaboration & Virgo Collaboration, 2022, *ApJL*, 915, L5
 Metzger B. D., 2019, *Living Rev. Relativ.*, 23, 1
 Nitz A. H., et al., 2023, *ApJ*, 946, 59
 Noysena K., et al., 2020, GRB Coord. Network, 26820
 Perkins H., et al., 2024, *ApJ*, 961, 170
 Punturo M., et al., 2010, *Class. Quantum Grav.*, 27, 194002
 Turpin D., et al., 2020, GRB Coord. Network, 26687

SPECTRAL AND PHOTOMETRICAL PROPERTIES OF SELECTED MASSIVE HERBIG AeBe STARS

F. S. Huseynova^{1*}, N. Z. Ismailov², U. S. Veliyev¹

¹*Batabat Astrophysical Observatory, Nakhchivan State University, Nakhchivan*

²*Tusi Shamakhy Astrophysical Observatory, Ministry of Science and Education of Azerbaijan, Shamakhy*

Last updated 2025 October 19; in original form 2025 November 28

ABSTRACT

This paper presents the results of spectral and photometric studies of six selected massive Herbig Ae/Be stars conducted during 2023–2024. Spectral observations reveal significant variability in the emission-line spectra over time intervals ranging from one month to one year. Spectral energy distributions (SEDs) were constructed to characterize the state of the circumstellar disks. Our analysis shows that two of the six stars possess evolved debris disks with weak residual dust emission. The fundamental physical parameters of the stars were calculated, and their evolutionary status was determined. MWC 300 appears to be a more evolved system exhibiting strong excess infrared radiation, which is likely related to its binary nature.

Key words: stars: pre-main sequence stars, massive H AeBe stars, circumstellar disks, evolution state

1 INTRODUCTION

Herbig AeBe stars (HAeBe), as a group of stars with common physical characteristics, were first identified in the work of [Herbig \(1960\)](#). By that time, a group of T Tauri stars (TTS) was known low-mass ($0.5 \leq M_*/M_\odot \leq 2.0$) stars with emission lines in the spectrum. HAeBe stars are now believed to have intermediate masses of $2.0 \leq M_*/M_\odot \leq 10$, and have the same physical properties as TTS. HAeBe stars have emission and absorption lines in the spectrum, typical spectral types A-B, are located in dark gas and dust nebulae, have excess radiation in the infrared (IR) part of the spectrum [Finkenzeller and Mundt \(1984\)](#); [Herbig and Bell \(1988\)](#); [The et al. \(1994\)](#); [Carmona et al. \(2010\)](#); [Chen et al. \(2016\)](#).

To date, more than 300 HAeBe type stars are known [Guzmán-Díaz et al. \(2021\)](#). This is much smaller than the thousands of known TTSs, and this discrepancy can be partly explained by the shape of the initial mass function (IMF), which favors the formation of less massive objects and the faster evolution of massive stars [Miller and Scalo \(1979\)](#). Statistical studies of HAeBes are generally less reliable than those of TTS, as they are based not on complete samples from various star-forming regions but on small, disparate subsamples from the above-mentioned lists and assume different stellar and circumstellar characteristics.

An important step in the study was the use of parallax

and magnitude data from the Gaia DR2 archive [Lindegren et al. \(2018\)](#). The work of [Wichittanakom et al. \(2020\)](#) not only updated most of the spectroscopically determined stellar masses, luminosities, surface gravities, and ages of southern HAeBe stars obtained by [Fairlamb et al. \(2015\)](#) using Gaia DR2 distances but also extended the same spectroscopic analysis to additional HAeBe stars in the north. Thus, the data from [Wichittanakom et al. \(2020\)](#) represent to date the most robust and homogeneous stellar characterization of a broad sample of HAeBe stars, including definitive spectroscopic data for 121 such stars, mostly based on Gaia DR2 distances.

Following these studies, it became clear that, based on certain characteristics, HAeBe stars are conditionally divided into two groups. H Ae stars have lower mass ($2\text{--}3 M_\odot$) and greater ages ($t > 3$ Myr), while H Be stars have higher masses ($t > 3 M_\odot$) and ages $t < 3$ Myr. The deficit of more massive older H Be stars is due to the more rapid evolution of stars toward the main sequence (MS). The paucity of very young H Ae stars is likely due to two main reasons. First, H Ae stars become optically visible later in their evolution, and second, the younger population of intermediate-mass T Tauri (IMTT) stars that evolve into H Ae stars is not well studied.

To date, the formation and early evolution of massive stars has not been adequately studied. In their early stages, massive stars are hidden behind vast amounts of optical absorption. The significantly higher luminosity and intense ultraviolet radiation of young massive stars greatly influence their

* Contact e-mail: faidahuseynova@gmail.com

environment. Furthermore, the geometry and composition of the gas and dust around the star, as well as the dissipation time of this matter, may differ from those of low-mass stars. The existence of a strong stellar wind further complicates matters. The absence of a prolonged Pre-Main Sequence phase, during which circumstellar matter slowly dissipates and planetary systems can form, points to an important qualitative difference between massive and low-mass young stars. However, the maximum stellar mass required to form planetary systems is unknown.

This paper presents the results of spectral studies of Herbig Ae/Be stars with different masses, selected from the catalog of [Guzmán-Díaz et al. \(2021\)](#). Some physical characteristics of the program stars, collected from the scientific literature, are given in Table 1. The columns of Table 1 from left to right are object name, interstellar reddening coefficient A_V , distance D , stellar magnitude m_V , luminosity $L/L_\odot$, effective temperature T_{eff} , radius $R/R_\odot$, mass $M/M_\odot$, age t , spectral class Sp type, equivalent emission width $\text{H}\alpha$ EW($\text{H}\alpha$), and reference to the relevant literature (Ref.).

2 OBSERVATIONS AND RESULTS

2.1 SPECTRAL OBSERVATIONS

Spectral observations of the program stars were carried out at the Cassegrain focus of the 2 m telescope of the Tusi Shamakhy Astrophysical Observatory (ShAO) using the Modified Universal Astro Grid Spectrograph (MUAGS). An Andor CCD camera (model iKon L-936-BEX2-DD) with 2048×2048 elements and a pixel size of $13.5 \mu\text{m}$ was used as the detector. To adapt the CCD to the spectrograph, a fast Canon EF lens ($f = 200 \text{ mm}$, $f/2$) was installed in the spectrograph camera. The collimator has a focal length of 1100 mm , while the camera focal length is 200 mm . The angle of incidence α and diffraction angle β are 27.5° and 20.5° , respectively. The resolution in the camera focal plane is determined by the width of two pixels, giving a monochromatic slit image of $S' = 2 \text{ px} = 0.027 \text{ mm}$ for 1×1 binning. A diffraction grating with 651 lines/mm was used, which in first order with 1×1 binning provides a linear inverse dispersion of $144 \text{ \AA/mm}$ across the wavelength range of $\lambda = 3600 - 8000 \text{ \AA}$. In other words, in the region of the $\text{H}\alpha$ line ($\lambda 6562.816 \text{ \AA}$) in this mode, we have obtained a moderate spectral resolution of about $R = 3400$. A more detailed description of the spectrograph and the observation method is given in [Ismailov et al. \(2023\)](#).

