Searching for Oscillating M Giant Stars in Eclipsing Binary Systems

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Abstract

Distances to stars are critical to the understanding of the Milky Way galaxy and how it was formed. Asteroseismology, the study of stellar oscillations, is a powerful method for determining star distances because oscillation frequencies are related to the luminosity of a star. However, the accuracy of asteroseismic distances to the M giants, which probe the outer regions of our galaxy, is uncertain and needs to be calibrated. This can be achieved with eclipsing binaries, which are two gravitationally bound stars that appear to pass behind each other as they orbit and are also used to determine stars' luminosities and distances. We aim to combine these two methods of calculating distances by finding oscillating M-giant stars in eclipsing binary systems using light curves from two ground-based surveys: the Asteroid Terrestrial-impact Last AlertSystem (ATLAS) (Tonry et al., 2018; Heinze et al., 2018) and the All-Sky Automated Survey for Supernovae (ASAS-SN) (Shappee et al., 2014) skypatrol. Out of the 17 ASAS-SN stars analyzed, 3 of them show clear eclipses, but none show evidence of stellar oscillations. Out of the 465 ATLAS binaries we have looked through so far, only 1 has showed a clear eclipse while also having an orbital period longer than 10 days. However, after further investigation of the Fourier transform, this star did not have any evidence of containing an M-giant. We have detected oscillations in a found eclipsing binary system with an 11.9 year period (Rowan et al., 2021). We calculated an asteroseismic distance of this system of 3140 parsecs, and have made comparisons to the distance from Gaia of 2690 with an upper limit of 2865 parsecs. (Gaia Collaboration et al., 2016).

Keywords: asteroseismology, oscillations, M giant stars, stellar distance, ground-based astronomy, eclipsing, binary, phase

1. Introduction

Distances to stars are critical to the understanding of the Milky Way galaxy and how it was formed. However, Gaia distances do not probe far enough into the outer regions of the galaxy to help with this. This means we need alternate distance indicators.

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Atseroseismology is the interpretation of the characteristics of oscillation modes in terms of the physical parameters of the stellar interior. Larger, more luminous stars fluctuate with lower oscillation frequencies or longer periods, therefore we may infer a star's luminosity and consequently its distance by monitoring these frequencies. Periodic brightness fluctuations are caused by stellar oscillations, which can be identified by tracking the relative brightness of stars across time. Asteroseismology is also a powerful distance indicator since it precisely constrains essential parameters such as mass, age, and radius. While asteroseismic distances for M-giants are a promising method to understanding the outer galaxy, the accuracy is unknown and needs to be calibrated.

To address the issue of validating asteroseismic distances, we also search for eclipsing binaries (EB) with an oscillating M-giant as one of the two stars. When two stars orbiting each other appear to pass behind one another in turn, it is classified as an eclipse. The brightness of each star is affected when the other star passes in front of it, no matter how much larger one star is compared to the other. This means that the light curve (the brightness variation as a function of time) will show a decrease in brightness as a dip at the time when the primary star eclipses the secondary, and vice versa (2). However, when the mass of one star in the system is greater than the other the dip will be deeper when the more massive primary star eclipses the lesser secondary star. Using the eclipses we can find the luminosity of the 2 stars then use distance-luminosity relations to find their distance.

The distance derived from the eclipsing binary method is more exact, thus if the asteroseismic distance is significantly different, we can derive a correction factor which can then be applied to any other M-giant in the galaxy (whether or not they are in an eclipsing binary). As a result, we want to calibrate asteroseismic distances for M-giants using eclipsing binaries. Light curves for thousands of stars are provided by NASA space observatories such as Kepler and TESS (Borucki et al., 2010; Ricker et al., 2015). Kepler light curves are 4 years long and thus can be used. However, Kepler only surveys one particular patch in the sky and thus misses many other M giants in other parts of the galaxy. We will use light curves from two ground-based telescope networks for our project: ASAS-SN skypatrol and ATLAS (Shappee et al., 2014; Tonry et al., 2018; Heinze et al., 2018). Both have lower precision than space telescopes, but have been observing for much longer, and have been monitoring nearly the entire sky at nightly cadence. The all-sky surveys can be utilized to identify oscillations in M giants, as seen in our reference study (Auge et al., 2020). The goal of this project is to use the ASAS-SN and ATLAS variable star catalogs to find oscillating M giants in eclipsing binaries. This objective involves analyzing light curves for these binaries to look for the signature of oscillations. The main goal we are aiming to complete is finding eclipsing binaries to enable the calibrations of powerful asteroseismic distances.

