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CATS (COMETS, ASTEROIDS, EXOPLANETARY TRANSITS AND VARIABLE STARS
(July 1–2, 2023)

On 1–2 July 2023, NUAAR team (`http://nuaar.com`) has convened the conference called "CATS: Comets, Asteroids, exoplanetary Transits, and variable Stars" via Zoom. The conference was attended by representatives from scientific institutions of Ukraine, Canada, Belgium, Slovakia, and Germany. The talks covered different aspects of studying the objects of interest specified in the name of the conference. The abstracts of the presentations are provided below.

NEW INSIGHT INTO δ SCUTI AND CP STARS THANKS TO RAPID PHOTOMETRY DATA PROVIDED BY TESS

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A vast photometric survey of both stellar hemispheres performed by the Transiting Exoplanet Survey Satellite (TESS) during the last 5 years provided an extensive dataset to study variable stars. δ Scuti variables and Chemically Peculiar (CP) stars are the most interesting objects among them. The most common origins of variability found in these objects are stellar pulsations, orbital motion in a binary system, and rotational modulation due to inhomogeneous temperature distribution on stellar surfaces. The most interesting cases involve a combination of these three sources. Though the analysis may be complicated, it still provides useful information on the global stellar parameters. Analysis of pulsations in δ Scuti stars results in estimates of their stellar luminosity, mass, and radius. Similar information can be deduced from the analysis of light curves and variations of radial velocity for any kind of binary stars. This is especially useful for the HgMn stars with enhanced mercury and manganese abundance, which usually are found to be members of binaries. Analysis of the magnetic CP stars with roAp type (high overtone) pulsations involves reconstructing their global magnetic field configuration and mapping abundance inhomogeneities on their stellar surface. To achieve these steps, one needs to accumulate high-resolution spectra for the most interesting selected targets using the world's largest telescopes and perform complex analysis of all available data.

ANALYSIS OF STELLAR PULSATIONS IN HD 159541 AND HD 192640

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HD 159541 and HD 192640 belong to the class of δ Scuti stars and show stellar pulsations at frequencies larger than 10 d-1. HD 192640 also shows high-overtone pulsations at frequencies around 70 d-1. To study their pulsation properties, we used 2-minute cadence photometric observations provided by TESS for these stars during cycle 4 of its operation. The Python-based Lightkurve package and the Period04 software are used to retrieve, reduce, and process the light curves. Our analysis resulted in determination of pulsation frequencies, their amplitudes and phases, and corresponding error bars for signals with SNR more than 4.0.

Large frequency separation is the key parameter for estimation of global stellar parameters like mass, radius, and luminosity. For determination of the large frequency separation in both stars, we employed two methods: the method of Histogram Method and the method of 2D autocorrelation function. With the help of 2D autocorrelation function, we estimated a frequency range that corresponds to the p modes of stellar pulsations in these stars. Analyzing the signals detected within the derived frequency range allowed us to estimate the large frequency separation and the frequency with the highest pulsation amplitude for each target. Both methods provided consistent results for the aforementioned parameters that well agree with the published data for HD 159541 and HD 192640.

PERIOD ANALYSIS OF 6 ECLIPSING BINARY STARS OF EA TYPE WITH TESS DATA

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We studied 6 eclipsing binary stars using the TESS photometry data by downloading them from the Mikulski archive for space telescopes. The objects of our study are: TIC 32000625, TIC 32150630, TIC 55524055, TIC 233006806, TIC 379628805, and TIC 396059992. We have defined types for each binary system in our research. To determine the types of these stars, we plotted phase curves and periodograms. Phase curves are necessary in order to detect various fluctuations that may be present on the light curve. In addition, the periods, initial epochs, and errors for each of the periods were calculated. Moreover, we calculated and plotted the O-C curves in order to understand the evolution of binary systems and to calculate the period with better accuracy.

