

# The Transiting Exoplanet Survey Satellite (TESS) Observations of Eclipsing Binary V477 Cyg

**Abstract:** The Transiting Exoplanet Survey Satellite (TESS; Ricker et al., 2015) has produced extremely accurate observations of eclipsing binary systems that contain pulsating components, particularly  $\delta$ -Scuti pulsators. These binaries fall into two basic types, detached systems and semi-detached systems. This study looks at V477 Cyg which is a detached binary system with no past or present mass transfer. The light curve and the periodogram are analyzed from TESS photometry data contained in the Mikulski Archive for Space Telescopes (MAST) database. Pulsations within the  $\delta$ -Scuti component of the binary system are examined in detail to extract the frequency/period relations among the pulsations. The variation of the pulsation components are shown as the system transits through the eclipse cycle. This paper highlights the pulsation period/frequency analysis and the discovery of a  $\delta$ -Scuti component. Additionally, this study explores the possibility of the existence of a third component in this system which seems to have the characteristics of a compact object, specifically a white dwarf.

## 1. Introduction and Background

Asteroseismology is the study of the interior physics and structure of stars using their pulsations. It is applicable to stars across the Hertzsprung-Russell diagram and is a powerful technique for measuring masses, radii, and ages, but also to directly study interior rotation, chemical mixing, and magnetism. In the case of eclipsing binary systems, important orbital information can also be determined. As such, asteroseismology would seem to be an underutilized tool for studying stars. In particular, the asteroseismology of eclipsing binary systems is an especially fruitful area for continuing research.

The Transiting Exoplanet Survey Satellite (TESS; Ricker et al., 2015) has produced extremely accurate observations of eclipsing binary systems that contain pulsating components, particularly  $\delta$ -Scuti pulsators. This study looks at V477 Cyg which is a detached binary system. Additionally, time dependent periodic tidal forces in an eccentric binary may induce pulsations called tidally excited oscillations which can vary throughout the binary orbit. If the eccentricity is high enough ( $e > 0.2$ ), proximity effects lead to a sudden change in brightness/amplitude close to the periastron passage, which may resemble an electrocardiogram (photometric periastron variation). Both the tidally excited oscillations and the periastron brightening are hallmarks of the class of binary systems known as heartbeat stars, of which V477 Cyg is a member (Kolaczek-Szymanski et al. 2021). Delta Scuti ( $\delta$ -Scuti) is a variable star in the constellation Scutum in the Southern Hemisphere and is the prototype for Delta Scuti type variable stars.  $\delta$ -Scuti pulsators are main sequence or post main sequence stars

with [luminosity classes](#) between III and V. Their spectral types range from A1 to F7 and are located in the lower part of the classical Cepheid instability strip of the Hertzsprung-Russell diagram. V477 Cyg has a spectral type of A1V+F5V (Kloppenborg, 2022, AAVSO VSX).

Eclipsing binary V477 Cyg (TESS Input Catalog (TIC) 89522181) is a detached binary system with two components. The primary component of this system is a  $\delta$ -Scuti pulsator (Soydugan, E. et al., 2006) and a secondary component, creating the binary system with a moderately eccentric orbit ( $e=0.3416$ ) (Kolaczek-Szymanski, P.A., et al., 2021). This binary system produces a complex signal structure that can be analyzed with traditional signal analysis techniques. There is some evidence of a third smaller component in this system.

## 2. Methods

This study looks at eclipsing binary V477 Cyg (TIC 89522181). The light curve and the periodogram are analyzed from TESS photometry data contained in the [Mikulski Archive for Space Telescopes \(MAST\)](#). All of the TESS photometry files (seven of them) were downloaded and a light curve was generated by the American Association of Variable Star Observers (AAVSO) VStar software (Benn, D. 2012, Algorithms + Observations = VStar, Journal of the AAVSO (JAAVSO), v40, n2, pp.852-866). Prior to mode identification of pulsation mode frequencies (or periods), the frequencies themselves must be extracted by assembling time-series data of the star's observable surface properties. Such time-series data can be obtained from time-series photometry with the periodic variability of the star's brightness as a function of time. This is the star's light curve. To extract pulsation mode frequencies/periods, it is common practice to employ Fourier analysis, specifically Discrete Fourier Transforms (DFTs) for unevenly sampled time series or a Lomb-Scargle periodogram (Scargle, 1982). The frequency spectrum is calculated up to the Nyquist frequency, defined as:

$$F (\text{Nyquist}) = 1/2\Delta t$$

where  $\Delta t$  is the cadence of the time series. Once the frequency spectrum has been calculated, peaks are noted that are statistically significant and represent pulsation mode frequencies based on satisfying a significance criterion. This is the periodogram.

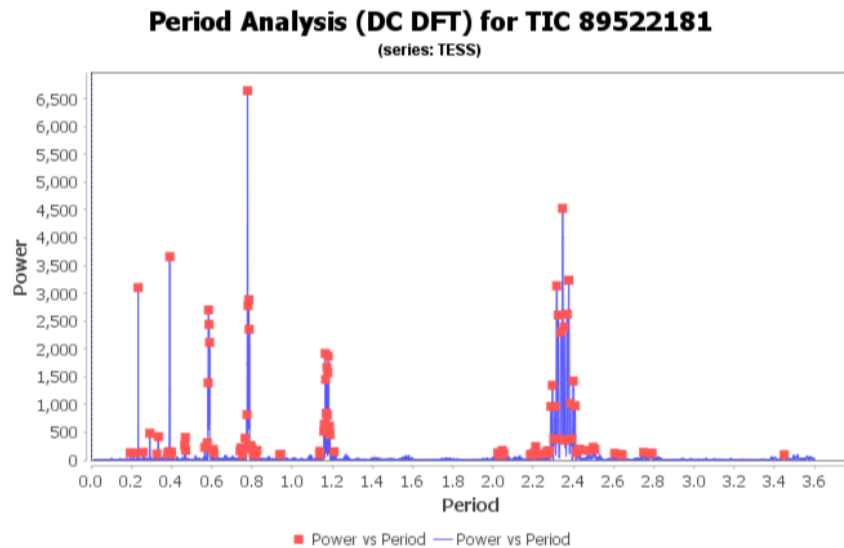
The data are analyzed with VStar. Specifically, Fourier analysis of the combined photometric data is performed to yield a detailed periodogram for the binary system from which periodicities and other variations can potentially be identified. VStar utilizes the Date Compensated Discrete Fourier Transform (DCDFT) algorithm (Ferraz-Mello, 1981) to produce a power spectrum, a period range, and a resolution. The Date

