Observations of Pulsating Stars

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1 Introduction

Pulsating stars are stars that show some sort of instability, often which can be called vibration or oscillation just as easily as pulsation. Just like in musical instruments such as violins, stars can vibrate with multiple frequencies at once. Pulsations of stars provide the means of determining distances, of which the classic examples are the Cepheids and RR Lyrae stars.

Pulsations discussed will begin at the "top" of the instability strip with pulsating red giants and Miras, which are evolved stars nearing their own demise. The next discussed will be the Cepheids, both the "Classical" ones as well as the W Virginis (Population II stars). While moving down the instability strip of the HR Diagram, the next major type of variable (pulsating) star are the RR Lyrae stars, moving along the horizontal branch. After discussing the major types of radial pulsations seen on the instability strip, I will discuss a few other types of pulsating stars. The first will be the β Cephei stars (not to be confused with the Cepheids. These are hot, short period and small amplitude variables found near the upper part of the main sequence for spectral type B. Then, I will discuss the pulsations that are inherent with the supergiants. Supergiants are nearing the end of their life, and their behavior in their atmosphere is stochastic with the best observations. Finally, I will discuss an even more extreme example of pulsations, that of the luminous blue variables. These stars are extremely massive, show great winds, and are inherently unstable.

This paper is on the observation of pulsating stars. Thus, some results will be presented and discussed, with little emphasis on the theoretical models needed to understand the underlying physics of these stars and their evolution. Some figures of the light curves or radial velocity curves will be presented at the end of this paper. A recent book by John Percy provides great analysis and examples of pulsations of stars, especially from the observational standpoint. This book provided the reference for anything not cited during this paper.

2 The Mira Variables and pulsating red giants

As stars evolve and move through the HR Diagram to become red giants or asymptotic giant branch stars, they expand and cool. During this evolution, these stars become unstable to pulsations. The coolest of these red giant / AGB stars are called Miras. Pulsating red giants show several properties including:

- Red giants that are later than spectral type K5III tend to be variable in magnitude.
- As the giant becomes cooler (and larger), the amplitude of the variability tends to become larger (of which the large amplitude Miras are the extreme case).
- Periods tend to increase towards lower effective temperatures.
- The periods, along with the radial velocity and light curves are consistent with radial pulsations of the atmosphere.
- The pulsating red giants tend to be semi-regular in their periodicity, with a tendency for there to be multiple periods present.

Miras (the most extreme pulsators of the red giants) have stable periods that range between approximately 100 and 450 days. Their masses range from $\approx 0.6\ M_{\odot}$ up to a few $M_{\odot}$. They appear to be the end stage of evolution of sun–like, low–mass stars, prior to becoming a planetary nebula and a white dwarf. Their radii are on the order of 100 $R_\odot$.

The first Mira variable discovered was *o* Ceti (= HD 14386). It was discovered to be a variable star by David Fabricius in 1596. In 1638, Johann Holwarda discovered that the variability was *periodic* and had an eleven month period (now known to be 331.96 days). This star was then named *Mira*, or "the wonderful" to celebrate its amazing variability, as every 11 months it would go from a magnitude 2 or 3 star to being too faint to see with the naked eye. The actual magnitude of *o* Ceti ranges from ≈ 3 to ≈ 9 during its cycle. The variability of Mira is not fixed, but the amplitude seems to change, as the maximal magnitude (≈ 3) is changing from cycle to cycle. The low flux state is fairly constant as *o* Ceti has a companion (a 9.5 magnitude hot dwarf companion). Recent Hubble images have revealed what might be a stream of matter flowing onto the companion from Mira. Another interesting thing to consider about the Miras is that because the spectral energy distribution peaks in the infrared, the visual ($\approx V$) magnitude is at the tail end of the distribution. As a result, the variability we see coming from stars such as Mira has a much larger amplitude in the visible than in the infrared, and is not as representative of the star's behavior.

