

**Signal Analysis of Stellar Pulsations: The Transiting Exoplanet Survey Satellite
Observations of Eclipsing Binary V477 Cyg
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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 δ -Scuti pulsators. These binaries fall into two basic types, detached systems and semi-detached systems. This study looks at V477 Cyg which is a combination of an EA β Persei-type (Algol) star and a Heartbeat star. 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 δ -Scuti component of the binary (the EA star) are examined in detail to extract the frequency/period relations among the pulsations. The pulsation components of the Heartbeat star are shown as it transits through the eclipse cycle. Traditional signal processing and analysis techniques, normally used in communications and radar applications, are incorporated in a unique way to identify the characteristics of stellar pulsations.

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](#) (Appendix Figure A1) 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 δ -Scuti pulsators. These binaries fall into two basic types, detached systems and semi-detached systems. This study looks at V477 Cyg which is a combination of an EA β Persei-type (Algol) star and a Heartbeat star. 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 δ -Scuti component of the binary (the EA star) are examined in detail to extract the frequency/period relations among the pulsations. The pulsation components of the Heartbeat star are shown as it transits through the eclipse cycle. Traditional signal processing and analysis techniques, normally used in communications and radar

applications, are incorporated in a unique way to identify the characteristics of stellar pulsations.

An EA β Persei-type (Algol) eclipsing system is a binary with spherical or slightly ellipsoidal components. The light may remain almost constant between eclipses and a secondary minimum may be absent. Periods can range from 0.2 to over 10000 days with amplitudes which can vary by several magnitudes. Heartbeat stars are eccentric ($e > 0.2$) stars whose light curve resembles a cardiogram. They are ellipsoidal variables that undergo extreme dynamic tidal forces, especially during periastrons, that cause changes in brightness (photometric periastron variation or heartbeat). Delta Scuti (δ -Scuti) is a variable star in the constellation Scutum in the Southern Hemisphere and is the prototype for Delta Scuti type variable stars. δ -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](#) (Appendix Figure A1).

Eclipsing binary V477 Cyg (TESS Input Catalog (TIC) 89522181) is a detached binary system with two components, an EA β Persei-type (Algol) star and a Heartbeat star (Kloppenborg, 2022, AAVSO VSX). The EA star is the primary star of this system and is the δ -Scuti pulsator (Soydugan, E. et al., 2006) and the secondary component is the Heartbeat star (Kloppenborg, 2022, AAVSO VSX) and (Kolaczek-Szymanski, P.A., et al., 2021). Typically, an EA β Persei-type system is a binary with spherical or slightly ellipsoidal components. In this case, the secondary component (the Heartbeat star) creates a much more elliptical 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.

2. Methods

This study looks at V477 Cyg (TIC 89522181) which is a combination of an EA β Persei-type (Algol) star and a Heartbeat star. The light curve and the periodogram are analyzed from TESS photometry data contained in the [Mikulski Archive for Space Telescopes \(MAST\)](#). Pulsations within the δ -Scuti component of the binary are examined in detail to extract the frequency relations among the pulsations. For the binary system, the common name of the star from SIMBAD Astronomical Database-CDS Strasbourg or other databases (V477 Cyg) is entered in the MAST portal along with the desired search radius (the default being 0.2 degrees). From this, the TESS Input Catalog (TIC) number will be displayed (TIC 89522181). One or more downloadable files are listed. The target file(s) are then downloaded and unzipped, yielding light curve information.

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, 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 Δt 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 is analyzed with 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). [VStar](#) is a multi-platform variable star data visualization and analysis tool. 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 is 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 that analysis that do not actually correspond to pulsations within the star. That does not seem to be an issue in this analysis, as all components can be accounted for and are the result of stellar processes.

Finally, in order to compare this complex binary system with more typical binary systems, two such systems are selected and analyzed.

3. Analysis and Results

The V477 Cyg eclipsing binary variability type is EA + HB (Algol + Heartbeat) and the spectral type is A1V+F5V, respectively (Kloppenborg, 2022, AAVSO VSX). The orbital period is 2.34699 days (Kloppenborg, 2022, AAVSO VSX). For the EA, the mass is 1.80 solar masses, the radius is 1.60 solar radii, and the temperature is 8730 K. For the HB, the mass is 1.35 solar masses, the radius is 1.42 solar radii, and the temperature is 6531 K. The EA star in this system is the δ -Scuti pulsator (Soydugan, E. et al., 2006). Figure 1 shows the light curve for V477 Cyg and Figure 2 shows the periodogram for the entire analysis range of 0.01 days to 5.0 days. Figure 3 shows the subinterval from 0.5 to 5.0 days, and Figure 4 shows the subinterval from 0.01 to 0.50 days. The various pulsation periods are indicated in Figures 3 and 4.

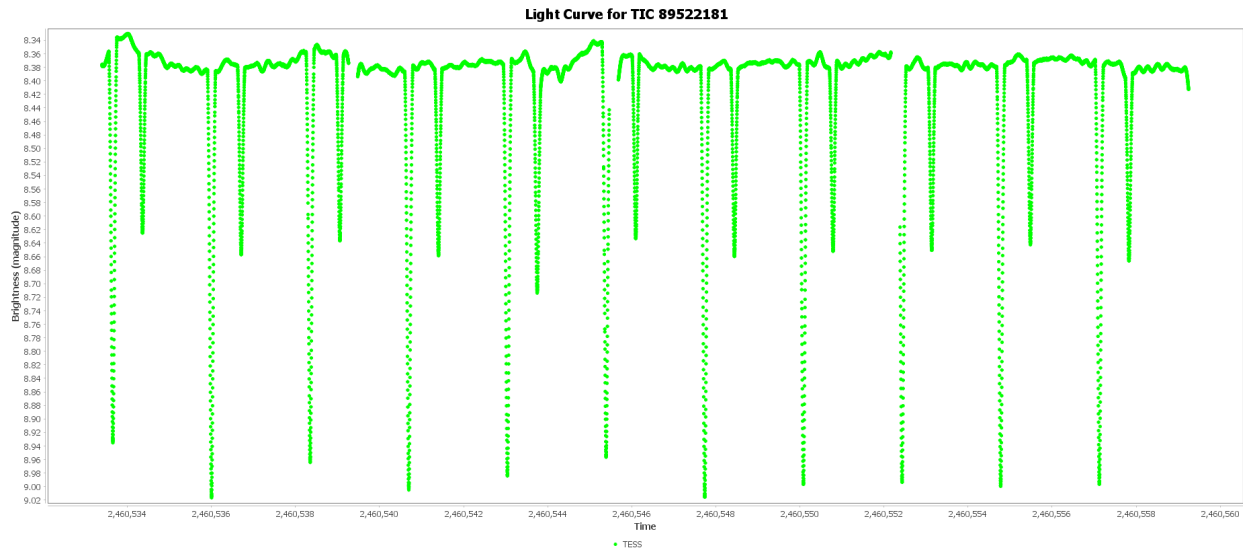


Figure 1: Light Curve for V477 Cyg/TIC 89522181

Period Analysis (DC DFT) for TIC 89522181 (series: TESS)

