

TLRBSE RESEARCH PROJECT: Spectroscopy of Variable Stars: Background for Variable Star Research Program

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1. Introduction

Scattered across the night sky is a class of stars that are similar to our Sun in surface temperature, but 100 to 1000 times larger than the Sun and 1000 to 5000 times brighter. They range in mass from one to six times that of the Sun. These giant and supergiant stars are pulsating variable stars, but their pulsations are erratic: sometimes predictable, and sometimes not. Occasionally, they eject vast quantities of carbon atoms that form dense shells of opaque grains blocking much of the emitted light. Computer models of stellar evolution suggest that these strange variables are in the last stages of life and will shortly change dramatically, perhaps ejecting their outer layers to form planetary nebulae with remnant cores that will become white dwarfs, or perhaps exploding violently as supernovae. (For more on stellar evolution, see the on-line document by that name, or refer to Ch 12 in Seeds, Foundations of Astronomy)

We refer to the entire group as semi-regular variables and RV Tau stars. They exhibit complex, non-periodic changes in their brightness as well as dramatic changes to their spectra over relatively short time scales. The brightness variations for many of these stars are well documented, and about half of them show aperiodic behavior interpreted as two or more periods beating against each other. A few show what appears to be a single period in their light output, but the duration of the period changes over time. Changes in the spectra of these variables can be quite rapid and dramatic. Some of the stars show such significant changes over a few weeks that they appear to be completely different stars. The spectral changes in nearly all of these stars are poorly studied and their connection to the light changes is generally unknown.

In this research project we will use our new and archival spectroscopy to begin to correlate spectral changes over time with their brightness variations. We will use the same data to study the star's surface temperature, radius, luminosity and age. The research goal is to improve our understanding of the RV Tauri stars, their physical state and the nature of their changes, and how they fit into the general scheme of stellar evolution.

2. An Overview of Variable Stars

Broadly speaking (and ignoring most, but not all stellar end-products), stars can be placed into two categories: main sequence and variable. Stars spend 90% of their lifetime

on the main sequence quietly converting hydrogen to helium in their deep interiors by thermonuclear fusion, a process that will continue until the hydrogen “fuel” runs low. While on the main sequence, stars maintain “hydrostatic equilibrium,” a balance between the outward pressure of hot gas and radiation produced by the fusion in the core and the inward pressure of the outer layers of the star itself due simply to gravity. The laws of physics finely tune this balance to allow a star to have a long and stable main sequence life. The Sun is currently about halfway through its 9 billion year main sequence lifetime. During their main sequence lives, stars are not generally thought of as variable. Many main sequence stars do show decade-scale sunspot (“starspot”) cycles (the Sun has an 11 year cycle) and an occasional large flare. A few show stronger than normal magnetic fields, and some even have Jello-like ringing pulsations throughout their interiors allowing astronomers to apply Earthquake techniques to “see” deep into their interiors. But in general, main sequence stars are considered to be docile and non-variable.

Variable stars are taken to be stars that show larger amplitude brightness changes and/or spectral changes. Spectral changes cause a star to morph from one spectral type to another and back again. Truly a thing that dreams are made of if you are an observer! Note that during this change its mass is unaffected. Variable stars (in fact all stars) do lose mass and some variable stars even gain mass, but the amount lost or gained, over 10^4 - 10^5 year time scales, is very small in most cases. Variable stars encompass a large and wide array of types and phenomena and so a brief introduction is in order.

