https://doi.org/10.18524/1810-4215.2023.36.289990

A NEW APPROACH TO THE ANALYSIS OF LIGHT CURVES OF PULSATING RR LYRAE STARS WITH THE BLAZHKO EFFECT

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ABSTRACT. We discuss the new approach for the analysis of the long-term dense series of observations of RR Lyr-type pulsating stars with the Blazhko effect. The standard way, namely The frequency analysis of the O–C values for the times of maxima does not allow for to detection of the complex nature of the periodic changes in the shape of the light curves, including bi-cyclicity. We have shown the perspectives of a new approach on the example of the analysis of FI Sge variable observations containing a total of 55 observational nights during a period of five years (AZT-3 Telescope, Mayaki Observational Station, SRI "Astronomical Observatory", I.I. Mechnikov ONU). The study is based on the data obtained by S.N. Udovichenko during the 2013 and 2014 observational seasons as well as on data obtained by S.N. Udovichenko and the author during the 2018 observational season.

Our results show that in order to understand the features in the shape of the light curve variations for RR Lyr type pulsating stars with the Blazhko effect, it is necessary to have data for full cycles of variability over a long time, and not just the moments of maxima.

Keywords: pulsating stars: RR Lyr type: Blazhko effect; data analysis.

АНОТАЦІЯ. Обговорюються результати нового підходу до аналізу довготривалих рядів спостережень пульсуючих зір типу RR Ліри з ефектом Блажка. Стандартний спосіб, а саме частотний аналіз значень O–C для моментів максимумів, не дозволяє виявити складний характер періодичних змін форми кривих блиску, в тому числі бі-циклічність, тобто, форми послідовних максимумів, що систематично розрізняються. Для уточнення періодів пульсацій та ефекту Блажка необхідно використовувати довготривалі щільні ряди спостережень, що охоплюють усі фази кривої блиску. Далі при аналізі необхідно враховувати вплив бі-циклічності, а також різний прояв ефекту Блажка для максимумів, що чергуються. Перспективність нового підходу ми показали на прикладі аналізу даних спостережень FI Sge, що охоплюють загалом 55 спостережних ночей за п'ять років (телескоп АЗТ-3, спостережна станція Маяки, НДІ "Астрономічна обсерваторія" ОНУ імені І.І. Мечникова). Спостереження 2013 та 2014 року було отримано С.М. Удовиченко. Спостереження 2018 року отримано спільно автором та С.М. Удовиченко.

Новий підхід дозволив уточнити період пульсацій FI Sge. Крім того, на підставі довгого ряду спостережень було виявлено новий ефект, а саме, зсув моментів максимумів блиску вбік початкової епохи. З новим значенням періоду та врахуванням виявленого ефекту ми побудували нову фазову криву блиску для повного ряду спостережень. Нова фазова крива відповідає теорії пульсацій для зір типу RR Ліри з ефектом Блажка. Наші результати показують, що для розуміння особливостей форми змін кривої блиску пульсуючих зір типу RR Лір з ефектом Блажка необхідно мати дані для повних циклів змінності протягом тривалого часу, а не лише для моментів максимумів.

Ключові слова: пульсуючи зорі: зорі типу RR Lyr: ефект Блажка; аналіз даних.

1. Introduction

At the present time, the technique for processing observation series of pulsating variable stars is currently established. Typically, the analysis of observational data begins with determining the period of variability. To do this, the brightness values and moments of brightness maxima are determined, and then a phase curve is plotted. In this case, a period of variability is selected such that the scatter of the moments of brightness maxima $(O-C)$ is minimal. However, the way minimizing the scatter of brightness maxima does not give both the good values of the period and a phase curve for the RR Lyrae-type stars with the Blazhko effect. The fact is that in pulsating variable stars of the RR- Lyrae type, in addition to the Blazhko effect, at least two more features of brightness changes are possible, which are lost with this data processing technique. They are the bi-cyclical effect and the effect of shifting the moments of maximums. Ignoring these phenomena leads to an incorrect determination of the period of variability, a distortion of the position of the observed data on the phase curve, and, ultimately, an incorrect analysis of the physical processes occurring in pulsating variable stars. We will look at the manifestations of both these effects and illustrate them using data for the star FI Sge.