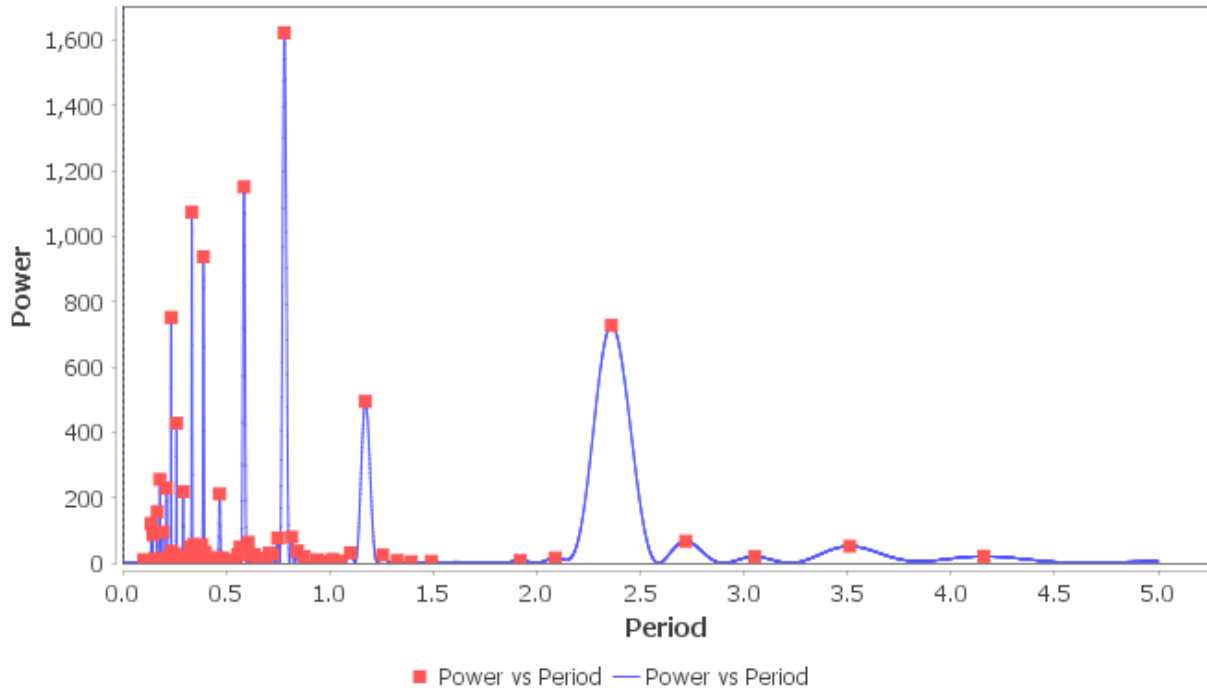


Figure 2: Periodogram for V477 Cyg/TIC 89522181 (0.01-5.0 days)

Period Analysis (DC DFT) for TIC 89522181 (series: TESS)

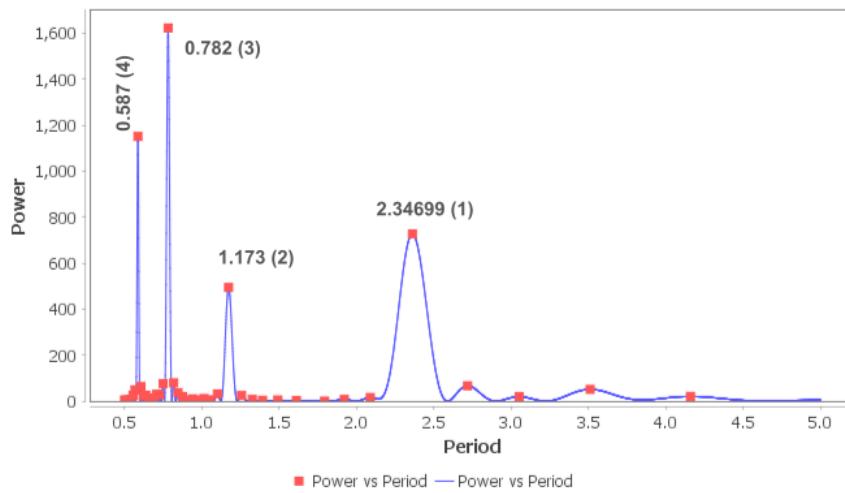


Figure 3: Periodogram for V477 Cyg/TIC 89522181 (0.5-5.0 days)

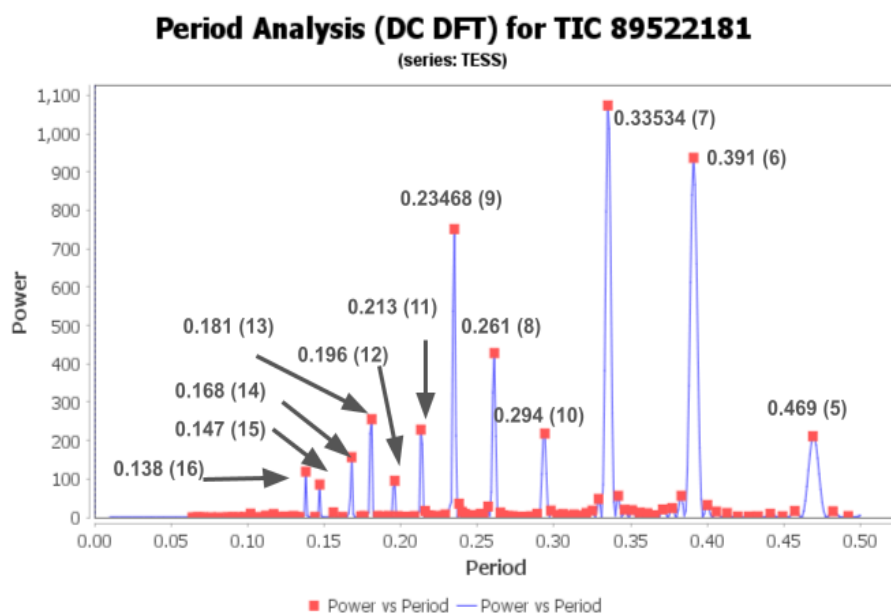


Figure 4: Periodogram for V477 Cyg/TIC 89522181 (0.01-0.50 days)

