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SUMMIT
SOFIA UNIVERSITY MARKING MOMENTUM FOR INNOVATION AND TECHNOLOGICAL TRANSFER

SOFIA UNIVERSITY -
MARKING MOMENTUM
FOR INNOVATION AND TECHNOLOGICAL TRANSFER

National Recovery and Resilience Plan
OF THE REPUBLIC OF BULGARIA

Study of High-luminosity Objects in the Field of Galaxies from the Local Volume

Project guidelines

- Quasars are the objects with the highest known luminosity in the Universe. They are powered by the accretion of matter into supermassive black holes at the centers of distant galaxies (Lynden-Bell 1969, Nature, 223, 690). Their study in the fields of nearby galaxies is important because they set a fixed reference frame for astrometric measurements, allow the estimation of the absorption in the galactic discs, and probe the kinematics and chemical composition of the galactic medium.
- High luminosity stellar objects in galaxies are the luminous blue variables (LBV). They are characterized by variability on different time scales. The largest changes in their brightness are associated with ejections of a solar mass over tens of years, but smaller brightness changes over weeks and months are also recorded. The study of LBV is crucial for understanding the physics and evolution of these massive and rare stars, as well as for the various mechanisms responsible for their variability.
- Another high luminosity stellar objects in galaxies are the novae (classical, recurrent, dwarf). They are important for studying the physics of the explosions in these binary systems and their physical characteristics. As well, they can be used as distance indicators in the Universe (Kasliwal et al. 2011, *ApJ*, 735, 94). Due to the unpredictability of these transients, their discovery, confirmation and follow-up observations are difficult which in turn hampers their detailed study.
- Globular clusters (GCs) are high-luminosity objects in the Milky way (Cruz Reyes & Anderson 2024) and the M31 galaxy (Agar & Barmby 2013, AJ, 146, 135). Ellipticity is a key structural parameter of GCs, likely linked to their rotation, and it correlates with various properties such as luminosity/mass, size, metallicity, and age. Recent catalogs of Milky Way GCs (Chen & Chen 2010; Cruz Reyes & Anderson 2024) provide ellipticity estimates; however, detailed studies on ellipticity radial variations remain scarce. Galactic M2 GC is an excellent target to study ellipticity variations since several optical data sources are available.

Our goals

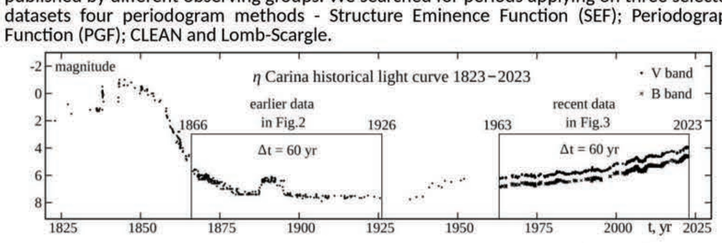
- Discovery and spectral confirmation of unknown quasars and search for periodic quasars in the field of M31. Also, obtaining their redshifts through the prominent broad emission lines.
- Follow, analyze, and physically interpret the changes in brightness of LBVs and other variables through optical light curves and spectra. Measure the amplitude of brightness variation on arbitrary time scales and show the presence of potential quasi-periodicity.
- Detection and photometric classification of novae and recurrent novae in nearby galaxies (M31, M33, M81, etc.). Determining the spatial distribution of different types in different galaxies (Williams et al. 2016, ApJ, 817, 143) and their progenitors.
- Determine unmeasured structural parameters of GCs in the Milky Way and M31 galaxy. Study the radial distribution of their ellipticities and search for a relationship with different their properties - X-ray luminosity, mass, age, size, etc.