Aside: Variable star names are descended from an old naming system for bright stars within constellations. The system was invented by Johannes Bayer around the year 1600; it used the familiar Greek alphabet for the 24 brightest stars in a given constellation, and the Roman alphabet for fainter stars. Bayer never got past the letter Q in any of his catalogs, and in the mid-1800's, the German astronomer Friedrich Argelander came up with the exciting naming system we use today. We now designate variable stars in a given constellation with the letters R through Z, followed by the Latin three letter designation for the constellation in which the variable is located. For example, R Sct, AR UMa, and CH Cyg, note the upper case letter for each word in a constellation name. Argelander and others soon realized that there were far more than nine (R-Z) variable stars within each constellation, so once they got to Z, they started using double-letter combinations: RR-RZ, SS-SZ, TT-TZ, and so on. When those ran out, they went back to A again: AA-AI:AK-AZ, and so on up to QQ-QZ, but excluding AJ-QJ and JJ-JZ because J might be confused with I. After those ran out, astronomers gave up and sensibly started using numbers preceded by the letter V beginning with V 335 (as there are 334 possible combinations of the letters and letter pairs above). This naming scheme provided 334 entries, after that variables are named V335, V336, etc. again with the three letter constellation name after them (e.g., V482 Ori). It is amazing one needs so many variable star names in one constellation, but Sagittarius alone has over five thousand known variable stars.

3.0 Why Study Variable Stars?

At one level, studying variable stars is fun and easy. However, variable stars comprise several pieces of the puzzle of the origin and evolution of stars. How does one go about studying such seemingly ageless objects as the stars? Think about trying to learn about how birds fly by seeing only snapshots: a bird in mid-air, or a chick in a nest. Think about trying to understand how a river can cut a canyon or how a stream can provide

hydroelectric power without ever seeing flash flooding, or yearly wet/dry cycles, or knowing a bit about geology. The study of stars is no different. We see the stars about us in snapshots at different stages of their lives. We believe that Main Sequence stars show us the normal “adult” phase of stellar life. But how do we understand the process of a supernova – an end phase - or the role of giant molecular clouds in star formation – a birth phase, or the processes that create life-giving elements? We can learn these things by constructing life cycles of stars though the observational study of many snapshots of stars in different phases of their lives. Combined with theory and computer modeling, we try to piece the entire puzzle together.

In addition, study over the time of variability reveals some of the inner workings of stars - how they are structured inside. These secrets are revealed to us by translating astronomical observations into physical parameters. We cannot physically go to another star nor can we follow any single star for its entire life, so proxies must be used. We also can not see directly into the interiors of stars. Observations of various classes of variable star and observations of various stages within the evolution process are used to try to form a complete picture.

4.0 Examination of RV Tau and Semi-regular Variables

To provide a specific example, and as a lead in to things that follow, let us examine in some detail the evolutionary status of the RV Tau/Semi-regular (SR) variables and what mysteries may still lurk for these stars.

In order to get the reader directly into the mix, Figure 1 shows a long term light curve for a famous member of the RV Tau class – R Sct. This star is one of many RV Tau stars observed nearly every night by the AAVSO and the figure shows the behavior of the light output from this star over the past 90 years. Note how early in the plot, there appears to be regions that look like poor data (faded) regions. These places are periods of time when R Sct is “behind the sun” and few if any observations are available. We see that in recent years, these “faded” periods are mostly gone due to the increased number of amateurs, especially ones monitoring R Sct. The photometric behavior (that is brightness) of R Sct wiggles up and down with some occasional deep drops. This author’s involvement with R Sct started near the beginning of the 13th panel from the top. So what is the cause of these rapid changes in the light output from R Sct? Is such behavior typical?

Figure 2 shows a similar long-term light curve for another famous star R CrB. R CrB is the proto-type of a class of semi-regular variables that eject large shells of carbon which block a large fraction of the light output. While similar to R Sct, the light curves are not duplicates. Each RV Tau variable and each semi-regular variable has similar but unique photometric behavior. Are the classes of variable related to each other? Yes. Do we understand how they work, how they are related, and why they behave as they do? No. Let’s see if we can shed a bit of light on the subject.

