

Mira Variable Stars: Spectroscopic and Photometric Monitoring of this broad class of Long Term Variable and Highly Evolved Stars

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Abstract: Mira variable stars are a broad class of stars, which encompass spectroscopic classes of type M, S and C. These stars are closely related in terms of their long term variability, position on the Hertzsprung-Russell diagram their intermediate mass (from ~0.8 to ~8 solar mass) and the fact that class M evolves into the S and C type stars as certain stages of shell burning around the core proceeds. These shell burning episodes produce heavy elements beyond iron and also carbon which can appear at the surface of these stars during periods of convective instability resulting in greatly enhanced abundances of elements beyond the iron group and an increase in the carbon/oxygen ratio. In addition, it is suspected that these type stars, in particular, the M type Mira's can flare up over periods of hours to days by several tenths of a magnitude or more. The spectroscopic changes, which occur during these flare episodes, ultimately driven by core burning evolution, remain relatively unexplored. This project was initiated in order to monitor a group of program stars of these classes in the V and R photometric bands in the hopes of "catching" some of these stars during one of these flare ups and thus to be able to conduct spectral analysis of the flare-ups in real time and compare these spectra to the non-flare spectra. This talk will describe the background of these type stars, in particular, their evolutionary history and their spectroscopic differences. In addition, the strategies and initiation of this project will be described.

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1. Introduction

Among all the stars of the heavens, there exists a small sub-group, which has served as a key to our understanding of stellar evolution through spectroscopic examination. These stars are broadly called Mira variables and include the oxygen stars (M types), carbon stars (C type) and the S stars. They represent stars of the initial mass range from ~0.8 solar mass to ~8 solar masses which have evolved off the main sequence. These stars are peculiar in a variety of respects because of their high ratio of carbon to oxygen and the often-high abundance of heavy elements they contain, which are synthesized by the slow neutron capture process. They are also long

period variable stars, of the Mira class and the sequence from M to S to C types represent an evolutionary pathway during certain core burning events in their post-main sequence lives.

Recently, evidence has accumulated to suggest that Mira variables may go through flare up stages which result in brightening on the order of several tenths of a magnitude and can last hours to days in length (Schaefer, B., 1991, Maffei, P., and Tosti, G., 1995 and de Laverny, P., et. al., 1998). Very little is known about these events, especially spectroscopic changes that may occur during these events. This project was initiated with the view of monitoring a set of program stars in the V and R photometric bands and establishing baseline spectroscopic observations of moderate resolution in the red and near infra-red. In this manner, potential flare up episodes can be studied in this spectroscopic region.

2. Background, Results and Discussions

My primary instrument for spectroscopy is a Celestron 14 with a Paramount ME system. The Santa Barbara Instrument Group (SBIG) Self Guiding Spectrometer (SGS) is linked to the telescope with a focal reducer giving a final f6 ratio. The CCD camera attached to the spectrometer is the SBIG ST-8E with 9- μ m pixel size. In this paper only results obtained using the 18- μ m slit will be presented. The grating of 1200 or 1800 lines were utilized which represent a resolution of \sim 0.5 and 0.3 Angstroms per pixel, respectively. Wavelength calibration was carried out using the emission lines of a thorium-argon gas discharge tubes. Absorption and emission line identifications were carried out using tables from the Handbook of Chemistry and Physics.

Photometry was conducted with an Astrophysics 5.1-inch f6 refractor using an ST-10XME camera and 2x2 binned pixels and the Johnson V and R filters. Images were obtained in duplicate for each band and two reference stars used per variable star for analysis. Image reduction was carried out with CCDSOFT image reduction groups and specially written scripts for magnitude determinations, which allowed for rapid, nearly real time magnitudes to be found.

The currently believed interrelationships between the cooler M, S and C type stars are shown in Figure 1. As stars evolve into S and C stars, a number of changes are observed to occur in their outer atmosphere and these changes can be documented by examination of their spectra.

