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HD 51940[1] — A Probable New Heartbeat Star System

Tian Qiu[1*†], Yushu Liu[2†], Haoxuan Yu[3†], Changxuan Li[4†], Yurui Tao[5†]

[1]HT Nanjing School, Nanjing, China
[2]Beijing No.2 Middle School, Beijing, China
[3]The High School Affiliated to Renmin University of China, Beijing, China
[4]Beijing Haidian Foreign Language School, Beijing, China
[5]Saint John Preparatory High School, USA
**Corresponding Author. Email: 2305498@stu.htschools.org*
[†]co-first authors

Abstract: HD-51940 is a system with periodic variations in its light curve that resemble those of heartbeat stars(HBS). The system's host shows periodic flux changes. The period is approximately 1.87 days, with a transit depth of 0.15%. However, further research needs more information to study this system. It was initially classified as a possible host of a transiting planet. The number of potential hosts in the system is a mystery. Could HD-51940 be a heartbeat star? To find the answer, we first compared the characteristics of HD-51940 with other defined HBS. We used the Kumar model to fit the light curve and best period of HD-51940, and last, we computed the Fourier transform of the light curve to seek evidence for tidally induced oscillations that would be diagnostic of a heartbeat star. In our conclusion, the surge of flux on the light curve became apparent after we processed and fit the data. In addition, the periodic signal was found. Hence, we determined that HD-51940 is an HBS.

Keywords: Heartbeat stars (HBS), Binary star, Tidally Excited Oscillations, TESS

1. Introduction

Countless stellar systems exist in the universe, and the number of the hosts—stars in a system—is different. The range can vary from one to seven. Binary stars, called two-star systems, are quite common within this range. The two stars usually have strong interactions with each other due to their enormous mass and gravitational force, and the light curves we receive also show periodic dips in stellar flux. Nevertheless, Heartbeat Stars (HBS) are unique: their light curves look like EKG signals.

HBS are kinds of binary stars that process high eccentric orbits ($e \geq 0.3$) and have strong tidal distortion with each other [1-3]. Many HBS oscillate throughout their orbit due to the tidal excitation of stellar oscillation modes [3]. As a result of these tidal interactions, the stellar cross-section changes shape, and the temperature across the stellar surface varies due to reflection and gravity darkening [4]. The light curves of HBS show periodic brightening—the light curves in their initial states(the shape of the light curves in this state are usually different, based on different statuses of the stars) first decline to a relatively stable level, then the curves rise to a level higher than their original states. The section with higher light curves signals tidally excited oscillations(TEO). Since the shape of light

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curves looks like an electrocardiogram, the stars satisfying the above conditions are called HBS. Despite the fluctuation of photometric signals, what is more intriguing is that the HBS displays luminosity signals whether or not the system is eclipsed. Moreover, the stellar oscillations are critical to the internal properties of HBS. Hence, HBS is an astrophysical laboratory for studying tidal interactions between binary stars and the internal structure of stars [5].

Until now, a large number of articles have focused on the analysis of such mysterious systems. HBS was first defined by Thompson et al.[3], and then more and more researchers studied them. Thompson and his teams used the Fourier transform and Kumar et al. 's analytic model[6] to analyze the characteristics of the light curves of the binary stars, the effect of tidal distortion, and the orbital parameters of the stars. Finally, they concluded that the change in light curves was primarily caused by the different tidal distortions observed from different inclinations and periastron angles. For other researchers, some focus on special HDSs and investigate their characteristics, like Jayasinghe et al. [7], Kołaczek-Szymański et al. [8], and Pablo et al. [9]. Some focus on the theoretical explanation for the characteristics and features of HBS, like Cheng et al. [10] and Li et al. [11]. Since their goals are not closely connected with our direction, further details are not mentioned. However, the common feature of the HDSs is that they both have very short periods. For example, the 17 HBS mentioned by Thompson et al.[3] have the shortest period, 4.5 days, and the longest period, 41 days.