DISCOVERY AND PERIOD ANALYSIS OF 8 NEW TESS VARIABLES

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In this work, we present the results of the analysis of 8 eclipsing binaries: TIC 455732776, TIC 65106309, TIC 202601061, TIC 198555959, TIC 150783753, TIC 392536805, TIC 207504663, and TIC 160603897. Among them only TIC 150783753 and TIC 392536805 were previously known as variables, TIC 207504663 was known as X-ray source 1RXS J163228.4+585104, and TIC 160603897 was known as a White Dwarf Candidate. Moreover, none of them had the classification before. Thus, we report the discovery of variability of 6 stellar systems and the classification of all 8 objects. Some of them have additional interesting effects such as long-term pulsations, which were detected and described in this study. In addition, we calculated the period, and initial epoch, plotted and analyzed O-C curves (for minima and maxima) for each stellar system.

PERIOD ANALYSIS OF 3 ECLIPSING BINARY STARS BASED ON TESS DATA

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Our research is based on the processing of photometric data from the TESS space telescope for three eclipsing binary systems: TIC 30313682, TIC 32000625, and TIC 455153566. These star systems were chosen because their light curves promised certain interesting effects and these stars are not studied well as seen in SIMBAD and NASA ADS. We classified all three binary stars as EA. Additionally, we calculated the period, and initial epoch, and built the O-C curve of each star.

A core part of our research was calculation and plotting of the O-C curves. At first, photometric data of each star were divided into separate minima and maxima using a "Splitter v.2.6.1" Python script. Then data sets were processed using the "MAVKA v.201008" app. As a result, we've got the timing of extrema and their magnitudes for each data set. The calculation was done using various methods of data approximation: Symmetric polynomial, WSP, WSL, WSAP, NAV, and Mikulashek, considering accuracy of each method and light curve shape. Then by plotting and analyzing the O-C curves, we corrected the values of periods of each star.

THE NUMERICAL INTEGRATION OF THE EQUATIONS OF MOTION OF CELESTIAL BODIES

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Most of applied problems of astronomy are connected with the motion of celestial bodies. These include the problems of the dynamics of the Solar system, the evolution of the orbits of satellites of large planets, the problems of the dynamics of binary and multiple asteroids, the problems of the dynamics of binary and multiple star systems, star clusters, and others. The movement of celestial bodies occurs under the

influence of forces of gravitational and electromagnetic nature. To describe the movement, a mathematical model is built. A set of differential equations that interconnect physical quantities that characterize the dynamic state of a celestial body is called a mathematical model of motion. This is the application of Newton's second law for a given system of celestial bodies. In its most general form, this is a system of second-order differential equations. An analytical solution of systems of differential equations exists only for the problem of the motion of two material points.

Systems of differential equations of the mathematical model of motion can be integrated either by approximate analytical or numerical methods. The process of integrating a mathematical model by using a numerical method on a computer is called numerical simulation. In practice, numerical simulation is a sequential calculation of either state vectors or elements of the orbits of celestial bodies at certain time intervals. Numerical simulation is necessarily accompanied by: errors in determining the initial conditions; inaccuracy of the numerical method of integration; and rounding errors in the computing process of the computer. The efficiency of numerical simulation is determined by the accuracy of the results obtained and the computer time spent.

A feature of the equations of motion in celestial mechanics is the irregularity in the regions of approach, and the solutions of these equations are often unstable in the sense of Lyapunov. This enhances the disadvantages of numerical methods and leads to a decrease in the efficiency of numerical simulation. To reduce these features, methods of linearization and regularization of differential equations are used. Linearization brings the equations to a linear form. Regularization excludes singular points from the region of possible motion.

To reduce the instability of the numerical solution, its stabilization is used. The idea of stabilization methods is to use the known integrals of motion to correct the solution. The stabilized solution satisfies the known integrals of motion, for example, the integral of energy or angular momentum, if they are satisfied in this model. With the development of computer technology, the relevance of building mathematical models and methods of numerical integration will only increase.