Periodicity in the historical light curve of the LBV star η Carinae

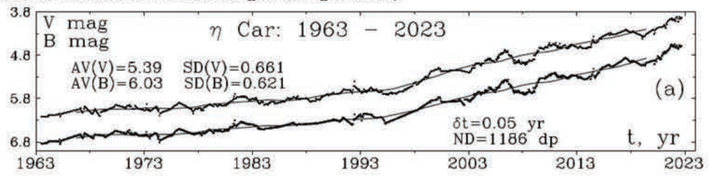
Georgiev Ts. B., Valcheva A., Nedialkov P. L., Stefanov S., Moyseev M.
published in Bulgarian Astronomical Journal, 2025, 43, 1

η Carinae is a nearby LBV binary system with a highly eccentric orbit (e∼0.9) and very high luminosity ∼5x10 L_{sun}. During its "Great Eruption" between 1837 and 1843, it reached a brightness of about −1 mag and after 1856, its brightness dropped well below naked-eye visibility. Since 1941, η Car's brightness exhibited a gradual increase (O'Connell 1956).

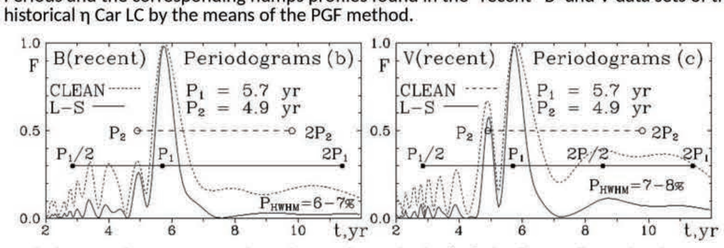
We compiled two centuries historical light curve (1823–2023) of η Car in BV band using photometry published in Fernández-Lajús et al. (2009) and photometry from the AAVSO published by different observing groups. We searched for periods applying on three selected datasets four periodogram methods - Structure Eminence Function (SEF); Periodograph Function (PGF); CLEAN and Lomb-Scargle.



The selected datasets cover two 60-yr long intervals, namely, 1866–1926 (V band) and 1963–2023 (BV band) and we used them for further analysis. The analysis yields two prominent periods: P_1 = 5.7 ± 0.1 yr (well established binary orbital period) and less prominent period of P_2 = 4.9 ± 0.1 yr (emissivity in the optical that probably originates in a larger volume than the NIR emission and manifesting in the light curve).



Periods and the corresponding humps profiles found in the "recent" B- and V-data sets of the historical η Car LC by the means of the PGF method.



Periodograms from CLEAN and Lomb-Scargle methods. (b,c): for "recent" B and V-data sets.

It is interesting to note that we obtained P_1=5.6 yr based on the "earlier" V band LC. The uncertainty in determination of P_1 based on "earlier" and "recent" LCs is about 0.05 - 0.1 yr, which does not make the change of ΔP_1=0.1 yr significant but it is confirmed by all methods applied in our analysis. η Car kept ejecting mass and the mass of the primary keeps decreasing. Hence, the orbital period would alter gradually at detectable levels within a century that is the timing between "earlier" and "recent" LC data.

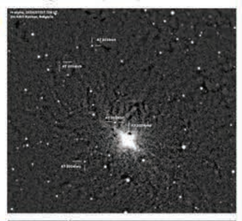
Novae in M31

Astronomical observations of M31 galaxy in BRHα filters with 2m RCC and 1.5m telescopes at NAO Rozhen, Bulgaria, were conducted to search for Novae in M31 galaxy or to confirm their nature. Since novae have strong Hα emission right after the maximum brightness, observations in this filter are important to reveal the transient nature and to study their Hα lightcurves. Our observations are published in "The Astronomers Telegram" (ATel).

- Detection of strong H-alpha emission from recent nova candidates in M31, Valcheva A., Kostov A., Ovcharov E., Nedialkov P., 2024, ATel #16716

  AT2024pbp, Hα = 15.98 ± 0.06 mag; AT2024nct, Hα = 15.51 ± 0.02 mag
  AT2024lwy, Hα = 15.73 ± 0.02 mag; AT2024ikt, Hα = 15.55 ± 0.02 mag

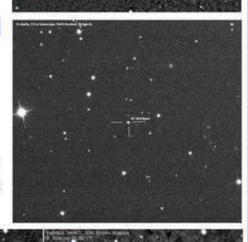
The strong Hα emission detected from AT2024pbp, AT2024nct, AT2024lwy, and AT2024ikt confirms that the transients are novae in M31. Our Hα observations showed that nova AT 2024ccb, discovered on 2024/02/10.594 UT by XOSS is still visible in Hα, five months later, with a magnitude of 17.31 ± 0.05 mag.



