Journal of the Korean Astronomical Society
53: 43 ∼ 48, 2020 April
Published under Creative Commons license CC BY-SA 4.0

https://doi.org/10.5303/JKAS.2020.53.2.43
pISSN: 1225-4614 · eISSN: 2288-890X
http://jkas.kas.org

Poorly Studied Eclipsing Binaries in the Field of DO Draconis: V454 Dra and V455 Dra

Yonggi Kim[1], Ivan L. Andronov[2], Kateryna D. Andrych[2], Joh-Na Yoon[1], Kiyoung Han[1], and Lidia L. Chinarova[2,3]

[1]Chungbuk National University Observatory, Chungbuk National University, 361-763, Cheongju, Korea
ykkim153@chungbuk.ac.kr, antalece@chungbuk.ac.kr
[2]Department "Mathematics, Physics and Astronomy", Odessa National Maritime University, 65029, Odessa, Ukraine
tt_ari@ukr.net, katyaandrich@gmail.com
[3]Astronomical Observatory, Odessa I. I. Mechnikov National University, 65014, Odessa, Ukraine; llchinarova@gmail.com

Received February 17, 2020; accepted February 27, 2020

Abstract: We report an analysis of two poorly studied eclipsing binary stars, GSC 04396-00605 and GSC 04395-00485 (recently named V455 Dra and V454 Dra, respectively). Photometric data of the two stars were obtained using the 1-m Korean telescope of the LOAO operated by KASI while monitoring the cataclysmic variable DO Dra in the frame of the Inter-Longitude Astronomy (ILA) project. We derived periods of 0.434914 and 0.376833 days as well as initial epochs JD 2456480.04281 and JD 2456479.0523, respectively, more accurate than previously published values by factors 9 and 6. The phenomenological characteristics of the mean light curves were determined using the New Algol Variable (NAV) algorithm. The individual times of maxima/minima (ToM) were determined using the newly developed software MAVKA, which outputs accurate parameters using "asymptotic parabola" approximations. The light curves were approximated using phenomenological and physical models. In the NAV algorithm, the phenomenological parameters are well determined. We derived physical parameters using the Wilson-Devinney model. In this model, the best-fit parameters are highly correlated, thus some of them were fixed to reasonable values. For both systems, we find evidence for the presence of a cool spot and estimate its parameters. Both systems can be classified as overcontact binaries of EW type.

Key words: binaries: eclipsing — methods: data analysis — stars: individual: V454 Dra, V455 Dra

1. Introduction

All stars are variable at certain active stages during their evolution. Of special interest are objects exhibiting specific types of variability like cataclysmic variables and other interacting binaries, pulsating, and eruptive variables. Photometric monitoring of such objects requires dozens or even hundred of nights and may not be done at large telescopes; instead, this is a proper task for meter and sub-meter class telescopes. There are several single- and multi-telescope projects monitoring selected stars, including the Inter-Longitude Astronomy (ILA) campaign (Andronov et al. 2003; see Andronov et al. 2017a for a recent review of key results).

One of the most interesting stars in our sample is DO Draconis which appears to represent an object category of its own, being simultaneously classified as a magnetic dwarf nova and an outbursting intermediate polar. It has shown a variety of new phenomena like quasi-periodic oscillations (QPOs), dependence of the slope of the outburst decay on the brightness at maximum, and a weak wave of the basic low brightness between the outbursts, many of which seem to be missing because of a short duration (Andronov et al. 2008). A statistical study of the QPOs was presented by Han et al. (2017). The peculiar nature of DO Dra has motivated extensive observations of this star and the surrounding field. Because of the fast variability of DO Dra, observations were limited to one filter (Rc).