A star is said to leave the main sequence when its core supply of hydrogen runs low. When this happens, gravity begins to collapse the star's interior until the compression heats the core to a high enough temperature to begin helium burning. Stars on the main sequence with masses of 2.5 times or less the mass of the sun do not form cores of sufficient mass as they evolve to ignite and burn helium. Post main sequence stars have energy outputs (luminosity) which are much larger than their main sequence level (albeit for short lived phases), and they become more luminous as they expand further to find a new (larger) equilibrium radius. As this expansion phase happens, the star begins its journey up the giant branch. If the star's mass - actually its core mass - is too low, the star will not be able to initiate carbon burning in its core and reach supergiant brightness, but instead will reach a peak luminosity of only few hundred times the sun's present brightness and a radius only about 100 times larger. After reaching peak brightness, the star gently ejects large amounts of its mass to form a planetary nebula. The remaining core (0.4 to 1.0 solar masses) cools down to become a run-of-the-mill white dwarf. More massive stars continue to go up and down the giant branch and then up again as carbon and other elements burn successively in the core. The most massive ones move into the supergiant realm, the location of the majority of RV Tauri and long-period variables, and become objects like Mira and Betelgeuse.

R Scuti (RV Tau type)
1910-2000 (1 day-means)

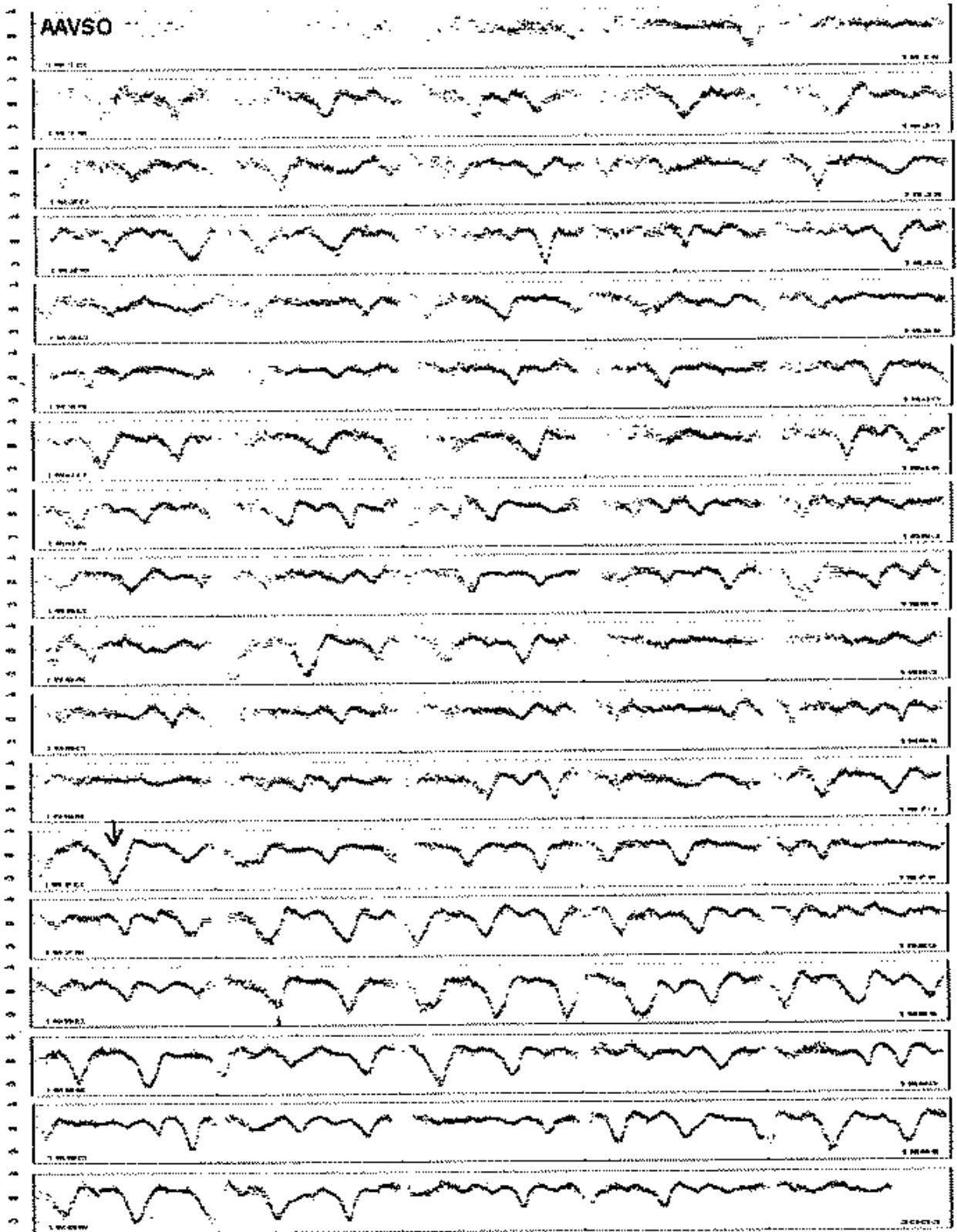
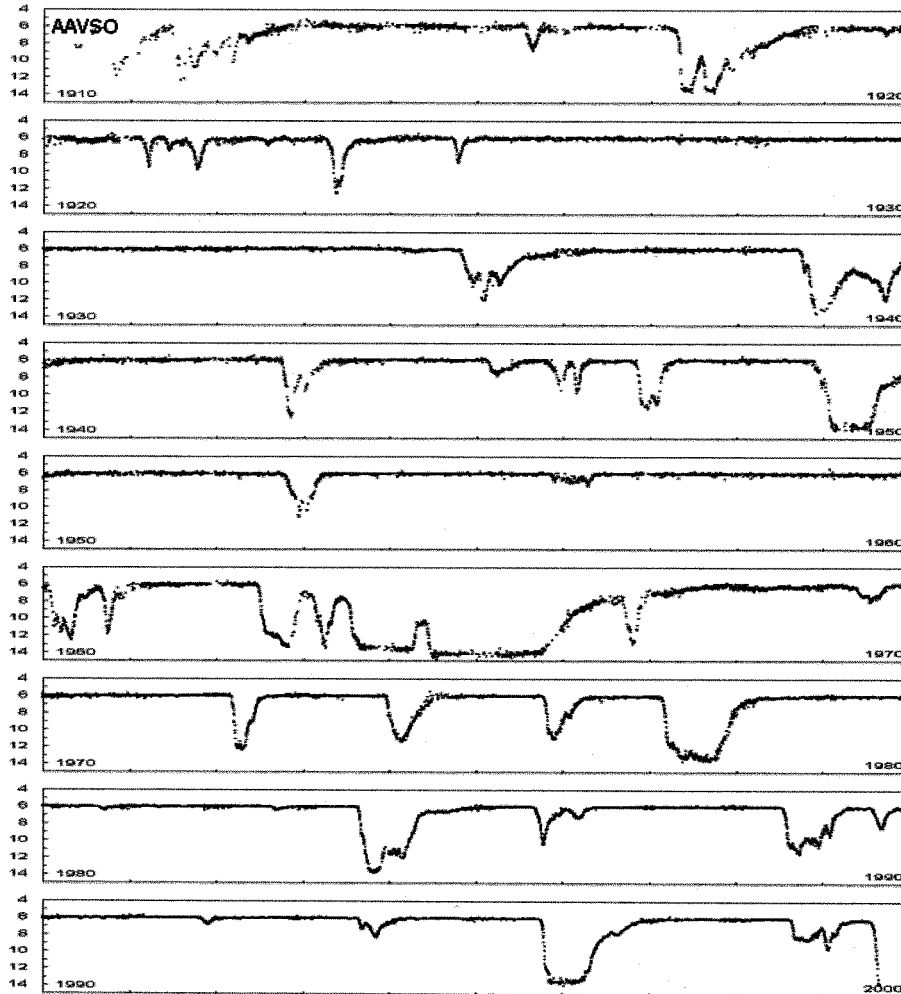


Figure 1 - 90 years of light curve data for the RV Tau star R Scuti.

R Coronae Borealis 1910-2000 (1-day means)

R Coronae Borealis is the prototype of its class. These rare supergiant stars have rich carbon atmospheres. They spend most of their time at maximum brightness but at regular intervals rapidly fade 1 to 9 magnitudes. The drop in brightness is thought to be caused by carbon clouds expelled from the atmosphere of the star.



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Figure 2 - 90 years of the Semi-Regular variable carbon star R CrB.