Our discovery that HD 51940 is a probable HBS was serendipitous. Our initial goal was not to verify whether HD 51940 is an HBS but to detect the companion(s) of defined hot Jupiters. We observed a lot of light curves of hot Jupiters, eliminated the transit effect of hot Jupiters, and processed the light curves, but no companions were found. To enlarge our database, we chose a star system from the list of TESS transiting planet candidates found at the NASA Exoplanet Archive, which means that the planet of the system has yet to be verified. But the light curve of that system showed a special pattern, just like an HBS. However, after we further searched for the system, we found that HD 51940 is quite interesting—its planet and the second star were not verified, but it shows the pattern of HBS, which means that there should be two stars in the system and a planet may or may not exist. Hence, we adjusted our direction and finally prepared to determine the authenticity of the HBS candidate.

We divided the rest of our paper into several sections. In section 1, we proposed and displayed basic information about HD 51940, including luminosity, effective temperature, and color, and its light curve using TESS data. Following some defined HBS, we selected some settled HBS to compare and contrast with HD 51940. Last, we briefly introduced TESS. In section 2, we displayed the methods we used, including a parameterized model for the light curve of a transiting planet, using the equations of Mandel & Agol [12]that take limb darkening into account; the Kumar model, a model to fit the light curve; and Fourier transform, a model to analyze the light curve of HD 51940. We briefly introduced how we used these methods to deal with and process our data in order to obtain the results. In section 3, we showed our results from section 2. Figures of fitted light curves were involved, and our analysis was also demonstrated. In section 4, we discussed our results and obtained a conclusion. Then, we discussed what other researchers can do in the future in this field.

2. Observations

HD 51940 is the major star system we chose, but other HBS systems were also involved in comparing and contrasting HD 51940. We collected the data from HD 51940 and other HBS systems from TESS. TESS, or *Transiting Exoplanet Survey Satellite,* is a satellite launched by NASA in 2018 to detect solar neighborhoods for planets transiting. The function of TESS was to make up for the fact that most of the stars in the Kepler mission were too faint to be studied in detail. The main objects of the detection in TESS were 10–100 times brighter than the stars detected in the Kepler Mission. There were four cameras on TESS, and they would collect light from most areas in the sky. The data

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collected by TESS would be transferred back to the ground and be processed in time, and light curves of detected stars would be created. By analyzing the dips that appear on the light curves, the existence of planets would get preliminary determinations. After that, other methods were still needed to verify the planets [13]. We used Jupyter Notebook and Python to draw the light curve and do further processing. According to our observation of several light curves, only Sector 1 and Sector 2 are available to illustrate the pattern of HBS. The data in the two sectors were obtained by TESS in 2020. The exposure times were 120 and 600 seconds.

Table 1: Basic properties of HD 51940

TESS mag	Period (days)	Duration (hours)	Depth (ppm)	Stellar T_{eff} (K)	Rp ($R_\oplus$)	Rp (R_{Jup})	ruwe
9.299501 ±0.058	1.867574 ±0.000003	1.408 ±0.184	1500 ±1.7584	8924 ±124	23.7529	2.11910	3.9254117

In this section, we compare HD 51940 with other HBS. Here, we list more light curve data from TESS for other HBS. They are similar to HD 51940 in several factors, including period.

Table 2: Basic properties of two similar confirmed HBS

KIC	Period(days)	RA	Dec	Parallax	pmRA	pmDec	ruwe
4377638	2.82187	294.743816	39.4993921	0.79172970	3.27733185	7.208340495	1.491712
7660607	2.76340	281.832415	43.4002422	0.94619317	2.440731010	0.763047734	1.181