- Strong H-alpha emission detected from M31 nova candidate AT 2024pns, Minev M., Valcheva A., Holvorcem Paulo, 2024, ATel #16721

We detected strong emission in Hα from AT 2024pns.

Date, Filter, Magnitude, Error
2024 July 18.0074 UT, Ha= 16.08 ± 0.04 mag
2024 July 18.0323 UT, R = 16.90 ± 0.01 mag
2024 July 17.9827 UT, B = 17.56 ± 0.01 mag
2024 July 17.9674 UT, V = 17.30 ± 0.01 mag.

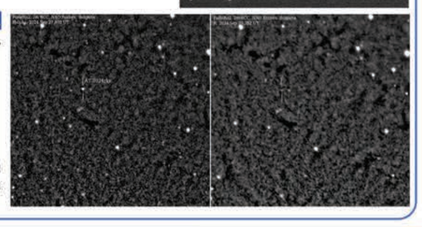


The strong Hα emission detected from AT 2024pns and its optical properties are consistent with those of novae in M31 close to the optical maximum.

- Detection of H-alpha emission from M31 nova candidate AT2024rkz, Valcheva A., Kurtenkov A., Stefanova D. 2024, ATel #16836

We detect strong Hα emission from M31 nova candidate AT2024rkz.

Date UT, Filter Magnitude Error:
2024 Sep 27.803 UT, Hα = 16.42 ± 0.02 mag,
2024 Sep 27.782 UT, R = 19.70 ± 0.20 mag.

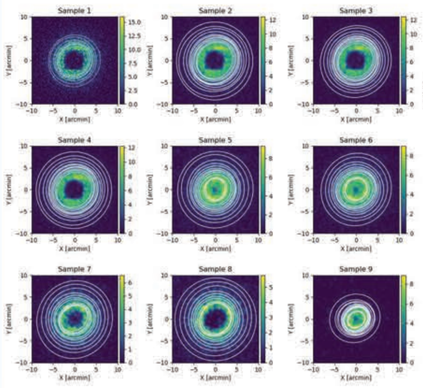


The strong Hα emission detected from AT2024rkz, 50 days after the optical maximum confirms that the transient is a nova in M31.

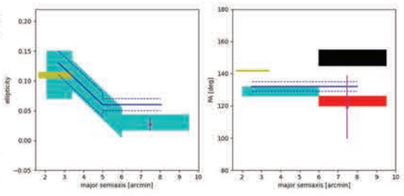
Structural parameters of the globular cluster M2 determined by ellipse fitting of stellar density

Botev S., Petrov G., Valcheva A., Nedialkov P., 2025, accepted for publication in Physica Scriprta

This research is focused on the estimation of structural parameters (center coordinates, ellipticity and position angle PA) of the galactic globular cluster M2 (RA = 21h 33m 27s.02 and DEC = -0° 49' 23''.7 (J2000)) by the use of the optical BV photometry from Lee & Carney (1999) and gi photometry from Pan-STARRS DR1 (Flewelling et al. 2020). The study was performed via ellipse fitting on 2D distribution of the number isodensity of stars derived by analyzing nine distinct data samples, each selected based on different criteria - apparent magnitude limit, isochrone fitting and photometry quality flag selections. Eight of the samples, the stellar densities were smoothed using a boxcar method with a 3x3 kernel and the only exception was the sample 1. We found that boxcar smoothed number density distributions provide more precise individual results. After analyzing all fitted ellipses, we derived the mean values of the structural parameters and identified observable trends. The estimation of M2 ellipticity is confined to an area of 20′× 20′, centered on M2.



Ellipse fitting results for the studied 9 samples with different number densities. The color scale on the right of the panels represents the density */px. The cluster's standard orientation is North to the top and East to the left.