Compensated DFT compensates for gaps in the data, which are common for variable star observations. The resulting analysis can include one or more periods, one or more harmonics, and one or more subharmonics. These can be selected to create a model that can also include a polynomial function that is used as a smoothing mechanism to capture key aspects of the data set without all the noise and fine fluctuations. When a model is created, it is subtracted from observations in the series to yield a second series called a residual. The residuals can also be analyzed to look for other signals (periods) in a process called pre-whitening. Periodicities and other potential variations are analyzed utilizing TESS photometry, models are created from the photometry, mean series are computed, and residuals are analyzed to obtain all possible variations. As discussed in Rea, B., 2022, pre-whitening can introduce new frequency data into the analysis that are artifacts of the analysis that do not actually correspond to pulsations within the star. That does not seem to be an issue in this analysis, as all significant components can be accounted for and are the result of stellar processes, specifically the pulsation behavior of the  $\delta$ -Scuti component and the varying tidally excited oscillations throughout the binary orbit due to the motion of the secondary component of the system.

### **3. Analysis and Results**

The V477 Cyg eclipsing binary consists of two components with an orbital period of 2.34699 days (Kloppenborg, 2022, AAVSO VSX). For the primary component, the mass is 1.80 solar masses, the radius is 1.60 solar radii, and the temperature is 8730 K. For the secondary component, the mass is 1.35 solar masses, the radius is 1.42 solar radii, and the temperature is 6531 K (Soydugan, E. et al., 2006). The primary component in this system is the  $\delta$ -Scuti pulsator (Soydugan, E. et al., 2006) and the secondary component is instrumental in producing the tidally excited oscillations. It should be noted that these oscillations may occur in one or both components, but the precise location is usually difficult to determine. Figure 1 shows the periodogram for the entire analysis range of 0.015 days to 3.60 days. There appears to be no frequencies/periods beyond 3.60 days.

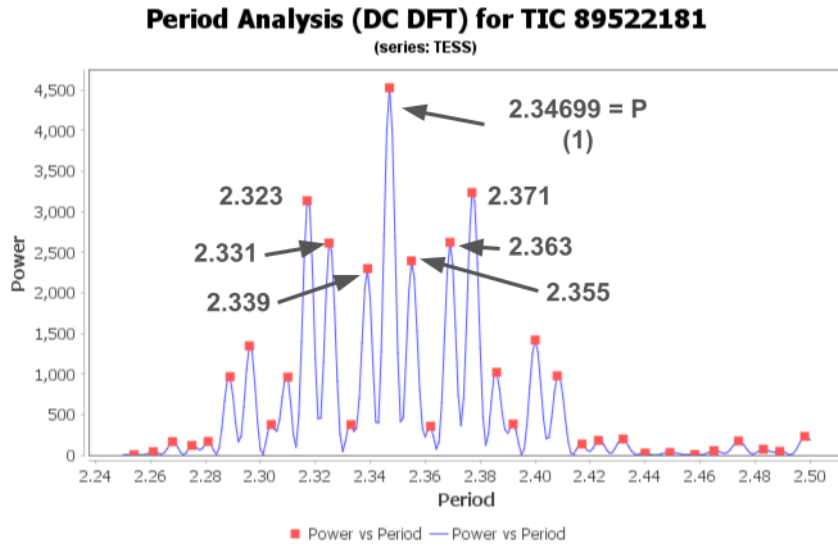
The 0.015-3.60 day period interval is divided into several subintervals and power/amplitude levels. As can be seen in Figure 1, there are numerous signals above the power level of approximately 500. These are shown in Figure 2 (2.25-2.50 days), Figure 3 (1.0-1.30 days), Figure 4 (0.50-1.00 days), and Figure 5 (0.01-0.50 days). Power levels below approximately 250 are shown in Figures 6-13.



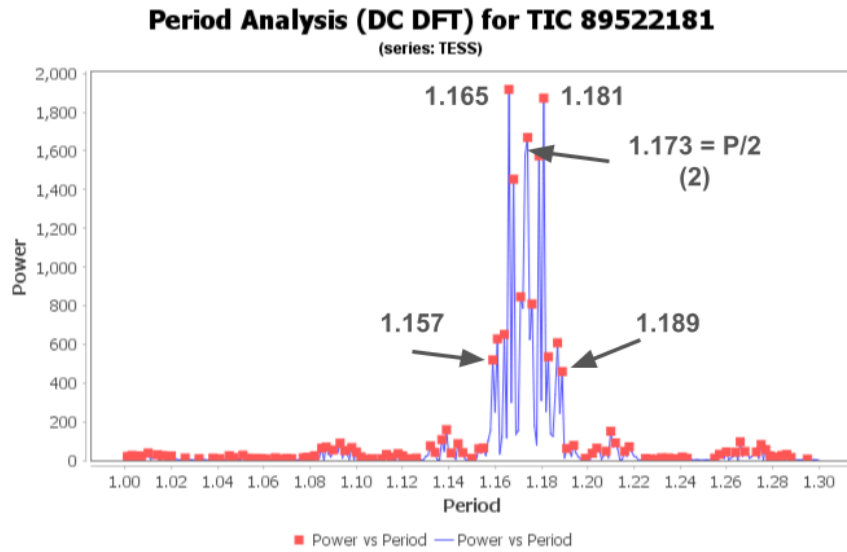
**Figure 1: Periodogram for V477 Cyg/TIC 89522181 (0.015-3.60 days)**

As can be seen from Figure 1, there are several obvious intervals that contain high power/amplitude spectra. Figure 2 shows the interval around the binary system orbital period of 2.34699 days (period 1). There is a symmetrical structure above and below the center period of 2.34699 days. These are sidebands of that period/frequency reminiscent of the sidebands that are produced by the modulation of a radio carrier frequency (such as amplitude modulation-AM). The offset frequencies (multiples of 0.008) are indicated in the figure.