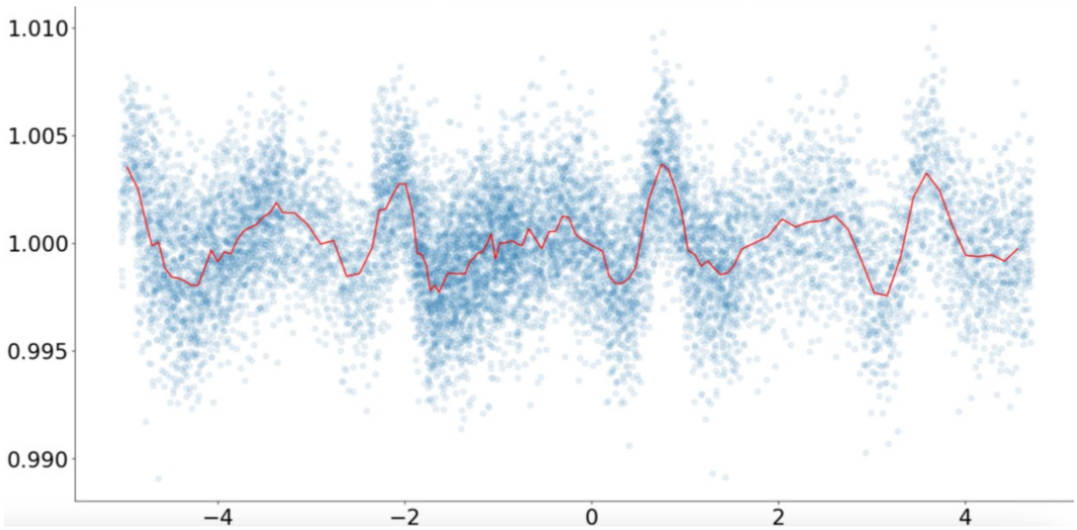

Figure 1: Folded lightcurve of *KIC 4377638*

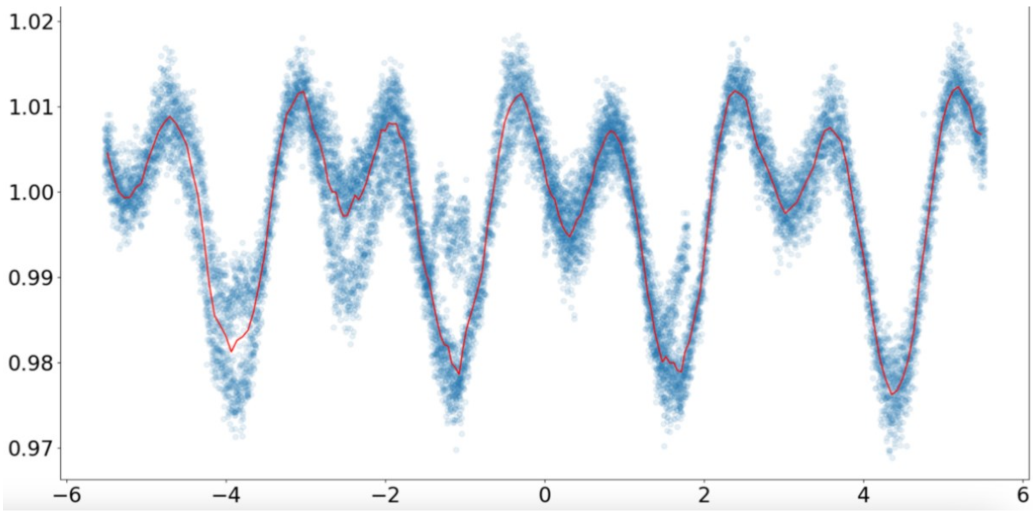

Figure 2: Folded lightcurve of *KIC 7660607*

The object was discovered through the Transiting Exoplanet Survey Satellite (TESS) mission observations. We utilized data specifically from TESS sectors 7 and 33 due to the lack of data from the TESS mission except for these periods.

We transformed the raw TESS data into obvious results for our target star. The inherently noisy TESS data required preprocessing to enhance its usability. We obtained data through Tess and made the first process, which is normalization. This step is a crucial adjustment of the data to transmit to a common scale, which enables a precise comparison of the light variations.

After normalization, we folded the light curve data. This step involves the alienation of the data points by phase, essentially by overlaying multiple periods of the star's cycle to enhance the signal-to-noise ratio. By averaging the data into bins of folded time, we enhance the signal-to-noise ratio of periodic signals to easily identify repeating patterns in the light curve.

Ultimately, we identified clear periodic oscillations in the flux of the system. The pattern of these variations of light curves implies an HBS system. In this system, two stars undergo regular close approaches. During these encounters, their mutual gravitational forces create tidal distortions that cause characteristic changes in brightness.