From Figures 2-4 we see the pulsation characters of this pulsator. 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 (4), one-eighth is 0.294 days (10), and one-sixteenth is 0.147 days (15). These are subharmonics of the binary system orbital period. The signals at 0.782 days (3), 0.23468 days (9), and 0.33534 days (7) are due to the heartbeat of the system as the secondary star approaches and transits through the periastron (point of closest approach). The signal at 0.782 days (3) is a fundamental pulsation as the star approaches periastron, the signal at 0.391 days (6) is one-half of this fundamental pulsation, and the signal at 0.196 days (12) is one-quarter of the fundamental pulsation. These are subharmonics of the primary pulsation. The signal at 0.23468 days (9) is a fundamental pulsation with a harmonic (2X) at 0.469 days (5). The signal at 0.33534 days (7) is another fundamental pulsation with a one-half subharmonic at 0.168 days (14). The other signals at 0.138 (16), 0.181 (13), 0.213 (11), and 0.261 (8) days have no obvious relation to the orbital period or the pulsation frequencies.

Figure 5 shows the folded phase plot for the binary system orbital period of 2.34699 days, clearly showing the eclipse. This can also be seen in the [Eclipsing Binary Simulator](#) software developed by the University of Nebraska. Appendix Figure A2 shows the output of this simulation for the orbital parameters presented herein.

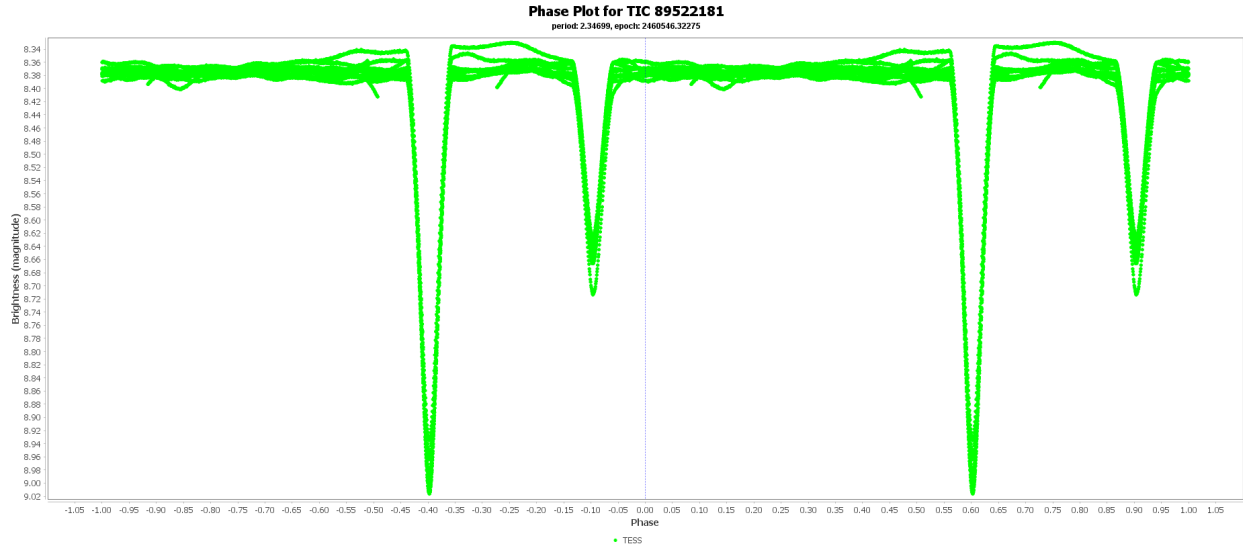


Figure 5: Orbital Folded Phase Plot for V477 Cyg/TIC 89522181 (2.34699 days)

Figure 6 shows the phase plot for the signal at 0.782 days (3) which is a fundamental pulsation of the heartbeat. Here, the secondary star is approaching periastron. Figure 7 shows the phase plot for the signal at 0.23468 days (9) where the system is at periastron and the light curve components are aligned. Finally, Figure 8 shows the phase plot for the signal at 0.33534 days (7) for the secondary star exiting periastron and continuing in its binary orbit.