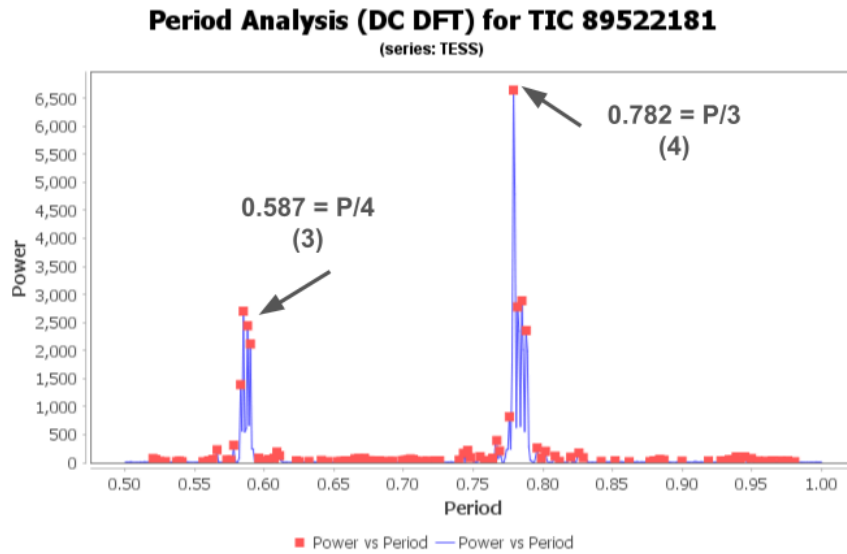
Figure 3 has significant power/amplitude at 1.173 days (period 2). This is one half the orbital period of 2.34699 days. The sidebands of the half orbital period are obvious with the offset frequencies as indicated. Figure 4 shows frequencies at 0.782 days (period 4) and 0.587 days (period 3). The 0.587 day signal is one-quarter the orbital period ( $P/4$ ). The signal at 0.782 is one-third the orbital period ( $P/3$ ). Again the signal structure around both frequencies can be clearly seen. Figure 5 shows periods at 0.391 days ( $P/6$ -period 7), 0.23468 days ( $P/10$ -period 5), 0.469 days ( $P/5$ -period 8), 0.33534 days ( $P/7$ -period 6), and 0.294 days ( $P/8$ -period 9).



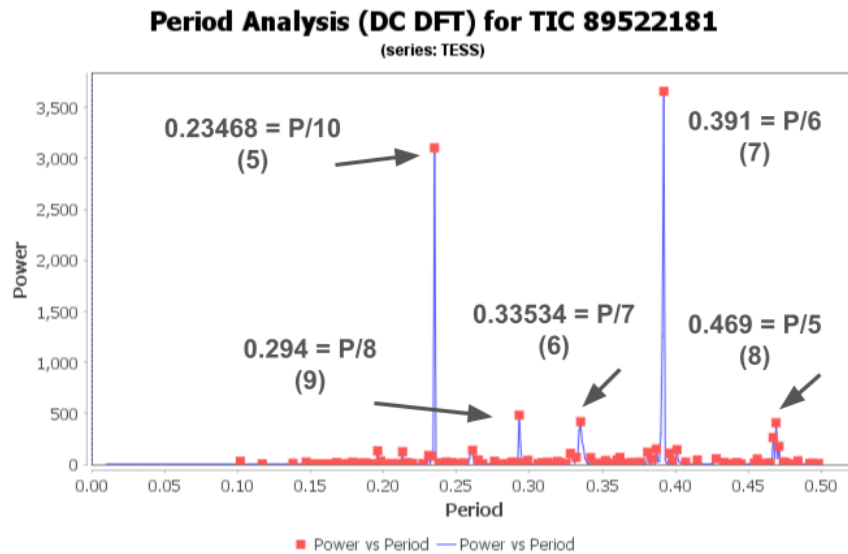
**Figure 2: Periodogram for V477 Cyg/TIC 89522181 (2.25-2.50 days)**



**Figure 3: Periodogram for V477 Cyg/TIC 89522181 (1.0-1.30 days)**



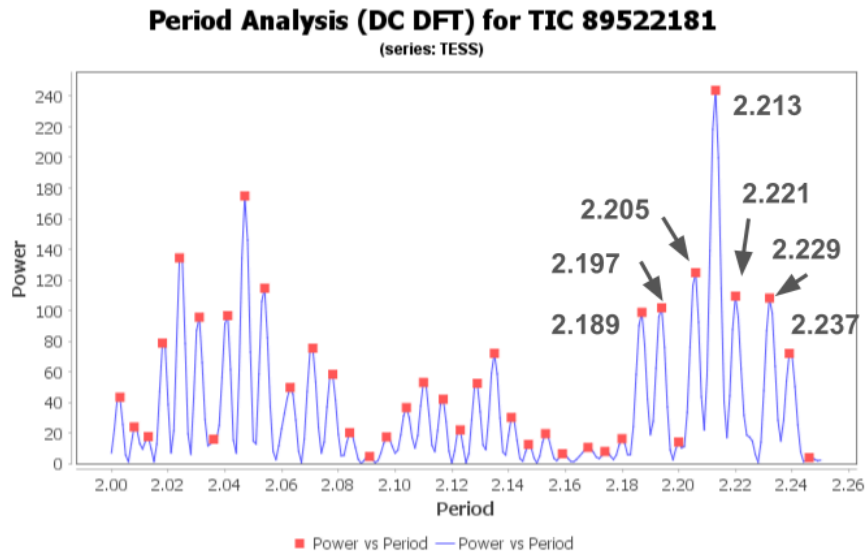
**Figure 4: Periodogram for V477 Cyg/TIC 89522181 (0.50-1.00 days)**