THE PHENOMENON OF COMET-LIKE ACTIVITY ON ASTEROIDS

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Comets, asteroids, and meteoroids constitute the population of small bodies in the Solar System. Since comets and asteroids are traditionally considered remnants of material left from the early stages of the Solar System formation, their study is crucial for understanding the early history of our Solar System. Recently, a group of small bodies known as "active asteroids" has been observed. This group expands the classical definition of asteroids and includes objects in the Main Belt (MB) of asteroids that exhibit both asteroid-like orbits and signs of cometary activity, such as the presence of comas with dust or gas tails. These signs of activity may occur periodically or sporadically. Various mechanisms have been proposed to explain the activity of these objects, including meteoroid impacts, rotational instability, thermal effects, electrostatic forces, and sublimation of volatile compounds. In some cases, primitive MB asteroids with typical asteroid-like orbits have also exhibited sublimation activity during their closest approach to the Sun. So far, cometary activity has been observed in approximately 20 small bodies in the Solar System, collectively referred to as active asteroids.

YARKOVSKY AND YORP EFFECTS: LIGHT PRESSURE FORCES ON ASTEROIDS

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Despite the smallness of the light pressure forces, we shouldn't be surprised that they are important for the evolution of asteroids: an asteroid presents almost a textbook example of an isolated body, and even a tiny force acting consistently over millions of years can cause a major change in its motion. The term "Yarkovsky effect" is used to denote the recoil force coming from the infrared light re-emitted by an asteroid's surface, which causes a secular change in the asteroid orbit. The Yarkovsky–O'Keefe–Radzievskii–Paddack effect, or the YORP effect for short, denotes the recoil light pressure torque acting on an asymmetric asteroid and changing its rotation state. Both these effects have been extensively studied theoretically over the last three decades. They have also been confirmed observationally for many asteroids.

To name just a few most important consequences of these effects, the YORP effect can speed up the asteroids to high rotation rates and cause their disruption by centrifugal forces, whereas the Yarkovsky effect can change the asteroid's semimajor axis sufficiently to lead it to a resonance with planets, where the resonant perturbations can change the orbit even more and, among other possibilities, bring it to an Earth-crossing orbit. Thus the YORP effect is largely responsible for the size distribution of small asteroids, and the Yarkovsky effect is a major ingredient helping to sustain the population of potentially dangerous Near-Earth asteroids.

In the talk, I will review the current theoretical understanding of the Yarkovsky and YORP effects. I will discuss how the Yarkovsky effect is successfully used to measure asteroid densities, how the YORP effect strongly depends on the small-scale structure of the asteroid surfaces, how it helps to create binary asteroids, and how it governs the evolution of such binary systems. Particular attention will be paid to the results of the reporter, especially to the concept of the YORP equilibria, in which the YORP effect self-compensates and the asteroid evolution stops.

IMPLEMENTATION OF PHASE-RATIO METHOD AND COLOR-RATIO IMAGERY TO DAWN MISSION IMAGES

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Due to the extremely rapid growth in the number of images obtained during space missions to minor bodies in the Solar System, it becomes possible to test effective imagery methods that were developed and used for the lunar surface, applying them to the images of surfaces of different planetary bodies which do not have atmospheres, particularly such as an asteroid. Global mapping of the asteroid (4) Vesta and the dwarf planet Ceres from two orbits (HAMO and LAMO) during the Dawn mission provide the necessary data for applying the phase-ratio technique to these bodies. The multispectral images obtained by the onboard instrument Framing Camera (FC) open the unique opportunity of using both phase- and color-ratio imagery to distinguish areas with distinct regolith optical roughness, as well as identify areas with anomalous spectral slope.

For detailed studies, we have selected several areas both on Ceres and Vesta. Some of them for Ceres (Ahuna Mons, Xevioso, and Occator craters) are so far among the most prominent regions on Ceres due to the presence of high-albedo material. Areas of interest on Vesta all demonstrate evidence of dark (low-albedo) ejecta associated with infall of exogenous carbonaceous chondrite material and at the same time significant absorption at 2.8 μm. For all studied regions, the phase-ratio distribution maps were built, while the color-ratio imagery was applied for additional characterization of the selected areas.