But whatever is going on during these different core burning stages, shells of material surrounding the cores become independent energy sources, pushing nuclear created luminosity both inward - further heating the core - and outward - helping expand the surface layers and increase the surface temperature. Nature often likes physics to behave in certain ways. One of these ways is called a limit cycle. You know limit cycles from experience with springs (bungee jumping for the brave at heart) or the lid of a steaming pan of cooking rice. In the case of a spring, if you hang a weight, pull the spring down a bit and let go, the spring goes into a nice relation (limit cycle) of amplitude and period.

The pot lid works its own limit cycle of rising up, spitting out some steam (and often hunks of rice to make a mess on your stove top) and then the lid falls down, awaiting the next steam driven pressure cycle.

The shell burning in an evolved star is similar. The cycle begins as a spherical shell of material tightly held by gravity against the radiating core is heated until the hydrogen in the shell begins to fuse, almost explosively. The fusion releases enormous amounts of additional heat within the shell, causing it to expand outward. However, as the gas of the shell expands, both its density and temperature drop until the nuclear fusion stops. Gravity then pulls the cooling shell back down against the core, compressing and heating it back above the fusion point, starting the cycle again. Each time the shell goes through the expansion part of its cycle, it sends a pulse outward through the star's atmosphere, causing the external variations seen by astronomers. In real stars this simple picture can be made very complicated by the complex relationships between different parameters such as shell composition (how many metals are present and the fact that the abundance changes with time due to burned material being moved through the stellar atmosphere), core temperature (related to core and thus stellar mass), location in evolutionary path (how far from the main sequence), whether more than one shell source exists, and whether shell fusion is spherically symmetric or not. These complexities produce research projects such as this one. The various sub-types of semi-regular variables have observational properties that can provide evidence about these details. We need to become detectives and dig them out.

Present day mysteries in stellar evolution particularly related to the RV Tauri and semi-regular variables concern the pulsation mechanism and issues of mass ejection prior to the planetary nebula phase. The first issue seemed well in hand until a large collection of photometric observations from the AAVSO were analyzed to determine periodicity. If shell burning is the culprit for the pulsations, then the periods can be complex – combinations of regular underlying periods mixed together into beat cycles – but not truly random. However, the period analysis revealed that about one-third of these variable stars seem to have random, chaotic behavior. A solution to this mystery lies in spectral work and relating the atmospheric conditions to the photometric light variations

The second mystery, which has been ongoing in stellar astrophysics for more than 100 years, is that related to mass loss. Stars on the main sequence have well established masses for their spectral type, Planetary nebulae are thought to represent a massive final shell ejection which strips off most of the star's initial mass, leaving behind only a small dense core – a pre-white dwarf. Adding the mass of the pre-white dwarf to the mass of the planetary nebula should equal the mass of the main sequence progenitor. However, in most cases, the combined star+nebula masses are far less than what astronomers believe the star started with. The answer has always been that somewhere in the giant/supergiant phase, additional, significant mass loss occurred (as winds, jets, shells) and that this mass loss accounts for the difference. Again, one can estimate the amount lost and add it to the star plus nebula mass – but it still does not seem to be enough.

However, phases of shell ejection and mass loss - the phases likely to be the largest contributor to the problem - are poorly studied spectroscopically for the RV Tau/SR stars.

So why study these evolved, non-periodic, misunderstood eclectic variables? We desire to formulate a *true* research project for TLRBSE, one that is not being done elsewhere and for which plenty of observational work is needed. We also wanted a research project that could be accomplished using the facilities at hand: a moderate to high resolution spectrograph, a modest sized telescope, and archival resources available on the web. Keying in on the skills available in the TLRBSE group and using the above criteria, bright variable stars were the ideal choice.

Our research project advantage is that we can obtain detailed, high-resolution spectra. Much observational work has been performed for the easy, nice pulsators such as the classical Cepheids, but the semi-regular variables are severely lacking in spectral observations, particularly spectra correlated with photometric data.