The results for M2 ellipticity and position angle as a function of the major semiaxis are plotted. The results of Kholopov (1953) and White & Shawl (1987) are shown in blue and yellow, respectively. The adopted values in this work are marked as follows: cyan for the mean values and the approximations, red for the results based on Lee & Carney (1999) photometry, and black for those based on PS1. The values of Cruz Reyes & Anderson (2024) with Y-error bars are plotted in magenta. Note that the widths of the bands in Y-axis are 2σ, while the dashed lines correspond to ± 1σ.

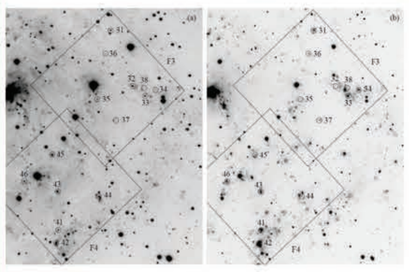
Results:

- The mean ellipticity of M2 decreases uniformly from 0.11 ± 0.04 (for major semi-axis a 2′ – 3′.4) to 0.03 ± 0.013 (for $a \approx$ 6′ – 9′.5), indicating that the cluster becomes rounder beyond 6′.
- The PAs, relative to the north celestial pole, show small variations around 129°± 3° for $a \approx$ 2′ – 6′. At larger distances, where the cluster's ellipticity decreases to as low as 0.03, some discrepancy occurs due to the increasing roundness of the cluster in its outer regions and the different completeness limits of the used photometric sources. Indeed, PA becomes more undefinable and the PAs measured by us differ within a wide interval (120° –150°).
- The lower limit of 13.2 Gyr ± 0.5 Gyr for the age of M2 was set by fitting its main sequence MS turn-off region on V vs. (B–V) and g vs. (g–i) Color-Magnitude Diagrams CMDs with two models of isochrones (MIST 1.2 and PGPUC) for fixed values of metallicity, distance and extinction, since lower extinction and/or smaller distance lead to the aging of the cluster.

Search and study of the brightest stars in IC342 Galaxy

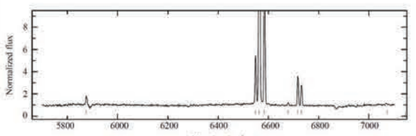
Sholukhova O., Tikhonov N., Solovyeva Yu., Sarksian A., Vinokurov A., Valcheva A., Nedialkov P., Bizyaev D., Williams B., Ivanov V., published in Astrophysical Bulletin, 2024, 79, 373

Discoveries from the follow up spectroscopy performed for 24 candidates with the 6m BTA telescope of the SAO RAS and the 3.5m Apache Point telescope (USA):



Images in filter B (left) and Hα (right) from the 2m telescope at Rozhen Observatory (Bulgaria) were used to select candidates for massive stars in IC342 galaxy.

a) 12 single O9I to F5I stars/spatially unresolved young compact clusters
b) 7 single Wolf-Rayet stars/compact clusters containing Wolf–Rayet stars
c) 2 LBV candidates in a quiescent phase
d) 1 B[e]-supergiant candidate
e) 1 Supernova remnant
f) 1 foreground Milky way star



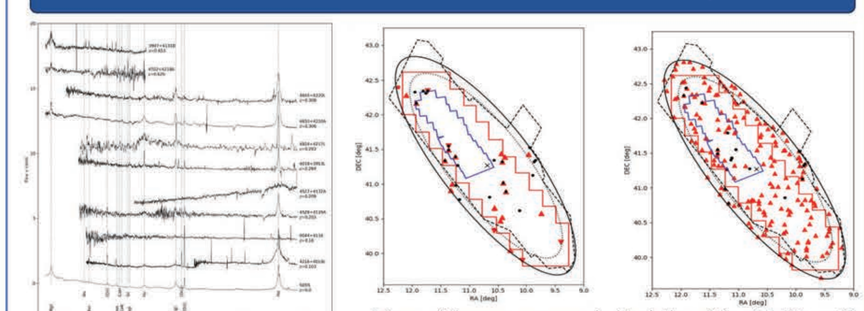
Spectrum of a typical supergiant star (BTA)

Discovered objects on the HRD with the evolutionary tracks for stars of 20 – 350 M_{sun}.