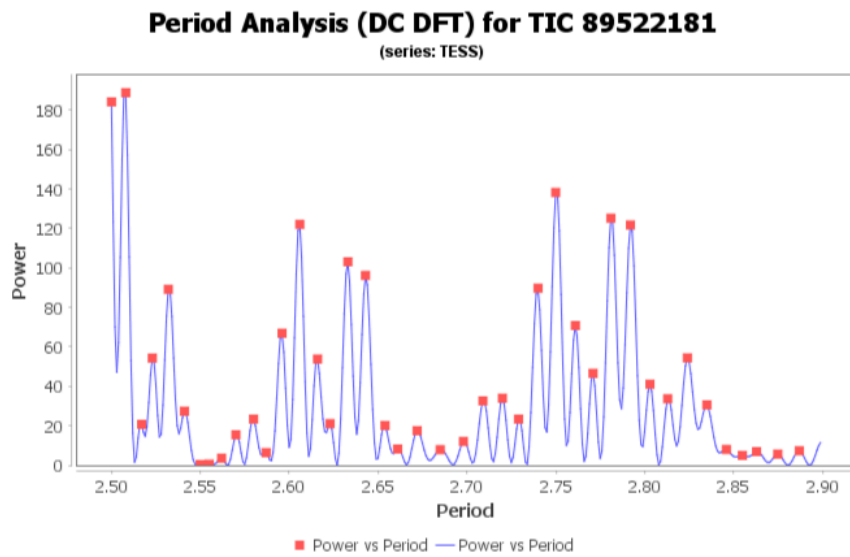
**Figure 5: Periodogram for V477 Cyg/TIC 89522181 (0.01-0.50 days)**

Figures 6-13 show the signal structure for low power/amplitude in the period intervals indicated. In particular, Figure 6 (2.0-2.25 days) again shows the presence of sidebands around the center period of 2.213 days. Close inspection of Figures 7-13

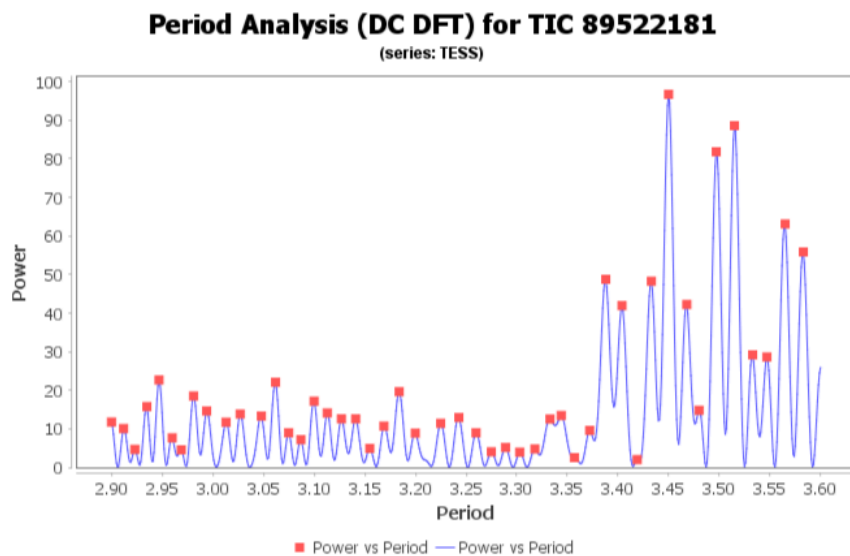
show significant signal structure, including repeating patterns. These signals appear to be the sums and/or differences of other frequency combinations. For example, the orbital period, 2.34699, minus  $P/3$  (0.782), yields 1.56399 which is shown in Figure 11. Additionally, the orbital period minus  $P/7$  (0.33534), yields 2.0116 which is shown in Figure 9. Other combinations are too numerous to present here, but illustrate how the various frequencies can combine to create new frequencies. These appear not to be artifacts of the filtering but are the result of significant stellar pulsations.



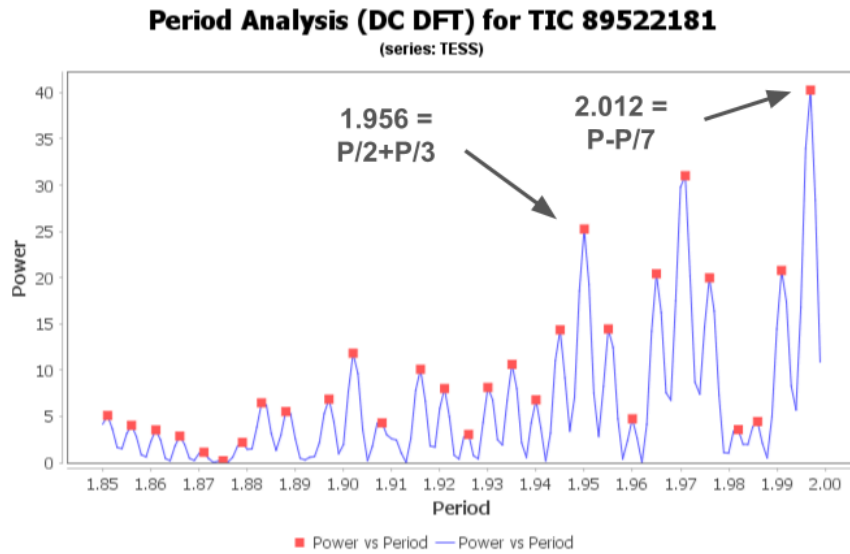
**Figure 6: Periodogram for V477 Cyg/TIC 89522181 (2.0-2.25 days)**



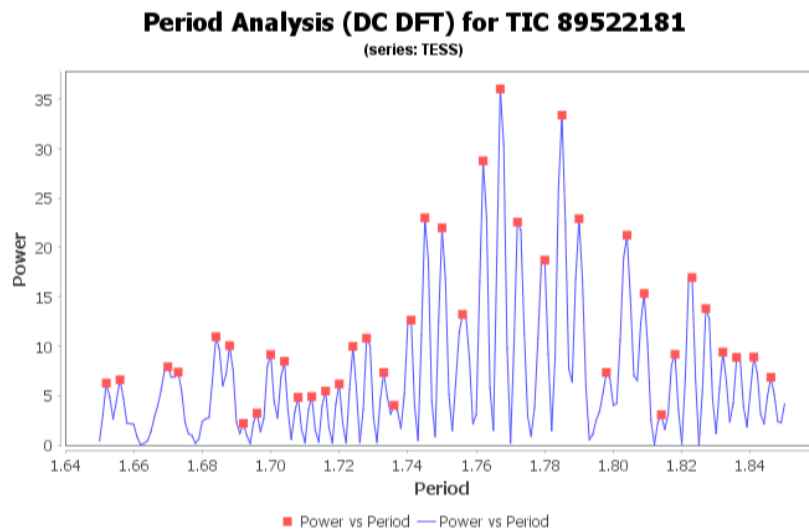
**Figure 7: Periodogram for V477 Cyg/TIC 89522181 (2.50-2.90 days)**