2. Methodology

2.1. Target Selection

Using ASAS-SN's variable stars database (Shappee et al., 2014) and the constraints of a max mean *vmag* minimum of about 12 and maximum of about 15, we were able to start analyzing 17 eclipsing binary systems with the potential of containing a M-giant star. A requirement that does need to be fulfilled for there to exist an M-giant star in the system is a long orbital period. We are looking for EBs with a period of at least 10 days. This is necessary because a star as large as an M-giant cannot orbit another stellar body in a short amount of time without affecting the other star in the system gravitationally because of how close the orbit would be. While going through the ATLAS binaries, we looked for eclipsing binaries with clear eclipses and a longer orbital period of at least 10 days.

2.2. Data Analysis

We performed several data analysis steps for our analyzed systems, as follows:

- First, we validate light curves that we generated using ASAS-SN skypatrol with the results from Auge et al. study using the Kepler ID's from the Auge et al. study. From the target ID, we can retrieve the coordinates of the target star. The process of downloading newly generated light curves from the ASAS-SN skypatrol involves either having a Kepler ID to put as the star name, or having the right ascension and declination of the star. Then, the number of days to go back are specified, and the skypatrol system begins generating the light curve and corresponding data for the star at the specified coordinates.

- The next step is plotting the light curve (Figure 1). For the light curves that contained a significant outlier that could possibly create noise in the power spectrum, we used a simple conditional statement to keep all data points with more than a relative amount of fractional flux. The light curve was then plotted again to show the light curve after the rejection took place. This was essential to practice inclusion and exclusion of data points in the light curves.

- We then moved onto phase folding the light curve on top of itself using the modulo of time divided by period. Phase folding the light curve allows us to see more clearly if any eclipses occur in the time that the system was being observed (Figure 2). The variable of time holds the array of heliocentric julian days downloaded within the light curve data. The orbital period is the amount of time observed for the stars in the binary to orbit around their common center of gravity. The period is important in an eclipsing binary system because the orbital period of the primary and secondary stars in the system directly relate to the radii of each star. Therefore, we are looking for an eclipsing binary system with a larger period in order to find a star with the larger radii of an M-giant. It is very unlikely that a binary with a shorter period will be able

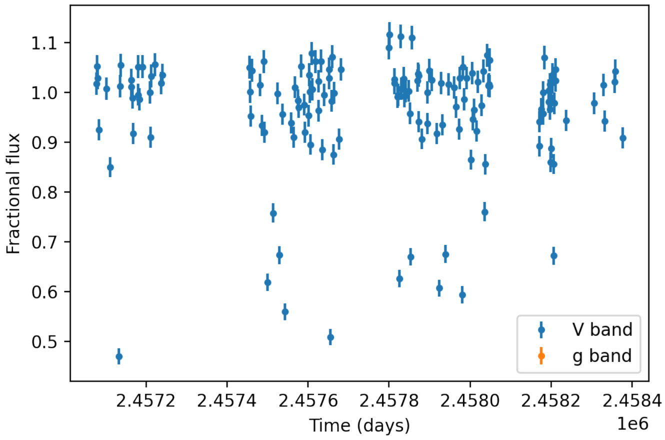

Figure 1: Target at coordinates of: 270.07298 right ascension ,-20.1787,14.09,14.1200645 declination on the list of 17 stars classified as an eclipsing binary. All datapoints are under one filter, the V-band filter, possibly because of data not being taken recently.

to contain an M-giant since a significant fraction of the orbit would be filled by the large M giant star. The period is included in the data (Shappee et al., 2014). Most often, there will be a deeper dip in the data points that is related to the primary star eclipsing the secondary, and a shallower dip related to the opposite with the secondary star. We estimated where the eclipses start and end then clipped them out in order to view the stellar oscillations on their own (Figure 2).

- A power spectrum is the power density plotted along the frequency spectrum of the star. Clipping will change the period power spectrum plot (Figure 4). If the eclipses remain in the light curve the power spectrum will be dominated by the signal from the eclipses. The oscillations will be masked by the dominant signal. Hence, removing them gives us a better chance of detecting the lower amplitude signal from oscillations. A sub-harmonic is an oscillation with a frequency equal to a sub-multiple of the original wave. In order to make the peaks at the orbital period and its sub-harmonics obvious we implemented dashed lines at the period, half of the period, and a fourth of the period. The sub-harmonic lines show how peaks related to the binary can still appear after clipping has occurred. This is due to the orbital periods being short. Shorter periods hint that the stars in the binary orbit closely to one another, and would cause gravitational deformations. An ellipsoidal variable means that brightness variations can still occur when not eclipsing. We generated plots like these for every system we picked from ASAS-SN and ATLAS and visually analyzed them.