Spectrum of a typical Wolf-Rayet object (APO)

Spectrum of a LBV object (BTA)

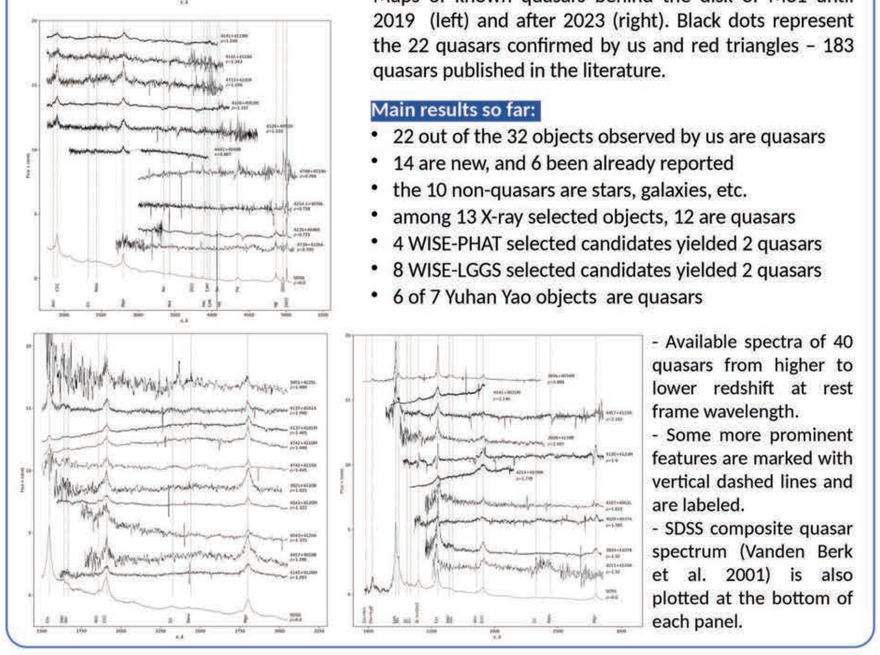
QSOs behind the disk of M31 Galaxy



Maps of known quasars behind the disk of M31 until 2019 (left) and after 2023 (right). Black dots represent the 22 quasars confirmed by us and red triangles – 183 quasars published in the literature.

Main results so far:

- 22 out of the 32 objects observed by us are quasars
- 14 are new, and 6 been already reported
- the 10 non-quasars are stars, galaxies, etc.
- among 13 X-ray selected objects, 12 are quasars
- 4 WISE-PHAT selected candidates yielded 2 quasars
- 8 WISE-LGGS selected candidates yielded 2 quasars
- 6 of 7 Yuhan Yao objects are quasars



- Available spectra of 40 quasars from higher to lower redshift at rest frame wavelength.
- Some more prominent features are marked with vertical dashed lines and are labeled.
- SDSS composite quasar spectrum (Vanden Berk et al. 2001) is also plotted at the bottom of each panel.

Long-term optical variability study of 11 quasars

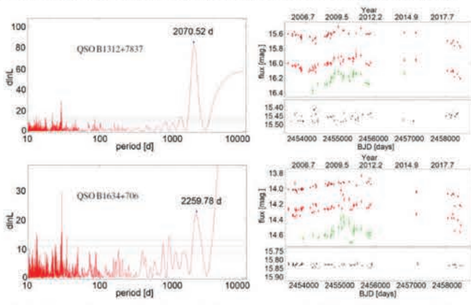
Minev M., Trifonov T., Ivanov V., Ovcharov E., Bozhilov V., Valcheva A., Kostov A., Nedialkov P., published in MNRAS, 2024, 531, 4746

A 15-yr long-term optical monitoring of 11 quasars is conducted with the 2-m Ritchey–Chretien–Coude and the 50/70 cm Schmidt telescopes at the Rozhen National Astronomical Observatory, Bulgaria. The observations are performed with standard Johnson-Cousins *VRI* band filters. The variability and periodicity of each quasar are analyzed individually and discussed, along with the physical properties of each quasar.