The first effect, "bi-cyclicality" was detail described in 2016, in the review paper by Smolec (2016), where he gave an analysis of the data available at that time regarding observations of pulsating variable stars with the Blazhko effect and highlighted the effect of bi-periodicity (period doubling), discovered due to observations of the Kepler space telescope. The term "period doubling" is used to the effect when two successive pulse cycles show systematically stable, alternating variations in the amplitude of the maxima. These variations for RR Lyrae-type stars were first detected in the observational data of the Kepler telescope (Kolenberg et al., 2010), and the typical light curve is shown in Fig. 1.

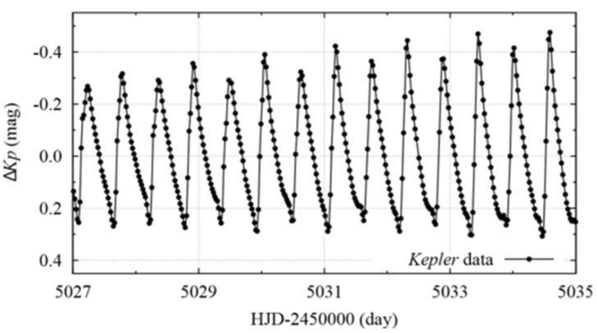

Figure 1: The bi-cyclicity (period-doubling) effect. Average light curve of RR Lyr according to Kepler space telescope data (from Smolec, 2016)

Subsequent studies (Szabo et al., 2010 and Szabo et al., 2014) indicated this effect could not be explained either by two oscillation modes or by oscillations of two different periods. In fact, the bi-periodicity effect is a fairly well-known phenomenon that is observed in type II Cepheids (Soszynski et al., 2011, Smolec et al., 2016). The alternation of amplitude changes is constant, although the pulsations themselves may be irregular for these stars, and modelling shows bi-periodicity may be the beginning of irregular variability (Kovacs & Buchler, 1988). The alternation of amplitude for RR Lyrae-type stars with the Blazhko effect has a different nature. We suppose the use of the term "bi-periodicity" for stars with the Blazhko effect will be false, and we'll use the term "bi-cyclicality" to denote the above effect. Surely, the question is why, for more than 100 years of observations of variable stars with the Blazhko effect from Earth, the bi-cyclicality effect was not discovered? Smolec (2016) explains this by the "unfortunate" average pulsation period for RR Lyrae-type stars, equal to 0.5 days. That is, due to the selection of observations we observe the star with such a period every night practically in the same pulsation cycle. The next pulsation cycle occurs during daylight hours and it is lost.

Fortunately, the pulsation periods of RR Lyrae-type stars do not always exactly coincide with 0.5 days. For example, for the star FI Sge, which was selected for the detailed study, the period of variability noted in the GCVS (Samus et al., 2017) is 0.5047545^d. This means that every night our observations shift along the light curve to the earlier phase, and after 106 cycles (or 53.42 days) we can observe the "previous" cycle. Why did never detect the bi-cyclical effect for FI Sge? The difference in the amplitudes of neighboring cycles reaches 0.1 magnitude, it is not a detection problem even for medium-size telescopes. The problem is determined by the duration of observations and mainly in the methodology for processing observational data of pulsating variable stars with the Blazhko effect. It has always been believed that for pulsating variable stars the most important part of the light curves is the region of the maxima. Determining the moments of the maxima allows to determine the pulsation period and combine all observations into one phase curve and the observation programs were built in accordance with this idea. Thus, the observers themselves increased the duty cycle of the observational data, skipping "unimportan" parts of the light curve. Observations became selective, only the maxima moments, as well as possible changes in their values and phase, were fixed. The base reason for not detecting the bi-cyclicality effect from the Earth is this approach: the short series of fragmentary observations.

The Blazhko effect consists of periodic modulation of the amplitude and period of the star brightness variability. The values of the brightness maxima change by no more than $0.3 \sim 0.4^m$, and the period does not change more than 0.2 of the period. If we place all the observational data on one phase curve, then even if they contain two cycles of different formats, the bi-cyclicality effect is silted up by the Blazhko effect, which has large changes in amplitude. Thus, it was impossible to identify the effect of bi-cyclicality using the short series of observations and a single-period phase curve for all observed data to analyze the variability.

