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THE FEATURES OF FI SGE PHOTOMETRIC VARIABILITY ON TRANSITING EXOPLANET SURVEY SATELLITE OBSERVATIONS

L. E. Keir[1,2], E. A. Panko[2], M. Yu. Pyatnytskyy[3],

[1] Vihorlat Astronomical Observatory, Humenne, Slovakia,
partneroae@gmail.com

[2] Odesa I. I. Mechnikov National University, Odesa, Ukraine,
panko.elena@gmail.com

[3] Private Observatory "Osokorky", Kyiv, Ukraine,
mpyat2@gmail.com

ABSTRACT. We present the result of the analysis of the FI Sge individual light curves constructed on Transiting Exoplanet Survey Satellite (TESS) observations. FI Sge the RR Lyrae pulsating variable star with bicyclicity effects and possible Blazhko effect. In the present study, we analyzed 3603 photometric data obtained by the Transiting Exoplanet Survey Satellite (TESS) in the special TESS IR bandpass with a time resolution of about 10 minutes. The observations covered a 27-day interval (BJD 2459769.90 – 2459796.12) with a small gap of about a day. The full data set contains 52 minima and 51 maxima of the seasonal light curve. We suppose that for this data set, the analysis of the light curve shapes in minima provides more reliable results. We studied the variations of the minima' shapes of the individual light curves at common and for the separate affinity groups. The last one allowed us to detect not only classical bicyclicity, but also secondary bicyclicity for FI Sge. This result was obtained at first and it is atypical behavior of light curves for pulsating variable stars.

Keywords: pulsating stars: RR Lyr type: light curves; Blazhko effect; bicyclicity; data analysis

АНОТАЦІЯ. Ми представляємо результат аналізу індивідуальних кривих блиску FI Sge, побудованих на основі спостережень Transiting Exoplanet Survey Satellite (TESS). FI Sge – пульсуюча змінна зоря типу RR Ліри з виявленою біциклічністю та ймовірним ефектом Блажка. У цьому дослідженні ми проаналізували 3603 фотометричних точок, отриманих супутником TESS в інфрачервоній фотометричній смузі TESS з часовою роздільною здатністю близько 10 хвилин. Спостереження охоплювали 27-денний інтервал (BJD 2459769.90 – 2459796.12) з перервою у спостереженнях близько доби. Повний набір даних містить 52 мінімуми та 51 максимум сезонної кривої блиску. Ми вважаємо, що для цього набору даних аналіз форми кривої блиску в мінімумах дає більш надійні та значущі результати. Ми проаналізували варіації форм мінімумів окремих кривих блиску для повного набору даних та для окремих груп спорідненості. Останній підхід дозволив нам виявити для FI Sge не тільки класичну біциклічність, але й вторинну біциклічність. Цей результат був отриманий вперше, і він є нетиповою поведінкою кривих блиску для пульсуючих змінних зір.

Ключові слова: пульсуючі зорі: RR Lyr тип: криві блиску; ефект Блажка; біциклічність; аналіз даних.

1. Introduction

The poorly studied pulsating variable of the RR Lyrae type FI Sge ($RA_{2000.0} = 20^h13^m16.2^s$, $Dec_{2000.0} = +17°30'37''$, RRab, magnitude in the limits of $13.2 - 14.3^m(p)$, Sp = A2) in a long dense series of observations shows atypical brightness variations for this type of star. The variability of the star was discovered in 1936 by Hoffmeister (1936) from photographic plates of the Sonnenberg Observatory. According to GCVS 5 (and GCVS 4), the initial pulsation epoch and period of the star are: $E = 2428333.441^d$ and $P = 0.5047545^d$ (Samus et al., 2017). Nevertheless, some other values of the pulsating period were published. Mainz (2017), based on her own observations, which were carried out over 5 nights in April 2017, determined the period value to be 0.50477d. She also analyzed the $(O-C)$ variations of the times of maxima using available literature sources (Richter, 1961, Wils et al., 2006, and Agerer & Hubscher, 2002), and suggested that the period changed after the epoch of 2452000 J.D. As a result, the phase light curves with the new period value, constructed using the NSVS and ASAS data, differ from each other in amplitude and phase. The phase shift from the initial epoch of the phase light curve according to the NSVS data was 0.15 of the variability period. Skarka and Cagas observed FI Sge without a filter over 14 nights in August, September, and October of 2017 (Skarka & Cagas, 2017). Based on these observations, they found evidence of the Blazhko effect for FI Sge with a period of 22.4 days, in contrast to Mainz, who did not detect this effect (Mainz, 2017). More, in the list of 242 known Galactic field stars exhibiting the Blazhko effect FI Sge does not present (Skarka, 2013).

