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VARIABLE STARS AND STAR CLUSTERS

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

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

1. INTRODUCTION

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

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

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

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

Fig. 1. Ancient Koy-Kryilgan-kala Observatory

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

2. BACKGROUND

2.1. ANCIENT HISTORY

Ancient astronomy in the territory of Uzbekistan has been proven based on various archaeoastronomical research instruments, and excavations have led to the discovery of many observatories and astronomy-related signs in various regions of the country. The solid evidence of the very ancient roots of astronomy in Uzbekistan is the discovery of very ancient observatories and places with astronomical signs in Khorezm, between Bukhara and Samarkand, in the Surkhandarya region and other places. As example, Koy-Kryilgan-kala was built in 4^{th}-3rd centuries BC and was used until the 4^{th} century AD [4, 5]. Fig. 1 shows a bird's eye view (photograph) of this ancient observatory taken from above.

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

2.2. PREAMBLE OF COLLABORATION

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

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

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

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

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

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

3. RATIONALE AND OBJECTIVES

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

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

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

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

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

Table 1. Observation statistics of clusters and associations

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

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

4. OBSERVATIONS, PROCESSING AND ANALYSIS

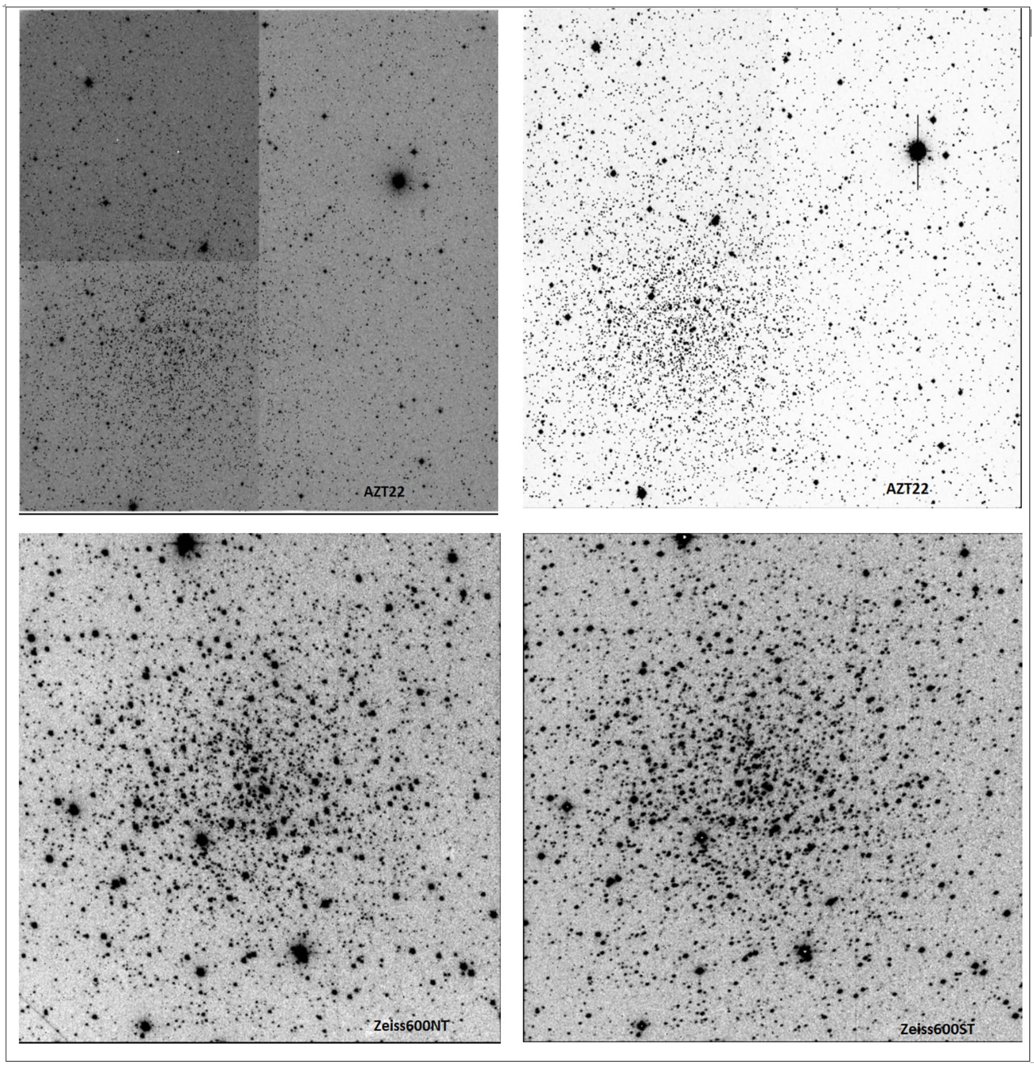

Fig. 3. Mosaic of original observational image-frames of open star cluster NGC 6791 obtained at different telescopes of Maidanak Observatory