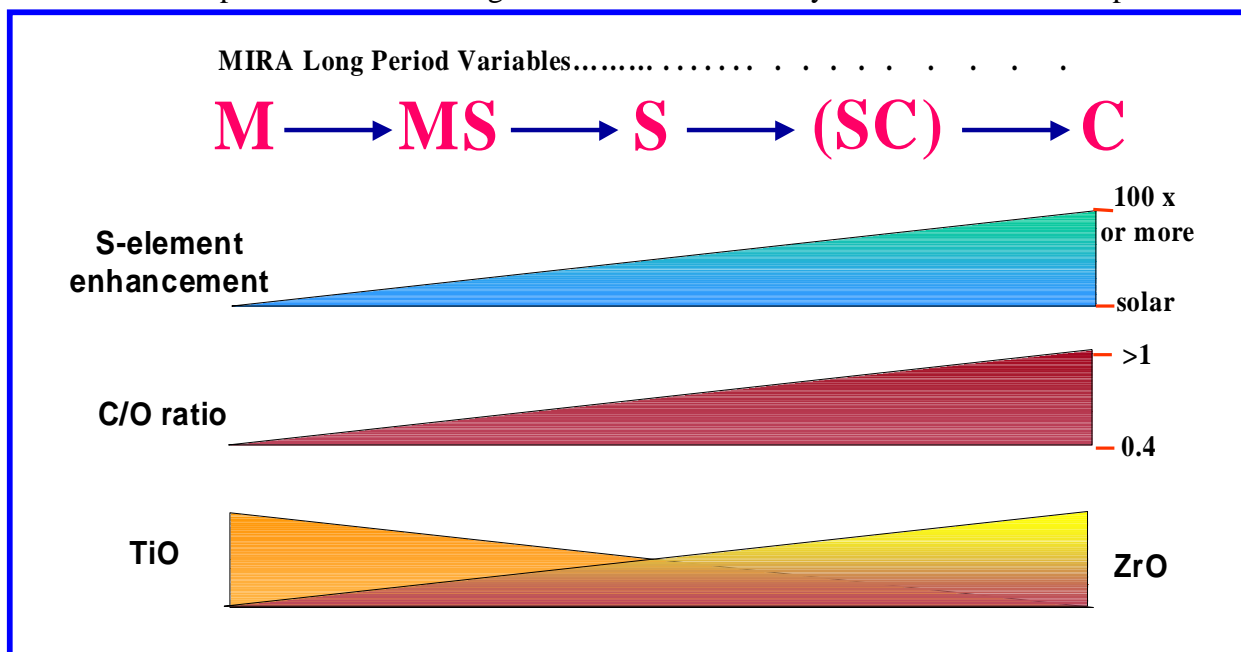


Figure 1. As stars of \sim 0.8 to 8 solar masses evolve away from the main sequence, they expand and cool and move into the red giant M type stars. From here they enter into Mira type long period variability and

gradually evolve into S and ultimately C type thermally pulsing phase where alternating burning of hydrogen to helium, helium burning to carbon and phases of slow neutron capture reactions. Intermittent convection sets in bringing many of these heavy elements to the surface including carbon and zirconium. As a result, enhanced s-elements are observed, increased carbon as expressed as a C/O ratio and the newly made zirconium has a higher affinity to react with free oxygen than titanium, resulting in the disappearance of TiO bands and the appearance of ZrO bands in their place. Either of these molecular species can be observed only in cooler stars such as M, S or C types. Whether the SC transitional class actually exists remains a bit controversial.

For example, one often observes an enhancement of s-elements in their atmospheres. These are elements synthesized by the slow neutron capture method in shell regions around the core of these stars. More will be said about this later. In addition, the carbon/oxygen ratio increases in these stars from a typical value of 0.4 up to values often greater than 1. Finally, the molecular bands of titanium oxide (TiO) observed in the spectra of cooler M type stars often disappears and are replaced by zirconium oxide (ZrO) bands and vanadium oxide (VO). (Zirconium is a slow neutron capture element).

Where do these stars lie on the Hertzsprung-Russell diagram? Figure 2 shows this diagram with the main sequence indicated. The main sequence represents where the vast majority of stars are found. These are “normal” stars in that they are burning hydrogen into helium in their cores. When stars have exhausted this hydrogen, they begin to evolve. How this evolution will proceed depends upon the mass of the star. Our discussion will focus on stars in the mass range of 0.8 to 8 solar masses. In this range, which includes the sun, stars migrate to the right of the diagram and upward. The green paths represent two such migrations for two different mass stars. These stars outer atmospheres expand and cool as helium ignition begins in the core and hydrogen burning in a shell around the core gets underway. As the stars cool they become M type stars and enter a region of the H-R diagram populated by long period and MIRA type variable stars. It is while stars are in this region of the H-R diagram that some very interesting things occur. Figure 3 is an enlargement of Figure 2 focusing on the variable star region of the diagram. It is while stars are in this region of the diagram that a series of nuclear reactions take place with profound evolutionary consequences.