In the Gaia DR2 (Gaia Collaboration, 2018) the period for FI Sge, corresponding to the fundamental pulsation mode, is noted as 0.50479709^d. Keir (2023) determined pulsation period as 0.50500^d, based on the long-term dense series of observations, which contained total data of 55 nights of the observation seasons of 2013, 2014, and 2018. These data also allowed detection of the bicyclicity effect for FI Sge(Keir, 2023, Keir & Udovichenko, 2024). So, FI Sge is a star RRab type with bicyclicity and possible Blazhko effect.

The bicyclicity phenomenon in RR Lyr stars with the Blazhko effect was discovered in 2010 from Kepler observations and described by Smolec (2016). For the stars showing the bicyclicity effect, two consecutive pulsation cycles have different amplitudes of the light-curve maxima and different modulations of these maxima. Nevertheless, the difference in the amplitude of successive maxima alone cannot be a determining feature of this phenomenon. With different modulation dynamics in adjacent cycles, a situation may arise in which the observation period coincides with the moment when the amplitudes of consecutive maxima will differ slightly. In this case, the effect of bicyclicity will be smoothed out. We believe that the phenomenon of bicyclicity is determined precisely by the difference between two adjacent pulsation cycles. Namely, bicyclicity manifests itself in differences in the amplitude and shape of both minima and maxima, as well as in the dynamics of these differences. Taking into consideration all these differences, the phenomenon of bicyclicity cannot be explained by oscillations with two different periods or two different pulsation modes.

2. Observational data

Our observational data set contains 3603 individual photometric data obtained by the Transiting Exoplanet Survey Satellite (TESS) in the $600 - 1000\,nm$ photometric bandpass. The red end of the bandpass represents the red limit of TESS detector sensitivity, and the width of $400\,nm$ was the largest practical choice for the cosmic IR observations. This bandpass is centered on the traditional I_C band but is much wider. It is comparable to the union of the R_C, I_C, and z bands (Ricker et al., 2015). The observations span a 27-day interval (BJD 2459769.90 $-$ 2459796.12) with a small gap over a day. The full data set contains 52 minima and 51 maxima of the seasonal light curve. The brightness of the star varied from 12.829^m to 13.616^m.

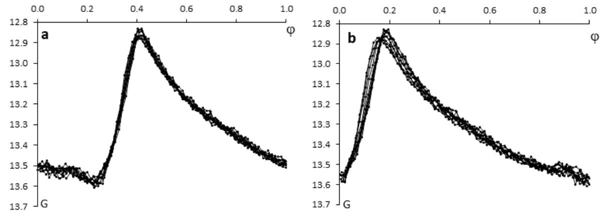

Figure 1: TESS observation data for FI Sge. They are shown: *a*) 10 phase light curves of FI Sge, constructed with a variability period of 0.504748^d, and *b*) the same data constructed with a period of 0.50500^d

If we represent the observation data in a dot plot, we can't detect the relationships between individual light curves (Fig. 1*a*, for example). In the classical dots' representation, we lose the opportunity to trace the dynamics of the light curve changes from cycle to cycle. We assume all points are important and reflect the individual characteristics of individual pulsation cycles. In a dot plot, we perceive the scatter of observational data points as variations in the light curves due to observational errors. Using the line-dot plots, we can trace to a change in the shape of light curves in the individual cycles. The result we obtained by applying the $O - C$ minimum method to determine the variability period is shown in Fig. 1*a*. We see scattered data defining some mean curve.

However, for pulsating stars, modulation of the brightness amplitude without modulation of the period contradicts the theory of these stars' pulsations. Using $O - C$ technique to determine the variability period of FI Sge, we obtain a false value for the variability period. Using the period determined for this star by another method (Keir, 2023), we obtain phase curves in which modulation of the brightness amplitude is accompanied by modulation of the pulsation period. Lower brightness maxima correspond to shorter pulsation periods. Maxima with a larger brightness amplitude correspond to longer pulsation periods (Fig. 1*b*).

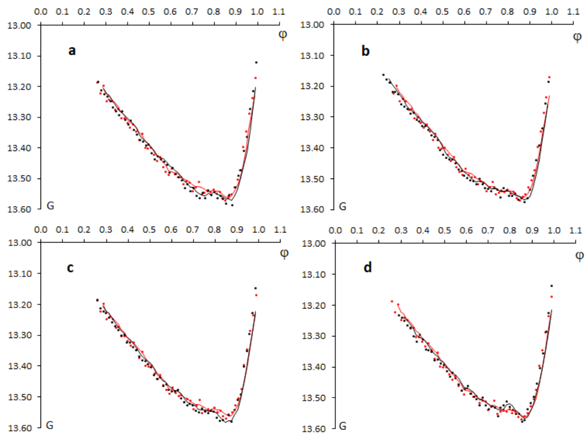

Figure 2: Difference in shapes of 5 sequential light curves' minima. Cycle number 1 is shown as red and others are shown as black: *a*) cycles 1 and 2, *b*) cycles 1 and 3, *c*) cycles 1 and 4, *d*) cycles 1 and 5

3. Light curves analysis and discussion

We approximated the light curves' maxima and minima by sixth-degree polynomials and determined phases and amplitudes of the maxima and minima (Fig. 2*a*,*b*). The amplitude of adjacent maxima changes only slightly over this time ($0.01 - 0.02^m$). The TESS telescope's time resolution is 10 minutes, so the maxima are recorded by 3 or 4 points only. Given that the shape of this star's light curve changes during pulsations, we suppose that maxima approximating do not provide a very reliable result in this case. Therefore, we investigated the dynamics of changes in the light curve shapes at minima in all pulsation cycles.

