Pulsation Properties in Asymptotic Giant Branch Stars

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Abstract

Asymptotic Giant Branch (AGB) stars are stars with low- to intermediate mass in a late stage in their stellar evolution. An important feature of stellar evolution is the ongoing nucleosynthesis, the creation of heavier elements. Unlike main sequence stars, the AGB stars have a thick convective envelope which makes it possible to dredge-up the heavier fused elements from the stellar core to its surface. AGB stars are also pulsating variable stars, meaning the interior expands and contracts, causing the brightness to fluctuate. These pulsations will also play a major role in the mass loss observed in these stars. The mass loss is caused by stellar winds that accelerate gas and dust from the surface of these stars and thereby chemical enrich the interstellar medium. It is important to understand the properties of these pulsations since they play a key role in how stellar winds are produced and then enrich the galaxy with heavier synthesized elements. These pulsation periods can be observed with their corresponding Light-Curves, where the periodic motion of the brightness can be clearly seen. The main goal with this project is to calculate these pulsation periods for different AGB stars and compare these values with the periods listed in the General Catalogue of Variable Stars (GCVS). The comparison between these values gives a better understanding of methods of determining these periods and the uncertainties that follow.
Sammanfattning

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1 Introduction

Stars with an initial mass ranging from 0.8 to 8 solar masses will evolve into asymptotic giant branch (AGB) stars. AGB stars have exhausted all of the hydrogen and helium burning in their stellar cores and instead burn these elements in thin shells around the dormant core. Unlike main sequence stars, AGB stars have a thick convective zone which is able to dredge-up the heavier synthesized elements from the stellar interior to the surface of the star. These elements will then be transported into the interstellar medium by stellar winds. So the AGB phase plays an important role in galactic enrichment.

A characteristic feature of these stars is the existence of a stellar wind. These stellar winds cause a heavy mass loss, with typical mass loss rates between $M \sim 10^{-8} - 10^{-4} M_\odot yr^{-1}$. The process behind this mass loss is related to the stellar pulsations of AGB stars. The stellar pulsations push material periodically outwards from the outer layers of the star, giving rise to shock waves in the atmosphere. Dust grain will then form in the post-shock gas. Radiation pressure on these newly formed dust particles will accelerate dust and gas. If these velocities reach the escape velocity the star will lose mass. This mass loss will determine the lifetime of the star on the AGB. Understanding these pulsations and the mass loss is important for understanding the evolution of low- to intermediate mass stars.

This project will focus on observing the pulsations periods of several Asymptotic Giant Branch Stars. The purpose of this project is to analyze how well we can determine these periods by using public data from the American Association of Variable Star Observers (AAVSO). The validation of these calculations will be analyzed by comparing these estimated values to the values of the periods listed in the General Catalogue of Variable Stars (GCVS).
2 Background

2.1 Stellar Evolution

All stars shine due to the nuclear processes inside their stellar interiors. The radiation pressure from these processes keeps stars from collapsing under the gravitational pressure. When the fuel in the core is exhausted the core will contract and the outer parts of the stars will expand due to the energy released from thermonuclear reactions. This causes the star to evolve into a red giant. When all of the fuel inside the star has been exhausted the outflow of energy will come to an end and the star will reach its end state as one of three objects: a black hole, a neutron star or a white dwarf. The end state of the star is determined by its initial mass. Low to intermediate mass stars will cast away their outer mass layers and evolve into planetary nebulae and then eventually cool down as white dwarfs. Heavier stars will evolve into either a neutron star or a black hole, depending on the mass of the core [1] [2].

