POORELY STUDIED ECLIPSING BINARY IN THE FIELD OF DO DRA: V0455 DRA AND V0454 DRA

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Abstract: We report an analysis of two poorly studied systems GSC 04396-00605 and GSC 04395-00485, which were recently named as V0455 Dra and V0454 Dra, respectively. For two eclipsing stars, the periods and epochs were significantly corrected using our extensive data. 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 the accurate parameters using the "asymptotic parabola" approximations. The light curves were approximated using the Wilson-Devinney model, the best fit parameters are listed. For both systems, the presence of the dark spot is justified, the parameters are estimated. Both systems classified to be overcontact binaries of EW type. The observations were obtained using the 1-m Korean telescope of the LOAO while monitoring the cataclysmic variable DO Dra within the Inter-Longitude Astronomy" (ILA) project.

Key words: (stars:) binaries: eclipsing; methods: data analysis; stars: individual: V0455 Dra – V0454 Dra – DO Dra – GSC 04395-00485 – GSC 04396-00605 – V1517 Her

1. INTRODUCTION

All the stars become variable at some active stages of their evolution. Of the special interest, there are objects exhibiting few types of variability, e.g. cataclysmic variables and other interacting binaries, pulsating and eruptive variables. The photometrical monitoring of such objects needs many dozens or even hundred of nights, and may not be done at very large telescopes. This is a proper task for meter and sub-meter class telescopes. There are single- and multi-telescope projects on some selected stars. Among these projects, there is an international campaign ILA ("Inter-Longitude Astronomy", Andronov et al. (2003)). The most recent review on highlights was presented by Andronov et al. (2017).

One of the most interesting stars in our sample is DO Dra, which may represent a separate group of objects, being simultaneously the "magnetic dwarf nova" and the "outbursting intermediate polar". It has shown a variety of new phenomena like the "transient periodic oscillations" (TPO), dependence of the slope of the outburst decay on the brightness at maximum, 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).

Besides this very interesting object, there are other variables in the field. Two of them were discovered in a frame of the ILA project by Virina (2010) while searching for variability of stars on various fields. Virina (2011) reported on new variables in the field of DO Dra, presented finding charts and the preliminary parameters. The systems were classified as the \(\beta\) Lyr-type (EB) and W Uma-type (EW) objects. Recently, the stars got the official names V0454 Dra and V0455 Dra in the "General Catalogue of Variable Stars" (GCVS) (Kazarovets et al. (2015), Samus et al. (2017)). Names of the systems in other catalogues are 2MASS J11483649+7107507 = NOMAD-1 1611-1062691908235241216 = V0454 Dra = V454 Dra, 1611-00091333 = USNO-B1.0 1611-00091333 Gaia DR2 1062691908235241216 = V0454 Dra = V454 Dra, and 2MASS J11483649+7107507 = NOMAD-1 1611-0093251 = USNO-B1.0 1611-0091801 = V0454 Dra = V455 Dra.

The parallaxes for these stars are 0.7722±0.0201 mas and 0.8807±0.0186 mas (Gaia DR2 (2018), respectively).

2. OBSERVATIONS

Photometric observation data of DO Dra had been obtained from Mt. Lemmon optical astronomy observatory (LOAO) and Chungbuk national university observatory (CBNUO) for about 10 years from 2005 till 2014. The LOAO telescope located at Mt. Lemmon in Arizona is 1.0 m in diameter and the effective focal ratio
is \( f/7.5 \). It is mounted on a fork equatorial mount and adopts CCD with 0.64 arcsec/pixel, \( 2k \times 2k \) resolution, and its field of view (FOV) is \( 22.2 \times 22.2 \). The telescope at CBNUO is 0.6 m in diameter and its optical system is an R-C type with effective focal ratio of \( f/2.92 \). In 2012, a CCD with wide FOV of \( 72' \times 72' \) and \( 4k \times 4k (4096 \times 4096) \) pixel resolution was been installed.

The observations were made using the R filter, using the comparison star "Ref 2" from Virnina (2011) and adopting its magnitude \( RC = 13.04'' \) (\( V = 13.390'' \), \( V - R = 0.350'' \)) (Henden (2007)).

Totally, we have analyzed \( n = 1746 \) observations obtained during totally 112 hours distributed in 35 nights from JD 2456272 to 2456710 (total duration of the interval 438d).

### 3. Phenomenological Modelling

Phenomenological modelling of the light curves of eclipsing systems using "special shapes" (also called "patterns"), instead of trigonometrical polynomials, was proposed by Andronov (2012) initially for the Algol-type (EA) systems with very clear begin and end of the eclipse. Thus the algorithm was called NAV ("New Algol Variable").

However, it is effective also for EB (\( \beta \) Lyr) and EW (W UMa) type systems, also for the prototypes of these classes - \( \beta \) Per (Algol), \( \beta \) Lyr) and EW UMa (Tkachenko et al. (2016)).