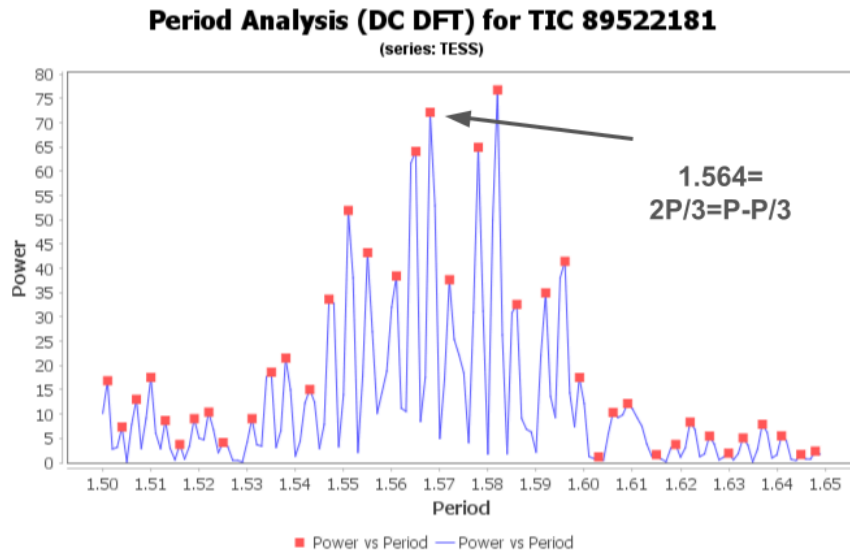
**Figure 8: Periodogram for V477 Cyg/TIC 89522181 (2.90-3.60 days)**



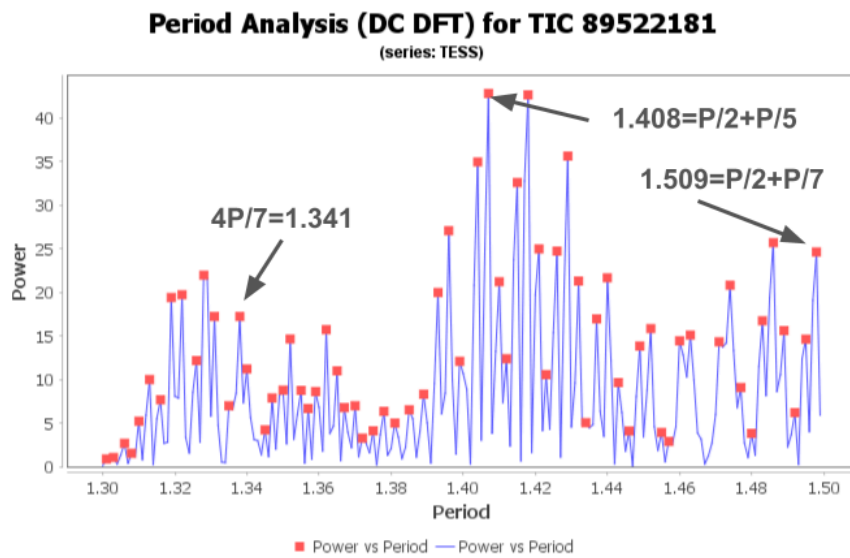
**Figure 9: Periodogram for V477 Cyg/TIC 89522181 (1.85-2.0 days)**



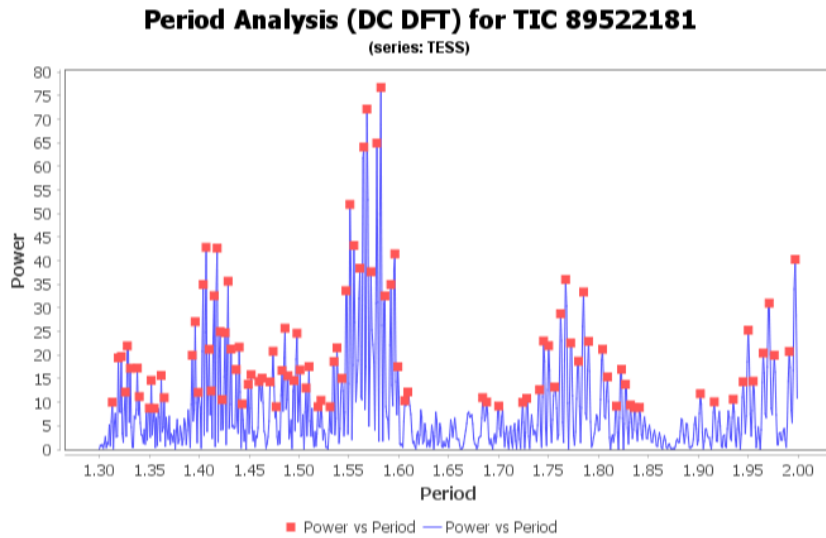
**Figure 10: Periodogram for V477 Cyg/TIC 89522181 (1.65-1.85 days)**



**Figure 11: Periodogram for V477 Cyg/TIC 89522181 (1.50-1.65 days)**



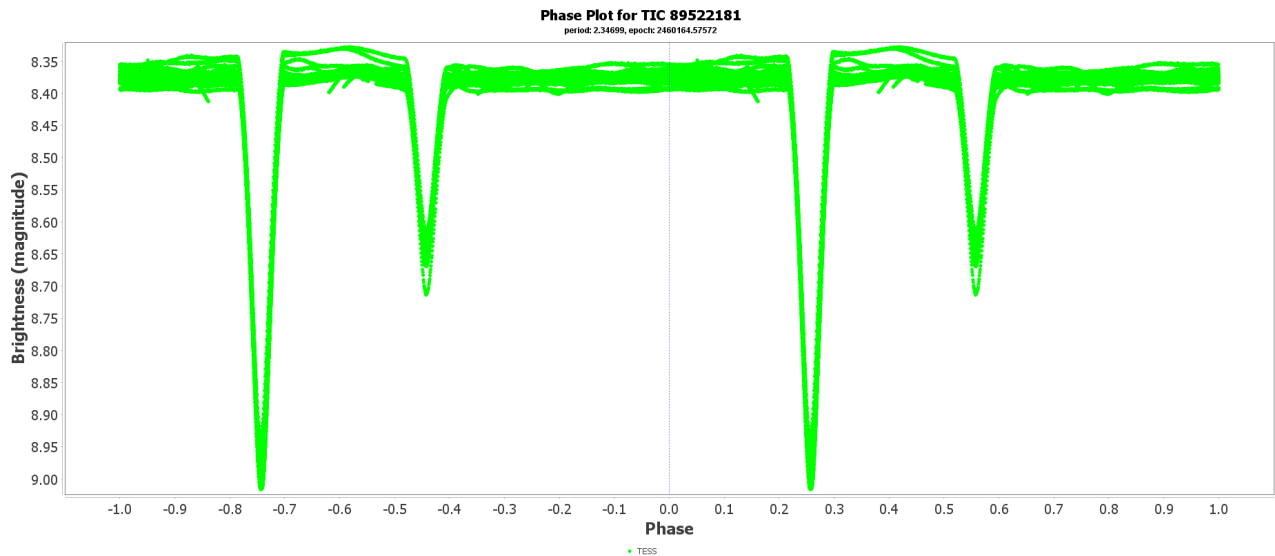
**Figure 12: Periodogram for V477 Cyg/TIC 89522181 (1.30-1.50 days)**