2.1.1 Stellar Evolution Pre-AGB Phase

Stars with an initial mass ranging from 0.8 to 8 solar masses will evolve into AGB stars and eventually reach their end states as planetary nebulae and white dwarfs. As can be seen in the Hertzsprung–Russell diagram in Fig. 1, when all the hydrogen has been fused into helium in the core, the star will leave the main sequence and begin to climb the red giant branch (RGB). As the star reaches the RGB the fusion of hydrogen is being ingrained in a shell around the helium core as the core becomes electron degenerate. At the same time, the outer parts of the star will expand, due to the nuclear reactions, and become convective. The convective layers will extend inwards towards the helium core, leading to the ”first dredge-up”. The star will continue to climb the giant branch as the He core continues to contract. The temperature at the centre of the star will increase and eventually lead to ignition of triple-alpha reactions, giving rise to the ”helium-flash”, where helium is converted into carbon and oxygen. At this point, the star will continue its evolution through the horizontal branch. During the horizontal branch, He burning occurs in the central core together with H shell burning surrounding the core. As the He is being exhausted the star will expand further and evolve into an Asymptotic Giant Branch star. During this ascend on the AGB the core will become electron degenerate as the fusion of H and He takes place in surrounding shells above the core [3].
Figure 1: A sketch of a Hertzsprung-Russell (H-R) diagram showing the stellar evolution for a low mass star. The H-R diagram shows how the stars luminosity changes accordingly to the effective temperature of the star. Image taken from [4].

2.1.2 Stellar Evolution During the AGB Phase

During the early AGB (E-AGB) stage H and He is burned in thin shells around the electron-degenerate core, that consists of carbon-oxygen (see Fig. 2). At this stage the size of the core is similar to the size of earth, meaning that the volume of the star is almost entirely made up by the convective envelope, where the stellar pulsations occur. This is when the ”second dredge-up” occurs. The convective layer will reach in and bring heavier elements fused up to the surface [3] [5].

Figure 2: Illustration of the inner structure of an Asymptotic Giant Branch Star. Image taken from [6].
As the He-burning is being exhausted the He shell will become extinguished, making the H shell burning more extended. When the He-burning ignites again the luminosity will fluctuate since the He shell burning contributes with most luminosity. These fluctuations distinguish the thermally pulsing AGB phase (TP-AGB). During the thermal pulses, a carbon-rich convective zone will establish above the H and He burning shells. Between the thermal pulses, the star will expand and cool down considerably. The hydrogen shell will be extinguished and another dredge-up will occur, bringing up carbon into the convective envelope. This event is called the "third dredge-up" [3] [5].

Another important effect of the thermal pulses is the so-called s-process. The s-process is the creation of elements heavier than iron in a neutron capture process. The convective layer mixes hydrogen from the envelope with the carbon-rich layer, causing these protons to react with the carbon; the protons are captured by $^{12}$C to make $^{14}$N which then undergoes positive beta-decay to produce $^{13}$C. $^{13}$C will then release neutrons which will be captured by other elements, thereby creating heavier isotopes. As mentioned, the nucleosynthesis in AGB stars plays an important part in the creation of heavier elements [3] [5].

2.2 Variable Stars

Variable stars are stars with a brightness that varies over time. There are different types of variations due to different factors. This is why the classification of variable stars is important. These stars can be divided into intrinsic variables and extrinsic variables. Intrinsic stars vary due to physical properties within the star itself, such as pulsation or eruption, whereas extrinsic stars are stars with a brightness that varies due to factors such as eclipsing or rotation. The intrinsic variables are divided into pulsation variables or eruption variables, which in turn can be further divided into different branches [7].

2.2.1 Pulsation Variables

The radial pulsations taking place in variable stars can be treated as standing waves in an open-ended pipe since the pulsations are approximately acoustic waves traveling through the stellar atmosphere. There are different modes in these pulsations, depending on the number of nodes present. In the fundamental mode, no nodes are present and all the material is moving in one common direction together. At the first overtone, one node is present be-
tween the stellar interior and the surface of the star and there are different directions of the movement on the opposite sides of the node. If more nodes are present in the interior of the star higher overtones will establish (see Fig. 3). The period of these pulsations is determined by the size of the star since it is related to the distance that the waves must travel. In other words, the pulsation period depends on the mass of the star [4].

Figure 3: Image of different pulsation modes in the stellar interior. The fundamental mode is shown to the left, the first overtone in the middle and the second overtone to the right. The direction of the motion on the different sides of the node is indicated with arrows. Image taken from [4].