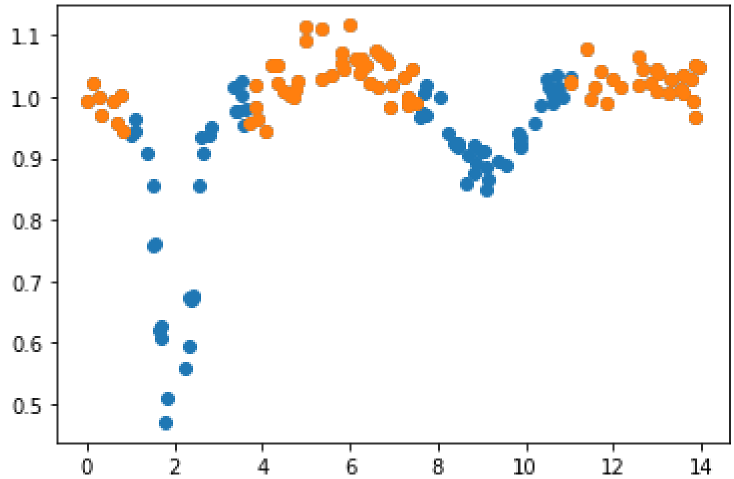

Figure 2: Same target as in Figure 1 but showing phase folded light curve has a primary eclipse at around 2 days and a secondary eclipse at around 9 days. The orange datapoints are kept, and the blue datapoints of the phase folded light curve are excluded.

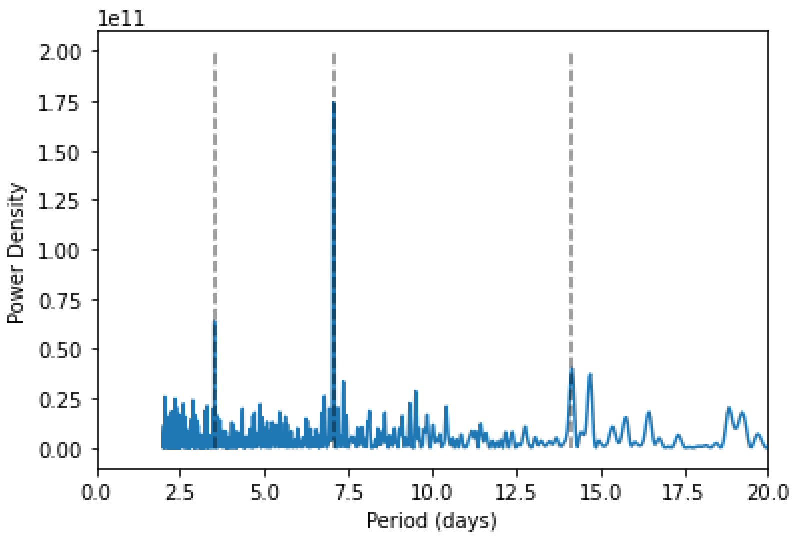

Figure 3: Same target as in Figure 1 but showing power density plotted over the period with dashed lines at the orbital period and its harmonics. Specifically, half of the period (p/2) and a fourth of the period (p/4). These lines align with significant peaks in power density which is related to the binary. This plot still includes the eclipse.