Corresponding author: Y. Kim

Besides this very interesting object, there are other variables in the field. Two of them, V454 Dra and V455 Dra, were discovered in the frame of the ILA project by Virnina (2010) while searching for variability of stars in various fields. Virnina (2011) presented finding charts and preliminary parameters. Kim et al. (2019) found the same variables from their time-series data obtained by the Chungbuk National University observatory. The systems were classified as W UMa-type (EW) objects. The light elements were found to be

$$\text{min I} = 2455192.4773(5) + 0.434911(9) \cdot E, \quad (1)$$
$$\text{min I} = 2455191.7896(6) + 0.376832(6) \cdot E \quad (2)$$

for V454 Dra and V455 Dra, respectively. (The number in brackets gives the accuracy in units of the last decimal digit).

Recently, the two stars were officially named V454 Dra and V455 Dra in the General Catalog of Variable Stars (GCVS) (Kazarovets et al. 2015; Samus et al. 2017). Corresponding designations in other catalogs are 2MASS J11403001+7111021 = GSC 4395.00485 = USNO-B1.0 1611-00091333 = USNO-B1.0 1611-00091333 Gaia DR2 1062691908235241216 = V0454 Dra = V454 Dra, and

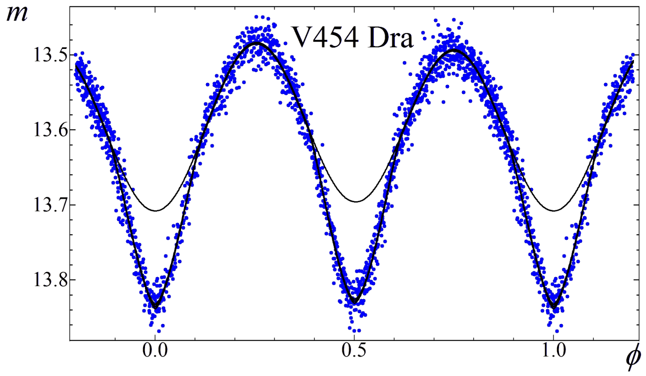

Figure 1. The phase light curve of V454 Dra together with the best-fit NAV model (continuous line following the data). The additional line above the eclipse corresponds to the "out of eclipse" continuum approximated by a trigonometric polynomial of order 2.

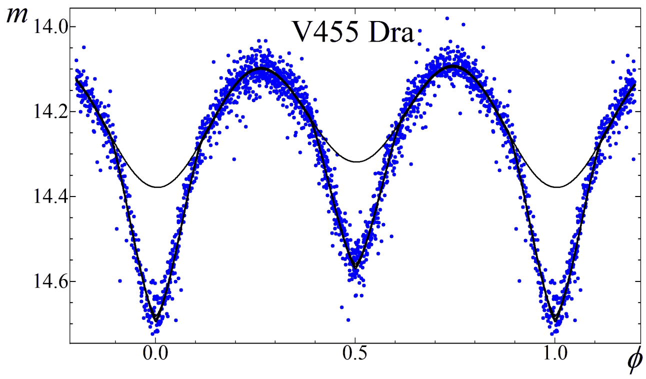

Figure 2. The phase light curve of V455 Dra together with the best-fit NAV model (continuous line following the data). The additional line above the eclipse corresponds to the "out of eclipse" continuum approximated by a trigonometric polynomial of order 2.

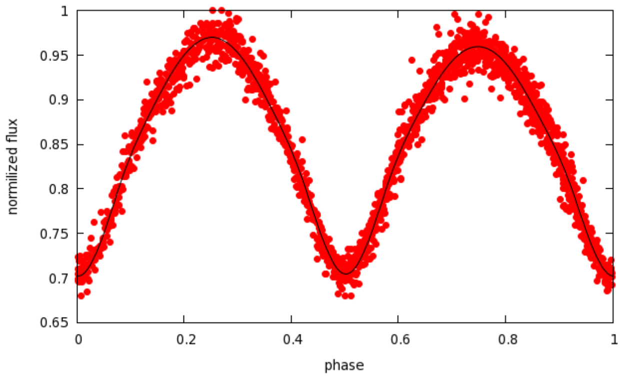

Figure 3. The phase light curve of V454 Dra with the best-fit Wilson-Devinney model.