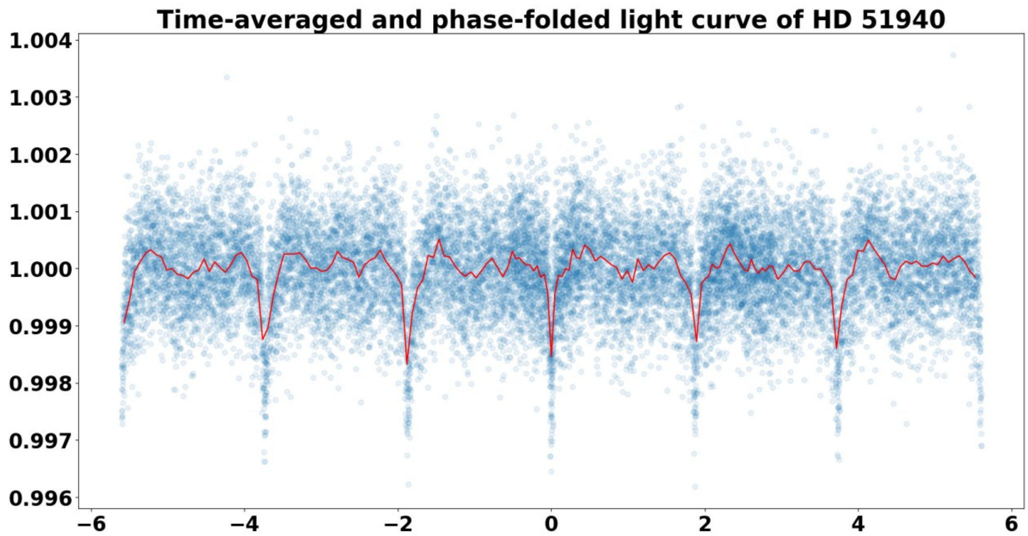

Figure 3: The phase-folded light curve of HD-51940 demonstrates periodic flux variations consistent with a heartbeat star system

We created a binned version to analyze the light curve further, as shown in Figure 3. Binning involves averaging data points within specified intervals to smooth out short-term fluctuations and highlight the overall trend. Our binned light curve exhibits a single-period eclipse [14], slightly increasing light flux around the dips. This pattern is consistent with the behavior of a HBS system[1].

Initially, the system was considered a candidate for hosting an exoplanet due to the periodic dips in the light curve. However, upon closer inspection and analysis, the light curve's distinctive shape and a single-period eclipse suggest that this object is more likely a HBS system. This conclusion is based on the observed light curve characteristics, which align with the known patterns of HBS.

Analysis of TESS data for HD 51940 yielded promising results. After normalizing and folding the data, we found periodic flux variations typical of HBS systems. The binned light curve shows a single-period eclipse, with flux increases near the dips - a pattern that differs from typical exoplanet transits.

3. Methods

3.1. lmfit and Kumar model

In order to get the best-fit light curve of HD 51940, we used the Kumar model [6]interpreted by another group of scientists like Thompson, S.E et al. [3], and the equation is shown below.

$$\frac{\Delta F}{F} = S\frac{1-3(i)sin^2(\varphi(t)-\omega)}{(R(t)/a)^3} + C \tag{1}$$

Equation (1) for the tidal oscillations induced in eccentric binaries to obtain the orbital parameters for HD 51940.

In this model, we set six parameters: e for eccentricity, i for orbital inclination, $\omega$for angle of periastron, and s for the amplitude scaling factor. The whole process $\frac{\Delta f}{f}$ represents the fractional flux variation. Δf is the actual change of flux, while f is the baseline flux, representing the average flux of the system without tidal distortion. S, which is the amplitude scaling factor just described before, adjusts the overall amplitude of the brightness. It adjusts the overall amplitude of the brightness variation. φ(t) stands for true anomaly, it describes the position of a star along its elliptical orbit in a given time. A is the semi-major axis. The component shows that the changing distance between stars influences tidal forces over time. The fractional offset C adjusts the baseline flux level in the light curve.