The entire process of observation and data reduction was performed using the DECH program ¹ ([Galazutdinov, 2025](#)). Table 2 presents the average UT time for the acquisition of two spectrograms per star. After calibration and processing, all spectra were averaged and normalized to the continuum.

Our spectral observations were executed during the period

2023 November 8–2024 August 9. Table 2 presents the observation log. The columns, from left to right, list the target name, observation date, exposure time, UT, binning, and signal-to-noise ratio (S/N) at the $\text{H}\alpha$ line region in the spectrum. After calibration and processing, all spectra were averaged for the nights and normalized to the continuum. For the spectra of standard stars, the standard deviation in measurements for the radial velocities (R_V) of strong lines is $\pm 5 \text{ km/s}$, and for the equivalent widths (EW) of hydrogen lines for A0–A6 type stars is $\pm 0.5 \text{ \AA}$.

Table 3 presents the results of measurements of individual spectral lines for the program stars. The absence of data for some lines indicates that, due to their weakness or absence in the spectrum, it was not possible to measure these lines from the spectra. For all stars, the $\text{H}\alpha$ line is observed in emission. Some spectral features of individual stars are discussed in separate comments.

3 PHOTOMETRIC BVR_CI_C OBSERVATIONS

Our photometric observations of the stars were carried out on the Zeiss-600 telescope using a BVR_CI_C photometer, which is mounted at the Cassegrain focus of the telescope ($F = 7500 \text{ mm}$) with a relative aperture $A = 1 : 12.5$. As a light detector, we used a FLI $4K \times 4K$ CCD camera with a pixel size of $9 \mu\text{m}$. The useful field of the image frames was $17' \times 17'$. When applying binning 2×2 or 4×4 , the resolution per pixel was $0.49''/\text{px}$ or $0.99''/\text{px}$, respectively. The photometric data were obtained and processed using standard procedures of the MaximDL software package. A detailed description of the photometric system is given in [Abdullaev et al. \(2012\)](#). Transformation of our photometric system to the international standard was carried out in [Ismailov and Valiev \(2022\)](#).

Under the astroclimate conditions at ShAO, the seeing disk is typically $1.5\text{--}2''$. Under such conditions, components located at an angular distance of $3\text{--}4''$, as noted in [Finkenzeller and Mundt \(1984\)](#), will not be resolved with a 4×4 binning combination. In the obtained FITS frames, the stellar images did not deviate from a circular shape, and when measuring brightness, the object's image was completely covered by the chosen aperture size of the measuring circle. In this case, the aperture of the measuring circle was about $6''$. The average root-mean-square measurement error according to our data in individual bands was $\pm 0.02 \text{ mag}$ in V , $\pm 0.008 \text{ mag}$ in B , $\pm 0.005 \text{ mag}$ in R_c , and $\pm 0.009 \text{ mag}$ in I_c . Details of the photometric observation results are provided in the individual star comments.

4 COMMENTS ON INDIVIDUAL STARS

4.1 V1478 CYG

Three pairs of spectra were obtained in 2023 and two pairs in 2024. Figure 1 shows sections of the star's spectrograms in different wavelength intervals. The strongest identified lines

¹ <http://www.gazinur.com/DECH-software.html>

Table 1. Physical characteristics of program stars collected from the literature

Target	A_V	D (pc)	$L/L_\odot$	T_{eff} (K)	$R/R_\odot$	$M/M_\odot$	t (Myr)	Sp. type	EW(H α)	Ref
MWC 1051	2.84	4530	4.03	20000	9	10.8	0.08		-157.7	11
	4.00									16
	4.84									15
	1.01				4	10.59				2
		2500								13
						16.08	0.04	B0pb		14
MWC 1080	5.40									1
	8.24			31500						5
	5.30	1000								9
		1000								4
	5.30	1000			7	20.6				13
	8.24		6.53			> 6	< 0.01			8
	1.67									15
AS 470		4040				7	0.1		-49.2	14
	2.27		3.01	8200						10
		700				9.36	0.1	B1Ia+e		3
MWC 300						9.36	0.1	B1Ia+e		14
	4.23				3.33	7.37				2
MWC 1021		3650				32	0.01	Bpe		14
	8.80									16
V1478 Cyg	3.10									15
										14

References: (1) Cohen M., Kuhl L.V. 1979, ApJS, 41, 743; (2) Liu T., et al. 2011, ApJ, 734, 22; (3) Terranegra L., et al. 1994, A&AS, 104, 557; (4) Eisner J.A., et al. 2004, ApJ, 613, 1049; (5) Mathew B., et al. 2018, ApJ, 857, 30; (6) Mendigutía I., et al. 2011, A&A, 529, A34; (7) Verhoeff A.P., et al. 2012, A&A, 538, A101; (8) Manoj P., et al. 2006, ApJ, 653, 657; (9) Corcoran M., et al. 1997, Nature, 390, 587; (10) Vioque M., et al. 2018, A&A, 620, A128; (11) Vioque M., et al. 2022, ApJ, 930, 39; (12) Henning T., et al. 1994, A&A, 291, 546; (13) Hillenbrand L.A., et al. 1992, ApJ, 397, 613; (14) Thomas S., et al. 2023, AJ, 165, 135; (15) Chen P.S. 2016, New Astron., 44, 11; (16) Hou J.L., et al. 1997, A&A, 327, 725.

Table 2. Log of spectral observations of program stars

Target	Spectra	Date	UT	Exp (s)	S/N
V1478 Cyg	KUA1541-42	11.08.2023	21:21	1600	28
V1478 Cyg	KUA1600-01	13.08.2023	23:59	1500	24
V1478 Cyg	KUA1653-54	16.08.2023	00:05	1500	22
V1478 Cyg	KUA1713-14	06.06.2024	21:24	1800	13
V1478 Cyg	KUA1744-45	05.07.2024	17:59	3000	15
MWC 1051	KUA1577-78	12.08.2023	00:08	1500	31
MWC 1051	KUA1787-88	04.08.2024	17:43	3000	32
MWC 300	KUA1524-25	11.08.2023	18:36	2000	25
MWC 300	KUA1667-68	17.08.2023	19:55	1800	22
AS 470	KUA1546-47	11.08.2023	22:43	900	30
AS 470	KUA1754-55	09.07.2024	18:55	2700	26
AS 470	KUA1248-49	08.09.2024	18:56	2400	36
MWC 1080	KUA1817-18	06.08.2024	19:18	1200	93
MWC 1021	KUA1535-36	11.08.2023	20:22	600	109
MWC 1021	KUA1596-97	13.08.2023	22:48	900	105
MWC 1021	KUA1649-50	16.08.2023	23:08	1200	112

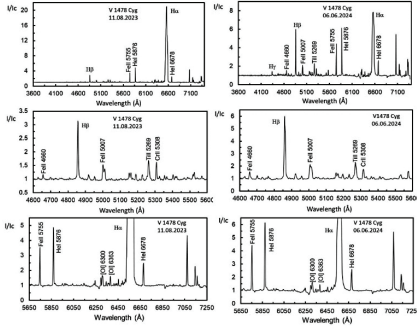
are marked. As can be seen, the star's spectrum exhibits pure emission features. The intensity level shows significant variability over time. The star's spectrum showed variability with characteristic timescales of months to years (Table 3). Almost all hydrogen lines (H α -H γ) and helium lines (He I 5876, 6678) showed significant variations in equivalent widths. Based on two brightness estimates, there is a brightness variability of about 0.2 mag in the V-band.