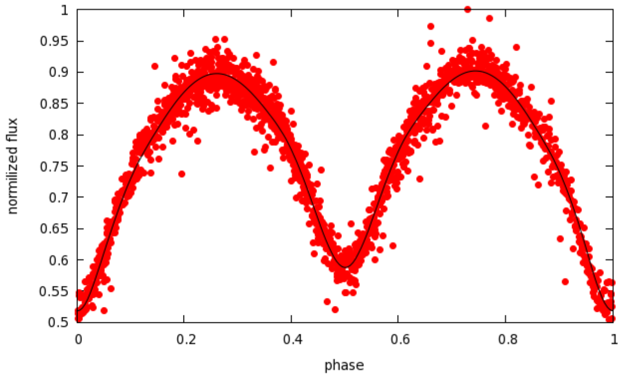

Figure 4. The phase light curve of V455 Dra with the best-fit Wilson-Devinney model.

2MASS J11483649+7107507 = NOMAD-1 1611-0093251 = USNO-B1.0 1611-0091801 = V0455 Dra = V455 Dra. (It should be noted that, obviously, V454 Dra = V0454 Dra, but an extra zero is a common designation in the GCVS, which is used for sorting numerous stars in one constellation.) The parallaxes for the two stars are 0.7722 ± 0.0201 mas and 0.8807 ± 0.0186 mas (Gaia DR2 2018a,b), respectively.

2. OBSERVATIONS

Photometric data for DO Dra were obtained by the Mt. Lemmon Optical Astronomy Observatory (LOAO) operated by the Korea Astronomy and Space Science Institute (KASI) and the Chungbuk National University Observatory (CBNUO) for about 10 years from 2005 till 2014. The robotic LOAO telescope, located at Mt. Lemmon in Arizona, has an aperture of 1.0 m and an effective focal ratio of $f/7.5$; it is mounted on a fork equatorial mount. The telescope is equipped with a 2048×2048 pixel CCD camera with a pixel scale of 0.64 arcsec/pixel and a field of view (FOV) of $22'.2 \times 22'.2$. The telescope at CBNUO is a Ritchey-Chrétien telescope with an aperture of 0.6 m and an effective focal ratio of $f/2.92$. In 2012, a new 4096×4096 pixel CCD providing a wide FOV of $72' \times 72'$ was installed in the camera; detailed information about the reduction process concerning data before and after the change of the CCD are given in Kim et al. (2019).

All photometric observations were made in the R filter band, using the star "Ref 2" from Virnina (2011) as calibrator, assuming the magnitudes $Rc = 13.04^m$ and $V = 13.390^m$ with a corresponding color of $V - R = 0.350^m$.[1] The angular distances of V454 Dra and V455 Dra from DO Dra are 2028.40″ and 2463.25″, respectively (Samus et al. 2017). Simultaneous observations of both stars are possible using wide-field CCD images, applying a focal reducer.

In total, we analyzed $n = 1746$ observations obtained during 112 hours distributed over 35 nights from JD 2456272 to JD 2456710, thus spanning 438^d. This time range was set by the availability of the focal reducer and is shorter shorter than the range spanned by the observations of the main target (i.e., DO Dra).

3. PHENOMENOLOGICAL MODELING

Phenomenological Modeling of the light curves of eclipsing systems using "special shapes" (also called "patterns"), instead of trigonometric polynomials, was ini-

[1] ftp://ftp.aavso.org/public/calib/dodra.dat; data courtesy AAVSO / Henden et al. (2007).

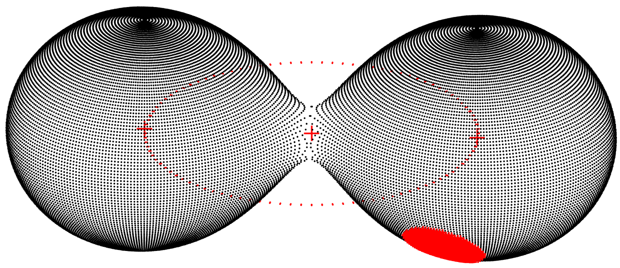

Figure 5. Model of V454 Dra with its cool spot (red area), as seen at an orbital phase $\phi = 0.74$. Red crosses mark the centers of the stars and the position of the center of mass of the system. The red circle indicates the orbit of the components around the common center of mass. To build the model, 120 points per meridian and 240 points per parallel were used for each star.

