Fourier Analysis of Light Curves in a Multi-Eclipsing Stellar System

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1. Introduction

1.1 Idea

Decomposing a compact triply eclipsing hierarchical triple star system into its composite pairs using the Lomb-Scargle periodogram technique (a direct extension of classical Fourier analysis for unevenly sampled time series data in astronomy).

1.2 Motivation

We drew inspiration for this analysis from reading about the properties of stars in multi-star systems, which are determined by the mutual gravitational influences. A recent discovery of the orbiting partner of Betelgeuse, based on the Great Dimming event (S. B. Howell et al., 2025), has further piqued interest.

2. Methodology

2.1 Data Collection

To begin with, we generated a triple-star light curve CSV data file using simulated data to test our methodology. We plan to later use real observational data of any actual multi-star system, such as EPIC 249432662 or HD 181068. The synthetic data was generated using the following parameters (taken from HD 181068):

1. **Inner binary period:** 0.906 days (with primary and secondary eclipses)
2. **Outer orbital period:** 45.5 days (third star eclipsing the binary)
3. **Time baseline**: 100 days

This is done to demonstrate the methodology confidently, as we know the exact input periods to test if the analysis recovers them correctly. This will also help us illustrate the concepts to the audience without the complexities that are inherent in real observational data.

2.2 Preprocessing

Before any meaningful analysis can be performed, raw data must undergo pre-processing. Pre-processing involves cleaning the data, handling missing or corrupted entries, removing