2.3 Classification of Asymptotic Giant Branch Stars

AGB stars are often classified by either variability or spectral type. When it comes to variability they are classified into four different groups: Mira Variables, Semi-regular variables type a/b or Irregular variables, where the variability is determined from the V-band light curve (see Fig. 4). Mira variables are evolved AGB stars with regular periods and large amplitudes (> 2.5 mag). Both types a and b of the semi-regular variables have smaller amplitudes (< 2.5 mag). Type a and b differs in the regularity of the period, where the period of type a is still regular while type b has poor regularity. The irregular variables are stars with both small amplitudes and poor regularity [4].
Figure 4: Three pictures of light-curves showing the different variability of AGB stars. In the top panel the curve of the Mira variable o Ceti can be seen, showing good regularity. In the middle panel the curve of the Semi-Regular type a star RU Cyg. In the lower panel the curve of R Dor, a Semi-Regular type b star. Image taken from [4].

Classification by spectral type reflects the atmospheric chemistry of the star. The stars can be classified into M-type, S-type, and C-type AGB stars. Since carbon and oxygen will create the stable molecule CO, the most abundant of these elements will dominate which molecules and dust are formed in the atmosphere. The atmosphere of M-type AGB stars is dominated by oxygen, with a carbon/oxygen ratio lesser than one. The atmosphere of S-type AGB stars is equally dominated by carbon and oxygen, with a ratio almost equal to one. The S-type AGB stars also show the presence of s-process elements in the atmosphere, such as technetium and zirconium oxide. The atmosphere of C-type AGB stars is dominated by carbon, with a carbon/oxygen ratio greater than one [4].

2.4 Stellar Winds

A characteristic feature for AGB stars is the presence of a stellar wind. The intrinsic pulsation of the star leads to contractions and expansions of the photosphere, which will give rise to sound waves propagating outwards through the atmosphere. These pulsations cause variations in both the brightness and radius of the star. The sound waves will give rise to prominent shock waves as they propagate through the stellar atmosphere. These shock waves
will lift gas from the exterior of the star outwards to distances where the temperature is lower and it is favorable for dust to form. The dust will then be accelerated outwards by the radiation pressure. Due to collision coupling, between the dust and gas, a general outflow of matter will occur. Through these stellar winds, the gas and dust will be transferred into the interstellar medium and the star will lose mass [4].

2.4.1 Mass Loss

Due to the stellar winds AGB stars will experience a mass loss at a rate between $M \sim 10^{-8} - 10^{-4} M_\odot yr^{-1}$. This mass-loss rate is more rapid than the time-scale for the nuclear burning in the stellar interior and the mass loss will, therefore, determine the lifetime of individual AGB stars and the duration of the AGB phase [8]. Determining the mass loss rates of AGB stars is important since the AGB phase significantly contributes to the chemical enrichment of galaxies. The stellar winds and the related mass loss causes these elements to spread out through the interstellar medium. [4] [9].
3 Method

3.1 Data

In this project data from six different AGB stars were investigated. The stars observed were: TX Cam, IK Tau, KU And, R Leo, R Hya and R Cas. All these objects are Mira variables of type M, meaning that their atmospheric chemistry is oxygen-rich. These stars were chosen from the DEATHSTAR project sample.

3.1.1 DEATHSTAR Project

The DEATHSTAR project is a project where the stellar winds around AGB stars are mapped out with the help of ALMA. ALMA, The Atacama Large Millimeter/submillimeter Array, is an array of radio telescopes able to measure the properties of the winds with very high sensitivity and resolution. The DEATHSTAR project currently includes about 70 AGB stars of M-, S- and C-type [10].

3.1.2 AAVSO

The observational data was downloaded from the American Association of Variable Star Observers (AAVSO) [11]. AAVSO is a non-profit organization, founded in 1911, that collects and analyzes data about variable stars. The publicly available data from AAVSO is from observations done by both amateurs and professionals. All data collected from observers is checked at the AAVSO headquarters where it is validated and handled before added to the database.