4.2 MWC 1051

Two pairs of spectrograms of the star were obtained at an interval of about one year. Figure 2 shows the spectrograms obtained in 2023 and 2024. The H α line exhibits a two-component profile with a very strong red component. The H β , H γ , and H δ lines display P Cyg-type emission profiles with an invisible blue emission component. A deep absorption component is particularly noticeable in the H β line in the blue wing, shifted by -350 to -400 km/s. The central absorption in the H α line is blueshifted by about 10 Å, equiva-

Table 3. The results of measurements equivalent widths of spectral lines

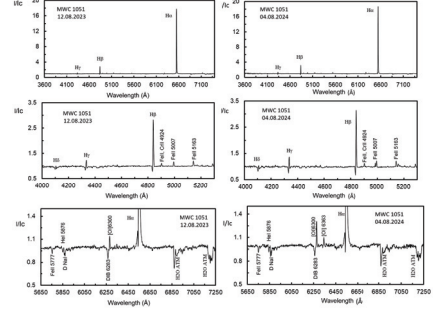
Target	JD 2450000+	EW(H α) [Å]	EW(H β) [Å]	EW(H γ) [Å]	EW(He I 5876) [Å]	EW(D Na I) [Å]	EW([O I] 6300) [Å]
V1478Cyg	60168.389	781.47	16.57	0.79	26.58		7.89
V1478Cyg	60170.499	1010.82	13.16	0.55	29.15		7.55
V1478Cyg	60172.503	1081.96	24.29	1.62	35.59		9.28
V1478Cyg	60468.391	365.45	43.45	5.45	46.81		12.04
V1478Cyg	60497.249	1000.30	32.26	2.42	38.61		9.20
MWC 300	60168.275	148.34	1.89	0.44	0.64		9.92
MWC 300	60174.329	128.28	0.99	6.18	0.42	1.7	8.80
MWC 1051	60168.505	142.34	10.53	0.58	0.63*	1.65	0.77
MWC 1051	60527.238	133.80	10.37	1.59	0.74*	1.7	1.46
AS 470	60168.446	45.26	3.79	0.46	0.92		1.94
AS 470	60501.288	46.46	3.58	0.58	0.80	2.77	3.00
AS 470	60562.289	34.53	2.67	0.26	0.80	3.44	
MWC 1080	60529.304	42.62	2.79	0.68		1.01	
MWC 1021	60168.344	236.10	11.63	0.67	1.59		0.35
MWC 1021	60170.450	138.77	2.03	0.11	1.701		0.10
MWC 1021	60173.460	199.23	7.97	0.39	1.09		0.23

**Figure 1.** Comparison of continuum-normalized spectrograms of V1478 Cyg from 2023 and 2024. Top panels show the full spectral range, middle panels show the $\lambda 4600$ – 5600 Å region, and bottom panels show the $\lambda 5650$ – 7250 Å region

lent to a velocity of approximately -450 km/s. This indicates that the star possesses a significant stellar wind and disk accretion. The He I 5876 and D lines of Na I are observed in absorption. The forbidden doublet [O I] $\lambda\lambda 6300, 6363$, as well as the interstellar absorption band DIB 6283, are clearly visible, indicating a complex circumstellar structure in the star's disk. A comparison reveals that in 2024 the star exhibits a more developed emission spectrum than in 2023.

4.3 MWC 300

The star MWC 300 exhibits properties of B[e] stars. Studies by different authors provide conflicting histories of its exploration. Merill and Bowen (1951) classified the star as intermediate between ordinary Be stars and planetary nebulae. Herbig and Rao (1972) included the star in their catalog, while Finkenzeller and Mundt (1984) noted that the object probably does not belong to young stars. Allen Swings (1976) classified the star's spectrum as Bep. Appenzeller (1977) was the first to note the rich photospheric spectrum,

**Figure 2.** The same as in Fig. 1 for the star MWC 1051

which agrees well with the spectrum of B1 Ia. This conclusion was confirmed by Wolf Stahl (1985).

Miroshnichenko et al. (2004) conducted extensive spectroscopic and photometric studies of MWC 300 and strengthened the case for classifying it as a supergiant with an effective temperature of $19,000$ K, a distance of 1.8 ± 0.2 kpc, and a luminosity of $\log L/L_{\odot} = 5.1 \pm 0.1$.

In spectroscopic observations by Corporon and Lagrange (1999) and Miroshnichenko et al. (2004), and astrometric measurements by Takami et al. (2003), the star shows signs of binarity.

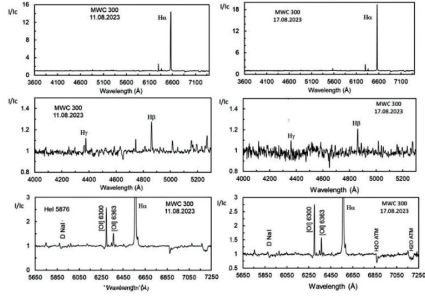
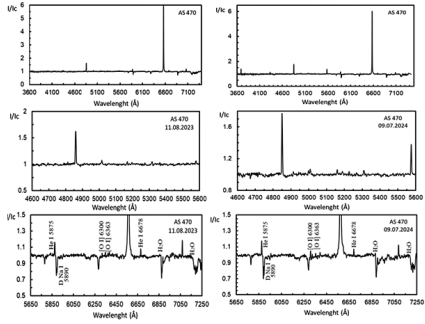
On August 11 and 17, 2023, we obtained two pairs of spectrograms of the star. The measured equivalent widths on August 11, 2023, are approximately 50% larger than those on August 17, 2023. Fragments of the star's spectrum are shown in Fig. 3. Over the course of our six days of observations, noticeable changes in the intensity of emission lines in the star's spectrum were detected.

4.4 AS 470

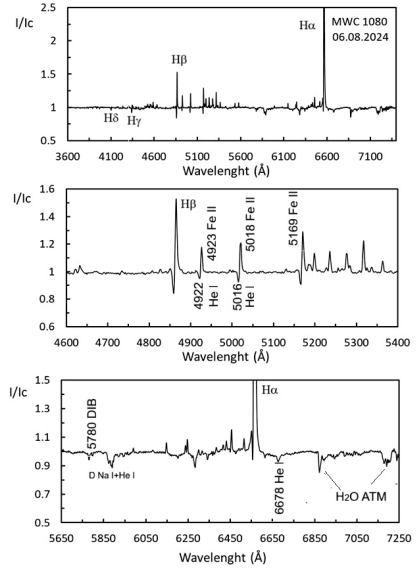
We obtained three spectra of the star on August 11, 2023, July 9 and September 8, 2024. Figure 4 shows fragments of the star's spectrum obtained at intervals of one year. On

Table 4. Results of photometrical observations of some program stars.