For another eclipsing binary 2MASS J18024395 + 4003309 = VSX J180243.9+400331 (currently named as V1517 Her) in the field of the intermediate polar V1323 Her, Andronov et al. (2015) estimated physical parameters of the components, using two-color photometry and a statistical mass-radius-color index relation.

For the stars V0454 Dra and V0455 Dra, such a complete analysis is not possible, as the photometry is in one color only.

We have computed periodograms using trigonometrical polynomial (TP) approximations of various orders \( s \). Then the periods were corrected using differential equations (Andronov (1994)) according to the algorithm described by Andronov (1994) and Andronov and Marsakova (2006). The statistically optimal values degrees of the trigonometrical polynomial are \( s = 6 \) and \( s = 8 \) for V0454 Dra and V0455 Dra, respectively. The corresponding number of parameters are \( m = 2s + 2 \), i.e. \( m = 14 \) and 18, more than in the NAV algorithm even in this case of relatively smooth curves.

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).

### 4. Times of Extrema

For further studies of the period changes, it is important to publish individual times of extrema (e.g. 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 modelled the complete phase curve based on all observations. In individual nights, the complete length of the observational run is smaller than the period. Thus algorithms should take into account only the intervals close to an extremum.

We have determined the times of either minima, or maxima using the "running parabola" approximations, initially proposed by Marsakova and Andronov (1996) and realized in the software MAVKA (Andrych et al. (2015), Andrych et al. (2020)). This is one among the best (in accuracy) methods for determination of extrema from a relatively short intervals of observations near extremum, which only partially covers the descending and ascending branches.

The "special shapes" allow to avoid apparent waves, which are similar to the Gibbs phenomenon.

For longer series of observations, which completely cover ascending and descending branches, one may propose many modifications of known approximations. Andronov et al. (2017) compared almost 50 functions and ranked them according to the accuracy estimate. Some of them are improvements of phenomenological approximations proposed by Mikulášek (2015).

Andrych and Andronov (2019) realized 21 approximations of 11 types for the shorter intervals.

In the moments of the individual minima and maxima are listed. To spare place, we have not marked the type of extremum. It is obvious that the moments, which correspond to phases near 0 and 0.5, are main (min I) and secondary (min II) minima, and the rest are the maxima.

These moments may be used in further analysis, after adding further observations from other seasons, as typical timescale of the period variations are from year(s) due to third bodies, and much slower for the mass transfer (e.g. Kreiner et al. (2003)).

### 5. Physical Modelling

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

The algorithm was proposed by Wilson and Devinney (1971) and improved by Wilson (1979) and Wilson (1994). The WD algorithm allows to determine physical parameters of binary system due to the phase curve and radial velocity curves. For this task, the user has to pre-set the intervals of the physical parameter values and to fix some of them for reasons related to the typical relationships for the stars of corresponding type of variability.
Eclipsing Binaries V0454 Dra and V0455 Dra

Table 1
Parameters of the phenomenological modelling

| Parameter          | V0454 Dra | V0455 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$m$  |
| $C_5$              | 0.0922 ±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 ±0.00030$^d$ | 2456479.05227 ±0.00023$^d$ |
| $P$               | 0.43491412 ±0.00000091$^d$ | 0.37683317 ±0.00000071$^d$ |
| $d_1$             | 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$m$  |

E.g. the temperature at the first component at the pole $T_1$ was fixed to a reasonable value, as typically assumed in the models, whereas the temperature of the second component $T_2$ is a parameter being determined. The best fit estimate of $T_2$ is dependent on $T_1$ monotonically, but not exactly linearly. The surface potential $\Omega$ is expressed in units of square of the orbital velocity. As both stars overfill their Roche lobes and are at an over-contact 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 and Milone (2009).

The algorithm is based on a geometry Roche (Roche model) for the construction of a binary system, and uses the Monte-Carlo method to specify physical parameters and construct physical light curve. In this case, the WD-code allows to simulate different types of eclipsing systems from contact system to exoplanet transit.

We used the program to determine the physical parameters of the system, that is a modified version of the original WD-code created by Prof. S. Zola et al. at the Astronomical Observatory of Jagiellonian University in Krakow (Zola et al. 1997, Zola et al. 2010). This version can take into account up to two spots on components. The differential code method in the original code has been replaced with the Price algorithm (controlled Monte Carlo method). The version we use involves concretely the contact system, when both objects fill the Roche lobes and they 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 tidal deformed and have circular orbits.

The co-latitude of the center of the spot varies from 0° at the north pole of the star to 180° at the south one. The spot center’s longitude varies from 0° to 360°, starting from the center line of the stars counter-clockwise.

Using the version of the original WD code created at the Jagiellonian Astronomical Observatory in Krakow by Prof. S. Zola and others, we did a physical simulation of the eclipsing binary systems V0455 Dra and V0454 Dra. For these objects, we have only the phase curve in one filter, so some parameters and their possible intervals we fix as they can be. Physical parameters of components in close binary systems were discussed e.g. by Kreiner et al. (2003).

The light curves for both objects obtained from the simulation are shown in Fig. 3 and 4 along with observations. The resulting physical parameters are shown in Table 2.