**Figure 13: Periodogram for V477 Cyg/TIC 89522181 (1.30-2.00 days)**

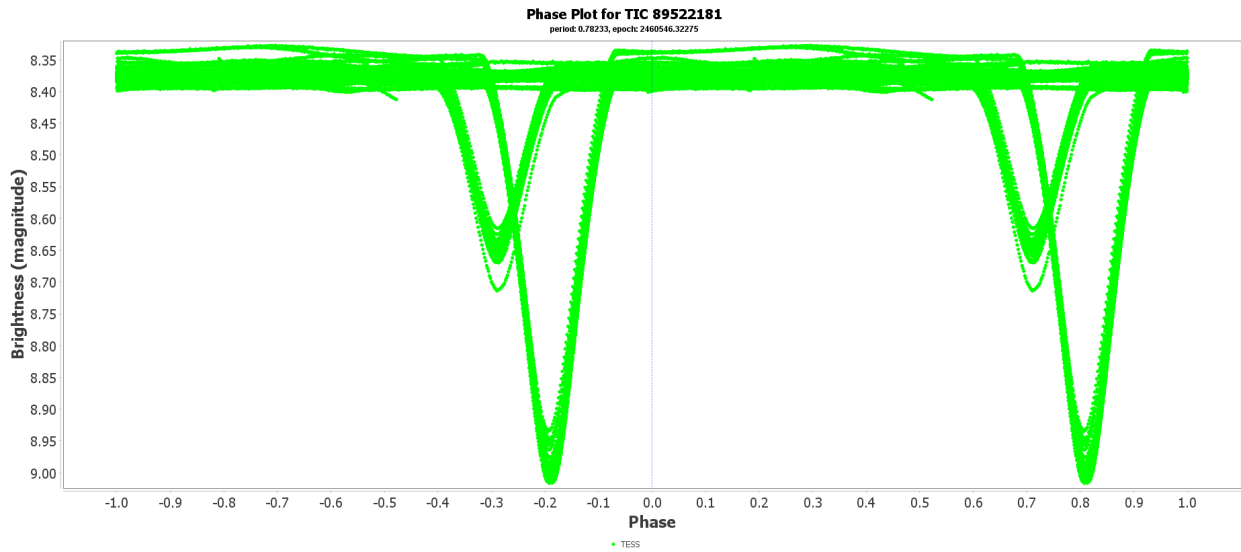
Returning to the high power/amplitude signals we see the pulsation characteristics of this system. Starting with the binary system orbital period of 2.34699 days (pulsation 1), half the period is 1.173 days (2), one quarter is 0.587 days (3), and one-eighth is 0.294 days (9). Other signals include 0.782 days ( $P/3$ , period 4), 0.23468 days ( $P/10$ , period 5), 0.33534 days ( $P/7$ , period 6) and 0.469 days ( $P/5$ , period 8).

Figure 14 shows the folded phase plot for the binary system orbital period of 2.34699 days, clearly showing the eclipse.