3.1.3 GCVS

The General Catalogue of Variable Stars (GCVS) is a project initiated in Moscow, after World War II, on account of the International Astronomical Union (IAU). The GCVS publishes an electronic catalogue of variable stars with a highly developed system of variable star classification. This catalogue only includes stars that are considered well investigated, with well-determined periods. The catalogue is currently at the 5th edition. GCVS is widely used by many astronomers [12].
3.2 Data Access

All the observational data available in the V-band (except for KU And) in the AAVSO database was used to calculate the dominant period for each star. With the Light-Curve Generator each of the stars V-band magnitude is plotted against the corresponding time in Julian Days (see Fig. 5). In the Julian calendar, the days are counted from the beginning of the Julian Period, which started on January 1st 4713 BC, at noon [13]. The Julian calendar is commonly used by astronomers. From the Light-Curves the periodic motion of the brightness can be clearly seen. The period varies from star to star, but since all the stars observed were Mira variables, they were believed to be pulsating in the fundamental mode [14].

![Figure 5: Light curve of star IK Tau generated by AAVSO [11].](image)

In this project, all the observations used of the stars were photo-electric observations done in the visual band, except for the star KU And which was observed in the TG band. V-band observations are observations of light between 500-580nm. TG-band observations, also known as Tri-Color Green filter, are observations of light between 500-565nm.

3.3 Theory

3.3.1 Lomb-Scargle Periodogram

The Lomb-Scargle method is a widely known approach for analyzing periodic properties in non-uniformly sampled data. This algorithm is commonly used by astronomers to analyze periodic brightness variations in stars. The Lomb-Scargle periodogram is able to produce a power spectra from the non-uniformed spaced data and thereafter detect the periodic element. The
Lomb-Scargle periodogram is based upon both Fourier transforms and methods of least square fittings. The Fourier transform of a continuous signal $g(t)$ (eq. 1) and the inverse relationship (eq. 2) is given by:

$$\hat{g}(f) \equiv \int_{-\infty}^{\infty} g(t)e^{-2\pi ift}dt$$  (1)$$

$$g(t) \equiv \int_{-\infty}^{\infty} \hat{g}(f)e^{2\pi ift}df$$  (2)

In actual calculations of a signal, the observations are done over a limited time period. Therefore the Fourier transform of a signal is the transform of both the continuous signal and the observing window (eq. 3). The observing window is a function portraying the observation and that extends through the given time interval.

$$F\{g_{obs}\} = F\{g\} \cdot F\{W\}$$  (3)

Where $F\{g\}$ is defined as the Fourier transform operator [15].

### 3.3.2 Power Spectrum

The power spectrum of a periodic signal is given by the absolute value of the Fourier transform squared:

$$P_g \equiv |F\{G\}|^2$$  (4)

The power spectrum of a data set is a function that estimates the input of each frequency to the total signal [15].

### 3.4 Data Processing in MATLAB

In MATLAB the data was uploaded into vectors, separating out the magnitude and time (see Appendix). After this the light-curves were plotted, i.e. the magnitudes against their corresponding time, were the periodic behavior of the brightness could be clearly seen. After this, a power spectrum was plotted with the help of MATLAB’s plomb (Lomb-Scargle periodogram) function.

$$[pxx, f] = plomb(x, t)$$  (5)

The plomb function evaluates the signal $x$ and sends back its power spectral density $pxx$. The signal $x$ is evaluated at an instant $t$ which is then converted into its corresponding frequency [16]. The time vector, $t$, has to be
non-repetitive so the vectors had to exclude the duplicate terms. The power spectrum was then plotted against frequency, which in turn can be converted into a period. A power spectrum is often used to determine the most dominant period. In this case, the spectrum will give a prominent power peak at a certain x-value, meaning that this x-value is the most dominant period of the star. Since each star observed is a Mira variable the dominant period is expected to be in the fundamental mode and give a prominent peak indicating this. When it comes to Irregular Variables it is not certain that the star will have a dominant period. Stars can also pulsate in different modes at the same time. This dominant period tells us that the brightness of the star will peak repetitive after a certain amount of time, given by the period.

The pulsation period for the dominant mode was decided by the power spectrum, by marking the highest peak to obtain its x value (see Fig. 6). The accuracy of these periods was determined by measuring the full width at half maximum (FWHM) of the different peaks with the same tool in MATLAB. These results were then compared with the General Catalog of Variable Stars [17] to analyze how well determined the estimated periods using the AAVSO data were.