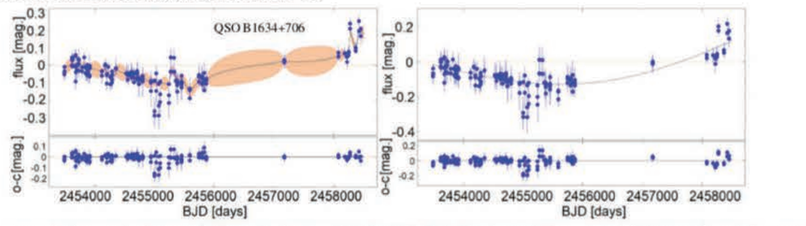
The analysis was made using the *QSO-Striker* (https:// github.com/ 3fon3fonov/ QSO-Striker).

Left panels: MLP periodorams of the Rozhen NAO photometry for two example quasars QSO B1312+7837 and QSO B1634+706. Horizontal dashed lines represent the FAP thresholds of 10 per cent, 1 per cent, and 0.1 per cent. The most significant powers are labeled.

Right panels: corresponding light curves of QSO B1312+7837 and QSO B1634+706 in *VRI* bands – V-green, R-red, I-brown, with check star (bottom panel).



To estimate the confidence of the periodic model, five theoretical models are used: (i) a 'flat' model – assuming there is no signal in the data; (ii) linear model – assuming there is a linear trend in the data; (iii) periodic model – assuming there is a sinusoidal periodicity in the data; (iv) periodic plus linear model – assuming there is a periodic change with linear trend and (v) DRW model – assuming there is a stochastic process (Kelly et al. 2009). A strongly favored model is granted if the difference of the Bayesian log evidence of the competing models is Δ lnZ >5.



As an example for periodic model fitting is shown QSO B1634+706. The best-fitting model (left panel) and the most competitive to it (right panel). lnZ_{DRW}=261.9 and $lnZ_{per+lin}$=247.4 (lnZ=14.5). It is at z=1.33 (Koratkar at al. 1992).

Results:

- QSO B0014+812 is the least variable quasar in our sample, with no significant periodicity.
- QSO B0153+744 is most 'active' quasar with a fast stochastic variability of 0.4 mag in our sample.
- 8C 0546+726; QSO B0933 + 733; QSO B1039+811; QSO B1312+7837; QSO B1759+7539; and HS 1803 + 7517 have evidences of periodic variability in the light curves and they are a valuable addition to the growing sample of quasars with periodic flux variation.
- QSO B0014+812, QSO B0933+733, QSO B1634+706, and QSO B1946+770 show significant color change which may uncover valuable information about the SED and the evolution of the accretion disc structure surrounding supermassive black holes. They can be targets for a study of the various emission mechanisms within quasar environments.

Conclusion

- Within the framework of the project, the active study of the photometric variability of high-luminosity stars in galaxies from the Local Volume continues, as well as the active search and study of the properties of novae (classical and recurrent) in the nearby galaxies M31, M33, M81.
- Research continues on the discovery of unknown quasars, confirmation of their nature through spectral observations and the search for periodic changes in their luminosity. Long-term observations allow for the tracking of quasar behavior over extended periods, revealing trends and gradual changes in brightness properties. Detection of periodic variability in their light curves suggests the presence of underlying physical processes related to the binary black hole system.
- Ongoing studies are focused on determining previously unmeasured structural parameters (ellipticity, position angle, center's coordinates, orbital eccentricity, etc.) of globular clusters and studies how these parameters are influenced by their X-ray luminosity.

Research field:

Astronomy and Astrophysics

Head of the research group

Assoc. Prof. Antoniya Valcheva

Members of the group

Assoc. Prof. Petko Nedialkov
Assist. Prof. Georgi Petrov
Dr. Milen Minev
Svetoslav Botev, PhD
Maria Petkova, MSc

Contract BG-RRP-2.004-0008 for the financing of project "Sofia University - Marking Momentum for Innovation and Technological Transfer" under pillar 2 "Establishing a network of research higher education institutions in Bulgaria", component "Innovative Bulgaria" from National Recovery and Resilience Plan part of the program to accelerate economic recovery and transformation through science and innovation