Recently, Whitelock et al. published a period–luminosity relationship for the Miras using the K band magnitudes, by calibrating galactic Miras with known distance as well as for Miras in the Large Magellanic Cloud (from using a distance modulus of 18.39±0.05). The resulting relationship (for Oxygen rich Miras) is:

$$M_K = (-3.51 \pm 0.20)[\log P - 2.38] + (-7.15 \pm 0.06) \tag{1}$$

As the pulsations of these stars are so large, and as near–infrared instrumentation becomes more and more common, this relationship will help to constrain the distances to nearby galaxies and prove increasingly more important to determine large distances to clusters or nearby galaxies. See Figure 1 for an example light curve (of Mira = *o* Ceti).

3 The Cepheid variables

The Cepheids may be the most important type of pulsating star, or at least one of the most famous. They come in two types: Classical Cepheids and Population II Cepheids (W Virginis stars). All of these stars are yellow supergiants that lie on the instability strip of the HR diagram and pulsate. Periods range between one and about one hundred days, and their effective temperatures are between 6000 and 8000 Kelvin. They are extremely important due to a period-luminosity relationship that can yield extra-galactic distances.

The first Cepheids were discovered in 1784. Edward Pigott discovered η Aquilae to be varying in brightness, and John Goodricke discovered the prototype δ Cephei. The cause of the variability was uncertain for a long time. The first explanation was that the changes in brightness was linked to the rotation of the star. However, in 1894, A. Belopolsky discovered that δ Cephei exhibited radial velocity variations with the same period as the light variations. Five years later, in 1899, Karl Schwarzschild discovered that there were accompanying changes in temperature. Finally, in 1914, Harlow Shapley put all of these observations together with the new theory of stellar pulsation by August Ritter to find that the Cepheids were radial pulsators.

3.1 Classical Cepheids

The Classical Cepheids are bright, numerous, and have large amplitudes of variability. Thus, when coupled with a relationship between period and luminosity, they can be used for such functions as:

- Survey and map the spiral arms of our galaxy
- Determine distances to nearby star clusters and galaxies
- Establish the size scale of the universe
- Test stellar evolution models when in clusters with a known age and distance
- Test models of stellar pulsation

The first period luminosity relationship was first postulated by Henrietta Leavitt in 1908, when she noticed that the Cepheids in the Small Magellanic Cloud that were brightest also had the longest periods. Besides the fact that the period luminosity relation is of fundamental use, it should also be noted that the periods of these stars are not static. Well studied Cepheids, such as δ Cephei, ζ Geminorum, η Aquilae, and Polaris have shown changes in their period. This can be attributed to the fact that the stars are evolving through the instability strip, and do not stay static in their position in the HR Diagram. In one instance, a Cepheid (Polaris) was observed to stop pulsating, or at least decrease and subsequently increase in amplitude (e.g. Usenko et al 2005). Example light curves can be found in Figure 2.

3.2 W Virginis Stars

W Virginis stars, also called Population II Cepheids, inhabit the same instability strip as the Classical Cepheids, and thus pulsate in the same manner. They were a problem to observers in the early part of the 20th century, when astronomers such as Hubble were using Cepheids for distances and finding that the universe is expanding.

These objects, while in a similar position in the HR Diagram, are at a fundamentally different point in their evolution. These stars are old, Population II stars that are low–mass ($\approx 0.5 to 0.6\ M_\odot$). However, not all Population II Cepheids are Population II stars, as some are just old Population I stars. These stars have moved from the horizontal branch and are looping around the instability strip as they climb the asymtotic giant branch towards their death. Unlike, the Classical Cepheids, W Virginis stars rarely show small amplitude variations. As the periods of Cepheids can change through the star's evolution, a slightly better relationship than just the period–luminosity relationship has been developed for W Virginis stars, involving the period, luminosity, and the *color* of the star. For example, Alcock et al, 1998, reported (where $(V-R)_0$ represents the average $V-R$ color):

$$M_V = -0.61(\pm 0.20) - 2.95(\pm 0.12 \log P + 5.49(\pm 0.35)(V - R)_0 \qquad (2)$$

It is still difficult to distinguish the two populations of Cepheids, which can cause trouble when determining distances, but some effort is being made to distinguish them from their light curves, but the best success has come from spectra, which may prove difficult in farther parts of the universe, and may yield unpredicted results in cosmology.