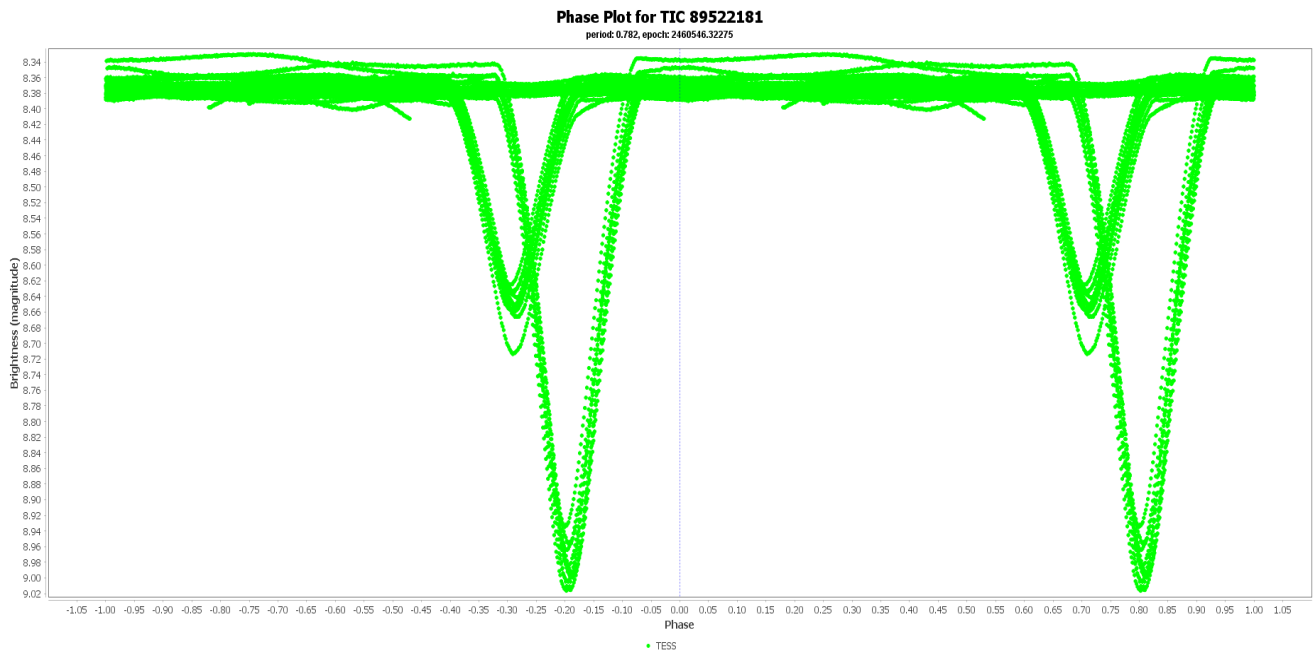


Figure 6: Folded Phase Plot for V477 Cyg/TIC 89522181 (0.782 days)

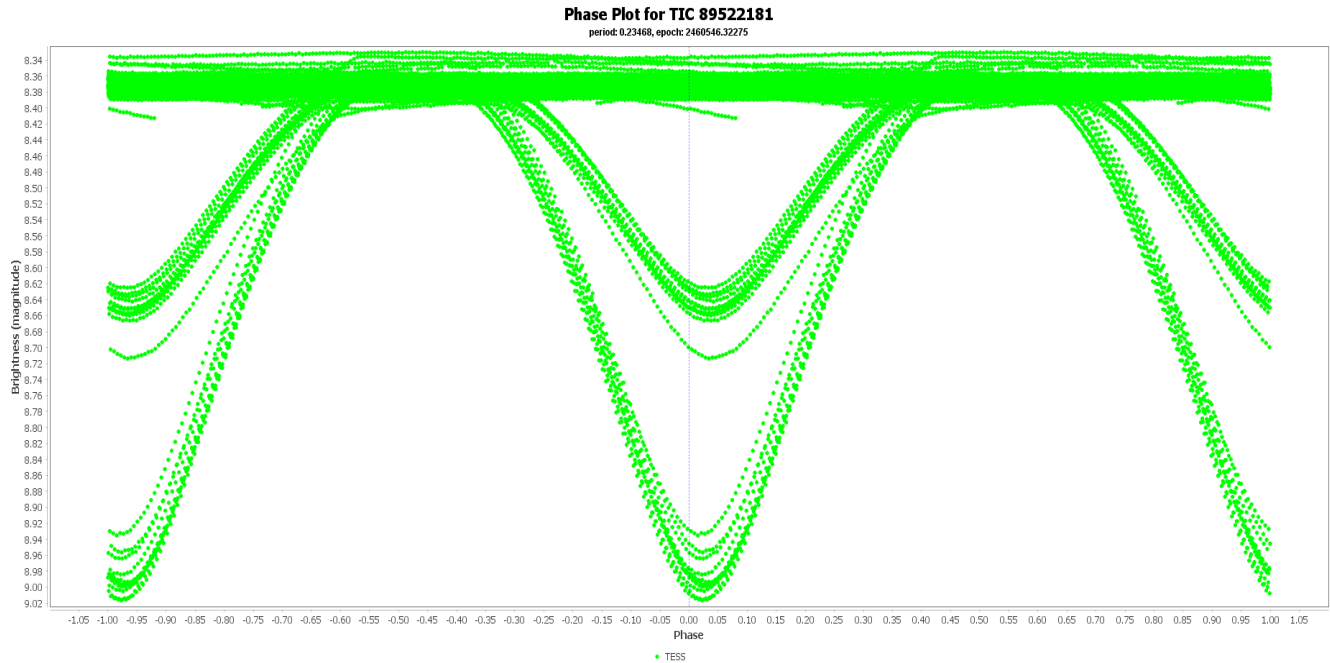


Figure 7: Folded Phase Plot for V477 Cyg/TIC 89522181 (0.23468 days)

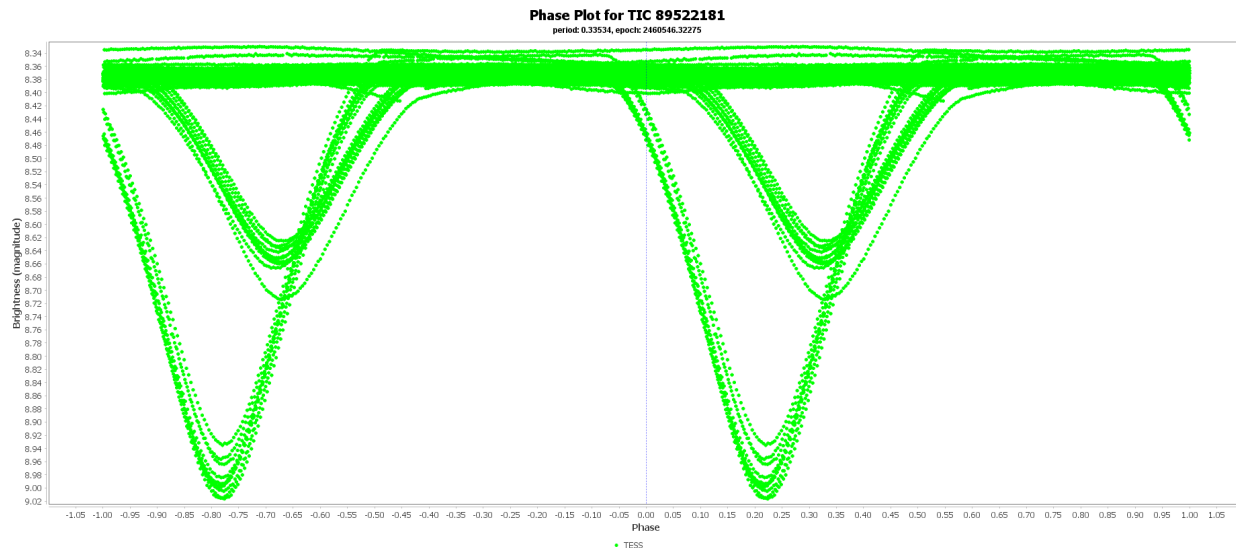


Figure 8: Folded Phase Plot for V477 Cyg/TIC 89522181 (0.33534 days)