Target	Date	JD (245+)	I_c	B	V	R
MWC 300	24.07.2023	60149.306	12.644	12.201	11.956	11.982
MWC 300	28–29.07.2023	60154.225			11.842	11.808
MWC 300	08–09.08.2023	60165.260	12.500		11.537	12.036
MWC 300	15–16.08.2023	60172.332	12.640		11.808	11.604
MWC 1080	23–24.08.2023	60180.356	9.842	12.480	11.559	10.674
V1478 Cyg	06–07.08.2023	60163.296	12.670	12.921	13.220	12.375
V1478 Cyg	21–22.08.2023	60178.293			13.038	12.352
AS 470	15–16.08.2023	60172.386	14.660	12.010	12.760	13.802
AS 470	16–17.08.2023	60173.352	13.907	11.421	12.761	13.800
AS 470	21–22.08.2023	60178.358	14.71	11.209	12.778	13.844

**Figure 3.** The same as in Fig. 1 for the star MWC 300**Figure 4.** Normalized spectra of the star AS 470 for the dates 11.08.2023 and 09.07.2024 are shown. The panels below show a larger-scale representation of the spectrum on those dates in the region of λ 4600–5600 Å, and λ 5650–7250 Å

August 11, the intensities of the emission lines in the spectrum noticeably weakened. During the observation period, the equivalent width of the H α emission line changed from 46 to 34 Å, which is consistent with the data from [Guzmán-Díaz et al. \(2021\)](#). Our photometric observations, conducted on three dates during August 15–22, 2023, revealed brightness variations in the B and V bands with amplitudes of 0.8 mag and 0.7 mag, respectively. In the red bands, the brightness change is insignificant.

**Figure 5.** The same as in Fig. 1 for the star MWC 1080

4.5 MWC 1080

For the first time, [Shevchenko et al. \(1994\)](#) found a photometric period of about 2.9 days and [Corporon and Lagrange \(1999\)](#) confirmed spectroscopic binarity with this period. We obtained only one pair of spectra of the star, which were averaged. Figure 5 shows fragments of the resulting spectrum of the star. In addition to strong hydrogen emission lines, the star's spectrum contains deep absorption lines of He I, lines of the interstellar band DIB 5780, and many lines of ionized iron. The hydrogen lines exhibit typical P Cygni profiles, indicating a strong outflow of matter. The Balmer decrement is steep (see Table 3), indicating a large optical depth of the envelope. The spectral type of the star corresponds to early B0–B1 Ve.

4.6 MWC 1021

According to the data from the catalog of [Guzmán-Díaz et al. \(2021\)](#), the distance to the star is more than 3090 pc, spectral

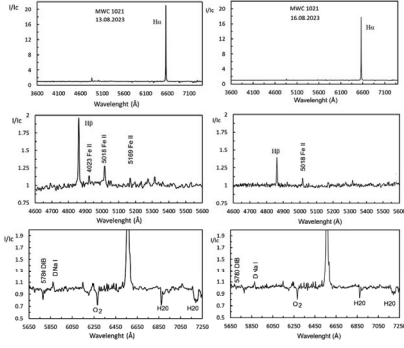


Figure 6. The same as in Fig. 1 for the star MWC 1021

class B6–B7, radius $R/R_{\odot} \sim 154$, luminosity $L/L_{\odot} \sim 5.8$, age $t < 0.01$ (Myr), and mass $M/M_{\odot} \sim 73.6$. We obtained three pairs of spectra of the star in 2023. As can be seen from Table 3, the equivalent widths of the emission lines are significantly larger in 2023. Figure 6 shows fragments of the spectrum of MWC 1021, obtained on two different nights. As can be seen, the star's spectrum is characterized by emission lines of hydrogen, ionized iron, and the 5780 Å DIB line of interstellar origin. A comparison revealed that over the four nights of observations between August 13 and 16, the star's emission spectrum showed a significant decrease in the equivalent widths of hydrogen and ionized iron emission lines.

5 SPECTRAL ENERGY DISTRIBUTION (SED) IN THE SPECTRUM AND PHYSICAL PARAMETERS OF STARS

Using data from Vizier catalogues and following the method described in Adigozalade et al. (2025), we constructed spectral energy distribution (SED) curves for the program stars. Figure 7 shows the energy distribution curves of the program stars in the range 0.36–22.1 μm . Observational data were taken from the 2MASS and WISE catalogs and transformed into absolute fluxes, taking into account interstellar reddening (see Ismailov and Valiev 2022). Data from the IRAS catalog are not available for these stars, so values from the WISE catalog were used in the far-IR region.

As can be seen from Fig. 7, individual stars show a complex distribution, which is poorly approximated by the model SED curve taken from Castelli and Kurucz (2004). The type of SED curves is determined from the magnitude of the IR excess emission. The star AS 470 shows a weak excess emission of cool dust, starting at 11.6 μm . This suggests that the disk of the star consists primarily of residual dust. The remaining stars show both gas and dust excesses in their disks. The stars AS 470 and MWC 1021 exhibit type III SED curves, the stars V1478 Cyg and MWC 1051 show type II, and MWC 300 and MWC 1080 belong to type I according to the classification of Lada (1987).

Knowing the value of interstellar extinction A_V , the refined

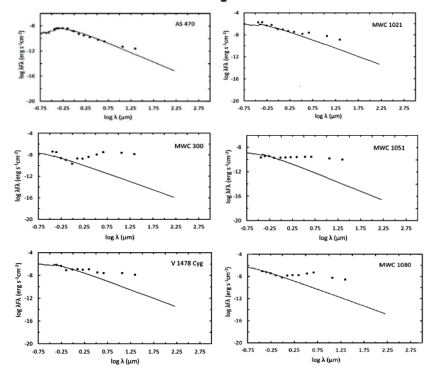


Figure 7. Spectral energy distribution (SED) curves for program stars. The solid line represents the model SED from Castelli and Kurucz (2004)

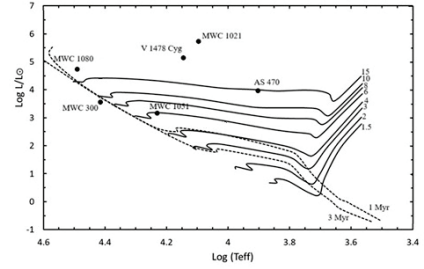


Figure 8. Theoretical HR diagram according to Bressan et al. (2012) for program stars. The solid curves represent evolutionary tracks labeled with masses (in $M_{\odot}$), and the dashed curves represent isochrones for ages of 1 and 3 Myr

distance to the star D according to Gaia data, the stellar magnitude V , and the bolometric correction m_b Pecaut and Mamajek (2013), the luminosity, radius, and absolute magnitude of the program stars were calculated using standard expressions. The effective temperature of the star corresponding to its spectral class according to Pecaut and Mamajek (2013) was used. The effective temperature and bolometric luminosity of the Sun were also used in the calculations. Table 5 shows the obtained parameters of individual stars, as well as the types of SED curves according to Lada (1987).

Figure 8 shows the theoretical HR diagram according to Bressan et al. (2012). The dots indicate the positions of the program stars. From this diagram, the masses and ages of the stars under study were determined. These parameters are also given in Table 5.