As a result, the consistent comparison of albedo images, phase, and color maps turned out to be effective for the identification of various slope processes on the crater walls for both Vesta and Ceres. Moreover, it throws light on the problem of space weathering rate estimation on the asteroids. Further studies based on the usage of the phase ratio imagery in combination with other methods (i.e., crater statistics) could lead in future to new significant results.

PHYSICAL PROPERTIES OF LOW-ALBEDO ASTEROID (439) OHIO

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Predominantly situated in the outer part of the main belt, low-albedo asteroids are composed of primitive matter that originated during the early stages of the Solar System's formation. Analyzing their surface structure and mineralogical composition in detail can offer valuable insights into the processes that shaped our planets and other celestial bodies. The magnitude-phase dependence, a crucial characteristic enabling the study of asteroid surface structure and optical properties, exhibits a diverse range among low-albedo asteroids. Particularly noteworthy is the presence of significant features in the surface structure of these bodies, especially in the region of the opposition effect, where brightness increases non-linearly at small phase angles. However, some P and D-asteroids lack the opposition effect, indicating linear brightness decreases at very small phase angles. These objects, characterized by their dark and organic material-rich spectra, represent the most primitive matter in our Solar System. Unfortunately, data on such asteroids remains extremely limited, underscoring the need for further research into their surface properties to gain a deeper understanding of their unique characteristics.

This study concentrates on the photometry of (439) Ohio, a low-albedo asteroid with a slow rotation period. The objectives of this work are to determine the asteroid's rotation parameters, refine methods for determining the rotation period of slowly rotating asteroids, and establish the magnitude-phase relation of (439) Ohio. The study involved processing CCD observations of the asteroid in V and R filters over a span of 20 nights in 2020. The obtained images were used to generate the asteroid light curves and determine absolute magnitudes. The rotation period of the asteroid was measured to be 37.4888 hours, and a composite light curve was constructed, showcasing an amplitude of 0.25 mag. This light curve facilitated the derivation of the qualitative magnitude-phase relation for the asteroid in the V and R filters, which did not exhibit a nonlinear increase in brightness during the opposition effect.

THE FIRST STARS

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When we are speaking about stars, we should remember that not all of them are the same. Except for even differences such as mass, spectral class, variability, and place on the Hertzsprung–Russell diagram, we should remember the chemical composition of the star and such parameters as metallicity. The abundance of elements other than hydrogen and helium roughly influences the history of the star and plays a vital role at the end of its life (including variable star stages).

When the universe was very young, there was only hydrogen and helium. A metal-free primordial gas filled all the space and the first stars (also known as Population III stars) fully consisted only of it. Although this type of star has not been observed yet, astronomers can predict some properties of such formations. These stars were formed at redshifts near $z \sim 30$ and can be found until $z \sim 15 - 20$ when Pop II stars start to form. In most situations, Pop III stars formed in small clusters (or binary or multiple systems) – primordial gas is highly susceptible to fragmentation. Masses of such stars lay in a wide range: from solar masses (long living stars) to objects of several 105 $M_\odot$ (that could be seeds of recent supermassive black holes).

Anyway, the topic remains extremely challenging both from the side of potential observations in the early Universe and from the side of the theoretical calculating and modeling of the properties of such objects.

COMPLETE MATHEMATICAL MODELS INSTEAD OF THOSE OVERSIMPLIFIED

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We review basic mathematical models which are used for data analysis. Especially interesting in astronomy are methods that may be applied to signals with irregularly spaced times. This situation is common to observations of variable stars and other celestial bodies — either for own observations or for photometrical surveys from ground-based or orbital observatories. The diversity of types of variability needs improvements in the methods, which are most statistically optimal for a given class of signals. More than 70 main types are listed in the catalogs of variable stars (e.g. GCVS, VSX), and hundreds of combined ("hybrid") ones.

Only in the case of regularly spaced data and a discrete set of frequencies, all methods will produce the same results, as the formulae of the classical Fourier Transform. In other cases, such oversimplified methods, which use preliminary "mean removal", "trend removal" or "pre-whitening" (removal of a periodic (typically, sinusoidal) variation) before further modeling, may produce a significant bias of the determined parameters, and so wrong conclusions and even "fake discoveries". We review mathematical models - either the popular "oversimplified" ones (and show cases with extremely wrong results), or the improved methods with complete mathematical models.