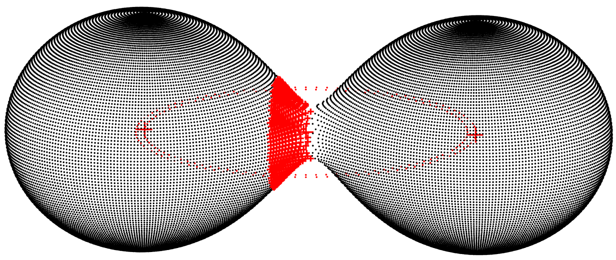

Figure 6. Same as Figure 5 for V455 Dra, as seen at $\phi = 0.24$.

tially proposed by Andronov (2012) for Algol-type (EA) systems with sharply defined beginnings and ends of eclipses. This approach resulted in the development of the New Algol Variable (NAV) algorithm. The algorithm can also be used for EB (β Lyr) and EW (W UMa) type systems, including the prototypes of these classes – β Per (Algol), (β Lyr), and EW UMa (Tkachenko et al. 2016). For the eclipsing binary 2MASS J18024395 + 4003309 = VSX J180243.9+400331 (also known as V1517 Her) in the field of the intermediate polar V1323 Her, Andronov et al. (2015) estimated the physical parameters of the components using two-color photometry and a statistical mass–radius–color index relation.

For the stars V454 Dra and V455 Dra, such a complete analysis is not possible because our photometry is monochromatic. We computed periodograms using trigonometric polynomial (TP) approximations of various orders, s, which correspond to the main wave and $(s-1)$ harmonics. The periods were corrected using differential equations (see Andronov 1994 for details) according to the algorithm described by Andronov (1994) and Andronov and Marsakova (2006). The statistically optimal degrees of the trigonometric polynomials are $s = 6$ and $s = 8$ for V454 Dra and V455 Dra, respectively. The corresponding number of parameters are $m = 2s+2$, i.e. $m = 14$ and 18, respectively; these numbers of parameters are higher than the ones required for the NAV algorithm despite the curves being relatively smooth.

The phenomenological parameters obtained using the NAV algorithm are listed in Table 1. Their detailed description may be found in Andronov et al. (2015) and Tkachenko et al. (2016). The corresponding phase light curves and approximations are shown in Figures 1 and 2. A detailed description of the time series analysis is presented in Andronov (2020).

4. Times of Extrema

For further studies of the period changes, it is important to publish the times of individual extrema (for example, Kreiner et al. 2003). Typically, only the moments of minima are published for eclipsing binaries. However, for both stars, the maxima are prominent, so we determined the maxima as well.

In the previous section, we modeled the complete phase curve based on all observations. In individual nights, the observation time is shorter than the period. Thus we take into account only the intervals close to an extremum. We determined the times of either minima or maxima using the “running parabola” approximations, initially proposed by Marsakova & Andronov (1996) and realized in the software package MAVKA introduced by Andrych et al. (2015) and Andrych et al. (2020). This method is among the most accurate ones for determination of extrema from relatively short observing runs which only partially cover the descending and ascending parts of a light curve around an extremum. The “special shapes” allow to avoid apparent waves, which are similar to the Gibbs phenomenon.

For longer observing times, which completely cover ascending and descending segments of light curves, one may use many modifications of known approximations. Andronov et al. (2017b) compared almost 50 functions and ranked them according to estimated accuracy. Some of them are improvements of phenomenological approximations proposed by Mikulášek (2015). Andrych & Andronov (2019) realized 21 approximations of 11 types for the shorter intervals.

In Table 2, the moments of the individual minima and maxima are listed. Moments which correspond to phases near 0 and 0.5 are primary (min I) and secondary (min II) minima, respectively; the other extrema are maxima. These moments can be used for further analysis after adding further observations from other seasons; he typical timescale of period variations is on the order of years for variations due to third bodies and much longer for variations due to the mass transfer (see, e.g., the monograph by Kreiner et al. 2003).