We used Professor Winn's program to visualize the formula and generate a best-fit curve. The original data points were plotted in the background to compare with the fitted curve. The next thing to do is to adjust the parameters. Since the Kumar model's parameters should be changed manually, we tried several parameters and found the best parameters for this heartbeat light curve. We set m1 and m2, the mass of the expected binaries, to be 1.5 solar mass, inclination to be 128.5 degrees, which is $128.5\frac{\pi}{180}$ arcs, semi-major axis to be 2.69, amplitude to be 0.00042, eccentricity to be 0.38, and omega to be $60.17\frac{\pi}{180}$. Furthermore, we can use the bin method, fold its time, and average it, therefore creating the bin line. Here is a figure of the red Kumar curve, dark blue bin curve, and light blue original data dots.

Moreover, we can also use other methods to make the curve fit better. Lmfit allows you to get a predicted set of parameters with residuals to show how good the fit is by reducing the chi-square if you give an initial set of parameters. Typically, such methods are called Levenberg-Marquardt optimization, a least square method. This is the method which perfectly fits our requirements.

The Chi-square is shown in the equation below:

$$X_c^2 = \sigma\frac{(O_i-E_i)^2}{E_i} \tag{2}$$

In this equation, chi-square is used to describe the variation between the observed value and the calculated value. The observed value is the real value; you can treat it as the original data dots in the figure. The estimated value is the y-axis value computed using the new parameter lmfit just worked out. Lmfit will repeat the fit process a lot of times, so the chi-square is the smallest. Thus, the line will fit in its best shape and place. Here, in order to use lmfit, we may also need to use the six parameters described before. We also need to define a calculating function and a residual function. The lmfit model uses the least square method to calculate. The function below shows how to calculate residuals.

$$res = \frac{flux - calc\ flux}{flux\ uncertainty} \tag{3}$$

Another path to get a better fit of the light curve is by using the Markov chain Monte Carlo method, often known as MCMC. It is a part of Bayesian statistics. MCMC algorithm generates a sample corresponding to the target distribution in a probabilistic manner [15]. Given a probability distribution, we can build a Markov chain whose stationary distribution of the Markov chain matches the target distribution. In order to do that, researchers can use Emecee. It is an MIT-based Python implementation of MCMC[16]. Researchers can use this method later on to make a better fit of the binned light curve.

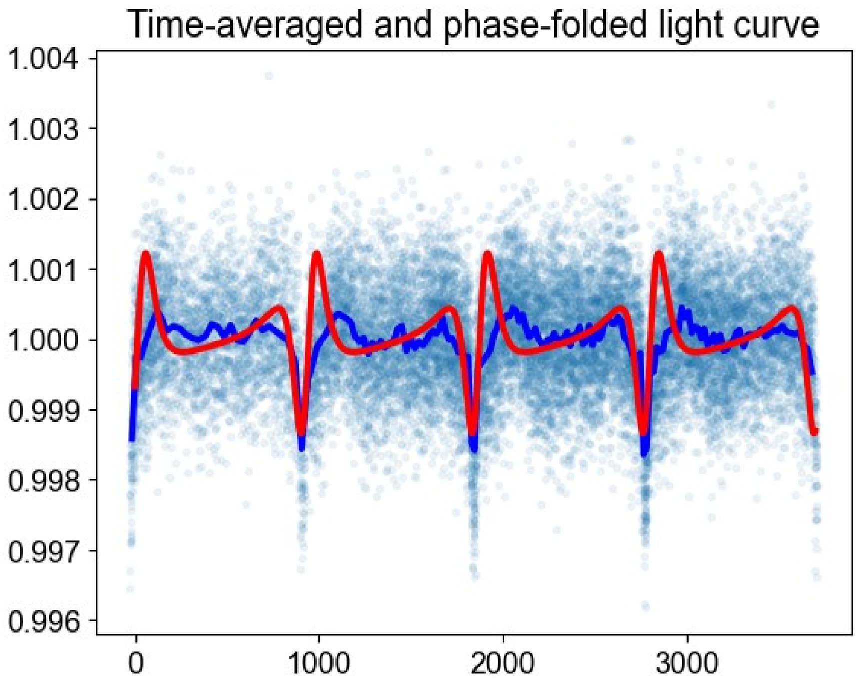

Figure 4: The combined result of folded data dots is represented in pale blue dots, the binned light curve is shown in a dim blue line, and the Kumar model best-fit line is shown in red. The dip in the graph shows the light blocked by the other star during highly eccentric orbiting. The peak shows the light increased by the tidal force between two stars