Photometric information is usually in good supply, because most of the stars we will be working with are regularly observed by the American Association of Variable Star Observers (AAVSO-- <http://www.aavso.org>). Their observations are easily accessible on-line, and additional photometry can be obtained using small telescopes. Spectroscopy is the key to this project. Spectroscopy is needed both due to its general dearth (particularly modern, high quality digital observations), and for its ability to provide physical data for the stars that can then be used to correlate their brightness changes. For a nice article detailing a similar research project on the Semi-regular pulsating hypergiant star Rho Cas, see Mercury Magazine Spring 2004.

5.0 The Research Question

How does the spectral type and spectral appearance of semi-regular variable stars correlate with their photometric brightness and general stellar properties? What can these measurements tell us about the properties of the variable star's atmosphere and evolution? Observations of simple pulsating stars, such as Cepheids, allow researchers to note trends between spectroscopic and photometric observations. These trends then lead to a physical understanding of the star. Figure 3 below shows how various observable and calculable properties change for a Cepheid variable, a well behaved, non-dust shell ejecting, type of pulsating star. The "phase" value runs from 0.0 to 1.0 for one complete pulsation period equal to a few days to weeks for Cepheids. We see in Fig. 3 that the star is brightest (delta mag near 0.0) when hottest (note both temperature and bluest spectral type), and near minimum radius. The phase lag between the plotted parameters is caused by the physics of the stellar atmosphere in a similar way to the Earth's atmosphere. We experience the hottest and coolest temperatures with a phase lag past the start of summer and winter. It takes a while to heat/cool large masses of gas. By studying the relationship between the changes in these physical parameters, we

can obtain clues about the true nature of the star's pulsations, its interior structure, and its age. One of our research goals will be to produce the first diagrams similar to Fig. 3 for RV Tau and Semi-regular variables based on the TLRBSE Coude Feed spectroscopy program.

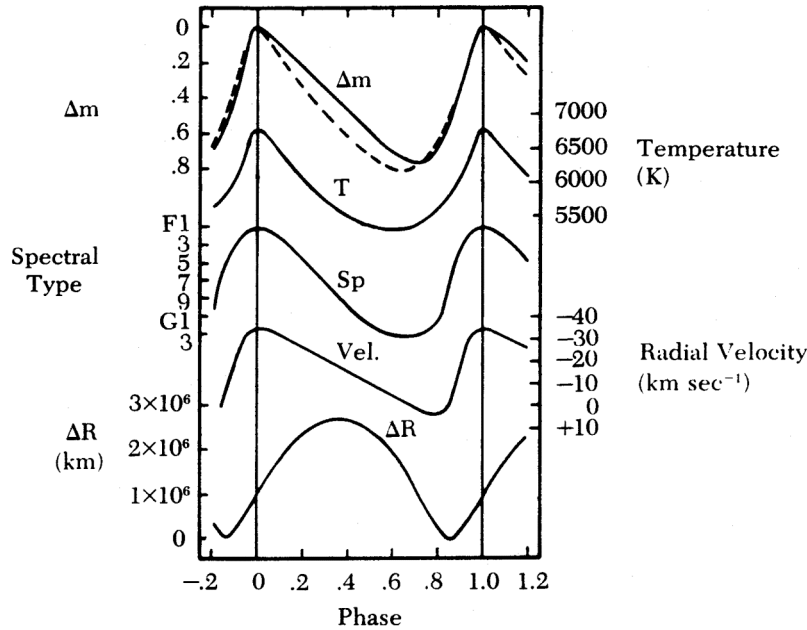


Figure 3 - Pulsational diagram for a Cepheid variable. The plotted curves are (top to bottom) magnitude, temperature, spectral type, radial velocity, and stellar radius. Units for each curve are given on the side of the figure in an alternating manner. A phase interval of 0.0 to 1.0 is one complete pulsational cycle for the star.

Using spectroscopic observations, the stellar properties we will determine are:

- 1) The spectral type which will provide the star's surface temperature.
 In general the use of Wein's Law to determine a stars' temperature is not possible with real spectral data.
 - 2) The luminosity of the star
 - 3) The mass of the star
 - 4) The distance to the star
 - 5) The radius of the star
- and, for advanced work,
- 6) The velocity of the atmosphere /shell of the star,
 - 7) The velocity dispersion of the material within the spectral line forming regions