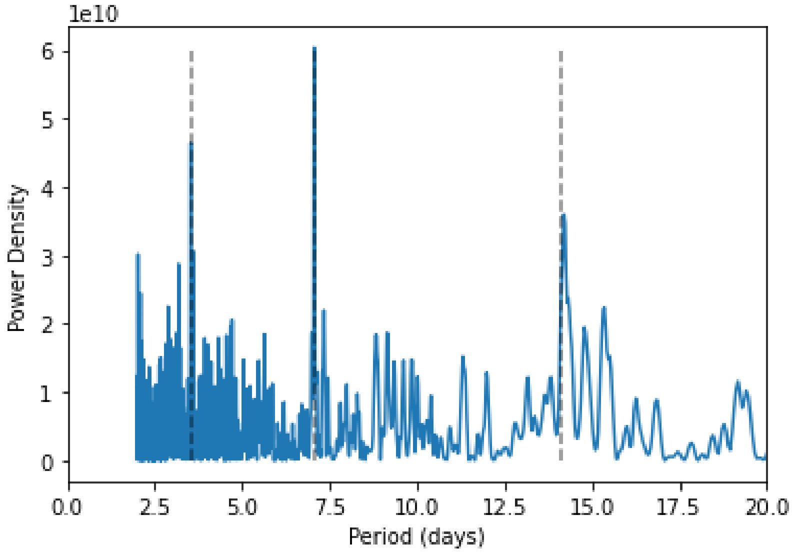

Figure 4: Same target as in Figure 1 but showing power density plotted over the period with dashed lines at the orbital period and its harmonics. Specifically, half of the period (p/2) and a fourth of the period (p/4). These lines align with significant peaks in power density which is related to the binary. The increased signal compared to the unclipped power spectrum was not predicted to occur, but they are not oscillations.

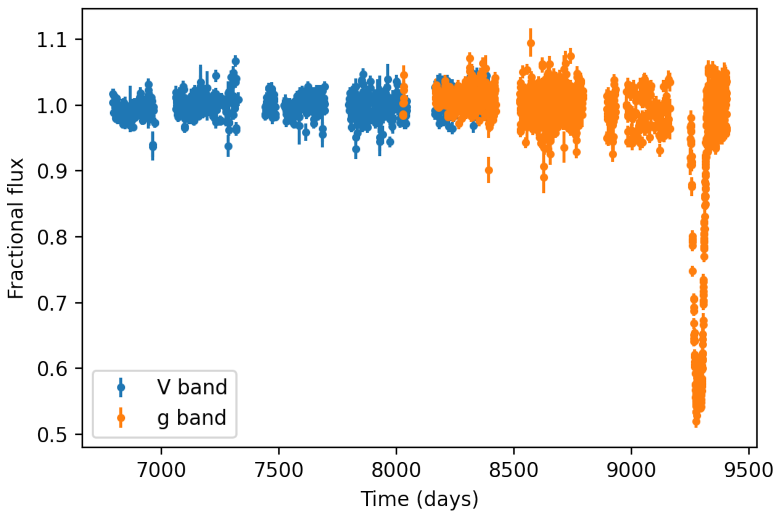

Figure 5: ASAS-SN light curve of the 11.9 year eclipsing binary ASAS-SN 21co. Colors show data taken in different filters. An eclipse at timestamp xxx is apparent. The light curve has a deep eclipse occurring sometime after 9000 days. The x-axis has 2450000 days subtracted.

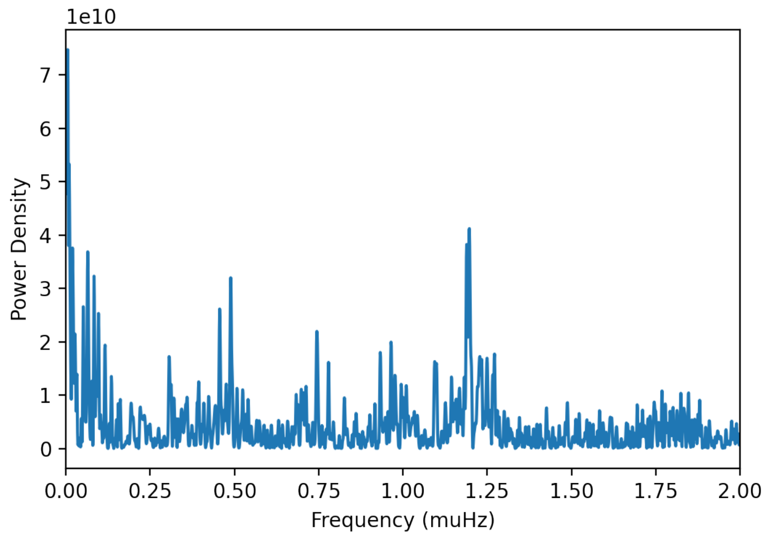

Figure 6: ASAS-SN 21co power spectrum of the oscillations contains a multitude of peaks across the frequencies. Four equally spaced peaks occurring after approximately 0.375 microhertz are confirmed to be related to oscillations of an M-giant star in the system.