It should be noted that this is not a unique solution. There is a region in the parameter space, where the quality of the approximation is almost the same. There are pairs of parameters, which can compensate the influence of another one significantly, e.g. the temperatures of both components, the inclination and the potential, the radius of the spot and the temperature parameter.

With Binary Maker 3 Bradstreet (2005), we built a visual model of the system with the appropriate physical parameters. In Fig. 5 and Fig. 6, the respective system models are shown. The phases are 0.24 and 0.74, where the spot and both components are seen. The red crosses represent the centers of stars and the positions of the center of mass of the system. The red circles indicate the orbits of the components around the common center of mass. To build the model, 120 points per meridian and 240 points per parallel are taken for each star.
Table 2
Moments of individual maxima and minima of V0454 Dra and V0455 Dra

|        | BJD-2400000 ± | BJD-2400000 ± | BJD-2400000 ± |
|--------|---------------|---------------|---------------|
| **V0454 Dra** | 56434.04771 0.0049 | 56394.07646 0.0007 | 56346.30781 0.0006 |
|         | 56272.36895 0.0006 | 56650.31266 0.0015 | 56394.16601 0.0005 |
|         | 56346.30781 0.0006 | 56654.33204 0.0008 | 56413.97503 0.0008 |
|         | 56357.18191 0.0008 | 56667.27487 0.0006 | 56413.10723 0.0007 |
|         | 56360.22388 0.0013 | 56710.22508 0.0019 | 56413.00769 0.0010 |
| **V0455 Dra** | 56429.03185 0.0026 | 56363.26942 0.0009 | 56366.02193 0.0009 |
|         | 56366.20593 0.0007 | 56346.31053 0.0019 | 56650.32477 0.0043 |
|         | 56373.05427 0.0013 | 56355.26561 0.0015 | 56658.52820 0.0015 |
|         | 56394.14774 0.0006 | 56355.06032 0.0012 | 56658.32863 0.0007 |
|         | 56401.10329 0.0012 | 56357.33556 0.0040 | 56409.04061 0.0012 |
|         | 56411.97798 0.0020 | 56360.16278 0.0009 | 56412.08446 0.0009 |
|         | 56412.08446 0.0009 | 56363.17623 0.0008 | 56413.06679 0.0006 |
|         | 56413.06679 0.0006 | 56363.26870 0.0020 | 56429.04618 0.0005 |
|         | 56432.98510 0.0009 | 56366.18734 0.0019 | 56432.98510 0.0009 |

Table 3
Parameters of the physical modelling

| Parameter | V0454 Dra | V0455 Dra |
|-----------|-----------|-----------|
| Orbit inclination | 74.67 ± 0.06° | 64. ± 0.03° |
| Temperature of the first star | 5800 K | 5500 K |
| Temperature of the 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 the spot’s center | 90° | 133 ± 1.3° |
| Longitude of the spot’s center | 356.9 ± 0.2° | 71 ± 1.3° |
| Spot radius | 22.5 ± 0.2° | 18.9 ± 0.74° |
| Spot temperature (in the star temperature units) | 0.8 | 0.6 |

6. Conclusions

Photometric series for two poorly known stars V454 Dra and V455 Dra were analysed using phenomenological approximations of the complete phase light curve (using the trigonometrical polynomial and the NAV algorithms), as well as individual series near maxima and minima (using the “asymptotic parabola” algorithm implemented in a recently developed software MAVKA), the corresponding database of almost 70 moments was compiled. It may be used after years of further monitoring, to look for possible period variations.

The NAV algorithm shows better approximation in a physical sense, as the minima are modelled using the special shape, instead of the trigonometrical polynomial. The eclipses split the phase curve into four parts, so the smooth approximation using the trigonometrical polynomial is not justified physically.

These observations were also used for physical modelling according to the Wilson-Devinney algorithm. The set of physical parameters, which were determined, may be used as an initial approximation, which may be improved using possible further spectral observations (to determine the mass ratio and temperatures) or well-calibrated multi-color photometry (to determine temperatures). For both systems, the dark spot is evident, the parameters are estimated.

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Figure 1. The phase light curve of V0454 Dra and it’s approximation using the NAV algorithm. A smooth line above the eclipse corresponds to the "out-of-eclipse" continuum approximated by a trigonometrical polynomial of order 2.

Figure 2. The phase light curve of V0455 Dra and it’s approximation using the NAV algorithm. A smooth line above the eclipse corresponds to the "out-of-eclipse" continuum approximated by a trigonometrical polynomial of order 2.

Figure 3. The phase light curve of V0454 Dra and it’s approximation using Wilson-Devinney algorithm.

Figure 4. The phase light curve of V0455 Dra and it’s approximation using Wilson-Devinney algorithm.

Figure 5. The model of V0454 Dra and it’s cold spot. The adopted phase for the best viewing is $\phi = 0.74$.

Figure 6. The model of V0455 Dra and it’s cold spot. The adopted phase for the best viewing is $\phi = 0.24$.

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