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

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

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

5. VARIABLE STARS IN CLUSTERS

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

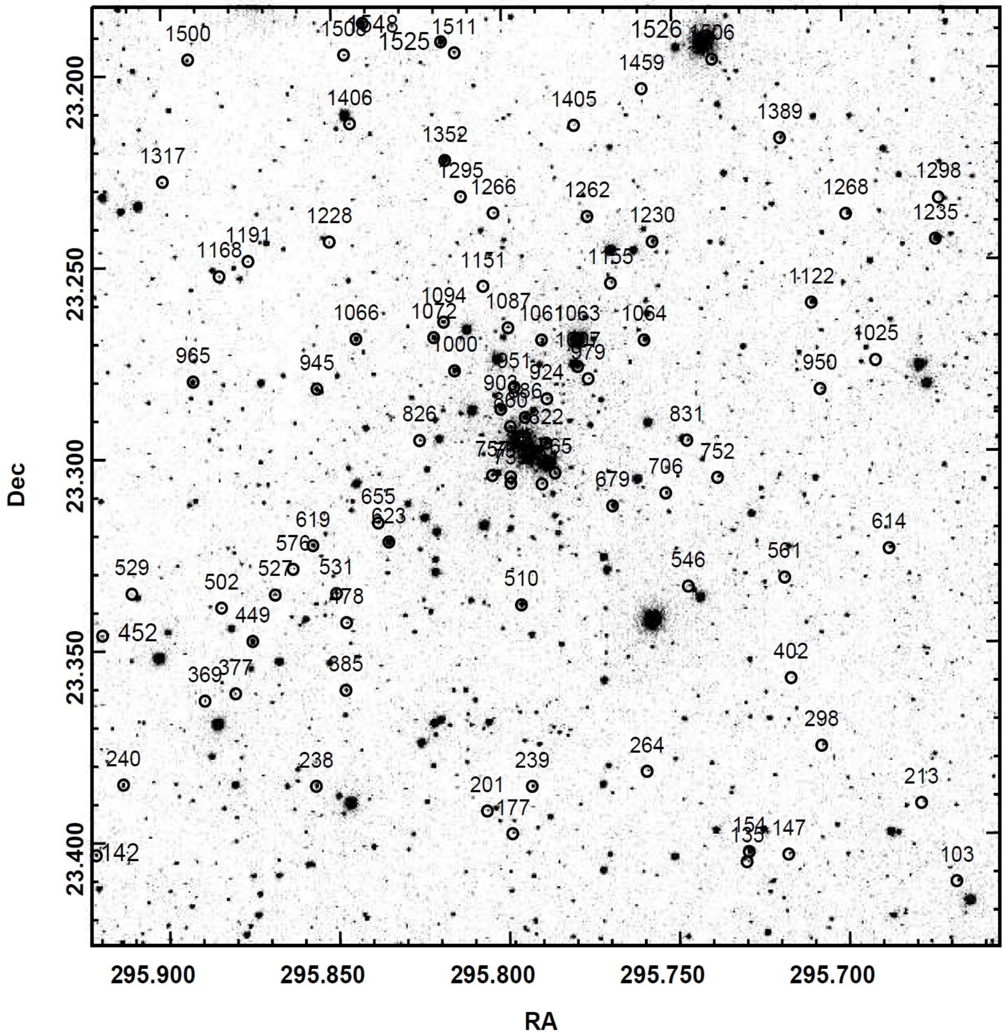