In order not to lose the bi-cyclicality effect during processing, we began to use double the pulsation period when constructing the phase curve. In this way the observational data are automatically divided into two cycles with different formats: the "main" cycle, with a larger maximum amplitude, and the "neighboring" cycle, with a smaller amplitude, and the identification of the bi-cyclical format of bi-cyclical maximum is strongly needed.

2. Observational data and light curve building

We select FI Sge for our detailed study of the RR Lyrae-type stars' light curve possible variations. FI Sge ($RA_{2000.0} = 20^h13^m16.2^s$; $Dec_{2000.0} = +17°30'37''$; type: RRab; $V = 13.2 - 14.3^m$ (p); $E = 2428333.441^d$; $P = 0.5047545^d$; Sp = A2; $P(Bl) = 22.4^d$ according to GCVS (Samus et al., 2017) is the star included in the program of RR Lyrae-type variables of the Scientific Research Institute "Astronomical Observatory" of Odessa I. I. Mechnikov National University. The star was observed for a total of 55 nights during the observation seasons of 2013, 2014, and 2018, at the observation station Mayaki of the SRI "Astronomic Observatory" using AZT-3 telescope equipped CCD Sony ICX429ALL. A total of 5500 frames were obtained in the V photometric band for the entire time of observations, including 26 photometrical maxima. The comparison star was UCAC4-538-127214 $RA_{2000.0} = 20^h13^m14.876^s$, $Dec_{2000.0} = +17○33'39.95''$, $V{=}13.36^m$). We also used data from Skarka & Cagas (2017), obtained in 2017.

The basis for constructing a phase curve is the period of variability and the initial epoch. Another value of the initial epoch results in a uniform shift of all observed data by a fixed value in time. On the contrary, a change in period leads to a radical change in the location of all observational data on the phase curve. Skarka & Cagas (2017) found another value $P = 0.5047544837^d$ using times of maxima obtained in 2017. We use this value for the building FI Sge light curve for our data set (Fig. 2, left panel). One can clearly see the different positions of the maxima relative to the zero value and the period value is needed if the updating.

We checked the possible influence of the bi-cyclical effect on the light curve and the result is present in Fig. 2, right panel. The maxima positions show a tendency to group together. In addition, we showed the time between neighboring maxima in the bi-cycles exactly corresponds to two pulsation periods, then the time between the maxima of cycles varies from 0.96 to 1.04 phases of the period depending on the location of the cycles (Fig. 3). Moreover, we can suppose the presence of the Blazhko effect for both elements of the bi-cyclisity. So, for FI Sge we must determine the period taking into account both the bi-cyclical and the Blazhko effects.

We concluded an attempt to minimize the scatter of observational data leads to an incorrect choice of period and, as a consequence, to a distortion of the entire picture of the overall phase curve. Therefore, we abandoned the generally accepted method of determining the period and began to look for another method based on a different period search criterion.

3. The Period Search

In our new approach, we assumed that the pulsations of RR Lyrae-type stars are a periodic, continuous process in which the light curves must smoothly transform into each other from night to night. The Blazhko effect should contribute to the dynamics of changes in light curves. The bi-cyclicality effect can be eliminated by considering the light curves of the different parts of bi-cycles (different formats of maxima). We took the longest continuous series of observations in September – October 2018 (15 nights), and analyzed changes in the amplitude, phase and shape of the brightness maximum depending on the selected period. The analysis showed that the best convergence of data and dynamics of changes in light curves for the star FI Sge is provided by a period of 0.50500^d. The difference between this period and that taken from the GCVS for this star is only 0.05%, however, over a large observational interval (5 years), this radically changes the appearance of the phase curve.