5. Physical Modeling

The main purpose of studies of eclipsing binaries is to build physical models. In contrast to spectroscopic, visual or astrometric binaries, it is possible to determine masses, luminosities, sizes, temperatures, surface brightness distributions and some parameters of the component orbits for eclipsing variables. For modeling and determination for these parameters we have to combine photometric observations, radial velocity curves, and spectroscopic observations.

Table 1
Parameter values determined by phenomenological modeling

Parameter	V454 Dra	V455 Dra
C_1	13.5955 ± 0.0011^m	14.2227 ± 0.0022^m
C_2	0.0061 ± 0.0011^m	0.0299 ± 0.0021^m
C_3	-0.0047 ± 0.0006^m	0.0032 ± 0.0012^m
C_4	0.1064 ± 0.0017^m	0.1259 ± 0.0032^m
C_5	0.0022 ± 0.0015^m	0.0054 ± 0.0021^m
C_6	0.1276 ± 0.0042^m	0.3101 ± 0.0088^m
C_7	0.1326 ± 0.0040^m	0.2464 ± 0.0075^m
C_8	0.1164 ± 0.0025	0.1159 ± 0.0025
C_9	1.369 ± 0.079	1.357 ± 0.068
C_{10}	1.539 ± 0.081	1.330 ± 0.069
T_0	$2456480.04281 \pm 0.00030^d$	$2456479.05227 \pm 0.00023^d$
P	$0.43491412 \pm 0.00000091^d$	$0.37683317 \pm 0.00000097^d$
d_1	0.1109 ± 0.0034	0.2484 ± 0.0061
d_2	0.1149 ± 0.0033	0.2031 ± 0.0055
$d_1 + d_2$	0.2258 ± 0.0058	0.4515 ± 0.0099
d_1/d_2	0.9646 ± 0.0291	1.2235 ± 0.0326
Max I	13.4845 ± 0.0012^m	14.0999 ± 0.0020^m
Min I	13.8355 ± 0.0032^m	14.6886 ± 0.0065^m
Min II	13.8284 ± 0.0027^m	14.5651 ± 0.0055^m

We use the Wilson-Devinney (WD) algorithm proposed by Wilson & Devinney (1971) and improved by Wilson (1979) and Wilson (1994). It determines physical parameters of a binary system from the phase curve and the radial velocity curves. For this task, the user has to pre-set the intervals of the physical parameter values and has to fix some of them for reasons related to the typical relationships for stars of corresponding type of variability. For example, the temperature of the first component at the pole, T_1, was fixed to a reasonable value, as typically assumed in those models, whereas the temperature of the second component, T_2, is a free parameter. The best fit estimate of T_2 depends on T_1 monotonically but not exactly linearly. The surface potential Ω is expressed in units of the square of the orbital velocity. As both stars overfill their Roche lobes and are at an overcontact stage, the potential is the same for the common envelope, i.e., for both stars. (More details may be found in the monograph by Kallrath & Milone 2009.) The algorithm is based on a Roche model geometry for the construction of a binary system and uses Monte Carlo simulations to specify physical parameters and construct a model light curve. The WD-code allows to simulate different types of eclipsing systems from contact systems to exoplanet transits.

To determine the physical parameters of our target binary systems, we used a modified version of the original WD-code created at the Astronomical Observatory of the Jagiellonian University in Krakow (see Zoła et al. 1997, 2010 for a full description). This version can take into account up to two spots on the surface of the companion stars in a given binary. The differential code method in the original code has been replaced with the Price algorithm (controlled Monte Carlo method). The version we use is specialized on contact systems where both objects fill their Roche lobes and both have the same potential on the surface, although they may have different temperatures (the temperature of one of them must be fixed while the other is simulated). Such a system is already tight, the components are tidally deformed and have circular orbits. The co-latitude of the center of a spot can vary from 0° (north pole of a star) to 180° (south pole). The spot center longitude varies from 0° to 360°, counted counter-clockwise from the line connecting the two stars.