Figure 6: Period of the star IK Tau determined with MATLAB, with the line indicating where the FWHM was measured.
4 Results

4.1 TX Cam

For TX Cam the available data in the V-band for \( t > 2452500 \) JD was used. The following results were obtained:

Fundamental period: 551.4 days
Full width at half maximum: 61.5 days

Figure 7: Light-Curve and Power Spectrum for the star TX Cam.
4.2 IK Tau

For IK Tau all of the available data in the V-band was used. The following results were obtained:

Fundamental period: 463 days
Full width at half maximum: 24.8 days

Figure 8: Light-Curve and Power Spectrum for the star IK Tau.
4.3 KU And

For KU And all of the available data in the TG-filter was used since there was not sufficient data in the V-band available. The following results were obtained:

Fundamental period: 668 days
Full width at half maximum: not measurable

Figure 9: Light-Curve and Power Spectrum for the star KU And.
4.4 R Leo

For R Leo the available data in the V-band for $t > 2452500$ JD was used. The following results were obtained:

Fundamental period: 311 days
Full width at half maximum: 13.5 days

Figure 10: Light-Curve and Power Spectrum for the star R Leo.
4.5 R Hya

For R Hya the available data in the V-band for $t > 2452500$ JD was used. The following results were obtained:

Fundamental period: 378.4 days
Full width at half maximum: 44.3 days

Figure 11: Light-Curve and Power Spectrum for the star R Hya.
4.6 R Cas

For R Cas the available data in the V-band for $t > 2452500$ JD was used. The following results were obtained:

Fundamental period: 433 days
Full width at half maximum: 23.9 days

Figure 12: *Light-Curve and Power Spectrum for the star R Cas.*
4.7 Summary of Results

The results from the period study of the six AGB stars are summarized in Table 1. The columns list the estimated period of the star from the Lomb-Scargle Periodogram method using AAVSO data, the period of the star listed in the 5th edition of the GCVS catalogue, the full width of the half maximum of the dominant peak in the power spectra and the time interval covered by the observational data.

Table 1: Tabular of the calculated periods using data from AAVSO, the corresponding periods listed in the GCVS, the full width of the half maximum for the dominant peak and the time interval covered by the observational data.

<table>
<thead>
<tr>
<th>Star</th>
<th>Period AAVSO [days]</th>
<th>Period GCVS [days]</th>
<th>FWHM [days]</th>
<th>Time Interval [days]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TX Cam</td>
<td>551.4</td>
<td>558.7</td>
<td>61.5</td>
<td>7000</td>
</tr>
<tr>
<td>IK Tau</td>
<td>463</td>
<td>470</td>
<td>24.8</td>
<td>6500</td>
</tr>
<tr>
<td>KU And</td>
<td>668</td>
<td>660</td>
<td>-</td>
<td>2500</td>
</tr>
<tr>
<td>R Leo</td>
<td>311</td>
<td>309.95</td>
<td>13.5</td>
<td>6000</td>
</tr>
<tr>
<td>R Hya</td>
<td>378.4</td>
<td>388.87</td>
<td>44.3</td>
<td>6000</td>
</tr>
<tr>
<td>R Cas</td>
<td>433</td>
<td>433.6</td>
<td>23.9</td>
<td>6000</td>
</tr>
</tbody>
</table>

4.8 Spacing of Observational Data

The different power spectra were also plotted together with the power spectrum of a known cosine function to see if the spacing of the observational data potentially creates false signals in the power spectrum (see Appendix). The data from the cosine function was sampled with the same time interval, at the same instants in time, as the data given by AAVSO. The results for the different observational samples are shown in Figure 13. The peaks produced in the power spectra of the cosine function not corresponding to the known period (or frequency) indicate that poor sampling alone can cause artifacts in the power spectra.
Figure 13: Plot of the Power Spectra, with magnitude against frequency, and a fitted cosine function. The amplitude in the cosine function was adjusted to fit the observational data.
5 Discussion