The other signals at 0.138 (16), 0.181 (13), 0.213 (11), and 0.261 (8) days have no obvious relation to the orbital period or the periastron pulsation frequencies. These are likely the pulsations of the EA δ -Scuti pulsator component.

As a comparison of this complex binary system with more typical binary systems, two such systems were randomly selected from the TESS Eclipsing Binary catalog ([TESS-EBs](#) | [MAST](#)) for analysis. These are TIC 185259483 and TIC 278822321.

Figures 9, 10, and 11 show the light curve, periodogram, and folded phase plot, respectively, for TIC 185259483. Figures 12, 13, and 14 show the light curve, periodogram, and folded phase plot, respectively, for TIC 278822321. Figures 10 and 11 clearly indicate a binary orbital period of 0.155485 days. Figures 13 and 14 show an orbital period of 0.31961 days for TIC 278822321. The other (lower power) signal in Figure 13 is the first harmonic of the orbital period (0.63922 days). No other signals are apparent for either TIC 185259483 or TIC 278822321. This is a further indication that V477 Cyg/TIC 89522181 has an uncommonly complex signal structure.

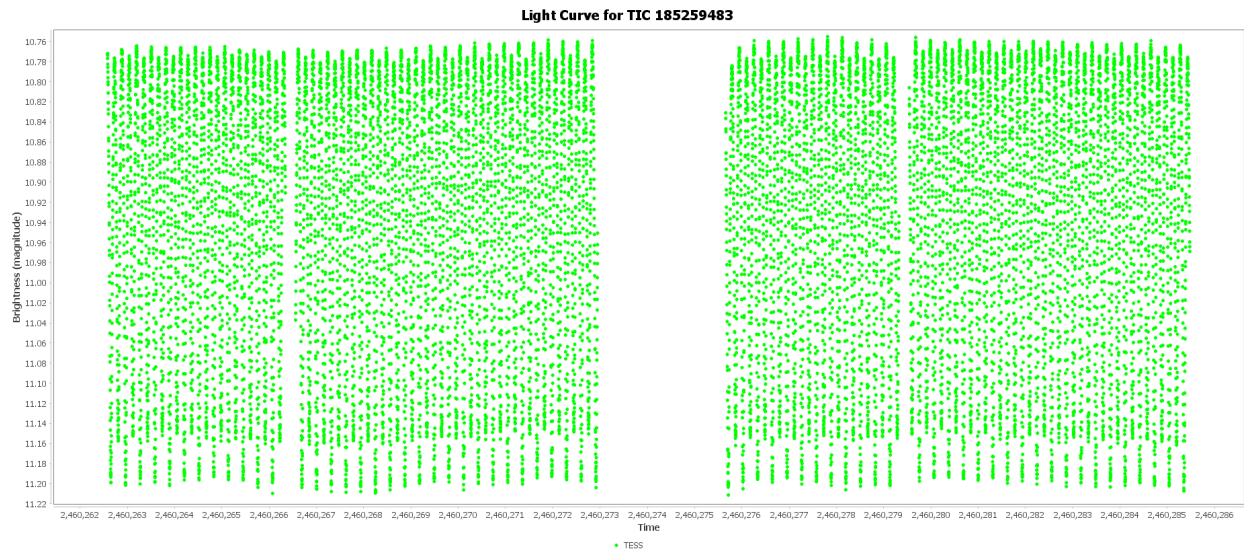


Figure 9: Light Curve for TIC 185259483

Period Analysis (DC DFT) for TIC 185259483 (series: TESS)

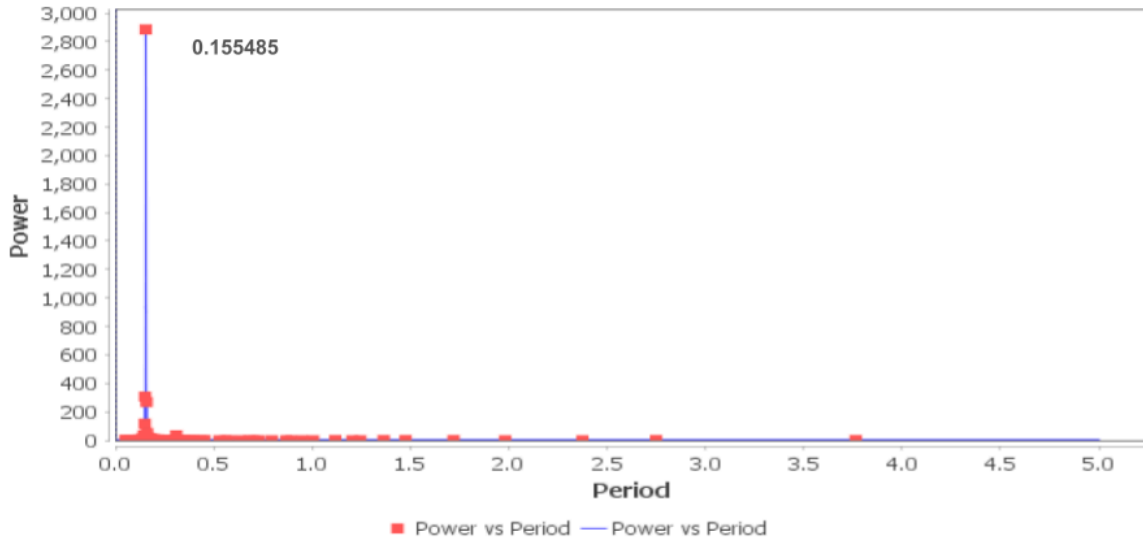


Figure 10: Periodogram for TIC 185259483 (0.155485 days)