3. Results and Discussion

3.1. ATLAS and ASAS-SN variable stars catalog

In Figure 3, three of the most distinct peaks are exactly lined up with the dashed lines. Out of the 21 stars we have, none of them appear to contain an oscillating M-giant. We looked through a total of 17 ASAS-SN light curves and 465 ATLAS light curves. Three of the ASAS-SN targets showed clear eclipses and none of the 17 showed evidence of stellar oscillations. Figure 3 shows a null detection of oscillations. Only 1 ATLAS target has showed a clear eclipse while also having an orbital period longer than 10 days. However, after further investigation of the Fourier transform, this star did not have any evidence of containing an M-giant (Figure 3).

3.2. ASAS-SN21co

An external study we found useful for observing what we are looking for in the oscillations is a study done on a detached eclipsing binary with an 11.9 year period (Rowan et al., 2021). We decided to investigate further into this system. We used the same methods for phase folding and clipping out eclipses. The authors of this paper found this system with a long period but did not look for oscillations. Our regenerated light curve only includes the newer ASAS-SN data on this system (Figure 5). Figure 6 shows the four equally spaced peaks in the frequency power spectrum that are very likely to be related to oscillations of a large eclipsing star in the detached binary system. These oscillations are unrelated to the period of the binary.

$$\frac{g}{g_{\mathrm{sun}}} = \frac{V_{\mathrm{max}}}{V_{\mathrm{maxsun}}}\left(\frac{\mathrm{T_{eff}}}{T_{\mathrm{effsun}}}\right) \tag{1}$$

$$\frac{g}{g_{\mathrm{sun}}} = \frac{\left(\frac{M}{M_{\mathrm{sun}}}\right)}{\left(\frac{R}{R_{\mathrm{sun}}}\right)^2} \tag{2}$$

$$\frac{L}{L_{\mathrm{sun}}} = \left(\frac{R}{R_{\mathrm{sun}}}\right)^2\left(\frac{\mathrm{T_{eff}}}{\mathrm{T_{effsun}}}\right)^4 \tag{3}$$

We calculated the approximate values of the radius, surface gravity, and luminosity of the 11.9 year binary using Equations 1-3. The average frequency was inputted as v_max and used to find the surface gravity in Equation 1. This value of 0.85 microhertz was found by finding the frequencies of all four peaks, then finding the mean of those four. We assumed an effective temperature of 4000 kelvin which is an appropriate temperature of an M-giant, and a mass of 1. We then used these values, as well as the absolute and apparent magnitude to get an asteroseismic distance of 3140 parsecs. Because of how close the system is located to us, we were also able to find a Gaia distance of 2690 parsecs with an upper limit of 2865 parsecs.

4. Conclusions

Here we presented a search for eclipsing binaries with oscillating M giants using the study of distances to stars and astereroseismology. This research plays into the overall purpose of learning about the development of the Milky Way galaxy, specifically by analyzing the growth of stars into M-giants. Our method is unique because we use the difference in brightness of stars that eclipse one another to compare with the relationship of brightness and distance of stars that are closer to Earth. Our main results are as follows:

- To investigate the possibility of M giants as asteroseismic distance indicators in eclipsing binary systems, we used light curves from ground-based transient surveys ATLAS and ASAS-SN. So far, only a few plots had a significant probability of containing an M-giant star. After further investigation into the oscillations of those plots, all 21 stars cannot contain an M-giant. Stars number 15 and 16 are useful to practice clipping out eclipses, calculating the period of peaks, plotting on both frequency and period, and observing differences between eclipses and oscillations. These methods have been used to analyze other eclipsing binary systems such as binaries from the ATLAS database and the ASASSN21-co detached eclipsing binary system (Rowan et al., 2021).

- We have looked through 465 binaries from ATLAS, specifically stars in an eclipsing binary system and analyzed their light curves and their phase folded plots containing at least one clear eclipse and a large period (10 or more days). We found one with a clear eclipse and a sufficiently long period, but did not find any with stellar oscillations.

- We have found one oscillating M giant in an eclipsing binary, proving that our method of finding these systems works. We have calculated the distance to this system and compared that to the Gaia distance. The asteroseismic distance agrees with the Gaia distance within 15 percent. We made assumptions in our asteroseismic calculations for effective temperature and mass of the 11.9 year binary. This means our measurement could become even more precise. The possible consequence of this is asteroseismic distance being about 15 percent higher than the seismic distance. The difference could be due to a constant systematic offset or it will become a difference we will have to continue to account for when using asteroseismic distance measurements. Further work should address this issue.
- Future work also includes finishing going through the ATLAS data to see if we can find another eclipsing binary containing M-giant oscillations.

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