4 The RR Lyrae stars

RR Lyrae stars are stars that, like the W Virginis stars, are Population II stars or old Population I stars. Their spectral types range from mid A through mid F, and have absolute visual magnitudes of $\approx +0.5$. With old populations, we observe (and should expect) low metal abundances ($Z \approx 0.00001$ to 0.01). The periods of variability range from 0.1 to 1.0 days, with an amplitude of less than 1.5 magnitudes in V. These stars are generally thought to be passing through the instability strip while on the horizontal branch. As the horizontal branch is rather thin on the HR Diagram, and the instability strip has a small width, this explains the small range of periods observed in these stars.

There are three different types of RR Lyrae stars, which are sorted by their light curves. They are:

- *Type a* which are distinguished by long periods, large amplitudes, and highly asymetric light curves,
- *Type b* which show longer periods, smaller amplitudes, and less asymmetric light curves, and
- *Type c* which have short periods, small ranges, and nearly symmetric light curves.

There is a smooth transition between Types a and b, but they are distinct in that the a and b types pulsate in a radial fundamental mode, whereas, type c RR Lyrae stars pulsate in the first radial overtone. Besides the fact that these stars can be used for distances to clusters of Population II stars, their short periods allow us to measure changes in the period with greater precision than we would be able to otherwise. Most of the observations support small changes in the period, but occasionally, large changes are observed, and this phenomenon has been attributed to semi-convection, a large and abrupt mixing process in the star, slightly changing the internal structure. See Figure 3 for a light and color curve example for this class of object.

5 β Cephei Stars

β Cephei stars are massive B0-B2 near main sequence stars. These stars are interesting as they pulsate with periods on the order of hours, typically periods range between two and seven hours. As with the Mira variables, the amplitude of the variability is greatest at shorter wavelengths. The time scale of these variations is too short to be accounted for by geometrical effects such as rotation or binary motion.

The first few β Cephei stars were discovered about a century ago by means of photographic spectroscopy. The discovered stars were β Cephei (which shows a dominant radial pulsation mode) and β Canis Majoris (which shows multiperiodic non-radial pulsation modes). The radial velocity variations of β Cephei were discovered by Frost at the Yerkes observatory in 1902. These variations in β Canis Majoris were discovered at the Lick Observatory in 1908 by Albrect (Campbell 1908). These discoveries were exciting at the time, and the variations were attributed to binary motion, which has since been determined to be physically impossible for these stars on these time scales.

The pulsation mechanism remained a mystery for many years. It was found that the typical pulsation mechanism, namely the He^+ ionization zone responsible for the destabilization of variables such as Cepheids or RR Lyrae stars, could not produce the variations in the β Cehei stars. The pulsation mechanism was postulated to be metal ionization zones by Simon (1982). In this paper, he called for a re-examination of the opacities from heavier elements.

It was found that an opacity bump for Fe could cause the instability for the short period oscillations observed in the β Cephei variables . Most of the β Cephei with known abundances show a solar metallicity, which is important in that the star then has enough Fe to produce the oscillations observed. Surveys have been performed in low metallicity clusters, as well as the Large and Small Magellanic Clouds to search for these stars in lower metallicity environments. Three β Cephei stars were found in the Large Magellanic Cloud, but the metallicity of these stars seems to be higher than for other stars in the LMC (Pigulski and Kolaczkowski 2002).

Balona et al. (1997) found that there is a relationship between mass and frequency for the β Cephei stars that is age dependent. They used the clusters NGC 3293, NGC 4755, and NGC 6231. Since the slope of the relationship between mass and frequency is age dependent, it yields another method of determining the ages of clusters.

6 Hot Supergiants

In 1957, Helmut Abt published one of the first papers on the variability of supergiants (ApJ, 126, 138). In this paper, he made some very interesting observations. Mainly, the radial velocity variations observed were most likely due to pulsations, as opposed to binarity, which had been previously suggested. He claimed (probably accurately) that all stars with $M_V > +1$, and to the right of the main sequence were most likely variable in both light and radial velocity (pulsations). The variability is most pronounced in light with lower effective temperatures, and in radial velocity for higher effective temperatures.