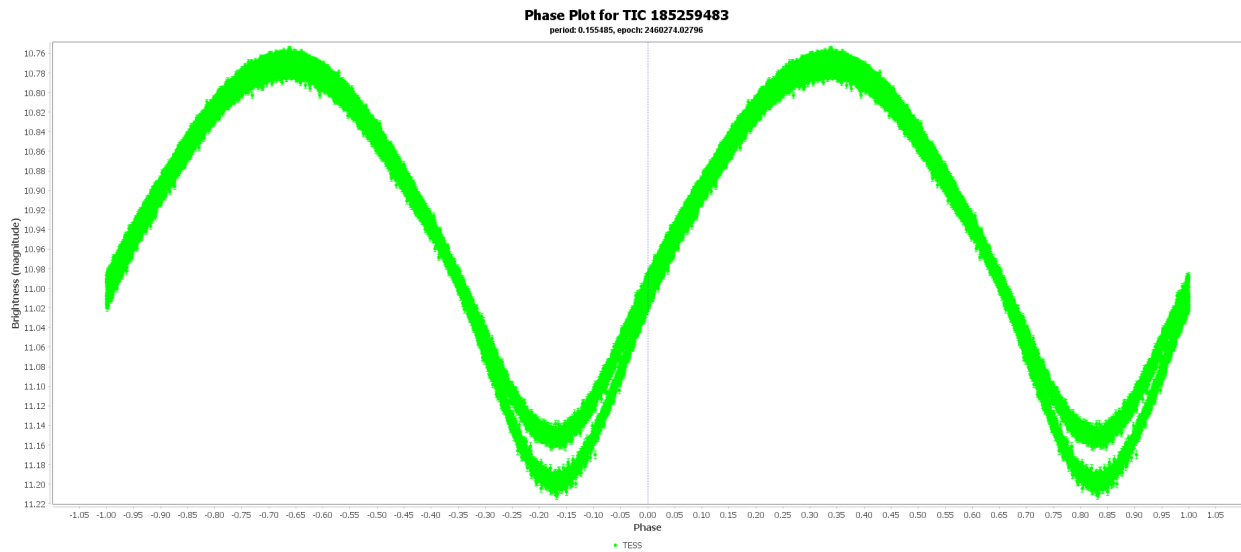


Figure 11: Folded Phase Plot for TIC 185259483 (0.155485 days)

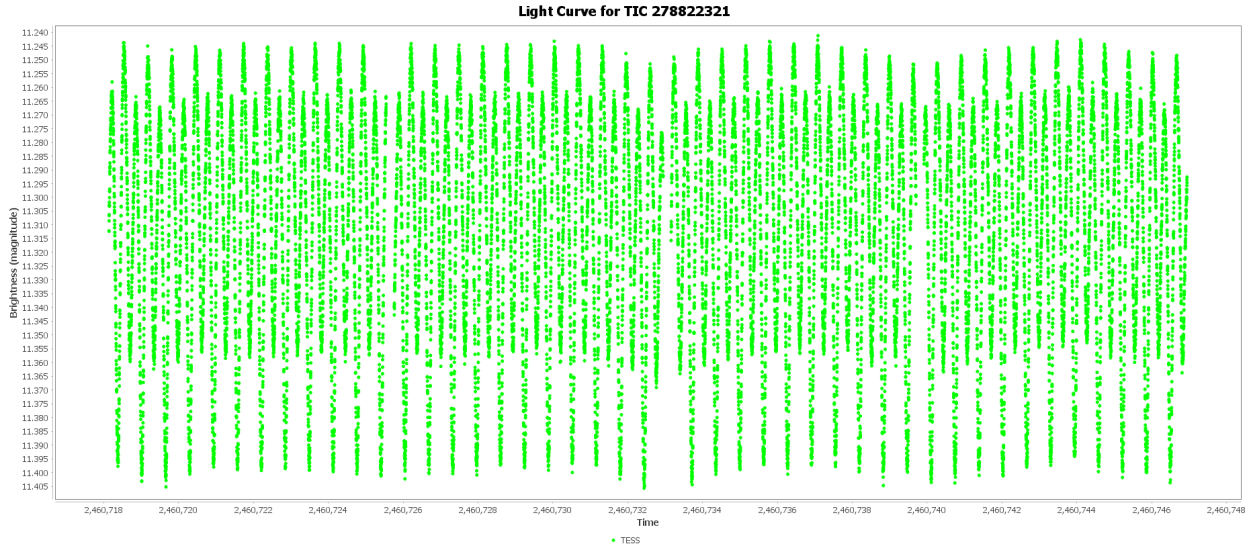


Figure 12: Light Curve for TIC 278822321

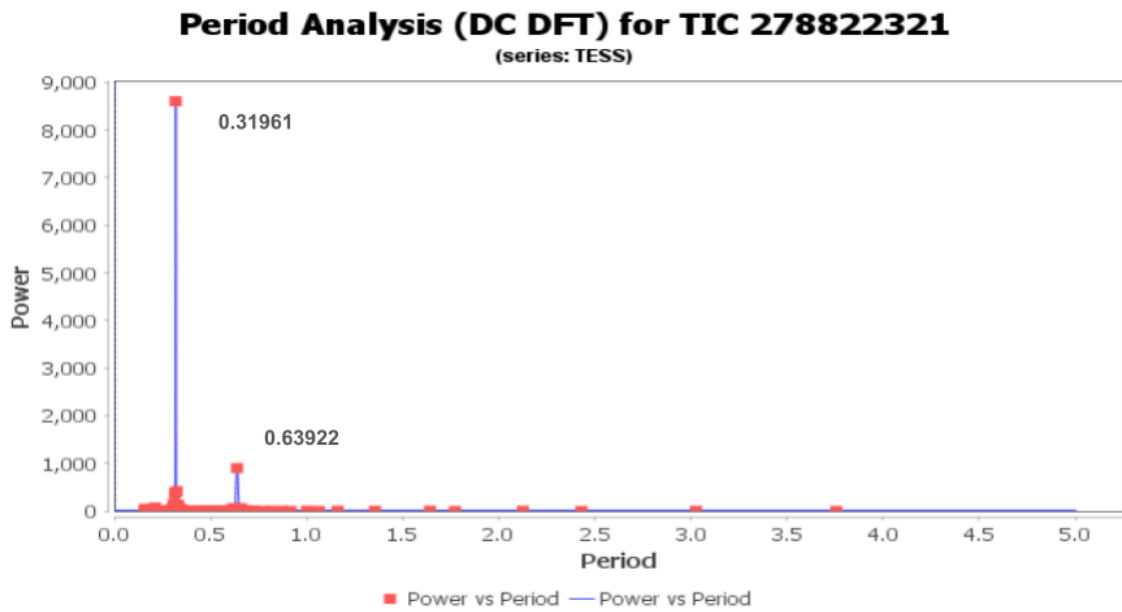


Figure 13: Periodogram for TIC 278822321 (0.31961 days)