Based on the new value of the pulsating period for the star FI Sge, it was possible to determine an additional period of brightness variations equal to 58 pulsation cycles, or 29.29 days. It is impossible to call this value the period of the Blazhko effect, since it is not possible to fit a change in amplitude 0.3^m into this time interval. The dynamic of changes in the amplitude of the maxima for individual series of observations shows that this is impossible. Changes in the brightness amplitude over such a time interval can be no more than 0.1^m. The result is not typical, but it has to be taken into account. The study of the phase curve with a new period revealed identical, discrete, irregular shifts of the moments of the maxima to the initial epoch (Fig. 5). That is, in addition to the Blazhko effect and the bi-cyclicality effect, the star FI Sge has a third effect that complicates the processing of observational data. It should be taken into account that a shift in the moment of maximum in any cycle leads to changes in all subsequent cycles. Based on the above, we assumed the dependence of such shifts on already known effects: the Blazhko effect and the bi-cyclical effect. The bi-cyclicality effect gives us the possibility of the existence of two successive shifts with a difference of 29.29 days,

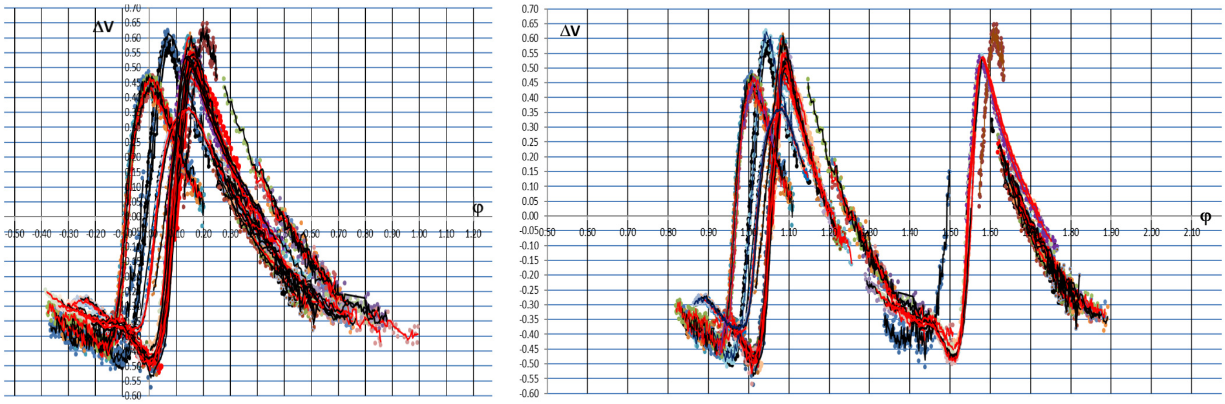

Figure 2: Average light curve of FI Sge for the period P=0.5047544837^d (Skarka & Cagas, 2017) for our data set, left. Bi-cyclical light curve of FI Sge for the same data and period, right

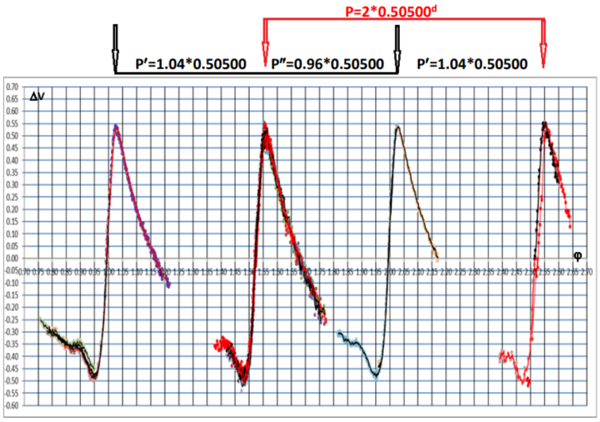

Figure 3: The difference between the tined if maxima for bi-cyclical light curve of FI Sge

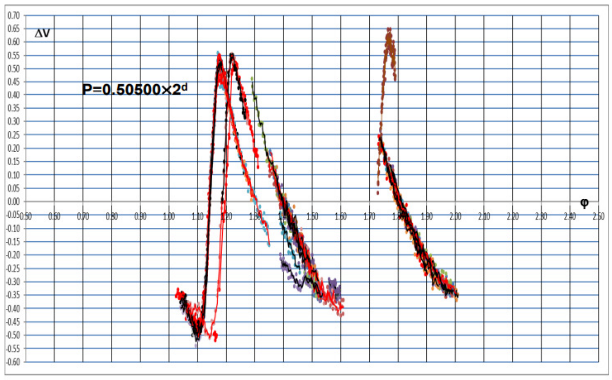

Figure 4: Observations of FI Sge 2018. Manifestation of the effect of displacement if times of maxima to the initial epoch for cycles of different formats

which corresponds to the maximum amplitude of cycles of two different formats, and the Blazhko effect gives a period of 29.29 days. However, between two shifts in the moments of the maxima there are five intervals of 29.29 days, when no shifts occur. It is this periodic order that makes it possible to explain the position of the moments of the maxima over the entire observation interval. It is this order that makes it possible to take into account the shift of the moments of the maxima and to construct for all observational data a common phase curve that corresponds to modern concepts of the theory of pulsations (Fig. 5).