We smoothed the observational data with a three-point moving average and constructed 2D affinity diagrams. In these diagrams, we horizontally plotted two light curves with two minima in the each diagram, namely: 1+2, 1+3, 1+4, 1+5. Vertically, we took all the minima in order: 1, 2, 3, ...52. We obtained an affinity matrix consisting of 208 diagrams. The first row of this matrix is shown in Fig. 2. The figure shows that the plots with adjacent minima (1+2, 2+3...) and minima separated by 2 (1+4, 2+5...) coincide with each other much worse than the plots with minima separated by 1 (1+3, 2+4...) and by 3 (1+5, 2+6...). Other rows of the affinity matrix show a similar coincidence. Therefore, we divided all the graphs with minima into two groups: odd (1, 3, 5,... 51) and even (2, 4, 6, ... 52). This division reflects that the shapes of the minima of adjacent pulsation cycles are different. Thus, the pulsation cycles are different. This behavior of pulsation cycles is characteristic of the phenomenon of bicyclicity.

We also compared similar affinity diagrams with

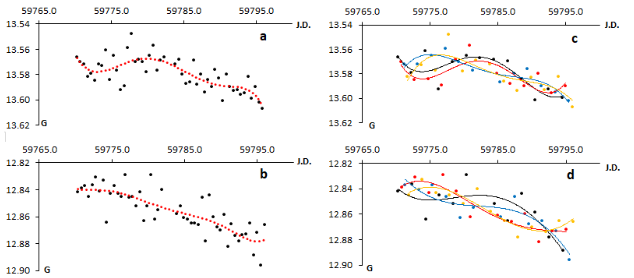

Figure 3: The BJD moments are shown: *a*) for minima for all cycles, *b*) for maxima for all cycles. The same diagrams: *c*) for the minima in the affinity groups, *d*) the maxima in the affinity groups, and the approximation for different affinity groups, are present as color lines

minima at intervals of 1 and 3 cycles, that is, 1+3, 2+4..., and 1+5, 2+6... The similarity of the diagrams at intervals of 3 cycles was better. Therefore, we further divided the odd and even minima into two groups. All odd ones at intervals of 1, 5, 9, 13,... 49 and 3, 7, 11, 15,... 51. All even ones at intervals of 2, 6, 10, ... 50 and 4, 8, 12, 16, ... 52. Thus, we obtained four groups of the most similar light curve minimum plots. This repeated division of minima characterizes a phenomenon that we conventionally call secondary bicyclicity. Next, we divided all the minima and corresponding maxima into four groups, accordingly to the above. In Fig. 3, we compare the BJD times of minima and maxima for all cycles (Fig. 3 *a*,*b*) and separately for affinity groups, approximating their points with fourth-degree polynomials (Fig. 3*c*,*d*).

From (Fig. 3*c*,*d*), it is clearly seen that graphs are divided according to the times of the minima and maxima. The times of the maxima are grouped according to the cycles' affinity: $1 - 3$ and $2 - 4$. The times of the maxima are grouped according to the cycles' affinity: $1 - 2$ and $3 - 4$. This division of the graphs of the moments of minima suggests that several processes overlap at the moments of minimum, and pulsations and minima for stars of this type are not an unambiguous criterion of their pulsation activity. The best marker for sorting a light curve by affinity group and secondary bicyclicity is its shape at the minimum. We suggest that this phenomenon still requires further study and analysis.

4. Conclusion

1. Our analysis of the FI Sge light curves' shape in minima indicated that, despite low pulsation activity at the dates of observations, bicyclicity and secondary bicyclicity were detected.

2. Dividing minima into affinity groups allows for

analysis of changes in stellar activity dynamics within each minima group separately.

3. Dividing minima into affinity groups allows tracing the bicyclicity and secondary bicyclicity effects.

4. In the star FI Sge, at certain time intervals, a decrease in the amplitude of maximum brightness is observed, accompanied by a decrease in the amplitude of minimum brightness, which is atypical for pulsating variable stars.

5. For pulsating stars with amplitude modulation, it is not recommended to determine the variability period using the $O - C$ minimum method. This can lead to a false determination of the variability period.

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