6 DISCUSSION AND CONCLUSIONS

As is known, the formation of circumstellar disks is a natural outcome of star formation, since a young protostar, forming from a parent molecular cloud, must preserve its initial angu-

Table 5. Physical parameters of the program stars

Object	V	A_V	D (pc)	M_V	BC	$\log(L/L_\odot)$	$\log T$	$R/R_\odot$	$M/M_\odot$	t (Myr)	SED
MWC 1051	12.837	0.9	4873	-3.1	-1.58	3.16	4.23	13.044	6	0.8	II
V1478 Cyg	13.15	9	1669	-8.0	-1.07	5.14	4.15	154.795	25	0.2	II
MWC 300	13.795	4	1786	-4.1	-2.61	3.56	4.41	13.469	9	3	I
AS 470	11.72	2.5	7278	-5.1	-0.02	3.98	3.90	70.5261	15	0.3	III
MWC 1080	11.859	5	1489	-7.0	-3.03	4.75	4.49	44.1734	20	0.5	I
MWC 1021	13.08	9	3649	-9.5	-0.79	5.74	4.10	344.106	35	0.1	III

lar momentum during compression. Ring-shaped dust structures have been discovered in disks around low-mass protostars, which may be remnants of early dust evolution (see, for example, [Mamedkhanova and Ismailov \(2019\)](#) and citations therein). Circumstellar disks likely facilitate the subsequent formation of planetary systems around stars. Therefore, circumstellar disks play a crucial role in the formation of stars and planets.

Our data showed that all program stars exhibit significant variability in their disk emission. This is reflected in the variability of the hydrogen emission lines of the Balmer series, the He I 5876 lines, and the doublet D Na I. Individual photometric observations indicate significant variability in the brightness of program stars. Theoretical work shows that non-stationarity in the disks of massive young stars is a completely expected real process that can arise due to the accretion of matter into the outer parts of the disk and the radiation of a high-temperature central source (see, for example, [Zhao et al. \(2020\)](#)).

As can be seen from Table 5, despite their young ages, two of the most massive stars, AS 470 and MWC 1021, are close to complete dissipation of their circumstellar disks. Their excess disk emission begins at $\lambda \geq 10 \mu\text{m}$. As shown in [Adigozalzade et al. \(2025\)](#) such stars have a residual dust disk that has virtually lost its gas component. Most often, these stars have type III SED curves according to the classification of [Lada \(1987\)](#). Similar residual disks have been observed, for example, in Vega-type stars (see, [Ismailov et al. 2021](#)). This shows that, despite their still young ages, two of the objects, AS 470 and MWC 1021, are already close to the end of the disk dissipation stage and have lost their gas component. Due to the large mass of the central star, their disk evolution was relatively rapid.

Thus, of the six program young massive stars, two have a debris disk, two have an intermediate disk, and one has strong disk emission. The characteristics of the star MWC 300 indicate that its IR excess emission may be due to the presence of a secondary component. The star is an interesting object that has characteristics of B[e] stars (see, for example, [Miroshnichenko et al. \(2004\)](#)). From Fig. 8 it is evident that the star MWC 300 has already reached the Main Sequence, and despite this, it still has powerful IR emission. Rather, the additional emission in the star's SED is an argument in favor of its binarity [Takami et al. \(2003\)](#); [Wang et al. \(2012\)](#) and the emission in forbidden lines is formed in the circumstellar gas ring.

- (i) All program stars show variations in their emission

spectrum and brightness. Disk activity in massive stars may be the result of accretion in the outer part of the disk and high-temperature radiation from the central star.

- (ii) The weak excess IR emission from AS 470 and MWC 1021 indicates that the circumstellar disks of these stars have lost their gas component and have weak dust emission, which is also characteristic of Vega-type stars.

- (iii) Despite its young age, MWC 300 has already reached the main sequence in its physical parameters. Despite this, the star possesses powerful disk radiation, which is rather formed within the ring-shaped circumstellar envelope.

REFERENCES

- Abdullaev B.I., Alekberov I.A., Gylmaliev N.I., et al., 2012, *Azerbaijani Astronomical Journal*, **7**, 39
- Adigozalzade H.N., Ismailov N.Z., Valiyev U.S., Huseynova F.S. et al., 2025, *Advances in Space Research*, **76**, 1854
- Allen D.A., Swings J.P., 1976 *Astrophysical Journal*, **47**, 293
- Appenzeller, I., 1977, *Astronomy & Astrophysics*, **61**, 21
- Bo Zhao, Tomida K., Hennebelle P., et al., 2020 *Space Science Reviews*, **216**, 43
- Bressan A., Marigo P., Girardi L. et al., 2012 *Monthly Notices of the Royal Astronomical Society*, **427**, 127
- Carmona A., van den Ancker M.E., Audard M. et al., 2010, *Astronomy & Astrophysics*, **517**, A67
- Castelli F., Kurucz R.I., ATLAS9, 2004
- Chen P.S., Shan H.G., Zhang P., 2016, *New Astronomy*, **44**, 1
- Corporon P., Lagrange A.M., 1999, *Astronomy & Astrophysics Supplement Series*, **136**, 429
- Fairlamb J.R., Oudmaier R.D., Mendigutía I., Ilee J.D., van den Ancker M.E., 2015, *Monthly Notices of the Royal Astronomical Society*, **453**, 976
- Finkenzeller U., Mundt R., 1984, *Astronomy & Astrophysics Supplement Series*, **55**, 109
- Guzmán-Díaz J., Mendigutía I., Montesinos B., et al., 2021, *Astronomy & Astrophysics*, **650**, 182
- Herbig, G.H., and Bell, K.R., 1988, *Third Catalog of Emission-Line Stars of the Orion Population: 3: 1988*
- Herbig, G.H., 1960, *Astrophysical Journal Supplement Series*, **4**, 337
- Herbig, G.H., Rao, N.K., 1972, *Astrophysical Journal*, **174**, 401
- Ismailov N.Z., Alyshov S.A., Ismailova Sh.K., Huseynova F.S., 2023, *Astronomy Reports*, **67**, 1056
- Ismailov N.Z., Kholtygin A.F., Romanyuk I.I., Pogodin M.A., Moiseeva A.V., 2021 *Astrophysical Bulletin*, **76**, 415
- Ismailov N.Z., Valiev U.S., 2022 *Astronomy Reports*, **66**, 965
- Lada C.J., *Proceedings of the Symposium, Tokyo, Japan, Nov. 11-15, 1985 (A87-45601 20-90)/IAU Symposium, Tokyo: 1987*, **115**, 1
- Lindgren L., Hernández J., Bombrun A. et al., 2018, *Astronomy & Astrophysics*, **616**, A2
- Mamedkhanova, G.B., Ismailov, N.Z., 2019, *Astronomy Reports*, **63**, 190.