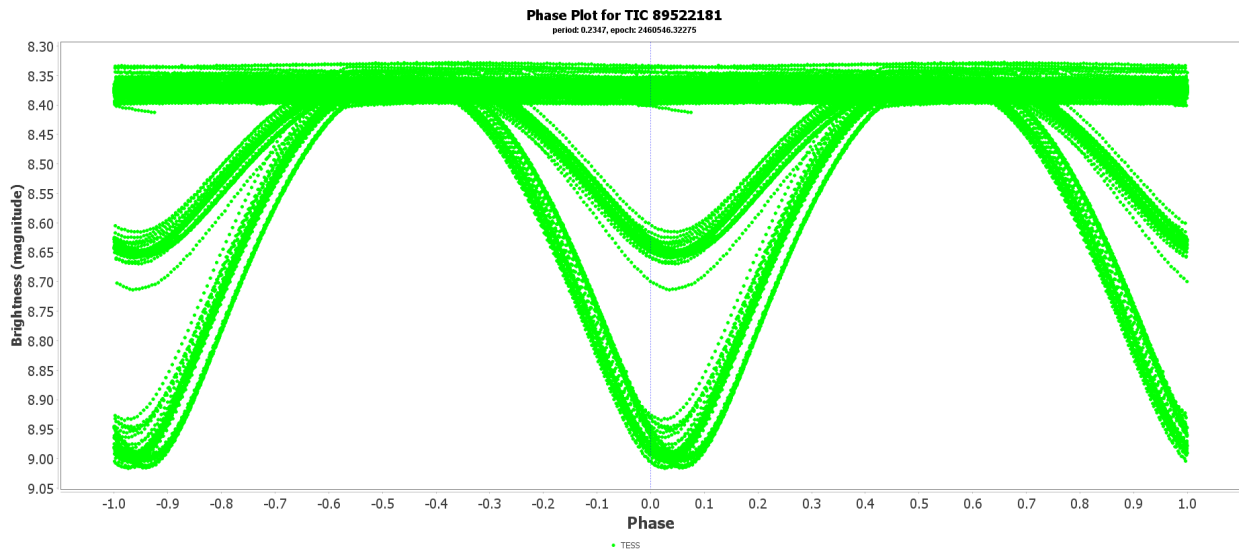


**Figure 14: Orbital Folded Phase Plot for V477 Cyg/TIC 89522181 (2.34699 days)**

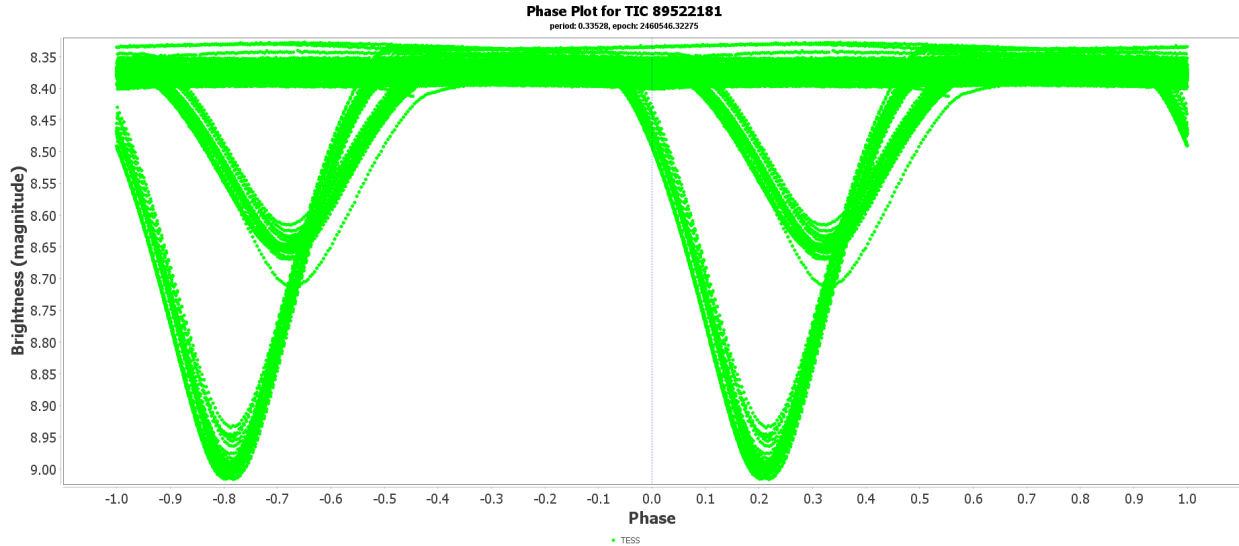
Figure 15 shows the phase plot for the signal at 0.782 days (4), Figure 16 shows the phase plot for the signal at 0.23468 days (5), and Figure 17 shows the phase plot for the signal at 0.33534 days (6). These are three of the subharmonics of the orbital period of 2.34699 days, showing the behavior of these periods as the system moves through the eclipse cycle.



**Figure 15: Folded Phase Plot for V477 Cyg/TIC 89522181 (0.782 days)**

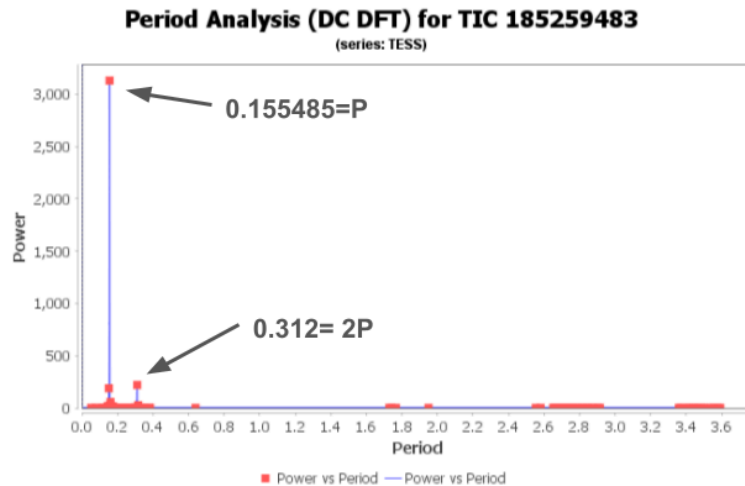


**Figure 16: Folded Phase Plot for V477 Cyg/TIC 89522181 (0.23468 days)**

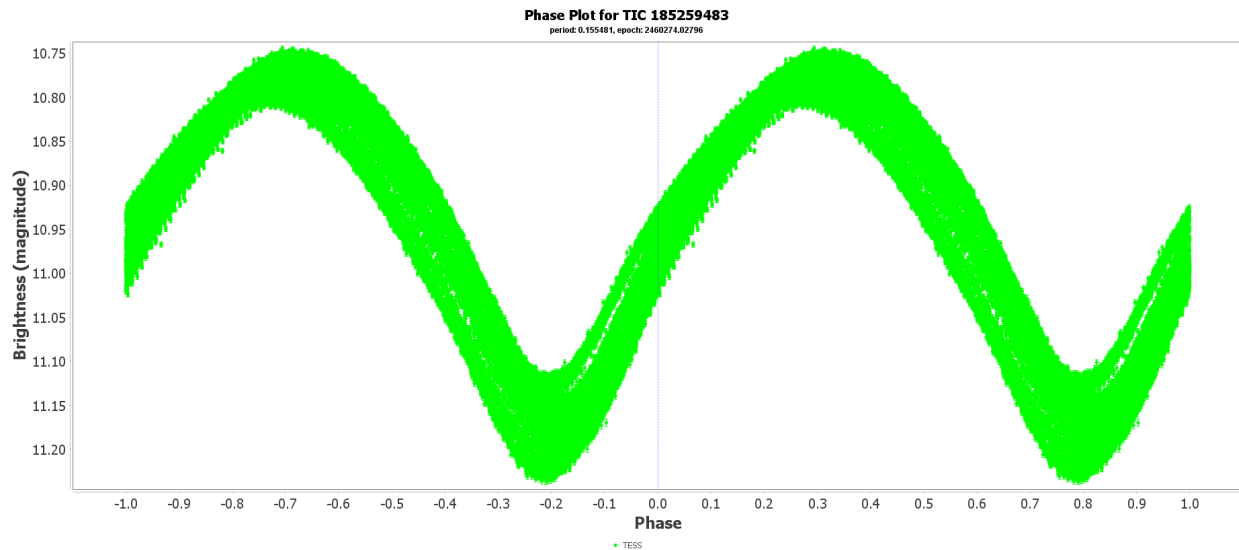


**Figure 17: Folded Phase Plot for V477 Cyg/TIC 89522181 (0.33534 days)**

As a comparison of this complex binary system with more typical binary systems, another system was randomly selected from the TESS Eclipsing Binary catalog ([TESS-EBs | MAST](#)) for analysis. This is TIC 185259483. Figures 18 and 19 show the periodogram and folded phase plot, respectively, for TIC 185259483 and clearly indicate a binary orbital period of 0.155485 days. The other (lower power) signal in Figure 18 is the first harmonic of the orbital period (0.312 days). No other signals are apparent for TIC 185259483. This is a further indication that V477 Cyg/TIC 89522181 has an uncommonly complex signal structure.