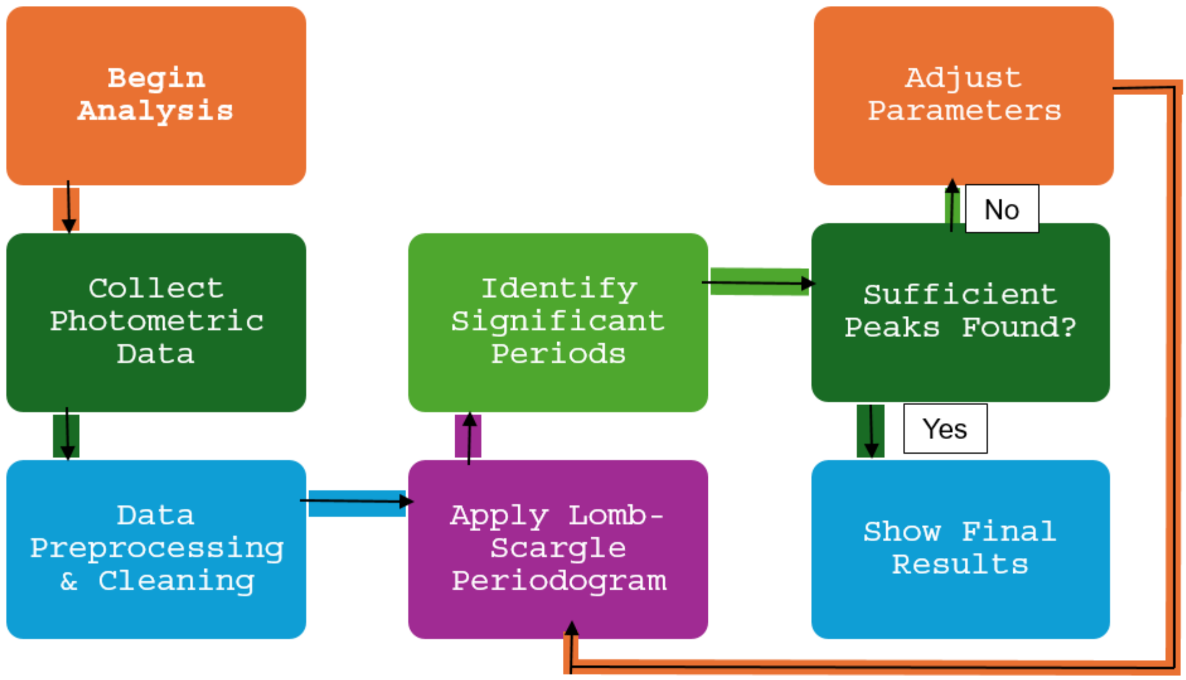

Figure 1: Methodology

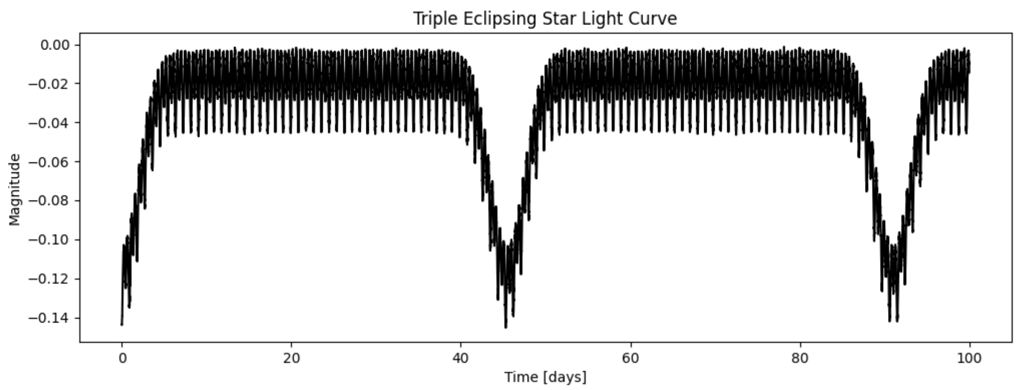

Figure 2: Light intensity curve over the 100 days

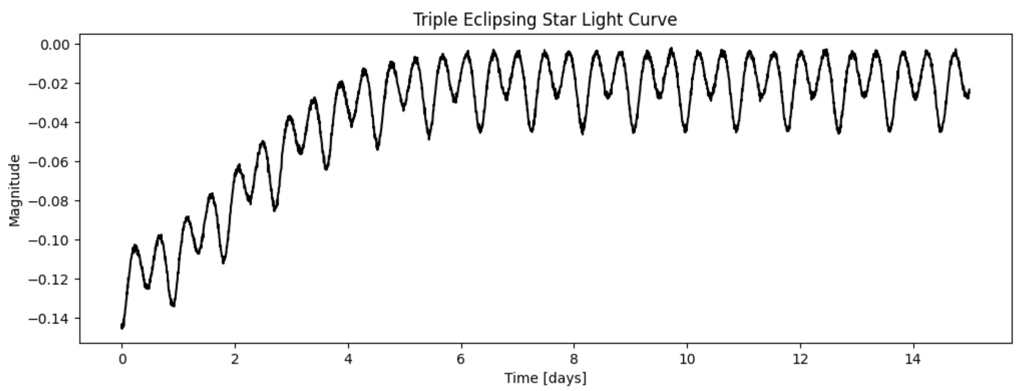

Figure 3: Light intensity curve for first 15 days

outliers, detrending, normalizing or scaling values, and sometimes transforming the data into a suitable format for analysis.

2.3 Fourier/Lomb-Scargle Analysis

We utilized the NumPy, Pandas, and SciPy libraries to define frequency ranges, perform Lomb-Scargle computations, and detect peaks. The code sets up a frequency array that covers periods from 0.2 to 500 days, using 10,000 logarithmically spaced frequency points for complete coverage. The periods are then converted into frequencies ($f = \frac{1}{T}$) with the units of cycles per day.

2.4 Period Identification

The peaks are extracted and sorted by power. The period that has the maximum component in the dipping of light intensity is identified as the time period or a harmonic of the time period of the star with the highest luminosity.

2.5 Validation

We then compare the results with the parameters set at the beginning to check the efficiency of the approach and identify any errors. This also allows learning the effects of various astronomical phenomena on the the observed light intensity and frequency distribution.

2.6 Presenting Final Outcomes

The obtained results are presented clearly and concisely, discarding those values that are less relevant.

3. Theory

In this section, we will explain the following concepts in an easy-to-understand manner:

- Astronomical concepts and the importance of choosing the specific system
- Lomb-Scargle Periodogram

The Sun, our nearest star, is our sole caretaker, responsible for fueling the food chain and acting as a source of light and heat. But it turns out that it is very rare to find a lone star in a family. A large number of stars found in the Milky Way occur in binary systems – they are seen as a pair of stars orbiting the barycenter, which lies between them. Furthermore, some stars are found in triplets, quartets, quintets, and even sextets and septets.

But not all stars are the same; stars come in different masses and surface temperatures, ranging from 0.013 $M_\odot$ to more than 11 $M_\odot$ and 600K – 2.1×10^5K. These differences affect the luminosity of a star. An eclipsing binary is a system wherein two stars orbit each other such that, from the point of view of an observer on Earth, one star hides the other for a brief moment. This can happen only when the plane of the stars' orbits is edge-on with respect to Earth.

During eclipsing, if the star in front is comparatively dimmer, then the overall perceived brightness of the system decreases significantly because the dimmer star blocks the light of the brighter star. Here, we have taken the example of a triply-eclipsing system, where all the stars eclipse each other. For this to happen, they must lie in the same plane of orbit, and the plane must be edge-on with respect to the observer.