- Merill P.W., Bowen I.S., 1951, Publications of the Astronomical Society of the Pacific, **63**, 295.
- Miller, G., and Scalo, J., 1979, Astrophysical Journal Supplement Series, **41**, 513.
- Miroshnichenko A.S., Levato H., Bjorkman K.S., et al., 2004, Astronomy & Astrophysics, **417**, 731.
- Pecaut, M.J., Mamajek, E.E., 2013, Astrophysical Journal, Supplement Series, **208**, 9.
- Shevchenko V.S., Grankin K.A., Ibragimov M.B. et al., 1994, van den Heuvel EPJ (eds.), **62**, 43.
- Takami M., Bailey J., Chrysostomou A., 2003, Astronomy & Astrophysics, **397**, 675.
- The P.S., de Winter D., Perez M.R., 1994, Astronomy & Astrophysics Supplement Series, **104**, 315.
- Valiyev U.S., Alishov S.S., Ismailov N.Z., 2022, Peremennye Zvezdy, **42**, 51.
- Wang Y., Weigelt G., Kreplin A., et al., 2012, Astronomy & Astrophysics, **545**, L10.
- Wichittanakom C., Oudmaijer R.D., Fairlamb J.R. et al., 2020, Monthly Notices of the Royal Astronomical Society, **493**, 234.
- Wolf B., Stahl O., 1985, Astronomy & Astrophysics, **148**, 412.

RESEARCH OF THE RELIEF FACTORS OF THE PIRGULU RESERVE BASED ON SATELLITE IMAGES

F.I. Ismailov*, N.S. Dzhaliyov, A.E. Humbatova

¹ *N. Tusi Shamakhy Astrophysical Observatory of Azerbaijan National Academy of Sciences, Shamakhy, Azerbaijan*

Last updated 2025 May 22; in original form 2025 November 21

ABSTRACT

Using satellite images from the ASTER Terra sensor and Landsat 9, the properties of the relief of the Pargulu Reserve around the Shamakhy Astrophysical Observatory were studied: NDVI, aspect, slope, height above sea level and river courses. It was shown that the negative impact on the astroclimate increases from the eastern side and the inner territory of the Shamakhy Astrophysical Observatory.

Key words: Pargulu Nature Reserve, relief properties, anthropogenic impact, astroclimate.

1 INTRODUCTION

In thematic studies of the Earth's surface based on satellite imagery, a detailed characterization of the natural features of the surveyed area is essential (e.g., Ismailov 2023; Chandra Ghosh 2008; Dubovik et al. 2000). One of the primary features of interest is the relief of the area (e.g., Ismailov 2023, 2024a). Satellite imagery complements traditional ground-based methods for studying surface relief.

For space-based studies of landscape features, it is important to combine optical and radar imagery. Processing optical satellite images involves several preliminary stages, including atmospheric correction methods that depend on the regional conditions and time of observation (e.g., Chandra Ghosh 2008; Dubovik et al. 2000).

Currently, a significant number of high- and ultra-high-resolution satellites provide radar data for constructing Digital Terrain Models (DTMs) <https://asterweb.jpl.nasa.gov/gdem.asp>. A Digital Elevation Model (DEM) is a three-dimensional representation of the Earth's surface given as an array of points with defined heights. DEMs capture the true surface relief, excluding vegetation, buildings, and other anthropogenic objects.

An important factor influencing the results of thematic satellite image analysis is the regional characteristics of the relief.

GIS-Lab, Geoinformation Systems and Remote Sensing of the Earth. Available at: <http://gis-lab.info/>; Georeferencing in QGIS: <https://gis-lab.info/qa/georef-qgis.html>; Atmospheric correction using the DOS method: <https://wiki.gis-lab.info/w/> (accessed DATE). Ismailov2023. In

this work, satellite imagery is used to study the most indicative properties of the relief surrounding the Shamakhy Astrophysical Observatory, located within the Pargulu Nature Reserve <http://gis-lab.info/>.

The Pargulu State Nature Reserve was established in 1968 on a 1,521-hectare site at the eastern end of the Greater Caucasus Mountains, in the Shamakhy administrative district (e.g., SimpleMaps 2024). Its main objectives are to prevent erosion and atmospheric dust pollution, which adversely affect the activities of the Shamakhy Astrophysical Observatory, and to preserve the characteristic mountain-forest landscape of the region. This study investigates the methodological aspects of analysing the relief of the Pargulu Reserve using the open-source Quantum GIS (QGIS) software (GIS-Lab 2024) in combination with multispectral satellite remote sensing imagery. A comprehensive assessment of the relief enables the derivation of robust conclusions regarding the landscape characteristics of the Pargulu Reserve.

2 SELECTING SOURCE SATELLITE IMAGES

Fig. 1 shows the original raw satellite images used in this study. Images 1 and 2 were obtained from the Landsat 9 satellite, corresponding to the red (B4) and near-infrared channels of the Earth's surface, respectively <https://landsat.gsfc.nasa.gov/>. They illustrate the administrative boundaries of the Shamakhy district <https://simplemaps.com/> and were used to calculate the NDVI vegetation index (Ismailov 2023). Fig. 1 also presents the Digital Elevation Model (DEM) of the study area, including the Pargulu State Nature Reserve.

Information on terrain is essential for geoinformation projects based on Earth Remote Sensing (ERS) data. Digital Elevation Models provide accurate data on surface height, in-

* Contact e-mail: isfazil555@gmail.com

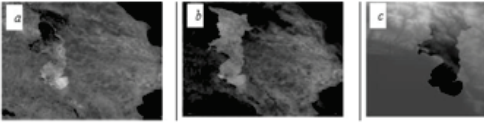


Figure 1. Satellite images: (1) LC09_L1TP_167032_20240826_20240826_02.T (2) LC09_L1TP_167032_20240826_20240826_02.T1.B5, (3) Digital Elevation Model (DEM).

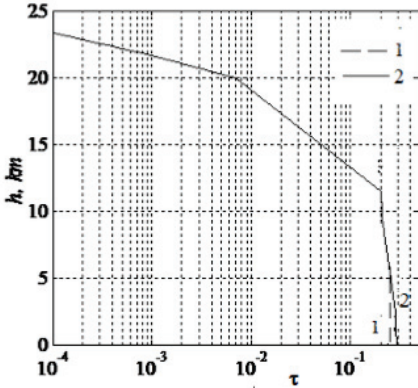


Figure 2. Vertical profiles of atmospheric optical thickness τ for Landsat 9 red (R, band 2) and near-infrared (NIR, band 1) channels

cluding buildings, vegetation, and other topographic features. Global DEMs are primarily constructed from stereoscopic optical and interferometric radar satellite data. In this work, we used the NASA ASTER GDEM (Global Digital Elevation Model) product derived from the ASTER sensor on the Terra satellite <https://asterweb.jpl.nasa.gov/gdem.asp>.