Using the version of the original WD code created at the Jagiellonian Astronomical Observatory in Krakow by Prof. S. Zoła and others, we did a physical simulation of the eclipsing binary systems V455 Dra and V454 Dra. For these objects, we have only the phase curve in one filter, so some parameters and their intervals need to be fixed to realistic values. Physical parameters of components in close binary systems were discussed by, e.g., Kreiner et al. (2003). The model light curves for both systems are shown in Figures 3 and 4 along the data. The resulting physical parameters are shown in Table 3. It should be noted that our solution is not unique. Several parameters show a pairwise degeneracy with other parameters, notably the temperatures of both components, the inclination with the potential, and the radius of the spot with the temperature parameter.

With Binary Maker 3 (Bradstreet 2005), we built a visual model of the system using the best-fit physical parameters. In Figures 5 and 6, the respective system models are shown. To build a model for a given binary, 120 points per meridian and 240 points per parallel are taken for each star.

6. Conclusions

Photometric time series for two poorly known binary stars, V454 Dra and V455 Dra, were analyzed using phenomenological approximations of the complete phase

Table 2
Moments of individual maxima and minima

V454 Dra		V455 Dra	
BJD−2400000	±	BJD−2400000	±
56272.36895	0.0006	56272.35864	0.0009
56346.30781	0.0006	56346.31053	0.0019
56355.22405	0.0008	56355.26561	0.0015
56357.07647	0.0016	56357.06032	0.0012
56357.18191	0.0008	56357.14830	0.0005
56357.28783	0.0013	56357.23665	0.0010
56360.22388	0.0016	56357.33556	0.0040
56362.18030	0.0003	56360.16278	0.0009
56362.29182	0.0012	56362.23293	0.0005
56363.26942	0.0009	56363.17623	0.0008
56366.20593	0.0007	56363.26870	0.0020
56373.05427	0.0013	56366.18734	0.0019
56394.14774	0.0006	56373.06110	0.0017
56395.12243	0.0015	56394.07646	0.0007
56398.16881	0.0015	56394.16601	0.0005
56401.10329	0.0012	56395.11733	0.0007
56409.04061	0.0020	56401.04896	0.0010
56411.97798	0.0020	56409.06225	0.0010
56412.08446	0.0013	56411.97503	0.0019
56413.06679	0.0006	56412.07457	0.0006
56429.04618	0.0020	56413.00769	0.0013
56432.98510	0.0026	56413.10723	0.0011
56434.04771	0.0049	56429.03185	0.0026
56650.31266	0.0015	56434.02193	0.0009
56654.33204	0.0008	56650.32477	0.0043
56658.35803	0.0013	56651.36037	0.0014
56659.33758	0.0007	56654.37722	0.0030
56667.27487	0.0006	56658.23820	0.0015
56686.30513	0.0017	56658.32863	0.0010
56710.22508	0.0019	56659.27614	0.0012
56710.32959	0.0011	56659.36724	0.0011
		56664.35500	0.0035
		56667.28187	0.0007
		56686.31136	0.0005
		56710.23717	0.0024
		56710.33230	0.0032

light curve (using the trigonometric polynomial and NAV algorithms), as well as individual time series around maxima and minima (using the "asymptotic parabola" algorithm implemented in the recently developed software MAVKA), and a database containing almost 70 moments was compiled. This database can be used in combination with further monitoring to search for possible period variations. We provide a table of individual extrema which may be used for future O-C analysis and searches for possible period variations.

The NAV algorithm achieves a better approximation of the light curve minima using the special shape approach instead of trigonometric polynomials. The eclipses split the phase curve into four parts, meaning that smooth trigonometric polynomial are a poor approximation. This special shape approach, along with a larger data set, has lead to a significant improvement of the accuracy of the model parameters compared to the discovery paper by Virnina (2011). For example, the accuracy of periods and initial epochs increases by factors of 9 and 6 for the two stars, respectively.