A system is called a hierarchical system if stars are arranged in nested orbits, with closer pairs orbiting a common centre of mass, and a third (or higher order) body orbiting this pair at a much larger distance. Thus, the outer star cannot enter the orbit of the inner pair at any instant. Due to the significant separation, the gravitational influences between the inner orbits and outer orbits are small, so that the system obeys Kepler's laws, and any two consecutive levels can be simplified as a two-body problem.

Such a system is called compact if the ratio of the outer time period to the inner time period is small. For the data that we have used to test the methodology in the beginning, the ratio is $\frac{45.5}{0.906} = 50.2$

Light curves from hierarchical multiple star systems represent composite signals containing multiple periodic components. Each binary pair contributes distinct frequencies corresponding to orbital periods of the component binaries and harmonic frequencies arising from non-sinusoidal light curve shapes.

The mathematical foundation relies on the decomposition of the observed magnitude time series m(t) into its constituent periodic components using the Fourier series expansion:

$$m(t) = A_0 + \sum_{i=1}^{N} A_i cos(2i\Phi(t) + \phi_i)$$

where,
A_0 is the mean magnitude
A_i and ϕ_i are amplitude and phase coefficients
$\Phi(t) = (t - t_0)/P$ represents the folded phase
N is the order of the Fourier fit

But classical Discrete Fourier Transform or Fast Fourier Transform do not give good results for astronomical data, which is generally unevenly sampled time series data. For astronomical treatment, we use the Lomb-Scargle method – a more general version of the Fourier analysis. It fits a sinusoidal model at each frequency using least-squares minimization, which is similar to the projection underlying Fourier methods. The Lomb-Scargle periodogram provides a statistically meaningful spectrum even for a data with noise and gaps. But it is not very different from the usual Fourier approach as both decompose the signal into sines and cosines at different frequences. Just like the Fourier periodogram, the Lomb-Scargle periodogram computes power at each frequency, identifies periodic components and outputs a frequency spectrum. Thus, for evenly spaced data, both the techniques yield identical results.

The Lomb-Scargle periodogram formula :

$$P(f) = \frac{1}{2}\left(\frac{[\sum_n (x_n - \bar{x})\cos 2\pi f(t_n - \tau)]^2}{\sum_n \cos^2 2\pi f(t_n - \tau)} + \frac{[\sum_n (x_n - \bar{x})\sin 2\pi f(t_n - \tau)]^2}{\sum_n \sin^2 2\pi f(t_n - \tau)}\right)$$

where:
x_n is the observed data point at time t_n
$\bar{x}$ is the mean of the observed data
f is the frequency being tested
τ is a frequency-dependent time offset defined to make the periodogram independent of time shifts (often chosen so that cross-terms vanish)

What this formula does step-by-step:

1. **Centering the Data:** Subtract the mean $\bar{x}$ so the signal oscillates about zero.

2. **Projecting onto Sine and Cosine Components:** For each frequency f, compute how much the data correlates with a cosine wave $\cos(2f(t_n - \tau))$and a sine wave $\sin(2f(t_n - \tau))$. Numerators are the sums of data weighted by sine or cosine, expressing the amplitude of oscillations at frequency f.

4. Results

The results obtained after analysis are displayed on the following page (Figure 4). In the figure, we see that instead of the period T_1 for the inner binary, we obtain a very strong signal for $\frac{T_1}{2}$. This is because in the inner binary system, we perceive two eclipses within one time period – one when the first star eclipses the second, and the other when the second star eclipses the first.

But we don't get a similarly strong signal for the second harmonic of the period of the outer star, i.e., $\frac{T_2}{2}$. This is because the eclipsing of the binary by the outer star and the eclipsing of the outer star by the binary don't produce similar dips in the light-intensity

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Top detected periods:
Rank   Period (days)   Power
----------------------------------------
1           46.6972       2.5015
2           22.6084       2.2473
3           15.0038       1.6698
4            0.4531       1.1883
5           11.2586       1.0654
6            9.0081       0.5477
7            0.9055       0.2647
8            7.4833       0.2569
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Figure 4: Result

curve. Additionally, the inclination needs to be a perfect 90 degrees for two eclipses to be observed within a single time period.

Higher-order harmonics arise because the light curve's shape is not a perfect sine wave — the eclipse dips and sharp features naturally generate additional frequency components at integer multiples of the base orbital frequency.

5. Conclusion & Future prospects

Thus, we have successfully obtained the principal component orbital periods of the simulated system using Lomb-Scargle periodogram technique. In the future, we plan to further refine the process to obtain more accurate results and test the method on more data sets, especially real data sets that have some amount of noise. Furthermore, these analyses can be coupled with spectroscopy to identify the velocities of stars to model their masses and other properties.