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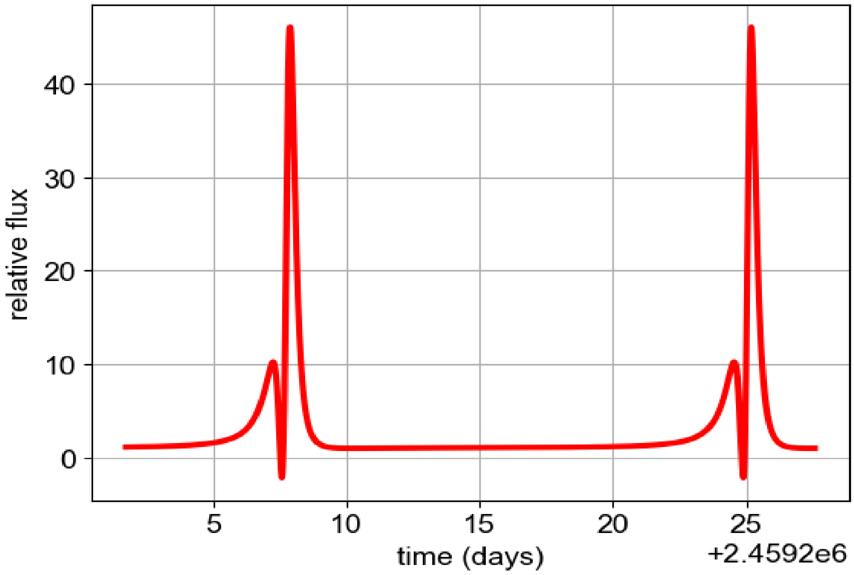

Figure 5: The lmfit result lightkurve. The dip in the graph shows the light blocked by the other star during highly eccentric orbiting. The peak shows the light increased by the tidal force between two stars.

3.2. Fast Fourier Transform

Because of the operational design of the TESS mission, there are significant gaps between the observations in Sector 07 and Sector 33. These gaps arise because TESS periodically pauses its observations when it transmits collected data to Earth, generating discontinuities in the light curve data. These gaps create discontinuities in the light curve data. To address this, we divided each sector's light curve data into two segments. Separate datasets for analysis to account for any potential discrepancies caused by those gaps in the data.

Our analysis began with a rigorous application of the BLS fitting method to each of the four segments. Using the BLS fitting method across all four segments, we identified an eclipse period of 1.8612413 days, establishing the foundation for our subsequent investigation.