Table 3
Parameter values derived from physical modeling

Parameter	V455 Dra	V454 Dra
Orbit inclination	$74.67 \pm 0.06°$	$64.0 \pm 0.03°$
Temperature of first star	5800 K	5500 K
Temperature of second star	5351 ± 5 K	5478 ± 3 K
Surface potential	3.62 ± 0.015	3.685 ± 0.0007
Mass ratio	0.95 ± 0.01	0.99 ± 0.005
Co-latitude of spot center	90°	$133 \pm 1.3°$
Longitude of spot center	$356.9 \pm 0.2°$	$71 \pm 1.3°$
Spot radius	$22.5 \pm 0.2°$	$18.9 \pm 0.74°$
Spot temperature[a]	0.8	0.6

[a]In units of stellar temperature.

We also applied physical modeling to our data using the Wilson-Devinney algorithm. The set of physical parameters which were determined should be regarded as an initial approximation, which may be improved using possible further spectral observations (to determine mass ratios and temperatures) or well-calibrated multi-color photometry (to determine temperatures). For both systems, a cool spot is evident whose parameters we estimated approximately. As we only have single-band photometry available, several parameters and parameter intervals needed to be fixed; thus, the formal errors for these parameters drastically underestimate the actual uncertainties.

Both stars were initially classified as being of EW type by Virnina (2011). Current physical modeling confirms this classification, as both systems are overcontact binary systems. For subsequent improvements of physical models, multi-color observations, as well as an accurate calibration of the comparison stars which is currently absent for this field, will be needed.

ACKNOWLEDGMENTS

The authors thank Prof. S. Zoła and Dr. B. Dębsky for allowing to use their software for physical modeling and fruitful discussions. This work was supported by the Overseas Dispatch Program of Chungbuk National University in 2017. The data acquisition and analysis was partially supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education, Science and Technology (2011-0014954). This study is a part of the Inter-Longitude Astronomy (Andronov et al. 2003, 2017a) and Astroinformatics (Vavilova et al. 2017) campaigns.

REFERENCES

Andronov, I. L. 1994, (Multi-)Frequency Variations of Stars. Some Methods and Results, Odessa Astron. Publ., 7, 49

Andronov, I. L. 2012, Phenomenological Modeling of the Light Curves of Algol-type Eclipsing Binary Stars, Astrophys., 55, 536

Andronov, I. L. 2020, Advanced Time Series Analysis of Generally Irregularly Spaced Signals: Beyond the Oversimplified Methods, in: P. Skoda et al. (eds.), Knowledge