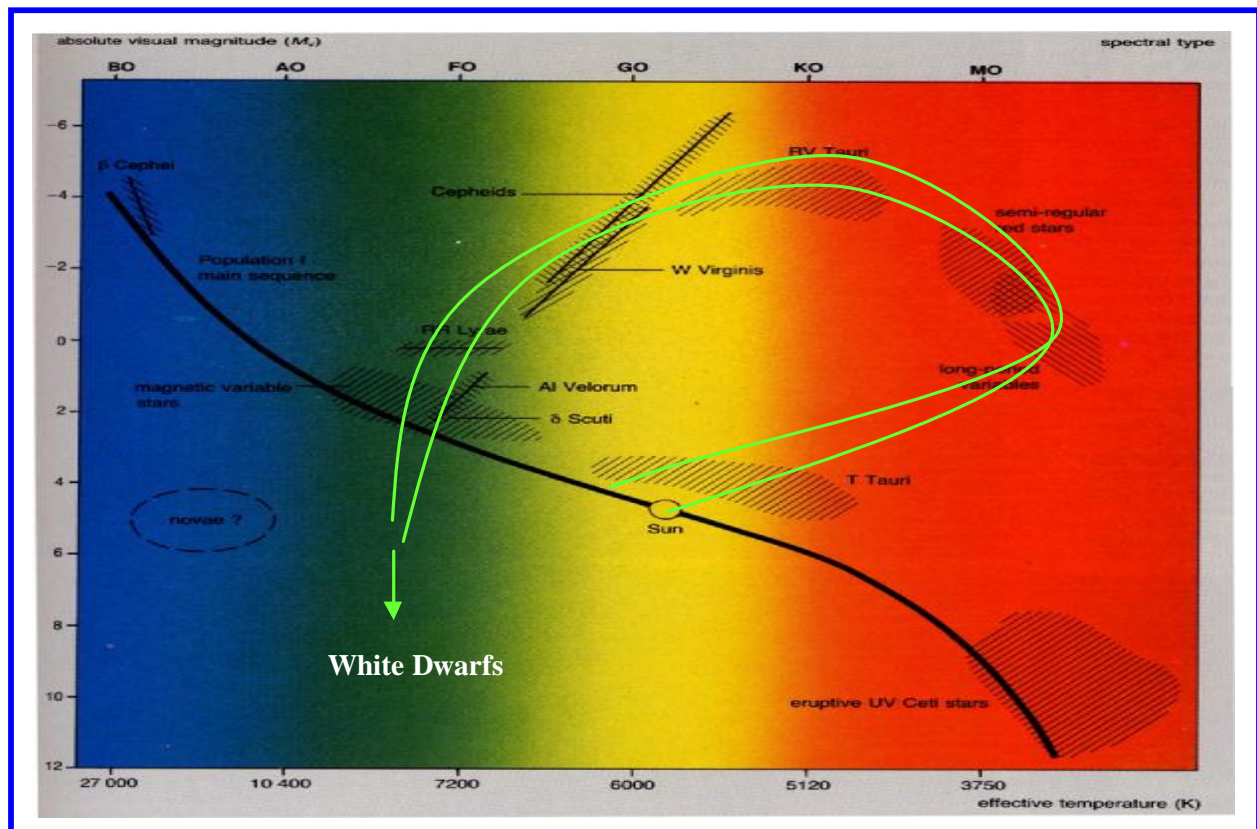


Figure 2. The Hertzsprung-Russell diagram showing the main sequence as a black line and various other areas where variable stars of different types are found. The green lines indicate the paths of evolution followed by typical stars in the solar mass range when they have exhausted their hydrogen supply in the core. They migrate into the region M type stars and long period variables of the Mira type (farthest right). After spending some time in this region, they ultimately shed their outer layers as planetary nebula and the stars enter into the white dwarf region.

Stellar evolution models show that while stars are residing in this area of the HR diagram they undergo a series of thermal pulses in which alternating burns of hydrogen to helium and helium to carbon can occur. At certain times during these alternating burns, there are regions where significant quantities of an isotope of carbon get made, ^{13}C , which contains one extra neutron in its nucleus over normal ^{12}C . At certain times during these alternating burn-rest periods, conditions can be appropriate such that the ^{13}C can fuse with helium yielding oxygen and, most importantly for our purposes, a free neutron. This appears to be the main source of neutrons for the slow neutron capture process and initiates at a temperature of $\sim 1 \times 10^8$ K. Another process that is relatively minor, but requires higher temperatures, is the burning of ^{22}Ne to give ^{25}Mg . Now, free neutrons do not survive very long, having a half-life measured in minutes. But the important thing about neutrons is that they can enter into and fuse with the nuclei of other heavy atoms without the temperature requirements usually required for fusion of nuclei to heavy elements. At times in between these pulses, convection sets in and some of the