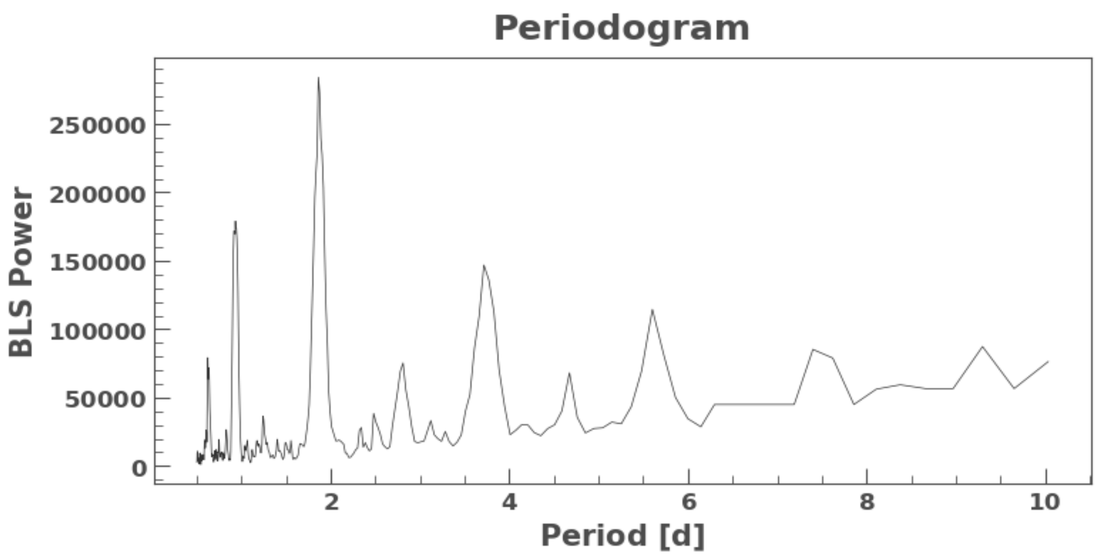

Figure 6: The BLS fitting diagram of HD 51940. The best period of which is 1.8612413

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The method from Tompson's paper[3] motivates us to use FFT to determine the TEO pattern of this star.

Our next step was to remove the data corresponding to the eclipse events from each segment. By replacing the eclipse data points with a normalized flux value of 1, we flattened the eclipse, which allowed us to concentrate on the underlying oscillations without interference from the eclipsing events.

With the eclipse data removed, we performed a Fast Fourier Transform (FFT) on each of the four segments. By analyzing the frequency domain, we could identify any oscillatory patterns within the star that might be indicative of TEOs or other intrinsic stellar oscillations.