In my Master's thesis, I examined photometry and spectroscopy of one of the brightest supergiants in the sky, Deneb. In my research, I found that the photometry (while difficult to do on such a bright object) combined with radial velocities from Si II lines showed that the variability of the pulsations was extremely stochastic. The "periods" one could measure from one observing season would change from year to year. However, from our five years of data, we found approximately a 2 month period where the pulsations were radial in nature. Few such examples exist in the literature, and my advisor and I will hopefully be publishing these results soon. [Graphs provided upon request.]

7 Luminous Blue Variables

Luminous Blue Variables are a short lived phase in the evolution of the most massive stars. These stars include some of the most famous stars in the sky such as η Carinae or P Cygni. One of the most remarkable features is that occasionally these stars go through an outburst where the star will brighten several magnitudes on very short timescales. P Cygni went into outburst in the year 1600, and was discovered by a celestial globe maker at the time. No star had been seen in that position prior to that epoch (implying at least a 3 magnitude rise). η Carinae went into outburst in 1867 and rose from approximately seventh magnitude to be just fainter than Sirius (≈ -1.5). These stars lie near the "Humphreys–Davidson limit" in luminosity for stars and are very scarce in the galaxy, with less than 50 examples known. (Clark et al. 2005)

These stars, also called S Doradus variables, after a "prototype" in the Large Magellenic Cloud are inherently unstable in their atmospheres. Mass loss rates are on the order of $10^{-5}\ M_{\odot}\mathrm{yr}^{-1}$, which is extremely large for a single star. While these stars are scarce in their existence, there are two examples of LBVs in eclipsing binary systems. While neither of these systems are adequately solved for with masses, radii, and other fundamental parameters, the system R 81 in the Large Magellanic Cloud, provides new insights into the pulsation of these stars.

During a conference celebrating the 400^{th} anniversary of the eruption of P Cygni, Tubbesing et al (2001) reported observations covering an entire orbit of this star. After finding a radial velocity curve for the primary, residual variations were still present. The amplitude of the variations that remained were a function of orbital phase, with the amplitude largest when the radial velocity is lowest. This was attributed to the fact that the circumstellar environment would change how we observe the pulsations at different orbital phases. See Figure 4.

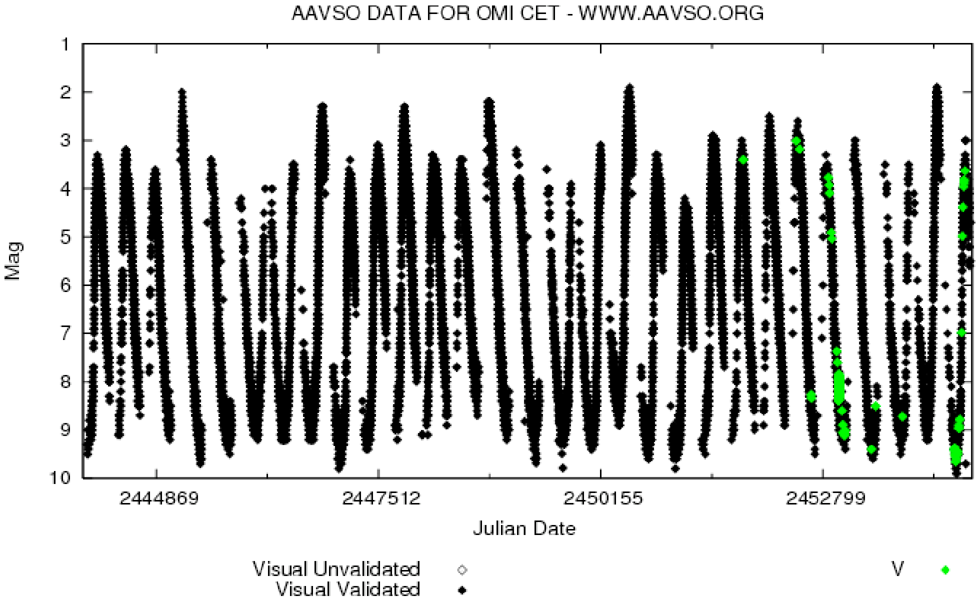

Figure 1: A "visual" (unfiltered) and V band light curve of Mira, *o* Ceti from Julian Date 2444000 through the present. Notice that the period is rather constant, but the amplitude changes for each period. The low flux state is nearly constant due to a small companion. Data from the American Association of Variable Star Observers (AAVSO).