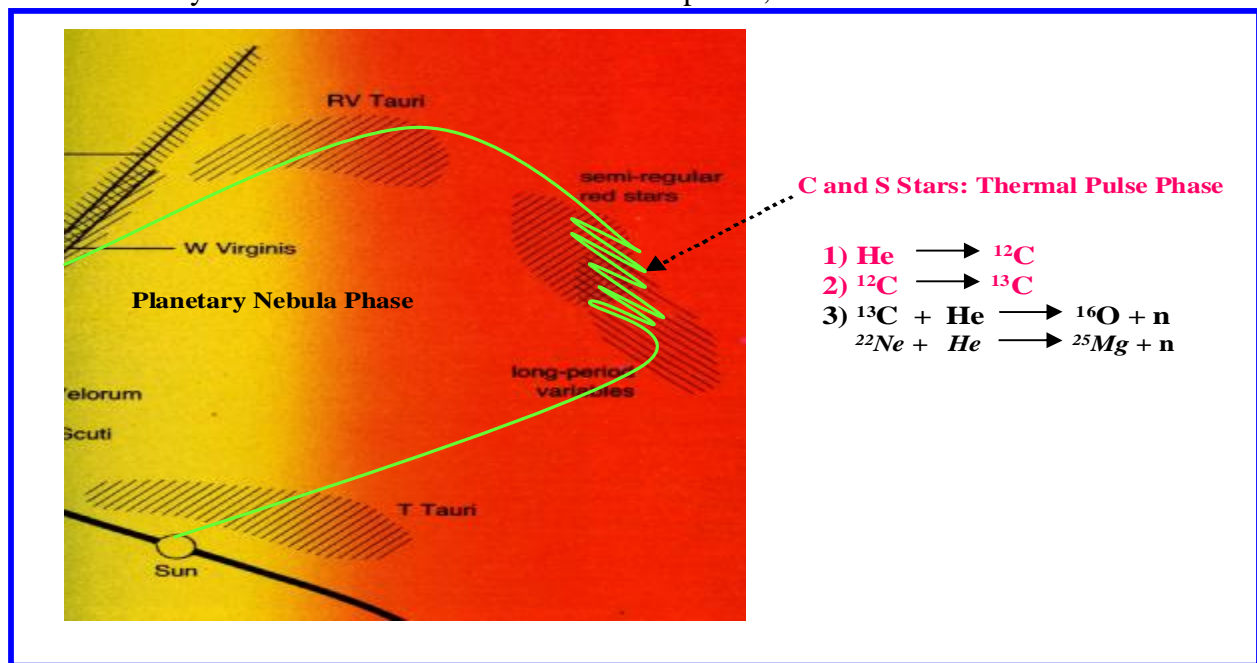


Figure 3. Close up of the region where stars enter the variable region of the H-R diagram and the thermal pulsing phase. In this phase, which can last a few million years, helium and hydrogen burning occur out of phase with each other and slow neutron capture reactions occur. The source of the neutrons appears to be ^{13}C with possible small contributions from ^{22}Ne . Dredge up periods between these episodes carries some of these products to the surface. Eventually, many of these slow neutron capture elements find their way back to interstellar space during the planetary nebula phase.

materials cooked up in these processes get dredged up and appears in the outer atmospheres of these stars. This represents the slow neutron capture process and can synthesize heavy elements beyond the most stable nuclei, iron. It is while stars are in this region of the HR diagram that they evolve into long period variables of the Mira type and this includes stars of type M and later, S and C types. Figure 4 shows a high resolution spectrum of omicron Ceti (Mira) in the blue region of the spectrum with some of the many lines identified. Note the prominent molecular TiO band around 4590 Angstroms. These type molecular bands (due to TiO) are the

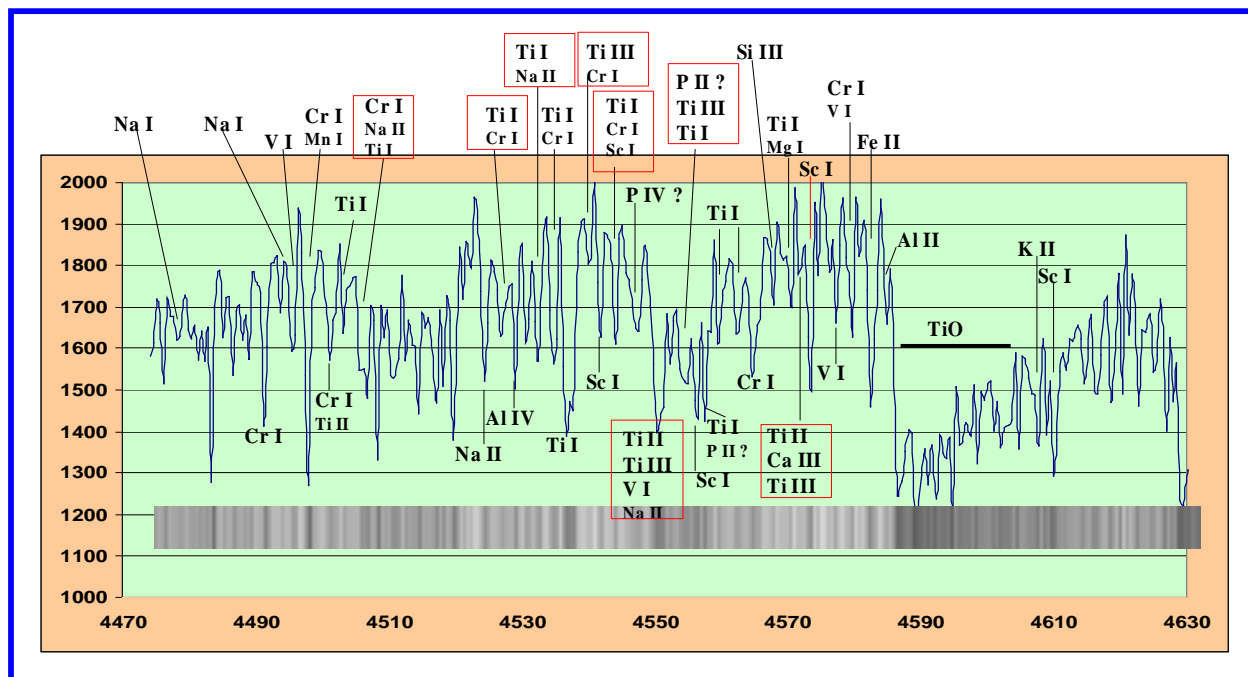


Figure 4. Spectrum of Omicron Ceti obtained near maximum light in the blue region of the spectrum using a moderate resolution grating (1200 line, ~ 0.5 Å/pixel). The large number of lines, many blended, is typical of these type cooler stars as is the molecular TiO bands (one such seen at ~ 4590 Å). These bands give way to ZrO bands in S stars and finally molecular C_2 bands in the C types as the evolution of these long period variables proceed.

first to go as stars evolve into S type (to be replaced by ZrO or ZrS bands). As the evolution proceeds into the C type Mira's, it is not uncommon to see essentially complete disappearance of the blue region of the spectrum due to the very heavy absorption of diatomic carbon (C_2). The ZrO bands remain but can be seen only more toward the red region of the spectrum.