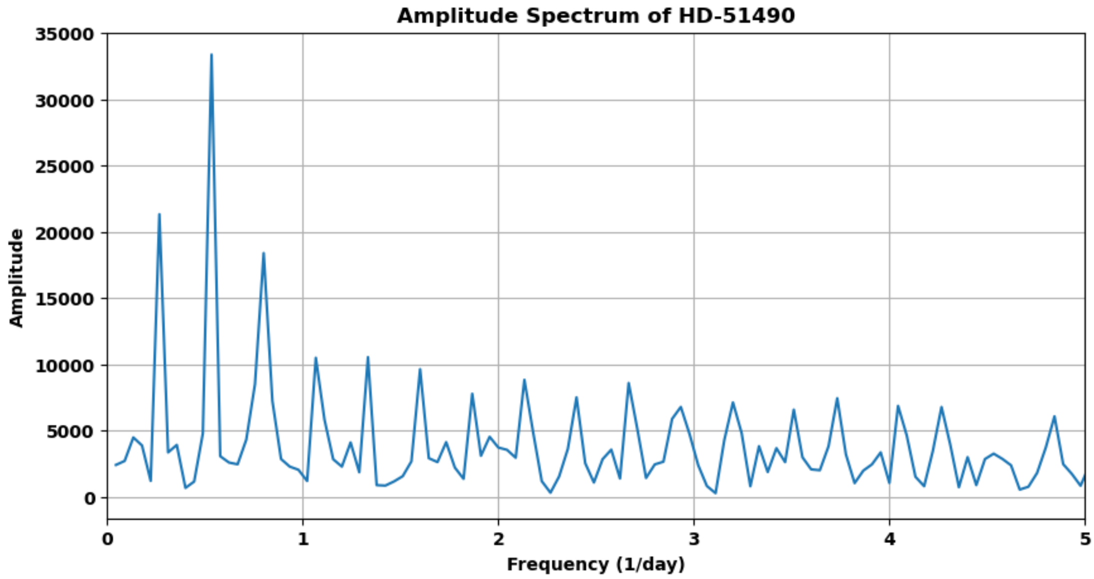

Figure 7: Amplitude Spectrum of HD-51490 with potential eclipse

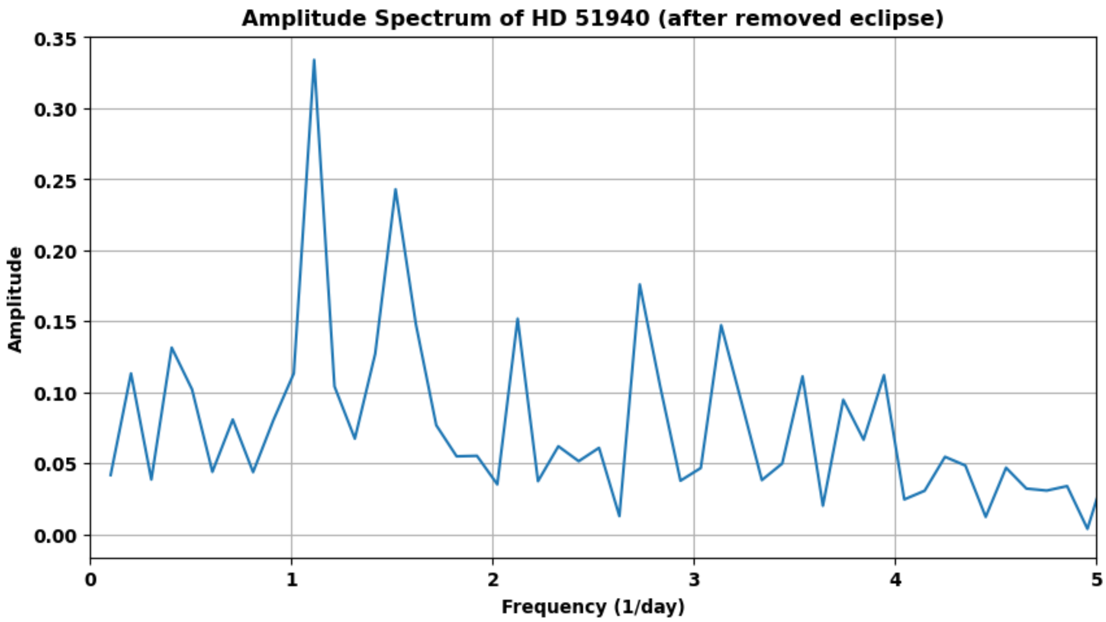

Figure 8: Amplitude Spectrum of HD-51490 without potential eclipse

We combined the FFT analysis results from all segments to generate a frequency spectrum spanning the full observation period across Sectors 07 and 33. The resulting spectrum showed patterns characteristic of an HBS system.

4. Conclusion

We use three methods to demonstrate the pattern of this star is classified as an HBS system. However, some factors may affect this conclusion.

The Transiting Exoplanet Survey Satellite (TESS) resolution is a challenge in our analysis. TESS excels at wide-field sky surveys, so its resolution limits our ability to isolate our target star from neighboring stars. This might be due to potential contamination from nearby stellar sources, which may affect our light curve measurements. As a result, the periodic variations we attribute to HBS behavior could potentially arise from eclipsing binaries or variable stars in the vicinity.

Moreover, this signal was selected from the NASA Exoplanet Archive, so there are a few exoplanet features in this star. For instance, we were not sure whether the eclipse was due to a star or a planet. In this case, the observed light curve shows the HBS pattern, proving that this is actually an HBS system.

Also, we obtained data from the Gaia telescope for more precise analysis, and one of the values that attracted us was the Renormalised Unit Weight Error (RUWE) value of this system, which is very high. According to the data from Gaia DR3, its RUWE value is 3.9254117. This value is much higher than one, showing that this probably is non-single or otherwise problematic for the astrometric solution. So, this is a good indicator that this is a three-body system: a short-period EB, a third star at wide separations. This is an interesting finding for further investigation into this system.

Future work should focus on obtaining higher-resolution data. We recommend follow-up observations using instruments with better resolution, either from ground-based telescopes or space observatories like Hubble or James Webb. Higher-resolution data would help separate our target from neighboring stars and clarify the true source of the observed variations.

Statement of work

Tian found HD 51940 from TESS project candidates and helped write and fix the code, which also stated the final vision of this essay. Yushu and Haoxuan wrote the first draft and contributed a lot to the code. Changxuan wrote most of the introduction and result sections. Yurui searched for the data and collated Tables 1 and 2. All authors read the paper carefully and helped to edit the paper.

We are grateful to the CIS staff for organizing the program. We also thank the Shanghai Jiao Tong University (Qibao Campus) for hosting our class.

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Acknowledgement

Tian Qiu, Yushu Liu, and Haoxuan Yu contributed equally to this work and should be considered co-first authors.

The main code of the Kumar model in section 3.1: Lmfit and Kumar model is provided by Joshua.N.Winn at Princeton University. We want to thank Professor Winn for his tremendous support of our research.

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