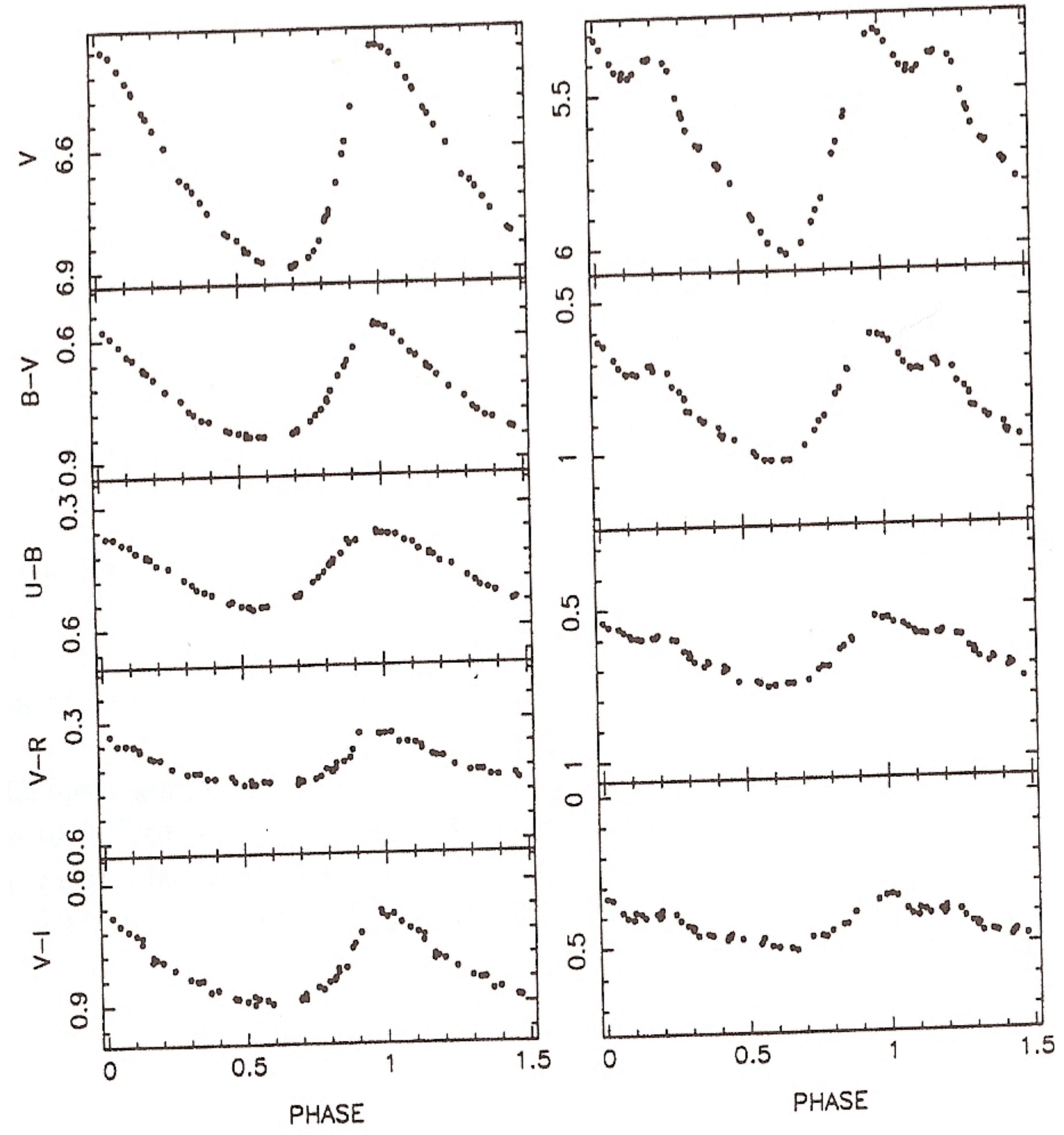

Figure 2: Light and color curves of two Cepheids: R TrA (left) and S Sge (right) phased to their periods. Note that the star S Sge shows an unusual double peak in its light curve. From Sterken and Jaschek, 1994.