There have been recent studies that suggest that these stars, especially the M type Mira's undergo flare up episodes with a brightening of several tenths to over 1 magnitude, lasting from hours to days. Schaefer (1991) reviewed what was known about these events from the literature and while suggestive, the evidence is not compelling; Maffei and Tosti (2000) performed a similar analysis. The strongest evidence came from a study of results obtained with Hipparcos observations by deLaverny et. al. (1998). Their analysis of thousands of individual observations on 251 Mira's over a 37 month period indicated what appeared to be 51 flare up events in 39 M type Mira's. No similar type flare-ups were observed with S and C type stars but the sample size was small for these type stars, which easily could account for the lack of observed events. De Laverny notes that these events occur in the later M type stars rather than earlier types and suggested that these events could be related to opacity changes that occur with the molecular bands of TiO and/or possibly VO.

Despite the challenges of verifying the existence and frequency of the "microflares" among selected Mira variable stars, it remains possible to speculate on causes. At least three scenarios present themselves: (1) shock induced; (2) magnetically induced, and (3) planet induced events.

(1) Many Mira variables exhibit radio maser emission arising from excited molecules of SiO in the outer atmosphere of such stars. The patchy nature of the bright SiO maser spots seen in VLBI maps varies in response to the Mira optical variation. If a consistent phase for microflares can be established, they could be related to shock propagation and interaction altitude.

(2) The same type of maser observations can be used to deduce magnetic field strengths via Zeeman line splitting. The analogy with solar magnetic phenomena [spots, flares, eruptive prominences, coronal holes and mass ejections] is compelling. However, in analogy to the R CrB phenomenon, brightness variation could also be a consequence of dust formation (fading) and dissipation (brightening) in front of a star's visible hemisphere. Additional observations will be required to discriminate which is occurring. True flare stars include Sun-like red dwarf stars with half the surface temperature and a fraction of the solar mass. These appear to have sizeable starspots and intermittent flaring behavior. In those cases, extensive spots and concentrated fields give rise to high energy output in UV and X-rays. The latter emissions are not seen in the case of Mira variables, suggesting a strong limit to the size and strength of spots. A more "dilute" and large-scale eruptive prominence analogy might suggest measurable changes in mass loss diagnostics, such as the cores of H-alpha or Ca II K, if these could be extensively monitored for microflares (Stencel, R., and Ionson, J., 1979, Stencel, R., 2000).

(3) An interesting speculation involves extending the discovery of extra-solar planets to their role around evolved stars like Mira variables. As the Mira red giant expands and engulfs its Jupiters, several kinds of accretion "fireworks" might accompany digestion (Struck et. al., 2002). However, the duration and frequency would be limited to either orbital periods or one-time events. Existing maser maps would appear to rule out large scale planetary wakes around some Mira variables, but additional observations are always merited.

The approach we took toward this project was to select a group of program stars. Of the 39 M type Mira's described in the deLaverny paper, 20 of them are relatively bright and visible from the northern hemisphere. These along with a variety of brighter S and C type stars were also chosen. The Hipparcos data did not rule out a sample size effect of the S and C types as to why none were observed in these stars. Therefore it was felt to be prudent to include a good size group. The brighter stars were chosen since they represented stars with magnitudes, especially in the H α region (6562 A) and higher, bright enough such that moderate resolution spectroscopy could be performed as part of the monitoring process. To accomplish this in a semi-automated