4. Complex Blazhko effect

Above we noted: "The dynamics of changes in the amplitude of the maxima for individual series of observations shows that it is impossible to fit changes in the amplitude of the Blazhko effect ($0.3 \sim 0.4^m$) into the period of change in the moments of the maxima of 29.29 days". We have to assume that during this period there is a modulation of the amplitude up to $\sim 0.1^m$, which has its own local minimum and its own local maximum. Thus, the amplitude of the maximum during three such intervals decreases by 0.3^m and reaches its minimum, then after another three such cycles it increases by $\sim 0.3^m$ and reaches a maximum. After six periods of 29.29 days, that is, after 175.74 days, the amplitude reaches its maximum possible value and a shift maximum occurs in the next cycle. This is a model for a cycle of one of the formats. The same thing happens with a cycle of different formats but with a time shift of 29.29 days. Since cycles of different formats influence each other, displacements occur only when each of the cycles of different formats is at its common maximum. As a result, we observe two consecutive shifts with an interval of 29.29 days

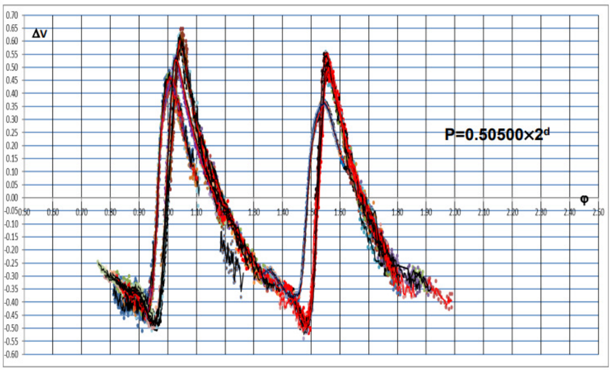

Figure 5: Observations of FI Sge 2018. The final phase light curve, taking into account the effect of bi-cyclicity and the effect of shifts of the brightness maxima

and five gaps between them. Then this entire cycle of changes is repeated periodically. Thus, we believe that the Blazhko effect for this star is a rather complex process, accompanied by shifts in the moments of the maxima to the initial epoch, and its period is 175.74 days. All of the above leads us to the conclusion that the Blazhko effect may be more complex than we imagined, and that the methodology for processing observations for pulsating variable stars with the Blazhko effect needs to be slightly changed.

5. Conclusions

Our analysis of the long-time series of observations of FI Sge allows to make the next conclusion:

Firstly, a much longer series of photometric observations are needed, since the period of the complex Blazhko effect can be more than six months.

Secondly, it is impossible to apply to pulsating stars with the Blazhko effect the method of determining the period by minimization $(O-C)$ values for the moments of maxima, since the existence of a bi-cyclicality effect and the effect of shifting the moments of maxima is leading to errors in determining the period using this method.

Thirdly, to construct the phase curve of such stars, it is necessary to use a double period to divide cycles into formats and be sure to identify observational data according to the bi-cyclical “phase”.

Fourthly, if the effect of shifting the moments of maxima is detected, it is necessary to determine its value and the order of periodicity in order to take these shifts into account when constructing the phase curve.

Further studies of pulsating variable stars with the Blazhko effect are very important to clarify the essence of the processes occurring in these stars and to construct a physical theory of the Blazhko effect.

Acknowledgements. This research has made use of NASA’s Astrophysics Data System. Author thanks S. N. Udovichenko for providing the data set of FI Sge of the observation 2013 and 2014 seasons and for the assistance in obtaining and data processing. Author thankful to E. Panko for fruitful discussions during the preparation of the paper.

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