3 ANALYSIS OF RELIEF PROPERTIES

We consider the following properties of the relief of the Pirgulu Reserve: slope is an inclined section of the Earth's surface that is formed as a result of relief-forming processes; aspect is one of the morphometric characteristics of relief, characterizing the spatial orientation of an elementary slope of a hill, mountain or mountain range; height above sea level, absolute height is a linear measure of the potential difference at a point on the earth's surface and at the beginning of the height calculation (the starting point);

Figure 2. Vertical profiles of the optical thickness of the atmosphere for the R (2) and NIR (1) channels of Landsat 9. The normalized difference vegetation index (NDVI) is a widely used metric for quantifying the health and density of vegetation using sensor data. It is calculated from spectrometric data at two specific bands: red and near-infrared. The spectrometric data is usually sourced from remote sensors,

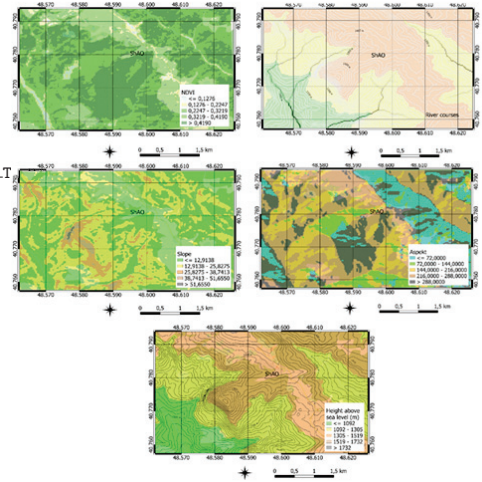


Figure 3. Fig. 3 Maps of relief factors

such as satellites; river courses is the bottom of a stream or river (bathymetry) and is confined within a channel, or the banks of the waterway; When calculating NDVI, preliminary processing of the red (R) (Fig. 1a) and infrared (NIR) (Fig. 2b) channels of Landsat-9 images was performed using the regional optical atmospheric model described by Ismailov (2023) and Ismailov (2024a) . Fig. 2 shows the vertical profiles of the optical thickness of the atmosphere τ as a function of altitude h for the red (R) and infrared (NIR) channels of Landsat 9. These data were used, respectively, for the atmospheric correction of images for the R (fig. 1a) and NIR (fig. 1b) channels of Landsat 9. In these figures, the vertical profiles differ significantly for the lower troposphere and the surface layer of the atmosphere.

Fig. 3 shows the mapping of the above-mentioned relief properties of the Pirgulu Reserve. Forest areas with high NDVI values > 0.4 are identified. At the same time, for the vicinity of highways, NDVI values > 0.4 . This indicates the expansion of anthropogenic impacts around the roads and in the wider vicinity of the ShAO, which is associated with the expansion of the reserve areas allocated for tourist settlements and the construction of holiday homes. River channels are located mainly in the forested areas of the reserve. These channels stand out significantly to the east of the ShAO. The slopes of the reserve are more significant to the east and southeast of the location of the ShAO. In these directions, the areas of the southern sections of the reserve are significant and greatly decrease in altitude from the altitude level $h \approx 1.500$ km of the location of the ShAO. In general, the eastern and western sides of the reserve from the territory of the ShAO are significantly different. To the east of the ShAO there are significant forest zones with a strong decrease in the slope of the terrain. To the east there are less significant forest areas, with comparatively smaller differences in altitude. Anthropogenic impact is significant along the roads and to

the east of the ShAO territory and on its internal territory of the observatory.

REFERENCES

- ASTER GDEM, 2024, ASTER Global Digital Elevation Map. Available at: <https://asterweb.jpl.nasa.gov/gdem.asp> (accessed DATE).
- Chandra, A. M., Ghosh, S. K., 2008, Remote Sensing and Geographic Information Systems. Moscow: Tekhnosfera, 288 p.
- Dubovik, O., Smirnov, A., Holben, B., et al., 2000, Accuracy assessments of aerosol optical properties retrieved from Aerosol Robotic Network (AERONET) sun and sky radiance measurements. *J. Geophys. Res.*, 105(D8), 9791–9806.
- GIS-Lab, 2024, Geoinformation Systems and Remote Sensing of the Earth. Available at: <http://gis-lab.info/>; Georeferencing of data in QGIS: <https://gis-lab.info/qa/georef-qgis.html>; Atmospheric correction using the DOS method: <https://wiki.gis-lab.info/w/> (accessed DATE).
- Ismailov, F. I., 2023, Space Monitoring Based on Regional Space Images. LAP LAMBERT Academic Publishing, 130 p.
- Ismailov, F. I., 2024a, Space monitoring on the territory of the Republic of Azerbaijan. *News Azerbaijan Natl. Acad. Sci., Ser. Phys. Tech. Math. Sci., Phys. Astron.*, No. 5, 103–111.
- Ismailov, F. I., Dzhililov, N. S., Humbatova, E. E., 2024b, About regional cosmic monitoring of snow cover in the south-eastern region of the Greater Caucasus. *Astron. J. Azerbaijan*, 19(1), 23–29.
- NASA, 2024, Landsat 9 Bands. Available at: <https://landsat.gsfc.nasa.gov/> (accessed DATE).
- SimpleMaps, 2024, Free Azerbaijan GIS Map Files. Available at: <https://simplemaps.com/gis/country/az> (accessed DATE).

DETERMINATION OF EFFECTIVE TEMPERATURES AND SURFACE GRAVITY OF A NUMBER F-SPECTRAL CLASS STARS BASED ON OBSERVED PHOTOMETRIC INDICES

Z. A. Samedov^{1,2*}, U. R. Rustam,² Z. F. Alieva,¹ S. Sh. Racabova,¹ A. A. Ganbarov²

¹*Department of Astrophysics, Faculty of Physics, Baku State University, Baku, Azerbaijan*

²*Department of Physics of Stellar Atmospheres and Magnetism, Shamakhy Astrophysical Observatory, Shamakhy, Azerbaijan*

Last updated 2025 October 17; in original form 2025 November 23

ABSTRACT

Basic atmospheric parameters — the effective temperatures and surface gravities — were determined for a number of F-type stars: HD 142 (F7V), HD 432 (F2III), HD 493 (F3V), HD 571 (F5II), HD 693 (F8V), HD 905 (F0IV), HD 1324 (F5V), HD 4919 (F3III), and HD 6210 (F6V). The determination of the effective temperature (T_{eff}) and surface gravity ($\log g$) of stars is one of the fundamental tasks of astrophysics. Knowledge of these parameters allows the derivation of evolutionary characteristics such as stellar mass, luminosity, radius, and age. The effective temperatures (T_{eff}) and surface gravities ($\log g$) of the investigated stars were obtained by comparing observational results with theoretically calculated values of the photometric indices $[c_1]$, Q , and β . The derived atmospheric parameters agree well with the spectral and luminosity classes of the stars.

Key words: stars: fundamental parameters, effective temperature, surface gravity

1 INTRODUCTION

The determination of the chemical composition of stellar atmospheres is one of the key problems in astrophysics. Recently, the chemical composition of supergiant star atmospheres has attracted increasing attention. During stellar evolution, significant variations occur in the abundances of certain elements in the atmospheres of A-, F-, G-, and K-type supergiant stars — in particular, an excess of nitrogen and a deficiency of carbon are commonly observed.

In giant and supergiant stars of spectral classes A, F, G, and K, deep convective mixing takes place. As a result, the products of thermonuclear reactions occurring in the stellar core are transported to the outer atmospheric layers. Therefore, observational determination of the chemical composition of stellar atmospheres is essential for testing predictions of modern theories of stellar chemical evolution.

We have previously investigated the atmospheres of numerous A-, F-, and G-type stars, including supergiants (e.g. Lyubimkov & Samedov 1985, 1987, 1990; Samedov 2019; Samedov et al. 2023, 2024). The first step in analyzing stellar chemical composition is the determination of the effective temperature (T_{eff}) and surface gravity ($\log g$). These param-

eters form the basis of stellar atmosphere models, and the accuracy of abundance determinations strongly depends on the precision of the adopted atmospheric model.