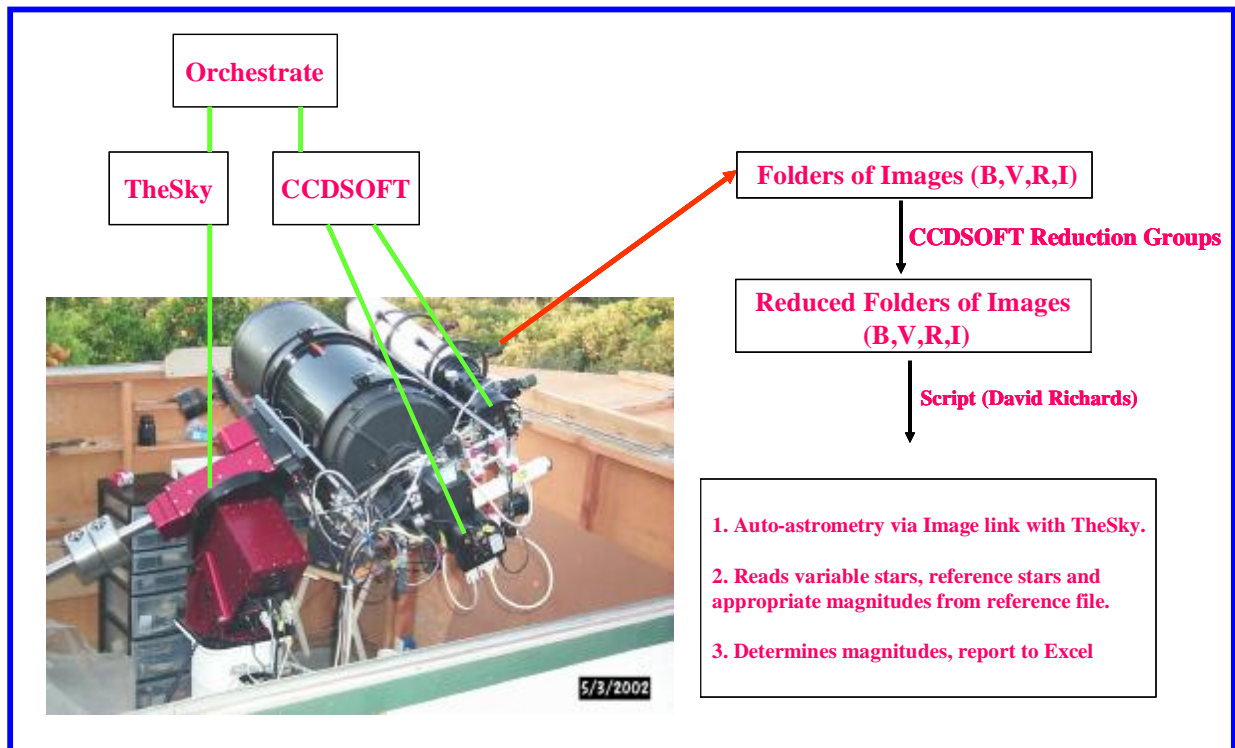


Figure 5. The flow of data acquisition and reduction for variable star monitoring. The imaging camera and filter wheel are controlled by CCDSOFT while the Paramount ME is controlled by TheSky. All of this is under the umbrella of Orchestra which allows for non-intervention in acquiring images of varying length with different filters, dark subtraction and saving of images. The images are then reduced using CCDSOFT reduction groups routines and finally the use of a visual basic script written by one of the authors completes the data reduction with the magnitudes reported in an Excel format.

manner, the telescope, camera and filter wheel are controlled by a single computer with Orchestra. Once the images are reduced, a script written by one of the authors (David Richards) runs through the images performing an image link with TheSky. The images obtained in this manner are stamped both with the name of the variable star, since this was how Orchestra was instructed to find the object, and the position of the image in the sky. This allows TheSky to quickly perform the linkage with its database. Once the astrometric solution is accomplished, the program reads through a reference file with the pertinent data such as