Fig. 4. The identification of variable stars in open cluster NGC 6823 and surroundings

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

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

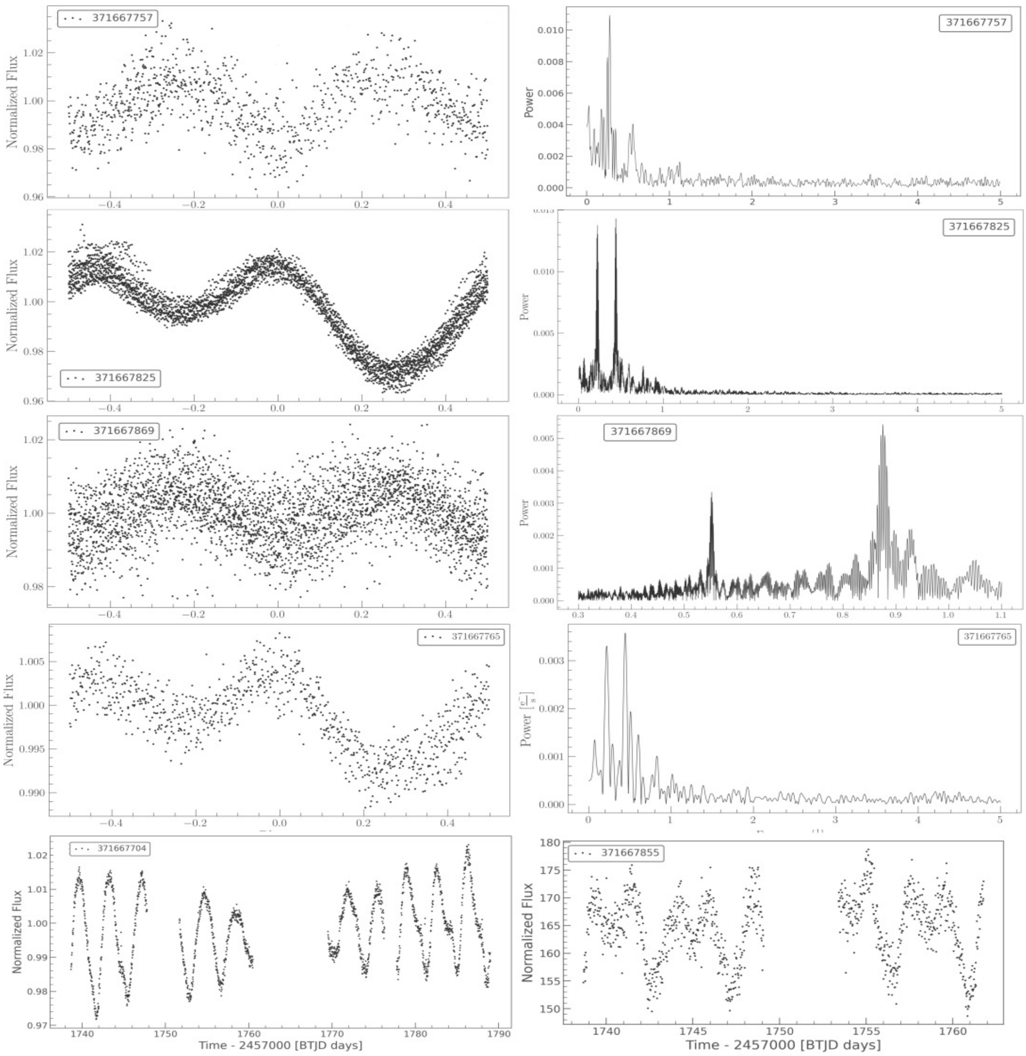

Fig. 5. Phased light curves and periodograms for new variable stars in open star cluster King 18