All of the power spectra, except the one of KU And, gave a clear prominent peak indicating a dominant fundamental period. The results obtained from the AAVSO database also gave similar results to the periods given by GCVS. The calculated period of TX Cam was 551.4 days compared to 558.7 days according to GCVS, with a difference of 7.3 days. The period of IK Tau was estimated to a value of 463 days, which also is a relatively good value compared to the GCVS value of 470 days, with a difference of a week. KU And was the only star observed in the green filter instead of the visual band. The estimated period for KU And was 668 days, while its value according to GCVS was 660 days, giving a difference of 8 days. R Leo had an estimated period of 311 days and a value of 309.95 days according to GCVS, which produces a difference of about one day. The calculated period of R Hya was 378.4 days, also a fairly similar value to the GCVS period of 388.7 days, resulting in a difference of 10.47 days. Finally, the period of R Cas was 433 days according to matlab and 433.6 days according to GCVS, which gives a small difference of 0.6 days.

Although all these values are close to the values from GCVS the FWHM of their fundamental peaks gives an insight into how exact the estimated value is. The star with the most certain estimated period is R Leo, which has a FWHM of 13.5 days. The star with the least certain estimated period is TX Cam, which has a FWHM of 61.5 days. This value is quite large which indicates that the calculation of this fundamental period is less certain. The FWHM of the fundamental peak for the remaining stars was estimated to be: IK Tau 24.8 days, R Hya 44.3 days and R Cas 23.9 days. For these stars, the peaks were quite narrow and the estimated periods more exact compared to the period of TX Cam. A wide peak gives a result where the period could take on varying values in a large interval, while a narrow peak shows that the period is most likely the x-value given at that peak. The FWHM for KU And was not possible to determine (see Fig. 9).

The uncertainties in the estimated periods are caused by several factors. The light curves of AGB stars do not show perfect regularity and the periods can vary over time. Another important factor for the uncertainty in determining the period is the poor sampling and the amount of data. The stars with the least certain estimations of the period are TX Cam, KU And and R Hya. The reason for this can be clearly seen in their respective light curves. The star TX Cam has few data points and the spacing between the data points is quite large (see Fig. 7) compared to IK Tau, R Leo and R Cas,
where there are more data points and less spacing between the points. The same applies to KU And and R Hya where the data points are very few and far apart, giving a non-conclusive result. For R Hya there is also a large gap in the sampling for $3000 < t < 4500$ which will lead to a less certain result. The FWHM of the period peaks for IK Tau, R Leo and R Cas are much narrower than compared to the other stars, which also can be anticipated by observing their respective light curves. These three stars have more data points and a more evenly distributed observational sampling than the other stars.

The time intervals during which the observations were done also affect the uncertainty of the calculations. The length of the time the star has been observed has to be larger than the period of the star for the observations to record the periodic variations in the light-curve. The more cycles covered during the total observing time the more certain the estimated period is. By observing the plots in the result section it can be seen that the lengths of observing time for all the stars cover at least a few cycles. The star with the smallest time interval is the star KU And, but it still covers almost four cycles, giving fairly good coverage. The time interval for the stars: TX Cam, R Leo, R Hya and R Cas was adjusted too avoid to much spacing in the data. The calculations for these stars were done for $t > 2452500$, while the calculations for IK Tau and KU And were done for $t > 0$. This was done to avoid large gaps and regions with very few data points in the observational data.

The problem with determining the FWHM of KU And may instead be related to the spacing in the sampled data. Since the phase-coverage of the sampled data is poor this may result in missing peaks or peaks with a smaller value than what should be expected. This can result in a misleading variation in the light curve, which shows up in the power spectra and therefore gives a false result of the period. One way to observe if these sampling holes interferes with the result given is to use a cosine curve with a known period but with the same time sampling (see Fig. 13). From these plots, we can see that some of the peaks are artifacts created due to poor sampling.
6 Summary and Conclusion

The main goal with this project was to analyze how well the pulsation periods of six different AGB stars could be determined by using data from the AAVSO database. The periods were estimated using the Lomb-Scargle periodogram method and then compared to the values from the GCVS catalogue to see if the method used gave accurate estimates. The investigated stars are all Mira variables and are therefore expected to pulsate in the fundamental mode. The uncertainty of these estimates depends on the measured data. If the sampled data is poor, with areas of missing measurements, the power spectra will give false artifacts. This effect was investigated by applying a known cosine function to see if the spacing in the data gave any misleading results. The amount of time during which the measurements were done also affects the uncertainty. Longer time intervals will cover more cycles and therefore gives a more certain result. All of the stars examined produced a good value of the period when compared to the GCVS catalogue.