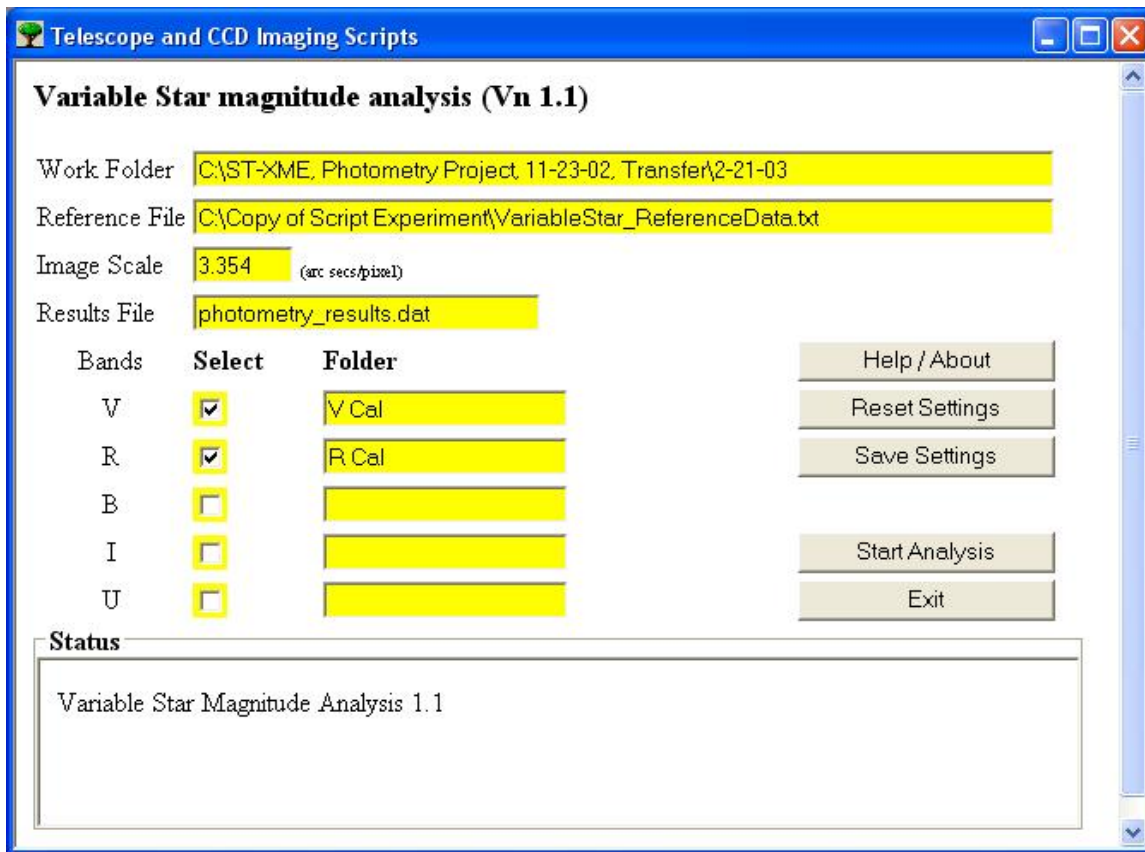


Figure 6. The window which appears when initiating the Variable Star Magnitude Analysis script. Several options are available such as which filters were used with the image sets to be analyzed. All that is required is that a reference file be created, just once, with the reference stars name and corresponding filter magnitudes along with the variable name. This list is flexible and other stars and/or filter set data can be added to be utilized by the script. Also required is the image scale in arc seconds per pixel. The more accurate this value, the faster the image link is performed and the astrometric solution determined.

reference star name and magnitudes along with variable star of interest. Figure 7 shows a portion of the reference file read by the script along with what the output file looks like. The input file is highly flexible, stars and filter magnitudes of reference stars can be added freely if your image sets so require it. This file only needs to be created once, especially convenient for a set of program stars which will have continuous coverage over time. There is no need for entering magnitude information of reference stars in a repeated manner. The results file is readily imported to excel where the various stars and their magnitudes can be plotted, almost in real

time. This is an important aspect of this project, the ability to see changes (flare-ups) quickly and as a result respond to these changes with spectroscopic observations.

A

SV_AND	GSC	2785:1315	V	GSC	2785:1549	7.899	GSC	2785:1090	8.399
SV_AND	GSC	2785:1315	R	GSC	2785:1549	7.59	GSC	2785:1090	8.32
R_CET	GSC	4691:926	V	GSC	4691:808	10.063	GSC	4691:808	10.06
R_CET	GSC	4691:926	R	GSC	4691:808	9.856	GSC	4691:808	9.856

B

Band	Variable	Time	Julian Da	MagV (Ca)	MagV (Ra)	MagC (Ra)	MagK (Ra)
V	GCVS W CAS	2:54:29	2452711	9.304	-2.604	-1.678	-1.618
V	GCVS W CAS	2:54:56	2452711	9.328	-2.589	-1.688	-1.595
V	GCVS V365 CAS	2:56:17	2452711	9.107	-1.254	-1.131	-0.64
V	GCVS V365 CAS	2:56:29	2452711	9.158	-1.248	-1.176	-0.65

Figure 7. Part A shows a portion of the reference input file which contains data to be read from the script such as the name of the variable star and the V and R magnitudes of 2 reference stars. Part B shows the output file which calculates the magnitude of the variable star along with all the raw magnitudes, Julian day, time, etc. The results file separates the filter sets being examined. For example in this case, the V magnitudes are shown first followed by a set of data for the R magnitude. U, B and I data could easily be added. You would only need to modify the reference star file to include the appropriate magnitudes at the appropriate filters and of course obtain the images with the desired filter(s).

The project has been underway now for only about 4 months and involves a total of 96 stars, 20 M type Mira's, 19 S types and the remainder C types. While there are certainly many more of these type stars, only those that had a significant part of their light curve under magnitude 8 were considered. This was because of magnitude limitations in the spectroscopy part of the project. Fortunately, these stars are much brighter in the R and I bands, often by 2-4 magnitudes when compared to their V magnitudes and many of the interesting molecular features are found in this region of the spectrum. Not all of the 96 stars have been observed yet since parts of the sky are not visible at this time of year. Gradually with time these program stars as they rotate into view, will be added to the list. Figure 8 displays 2 typical graphs obtained over the past several months for V Mon (M type) and R Gem (S type). The photometric analysis involves using 2 different reference stars. Their constant nature is readily discerned over the time period by the horizontal slope of their light curves, both in the V and R bands. After considerable effort, magnitudes are now determined at the 0.02 magnitude level. Thus any flare-ups in the range of 0.1 and above should be readily discerned.

Early on it was felt that semi-automating the process was the only way to go. The use of a mount such as the Paramount along with the Suite of software by Software Bisque got the project 80% of the way there. It turns out the real consumer of time in these efforts was the magnitude determinations. This took far longer than the actual acquiring and processing of the images. Fortunately, TheSky in conjunction with CCDSOFT lends itself to scripting and a script was put together that automated the magnitude determinations. It is now not even necessary to view any of the images. To give an example of how this has streamlined the effort, on a typical night using Orchestrate to control the telescope, camera and filter wheel, 40 stars, visible at the time, are imaged in duplicate in each of the V and R bands. This takes about 1 hour. Reduction of the images using image reduction groups in CCDSOFT takes another 5 minutes. The script that determines the magnitudes takes about 10 minutes to churn its way through all the images. Within another 20 minutes, the data, via Excel, has been added to each variable stars growing light curve. Thus in less than 2 hours all of the program stars have been observed and their

results tallied. Until more of your program stars rotate into view, one is free to pursue spectroscopic examination of the program stars, establishing baseline observations.