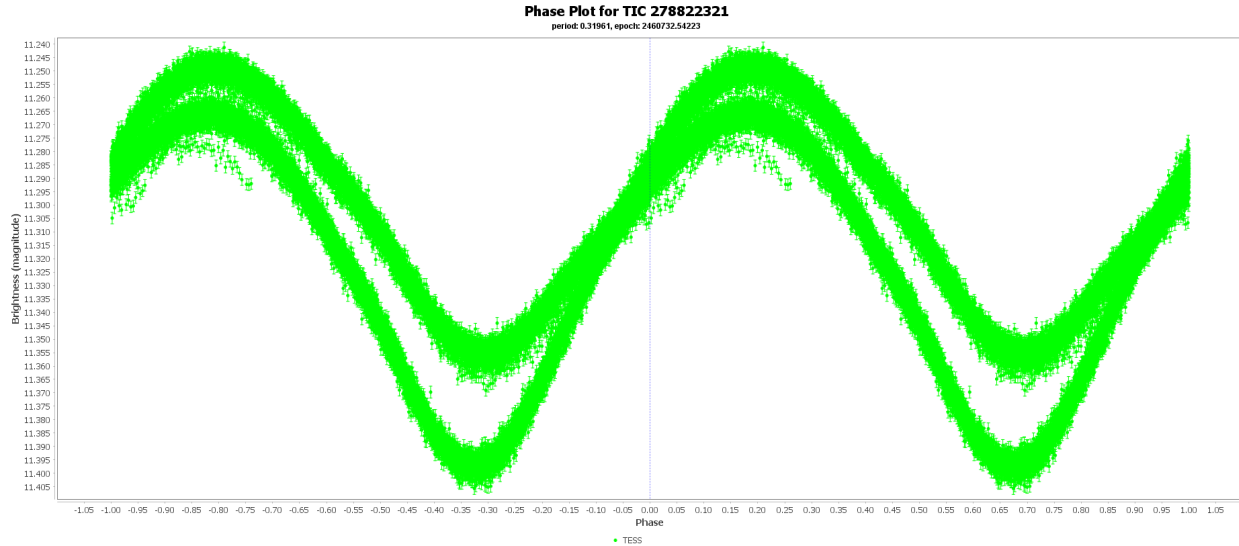


Figure 14: Folded Phase Plot for TIC 278822321 (0.31961 days)

4. Discussion

This analysis has highlighted two specific phenomena with complex signal structures, the heartbeat and the δ -Scuti pulsator. The heartbeat light curve resembles a cardiogram. This is due to extreme dynamic tidal forces, especially during periastrons, that cause changes in brightness (photometric periastron variation or heartbeat). As can be seen from Figures 6, 7, and 8, as well as the corresponding periodograms, the heartbeat becomes extremely strong as the system approaches and passes through the periastron. As the orbit continues toward apastron (furthest point in the orbit), the pulsations become extremely weak and likely undetectable. The signals approaching periastron (signal 3) and exiting periastron (signal 7) are noticeably stronger than the signal (9) at periastron. This is relatively straightforward.

The mechanism of the δ -Scuti pulsator, on the other hand, is more 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 Hertzsprung-Russell diagram. The TESS data for V477 Cyg/TIC 89522181 has revealed several pulsation signals. In addition to the binary system orbital period of 2.34699 days (pulsation 1 in Figure 3) and its subharmonics, several other fundamental pulsations and their harmonics or subharmonics have been identified as a result of the heartbeat process. Additionally, there are weaker pulsations not immediately related to the other signals in any simple harmonic way. It appears that the four lower period pulsations may be the g mode signals of the δ -Scuti pulsator. Figures 15 and 16 illustrate examples of typical stellar pulsations. The various lines and nodes represent individual pulsation modes.