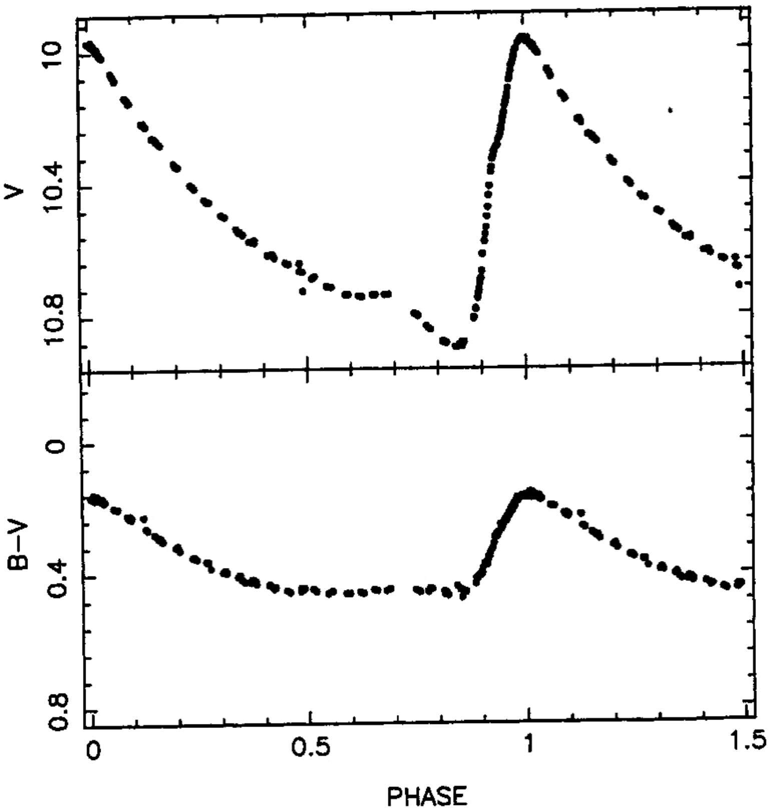

Figure 3: A light and color curve for the RR Lyrae star SW Dra. From Sterken and Jaschek, 1994.

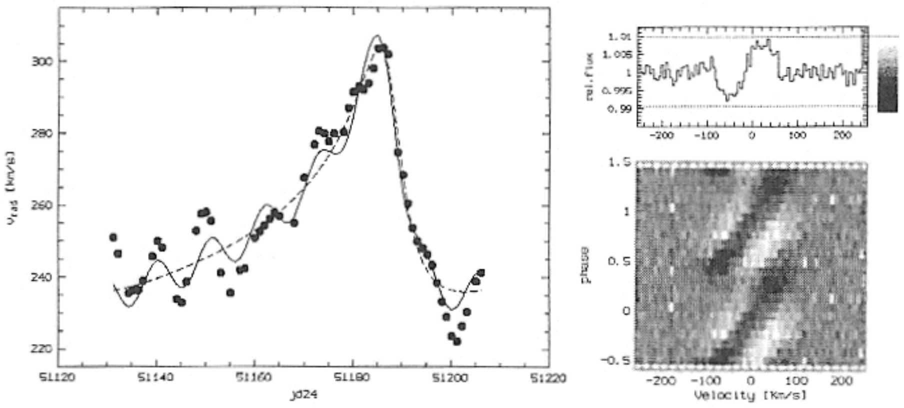

Figure 4: A radial velocity curve of the LBV eclipsing binary R 81. On the left is a plot of the radial velocities against date. On the left, the average profile is plotted over the residuals that remained, which are consistent with pulsations. From Tubbesing et al. (2001).

8 References

AAVSO archive, www.aavso.org

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