Another goal of this effort during the upcoming months will be to standardize the reference stars in each of the fields using the Landolt standards (Landolt, 1983). Once this is done all previous and subsequent observations of the variable stars will have their magnitudes expressed in absolute Johnson-Cousins magnitudes.

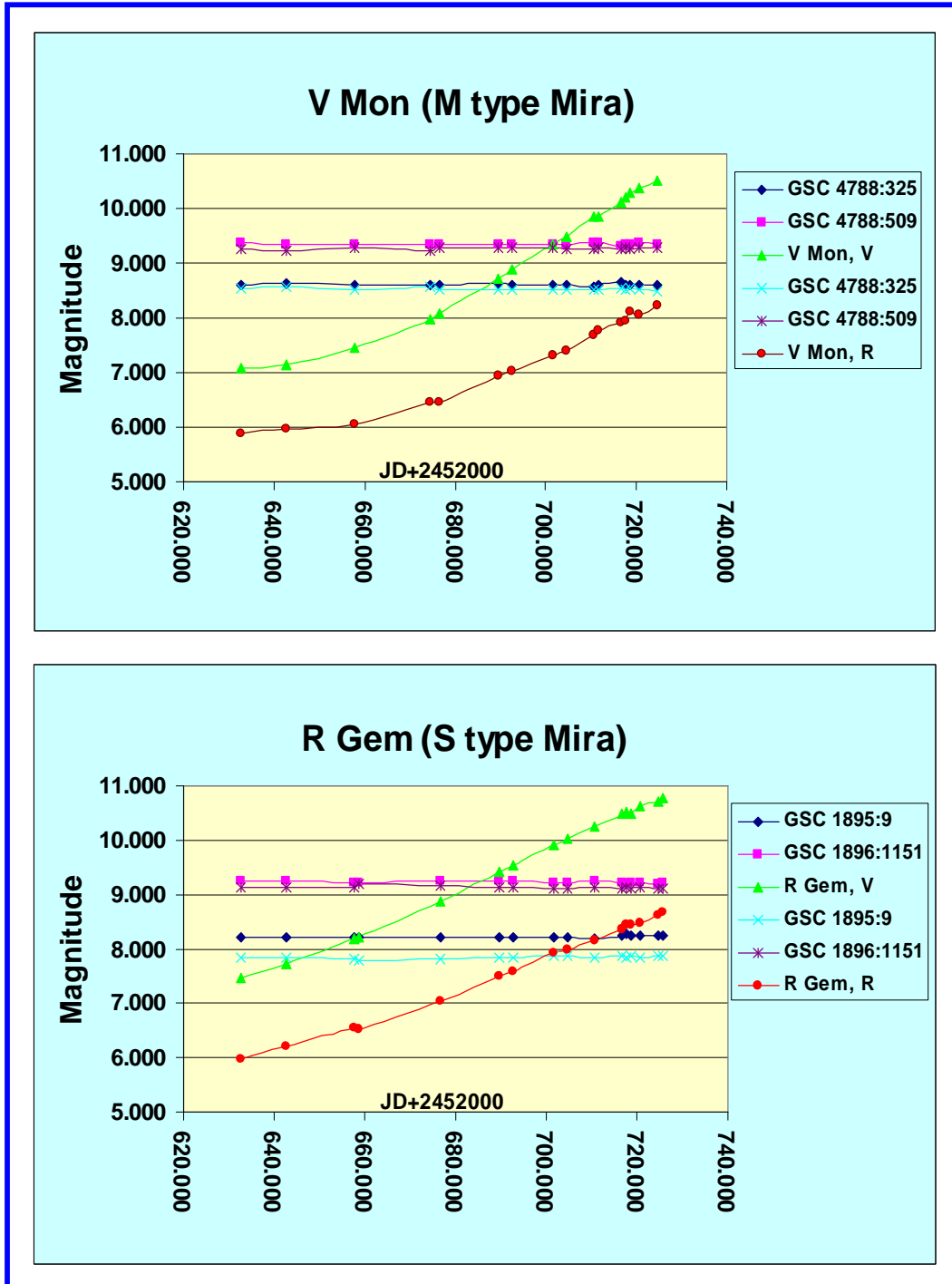


Figure 8. Typical light curves obtained for the first several months of the project. Shown above is a typical M type Mira, V Mon and below a typical S type, R Gem. Along the x-axis is plotted Julian day and magnitude is shown on the y-axis. The period of V Mon from the AAVSO database is 340 days. No data is available for R Gem.

3. Summary

We have described the initiation of a program to follow Mira type long period variables to attempt confirmation of flare-up episodes. If these flare-ups are observed, to follow up with spectroscopic observations of moderate resolution. A group of 96 stars are part of the program and photometric observations are being conducted, currently, in the V and R bands. The photometric observations and data reduction have been automated to a large extent using software aimed at control of telescope-camera -filter wheel for image acquisition and image reduction. A script is described which proceeds to carry out the magnitude calculations. Hands-on analysis is kept to a minimum. This script could find wider use among those in the amateur community interested in variable star work as it removes the most time consuming part of the analysis.

Acknowledgments

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