Overall these results show that the Lomb-Scargle periodogram is a good way to estimate the period, but that there are factors that have to be taken into consideration for a valid result. The factor that may give the largest error in the results is the poor sampling of the data points. If the data from the light-curve is poorly sampled it can show up in the power spectra as a long-periodic variation of the light-curve. This will, in turn, present misleading facts about the periodic motion of the light-curve and may provide a wrongful value of the period. To see if the data was too poorly sampled a cosine function with a known period was plotted together with the data from AAVSO. These plots showed that there were not any false artifacts that lead to a misleading result.

The star that was the hardest to get an estimate of was KU And. This may depend on the TG-band being used instead of the V-band since there were not enough observations done in the V-band. The fact that the time interval for the observations only covered nearly four cycles also gives a more uncertain power spectrum. The most likely reason for this though is, as mentioned, the poor phase-coverage of the data points (see Fig. 9). The spacing in the data gives a large peak connected to the fundamental period which gives an unclear and wide peak, and therefore a very uncertain measurement of the FWHM of the peak.
References


7 Appendix

MATLAB Code

close all
clear all

% Read in data from the csv file
Tbl1 = readtable('TXCam.csv');
Tbl1 = readtable('IKTau.csv');
Tbl1 = readtable('KUAnd.csv');
Tbl1 = readtable('RLeo.csv');
Tbl1 = readtable('RHya.csv');
Tbl1 = readtable('RCas.csv');

date = Tbl1.JD;
magn = Tbl1.Magnitude;
band = Tbl1.Band;
obsc = Tbl1.ObserverCode;

% Exclude all data entries with '<' in the magnitude value
l=[];
nn = size(date);
for i=1:nn
    k=strfind(magn(i),'<');
    j=cell2mat(k);
    if j==1
        l=[l,i];
    end
end
date(l) = [];
magn(l) = [];
band(l) = [];
obsc(l) = [];

% Find all data entries with a certain magnitude
ind = ismember(cellstr(band),'V');
lind = find(ind);
date = date(lind);
magn = magn(lind);
band = band(lind);
obsc = obsc(lind);

% Exclude data entries above a certain time (in JD)
ind = [];
ind = find(date<2452500);
ind = find(date<2452500);
date(ind) = [];

% Plot the data
m = str2double(magn);
for n = 1:length(date)-1
    t(n+1) = date(n+1) - date(1);
end
t(1) = 0;

subplot(2,1,1);
plot(date, m, 'ok');
title('Light Curve, TX Cam');
xlabel('Julian Days');
ylabel('Magnitude');
set(gca, 'Ydir', 'reverse')

% Remove the duplicate time values
[t, ind] = unique(t);
m = m(ind);

% Find the power spectrum using Lomb-Scargle periodogram
[pxx, f] = plomb(m, t);

% From freq to period
per = 1./f

% Plot period vs power
subplot(2,1,2);
plot(per, pxx, 'k');
% Calculating the FWHM of the peak
% Calculating the half max value, looking at interval where the estimated period lies
per2 = per(per > 400 & per < 650);
pxx2 = pxx(per > 400 & per < 650);
halfMax = (min(pxx2) + max(pxx2)) / 2;
% Find the index on each side of the peak at half maximum
index1 = find(pxx2 >= halfMax, 1, 'first');
index2 = find(pxx2 >= halfMax, 1, 'last');
fwhmx = per2(index1) - per2(index2)

Matlab Code for Power Spectrum with Cosine Function

%f_fund = 1/T, where T is the fundamental period
m1 = 2.*cos(2.*pi*f_fund*t);
[pxx1, f1] = plomb(m1, t);
plot(f1, pxx1, 'b', f, pxx, 'k')
title('Power Spectra, IK Tau');
xlabel('Frequency');
ylabel('Power');
legend('Data IK Tau', 'cosine function');