Furthermore, knowledge of T_{eff} and $\log g$ allows the derivation of fundamental evolutionary parameters, such as stellar mass, luminosity, radius, and age. Thus, accurate determination of T_{eff} and $\log g$ remains one of the important challenges in astrophysics.

2 DETERMINATION OF EFFECTIVE TEMPERATURES (T_{EFF}) AND SURFACE GRAVITY (G)

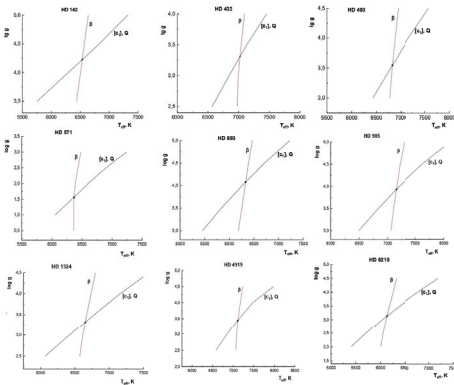
In this work, the main atmospheric parameters — effective temperatures (T_{eff}) and surface gravity (g) — of the F-type stars HD 142 (F7V), HD 432 (F2III), HD 493 (F3V), HD 571 (F5II), HD 693 (F8V), HD 905 (F0IV), HD 1324 (F5V), HD 4919 (F3III), and HD 6210 (F6V) have been determined. The effective temperatures (T_{eff}) and surface gravity (g) of the examined stars were derived by comparing the observed values with the theoretically calculated values of the $[c_1]$, Q , and β quantities. This method is a simple and accurate approach, allowing the determination of T_{eff} and g for a large number of stars.

The method was originally proposed by L. S. Lyubimkov

* Contact e-mail: zahir.01@mail.ru

Table 1. Observational values of photometric quantities of stars.

Star	Sp. Type	$b - y$	c_1	$[c_1]$	β	$U - B$	$B - V$	Q
HD 142	F7V	0.332	0.416	0.3496	2.639	0.022	0.516	-0.3495
HD 432	F2III	0.216	0.785	0.7418	2.709	0.101	0.341	-0.1445
HD 493	F3V	0.263	0.603	0.5504	2.682	0.060	0.424	-0.2453
HD 571	F5II	0.274	1.082	1.0272	2.650	0.252	0.396	-0.0331
HD 693	F8V	0.328	0.405	0.3394	2.621	-0.014	0.492	-0.3682
HD 905	F0IV	0.222	0.613	0.5686	2.717	-0.020	0.314	-0.2461
HD 1324	F5V	0.288	0.615	0.5574	2.665	0.069	0.453	-0.2572
HD 4919	F3III	0.212	0.792	0.7496	2.719	0.130	0.361	-0.1299
HD 6210	F6V	0.356	0.475	0.4038	2.615	0.110	0.547	-0.2838

**Figure 1.** $\log g - T_{\text{eff}}$ diagrams

(Lyubimkov et al. 2010). The Q index in the UB V photometric system is defined as

$$Q = (U - B) - 0.72(B - V),$$

while the $[c_1]$ index in the $uvby$ photometric system is defined as

$$[c_1] = c_1 - 0.2(b - y)$$

These indices are free from the effects of interstellar absorption. The observed values of c_1 , $b - y$, $U - B$, $B - V$, and β quantities were taken from the catalogue of Hauck & Mermilliod (Hauck & Mermilliod 1998). The theoretical values of c_1 , $b - y$, $U - B$, and $B - V$ were calculated by Castelli & Kurucz (Castelli et al. 2003), while the theoretical β values were calculated by Castelli & Kurucz (Castelli & Kurucz 2006). The observed photometric quantities for the investigated stars are listed in Table 1.

The theoretical values of the $[c_1]$, Q , and β indices were compared with the observed measurements, and for each index a pair of T_{eff} and $\log g$ values was determined. These $T_{\text{eff}} - \log g$ pairs were then plotted on the $\log g - T_{\text{eff}}$ diagram. In the $\log g - T_{\text{eff}}$ plane, the lines corresponding to the $[c_1]$, Q , and β indices were constructed, and the intersection point of these lines yields the final values of T_{eff} and $\log g$ (Fig. 1).

Table 2. Atmospheric parameters of F-type stars: effective temperature (T_{eff}) and surface gravity ($\log g$).

#	Star	Spectral type	T_{eff} [K]	$\log g$
1	HD142	F7V	6510	4.21
2	HD432	F2III	7024	3.31
3	HD493	F3V	6826	3.55
4	HD571	F5II	6368	1.55
5	HD693	F8V	6332	4.08
6	HD905	F0IV	7153	3.93
7	HD1324	F5V	6652	3.21
8	HD4919	F3III	7112	3.45
9	HD6210	F6V	6140	3.18

3 CONCLUSION

Based on the comparison of the observed and theoretically calculated values of the $[c_1]$, Q , and β quantities, the main atmospheric parameters—effective temperatures (T_{eff}) and surface gravity ($\log g$)—of the F spectral class stars HD142 (F7V), HD432 (F2III), HD493 (F3V), HD571 (F5II), HD693 (F8V), HD905 (F0IV), HD1324 (F5V), HD4919 (F3III), and HD6210 (F6V) have been determined. The following values were obtained: $T_{\text{eff}} = 6510$ K, $\log g = 4.21$ (HD142); $T_{\text{eff}} = 7024$ K, $\log g = 3.31$ (HD432); $T_{\text{eff}} = 6826$ K, $\log g = 3.55$ (HD493); $T_{\text{eff}} = 6368$ K, $\log g = 1.55$ (HD571); $T_{\text{eff}} = 6332$ K, $\log g = 4.08$ (HD693); $T_{\text{eff}} = 7153$ K, $\log g = 3.93$ (HD905); $T_{\text{eff}} = 6652$ K, $\log g = 3.21$ (HD1324); $T_{\text{eff}} = 7112$ K, $\log g = 3.45$ (HD4919); $T_{\text{eff}} = 6140$ K, $\log g = 3.18$ (HD6210).

REFERENCES

- Castelli F., Kurucz R. L., 2006, *A&A*, **454**, 333
 Castelli F., Kurucz R. L., Piskunov N. E., et al., 2003, *Proc. IAU Symp.*, **210**, A20
 Hauck B., Mermilliod M., 1998, *A&A*, **129**, 431
 Lyubimkov L. S., Samedov Z. A., 1985, *Bull. Crimean Astrophysical Observatory*, **72**, 99
 Lyubimkov L. S., Samedov Z. A., 1987, *Bull. Crimean Astrophysical Observatory*, **77**, 109
 Lyubimkov L. S., Samedov Z. A., 1990, *Astrophysics*, **32**, 30
 Lyubimkov L. S., Lambert D. L., Rostopchin S. I., Rachkovskaya T. M., Poklad D. B., 2010, *MNRAS*, **402**, 1369
 Samedov Z. A., 2019, *Astron. Rep.*, **63**, 944
 Samedov Z. A., Rustem U. R., Hajiyeva G. M., Aliyeva Z. F., 2023, *Odessa Astron. Publ.*, **36**, 86
 Samedov Z. A., Aliyeva Z. A., Hajiyeva G. M., Rustam U. R., Samedova N. H., 2024, *Astron. J. Azerbaijan*, **61**