Discovery in Big Data from Astronomy and Earth Observation (Amsterdam: Elsevier), 191
Andronov, I. L. & Marsakova, V. I. 2006, Variability of Long-period Pulsating Stars. I. Methods for Analyzing Observations, Astrophys., 49, 370
Andronov, I. L., Antoniuk, K. A., Augusto, P., et al. 2003, Inter-longitude Astronomy Project: Some Results and Perspectives, Astron. Astrophys. Trans., 22, 793
Andronov, I. L., Chinarova, L. L., Han, W., et al. 2008, Multiple Timescales in Cataclysmic Binaries. The Low-field Magnetic Dwarf Nova DO Draconis, A&A, 486, 855
Andronov, I. L., Kim, Y., Kim, Y.-H., et al. 2015, Phenomenological Modeling of Newly Discovered Eclipsing Binary 2MASS J18024395 + 4003309 = VSX J180243.9+400331, JASS, 32, 127
Andronov, I. L., Andrych K. D., Antoniuk, K. A., et al. 2017a, Instabilities in Interacting Binary Stars, ASP Conf. Ser., 511, 43
Andronov, I. L., Tkachenko, M.G., & Chinarova, L.L. 2017b, Comparative Analysis of Phenomenological Approximations for the Light Curves of Eclipsing Binary Stars with Additional Parameters, Astrophys., 60, 57
Andrych, K. D., Andronov, I. L., Chinarova L. L., & Marsakova V. I. 2015, "Asymptotic Parabola" Fits for Smoothing Generally Asymmetric Light Curves, Odessa Astron. Publ., 28, 158
Andrych, K. D., Andronov, I. L., & Chinarova L.L. 2020, MAVKA: Program Of Statistically Optimal Determination Of Phenomenological Parameters Of Extrema. Parabolic Spline Algorithm and Analysis of Variability of the Semi-Regular Star Z UMa, J. Phys. Stud., 24, 1902
Andrych, K. D. & Andronov, I. L. 2019, MAVKA: Software for Statistically Optimal Determination of Extrema, Open Eur. J. Variable Stars, 197, 65
Bradstreet, D. H. 2005, Fundamentals of Solving Eclipsing Binary Light Curves Using Binary Maker 3, SASS, 24, 23
Gaia Collaboration 2018, VizieR Online Data Catalog: Gaia DR2, 2018yCat.1345....0G
Gaia Collaboration 2018, Gaia Data Release 2. Summary of the Contents and Survey Properties, A&A, 616, A1
Han, K., Kim, Y., Andronov, I. L., et al. 2017, Quasi-periodic Oscillation of a Magnetic Cataclysmic Variable, DO Draconis, JASS, 34, 37
Kazarovets, E. V., Samus, N. N., Durlevich, O.V., et al. 2015, The 81st Name-List of Variable Stars. Part I – RA 00h to 17h30, IBVS, 6151, 1
Kallrath, J. & Milone, E. F. 2009, Eclipsing Binary Stars: Modeling and Analysis (New York: Springer)
Kim, D.-H., Kim, Y., Yoon, J.-N., & Im, H.-S. 2019, Development of a Period Analysis Algorithm for Detecting Variable Stars in Time-Series Observational Data, JASS, 36, 283
Kreiner, J. M., Kim, C.-H., Nha, I.-S. 2001, An Atlas of O-C Diagrams of Eclipsing Binary Stars (Cracow, Poland: Wydawnictwo Naukowe Akademii Pedagogicznej)
Kreiner J. M., Rucinski S., Zola S. et al. 2003, Physical Parameters of Components in Close Binary Systems. I, A&A, 412, 465
Marsakova, V. I. & Andronov, I. L. 1996, Local Fits of Signals with Asymptotic Branches, Odessa Astron. Publ., 9, 127
Mikulášek, Z. 2015, Phenomenological Modelling of Eclipsing System Light Curves, A&A, 584, A8
Samus, N. N., Kazarovets, E. V., Durlevich, O. V., et al. 2017, General Catalogue of Variable Stars: Version GCVS 5.1, Astron. Rep., 61, 80
Tkachenko, M. G., Andronov, I. L., & Chinarova, L. L. 2016, Phenomenological Parameters of the Prototype Eclipsing Binaries Algol, β Lyrae and W UMa, J. Phys. Stud., 20, 4902
Vavilova, I. B., Yatskiv, Ya. S., Pakuliak, L. K., et al. 2017, UkrVO Astroinformatics Software and Web-services, Proc. IAU, 12, 361
Virnina, N. A. 2010, New Binary Systems With Asymmetric Light Curves, Odessa Astron. Publ., 23, 143
Virnina, N. A. 2011, "Tsessevich" Project: An Attempt to Find the System YY Dra. I, Open Eur. J. Variable Stars, 133, 1
Wilson R. E. 1979, Eccentric Orbit Generalization and Simultaneous Solution of Binary Star Light and Velocity Curves, ApJ, 234, 1054
Wilson R. E. 1994, Binary-star light Curve Models, PASP, 106, 921
Wilson R. E. & Devinney, E. J. 1971, Realization of Accurate Close-Binary Light Curves: Application to MR Cygni, ApJ, 166, 605
Zoła, S., Kolonko, M., & Szczech, M. 1997, Analysis of a Photoelectric Light Curve of the W UMa-Type Binary ST Ind, A&A, 324, 1010
Zoła, S., Gazeas, K., Kreiner, J. M., et al. 2010, Physical Parameters of Components in Close Binary Systems – VII, MNRAS, 408, 464