The first stage of the study is the period search. The simplest case is when there are long series of observations (like that of the KEPLER or TESS space missions), but they are available in the selected fields of the stellar sky. To determine ToM (Time of Minima/Maxima, according to the AAVSO terminology), it is recommended using the software MAVKA. The majority of studies have sparse observations. In this case, a phase curve is used, when all times of observations are transformed to "phase", which is a float part of the scaled difference $(t - T_0)/P$, where t is the time of observation, T_0 is an "initial epoch", and

P is a (trial) period, and f=1/P is frequency. To estimate the quality of the periodogram, a test function is computed $\Theta(f, x, t, T_0)$, which numerically shows the "quality" of the phase curve. The "periodogram" is the dependence of this function on trial periods/frequencies. The possible period corresponds to the extremum (in some methods, the maximum, in others — the minimum).

There are many methods, which may be split into groups - either "non-parametric" (or "point-point"), or "parametric" (or "point-curve"). The "parametric" methods typically try to approximate the data with a sinusoid $x(t) = C_1 + C_2 \cos(wt) + C_3 \sin(wt)$, where the angular velocity $w = 2\pi f = 2\pi/P$. The coefficients C_α may be determined using the method of the Least Squares (LSq), which is statistically correct. However, there are "oversimplified" methods like that of Lomb popularised by Scargle, where, in fact, $C1$ is set to a sample mean value xmean, and this model is $x(t) - x_{\text{mean}} = C_2 \cos(wt) + C_3 \sin(wt)$ contains two unknown coefficients, and often they are called "the Fourier Transform" (FT). This simplification may lead to systematic errors in the period value up to two times, thus a complete mathematical model is needed. The software MCV ("Multi-Column View") has many features, particularly allowing to make a periodogram analysis using a periodic trigonometric polynomial superimposed on an algebraic trend. The period is determined using differential corrections. Also, it is possible to determine coefficients of a multi-periodic multi-harmonic model with a polynomial trend. For eclipsing variables, an algorithm NAV was proposed.

Another class of models is based on the so-called "local" approximations, where only the central point is used, whereas the data are taken in the interval $[t_0 - \Delta t,\ t_0 + \Delta t]$. Here Δt is a "filter half-width", which is determined to be optimal by minimizing the r.m.s. accuracy of the approximation at times of observations. This method is also effective for studies of flickering and quasi-periodic oscillations. For more periodic signals, e.g. semi-regular stars, the method of the "Running sines" was proposed and stress-tested. It was recently improved to take into account a possible trend and non-rectangular weight functions in the program VOB. The wavelet analysis was described using different test functions WWZ, WWT, WWA and WWS.

The principal components of variability may be computed either for simultaneous multi-channel signals or for the monochrome data with a shift. For such an analysis of the accretion structures near white dwarfs, the expressions for statistical properties of the auto-correlation functions for the detrended data were summarized in Andronov (1994).

ANALYSIS OF A VARIABLE STAR BASED ON TESS COSMIC STATION DATA

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Our investigation focused on the analysis and moderation of photometric data acquired from the TESS space telescope. We were observing three eclipsing binary systems: TIC 188816156, TIC-138476641, TIC-156892633. In the process of the investigation, we came up with the conclusion that all of them are the EA type systems. In addition, we constructed the O-C curves for the stars, determined the periods and initial epochs. Those stellar systems caught our attention due to the intriguing features observed in the light curves they emitted, and their limited exploration within the various databases.

Initially, the photometric data for each star was segregated into individual maximum and minimum using "Splitter v.2.6.1." Subsequently, the datasets were processed using the "MAVKA v.201008" application. Consequently, we obtained the timing and magnitudes of the extrema for each dataset. The pivotal aspect of our study entailed the computation and visualization of the O–C curves. By plotting and analyzing the resulting O–C curves, we were able to investigate the additional effects the stars had.