**Figure 18: Periodogram for TIC 185259483 (0.155485 days)**



**Figure 19: Folded Phase Plot for TIC 185259483 (0.155485 days)**

#### 4. The Possible Presence of a Third Object

Degirmenci, O.L., et al., 2003, discuss two photometric models utilizing the Wilson-Devinney method to determine the possible existence of a third component in this system. Their Model A is without the third object and Model B looks at the third body light contribution to the total light of the system. Their period analysis gives some slender evidence for an unseen third body with an orbital period of about 157 years. The results obtained from the simultaneous solutions of the U, B, and V light curves (U-B and B-V color indices for the components) suggest that the third body should be a compact star rather than a normal star (possibly a white dwarf). The estimated mass is 0.37-0.5 solar masses (0.5 is the mean value for white dwarfs). The details of this analysis are presented in Degirmenci, O.L., et al., 2003. Kolaczek-Szymanski, et al. (2021) also discusses suggestions of a third body in V477 Cyg.

#### 5. Discussion

As seen in the periodograms above, the spectrum of V477 Cyg is extremely complex. Assuming that the third body, if there actually is one, is not a significant contributor to the light curve, there are multiple frequencies/periods that contribute to the complex signal structure. These are the binary orbital period (2.34699 days) and the numerous subharmonics discussed above. The periodograms presented above all show amplitude modulation as indicated by the sidebands. As pointed out by Rea, B., 2022,  $\delta$ -Scuti pulsators have a known mechanism with non-stationary amplitudes where significant changes occur in the amplitude of one or more pulsation frequencies. Stationarity in a time series refers to the property that statistical characteristics of the series such as mean, variance, and covariance do not change over time. Additionally,

the effect of the tidal oscillation mechanism likely causes amplitude changes, particularly as the secondary component approaches periastron. Variable tidal potential drives tidally excited oscillations, which are gravity or g-modes. This may produce amplitude modulation to the basic orbital period and/or the other harmonic/subharmonic periods, creating the sidebands seen in the periodograms. The combination of these effects and the non-stationarity of the  $\delta$ -Scuti pulsator produce strong amplitude modulated sidebands as can be seen. Additionally, if the tidal effects are strong enough, nonlinear signal products could also be produced (such as  $2xP-3xP/3$ ,  $P/10+5P/7$ , etc.). Such nonlinear components are not immediately obvious in the periodograms, but could still be present.

The mechanism of the  $\delta$ -Scuti pulsator is complex. Stellar pulsation modes directly probe a star's internal structure, including interior physical conditions and transport processes. The self-excited resonant pulsation modes of a star represent small perturbations to the hydrostatic equilibrium structure. Each pulsation is a standing wave with unique geometry, frequency, and pulsation signal structure including harmonics, subharmonics and signal higher order products that reflect nonlinear processes within the star. The frequencies can be separated into radial and angular components. Radial components are characterized by a radial order  $n$ , describing the number of interior shells acting as resonant cavities. Each resonant cavity supports a characteristic vibration mode. Angular components are characterized by an angular degree  $l$ , and an azimuthal order  $m$ , that describes the number of surface nodal lines.

There are two main pulsation excitation mechanisms. The first is a stochastic mechanism that operates within large convective envelopes. Turbulent convection continually drives and damps the resonant frequencies of the star. These produce radial order pressure modes within certain frequency ranges determined by the resonant cavity. The second main pulsation excitement mechanism is a heat-engine mechanism in which mechanical work is converted to heat. This heats the various zones and causes them to expand. After expanding, the radiation is able to flow through the zones which releases the heat so the layers cool down and contract again. This periodic expansion-contraction cycle allows heat from the star to be converted into mechanical work and excite pulsations. Additionally, if the star is rapidly spinning, gravity can be important as a restoring force, resulting in additional frequencies and pulsation modes. Different stellar structures provide the necessary conditions to excite different pulsation modes with pulsations in stars across the Hertsprung-Russell diagram. The TESS data for V477 Cyg/TIC 89522181 has revealed several pulsation signals, namely the binary system orbital period and the various subharmonics. These are seen in the periodograms shown above.

## 6. Conclusions

Asteroseismology is the study of the interior physics and structure of stars using their pulsations. It is a powerful technique for measuring masses, radii, and ages, but also to directly study interior rotation, chemical mixing, and magnetism. In the case of eclipsing binary systems, important orbital information can also be determined. Signal analysis techniques are incorporated to identify the characteristics of stellar pulsations. In particular, these techniques have been applied to study the complex pulsations inherent in an eclipsing binary system with a pulsating  $\delta$ -Scuti component and a secondary component instrumental in producing tidal effect oscillations (photometric periastron variation). Both the tidally excited oscillations and the periastron brightening are hallmarks of the class of binary systems known as heartbeat stars, of which V477 Cyg is a member (Kolaczek-Szymanski et al. 2021). Three distinct signal types have been identified as a result of this analysis: 1) the binary system orbital period and related harmonics/subharmonics, 2) the signals and related harmonics/subharmonics that may be caused by tidal effects throughout the orbital period, including possible combinations of signals due to strong non-linear interactions, and 3) other pulsations within the binary system components that have no obvious relationship to the other signals (Figures 6-13). The periodograms and folded phase plots for these signals clearly support these conclusions.

## 7. Acknowledgements

The author would like to thank NASA for making data from its Transiting Exoplanet Survey Satellite (TESS) freely available and the Mikulski Archive for Space Telescopes (MAST) for the TESS photometry. Additionally, the author would like to thank the American Association of Variable Star Observers (AAVSO) for maintaining and making freely available the VStar photometric software that makes the analysis of TESS data possible.

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