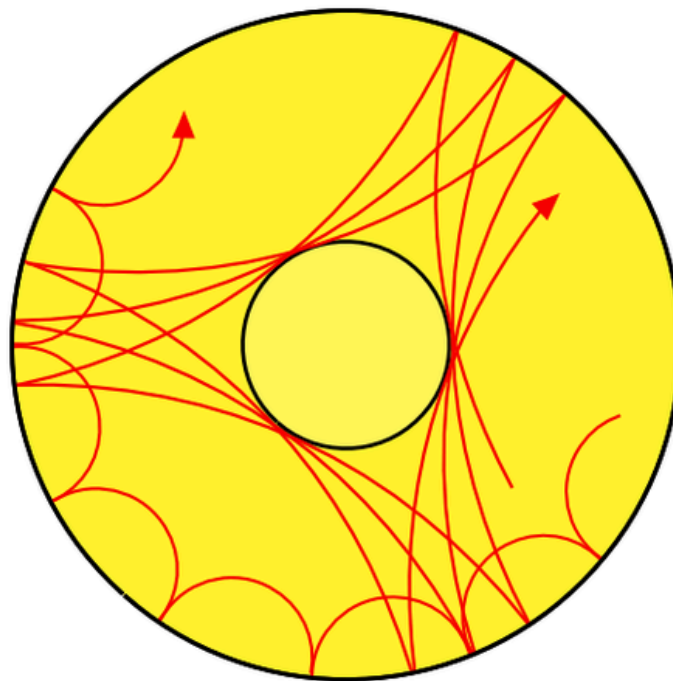


Figure 15: Example 1 of Stellar Pulsation Modes

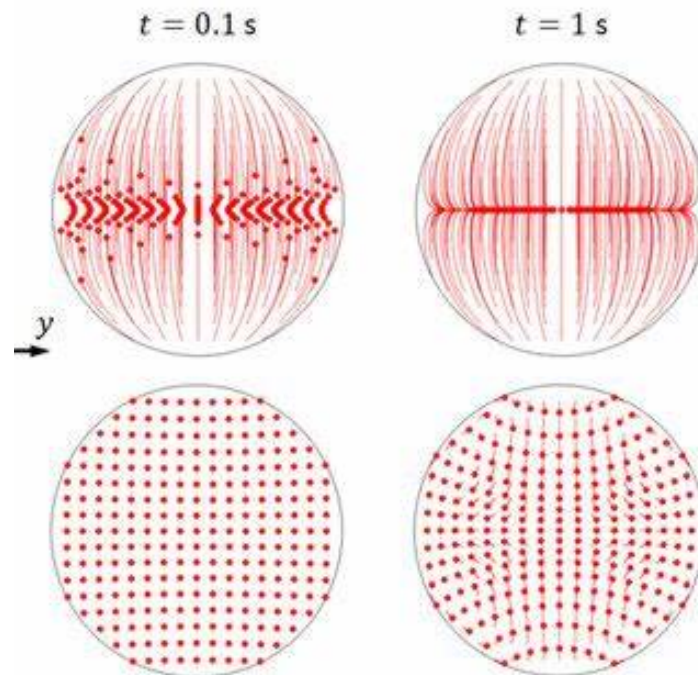


Figure 16: Example 2 of Stellar Pulsation Modes

5. 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. Traditional signal processing and analysis techniques, normally used in communications and radar applications, are incorporated in a unique way to identify the characteristics of stellar pulsations. In particular, these signal analysis techniques have been applied to study the complex pulsations inherent in an eclipsing binary system with a pulsating δ -Scuti component and a heartbeat component. 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 heartbeat signals and related harmonics/subharmonics as the system passes through periastron (point of closest approach), and 3) δ -Scuti pulsations within the primary EA component that have no obvious relationship to the other signals, indicating an independent signal source. The light curves, periodograms, and folded phase plots for these signals clearly support these conclusions.

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[MAST: Barbara A. Mikulski Archive for Space Telescopes](#).

[SIMBAD](#)

TESS Eclipsing Binary Table ([TESS-EBs](#) | [MAST](#))

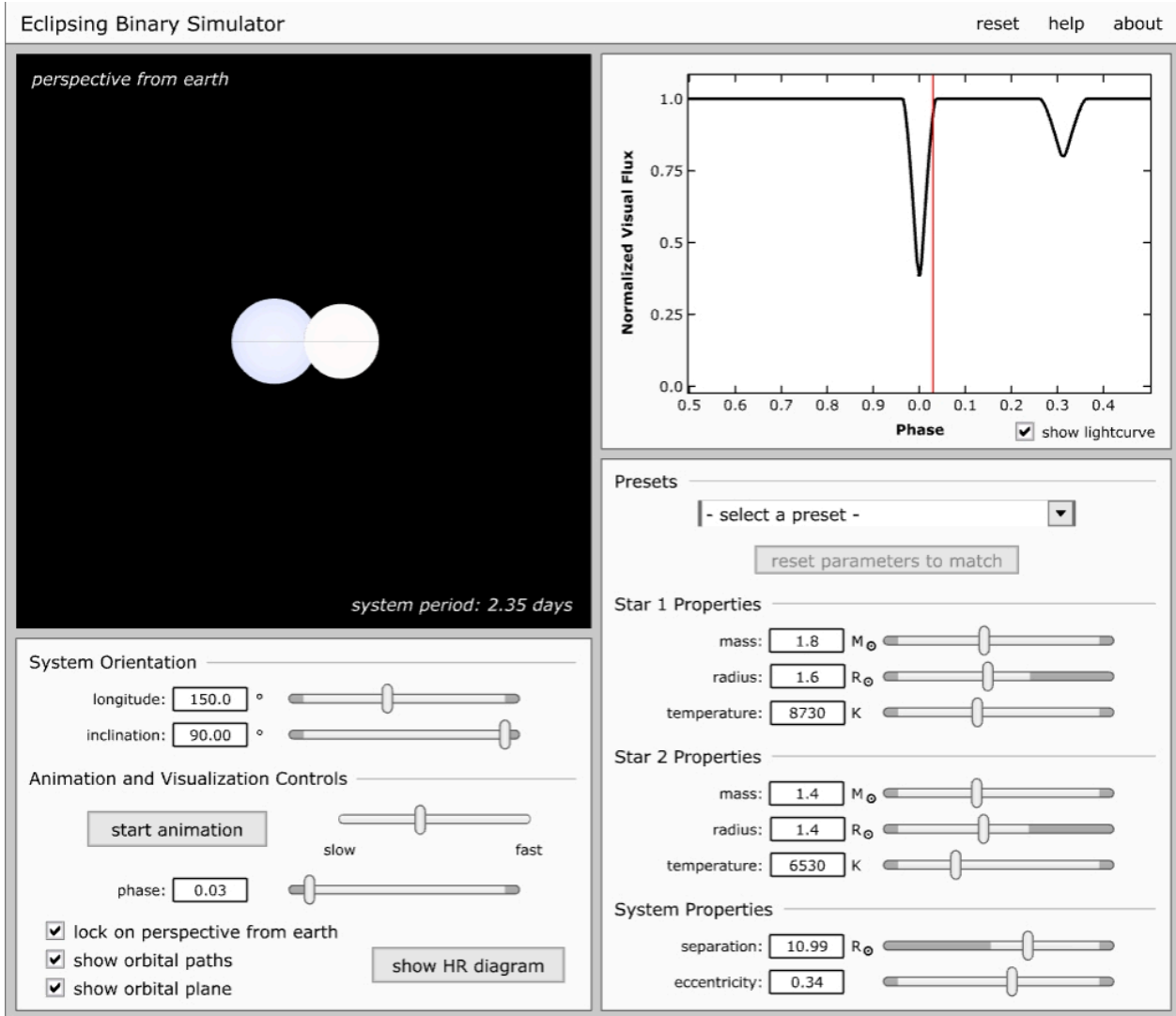


Figure A2: Eclipsing Binary Simulator
(Courtesy University of Nebraska)