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

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

Table 2. New variable stars in open star clusters

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

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

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

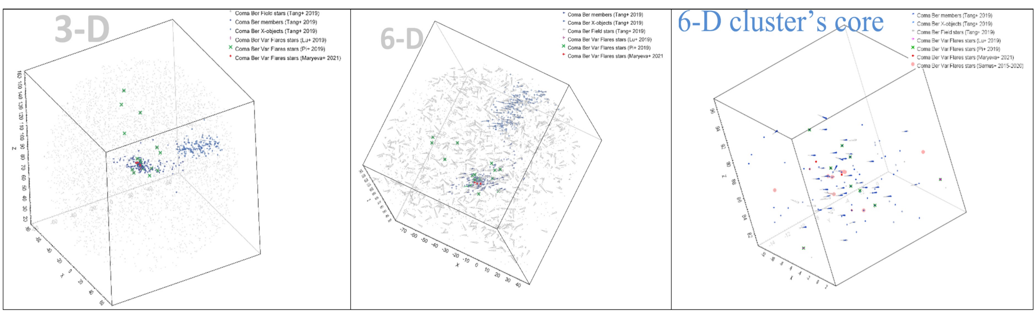

Fig. 6. 3-D and 6-D modelling of variable stars in open star cluster Melotte 111

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

Table 3. Observations of cataclysmic variables (MCV)

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

6. OTHER SELECTED VARIABLES

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

The phase light curve of the star 1RXS J174320.1-042953 (J1743) in the R-bandpass, obtained from our observations at Maidanak Observatory in 2021–2022, is presented in Fig. 7 together with its frequency analysis. It demonstrate the precision of data is sufficiently high to make analysis and modelling of the star. We could confirm two MCV as polars [15], namely 1RXS J174320.1-042953 (J1743) and YY Sex .

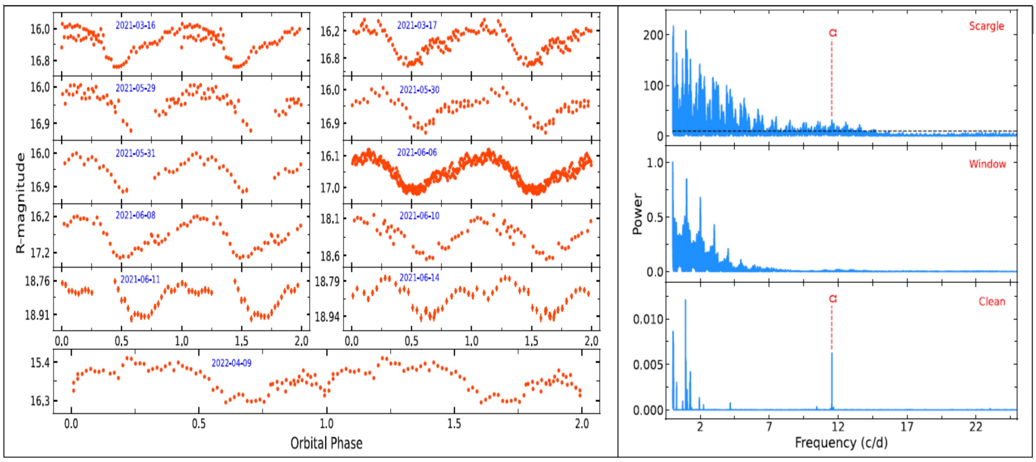

Fig. 7. Phased light curves and frequency analysis for MCV polar 1RXS J174320.1-042953 (J1743)

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

7. DISCUSSION AND CONCLUSIONS

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

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

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

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

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

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

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

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