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

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Abstract: We have been monitoring Mira variable stars, which encompass spectroscopic classes of type M, S and C during the past year and a half. 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. These stars are very interesting from the stand point that they can produce heavy elements beyond iron and also carbon which can appear at the surface of these stars during periods in their evolution. 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 paper will give an update of the project and describe the strategies being employed to monitor these stars.

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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.

Over the past several years, 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-µm pixel size. In this paper only results obtained using the 18-µm slit will be presented. The grating of 1200 or 1800 lines were utilized which represent a resolution of ~0.5 and 0.3 Angstroms per pixel, respectively. Wavelength calibration was carried out using the emission lines from a thorium-argon gas discharge tubes using the software package Vspec. Absorption and emission line identifications were also carried out using Vspec.

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 spectra of these stars are closely related, in part because their temperatures are nearly the

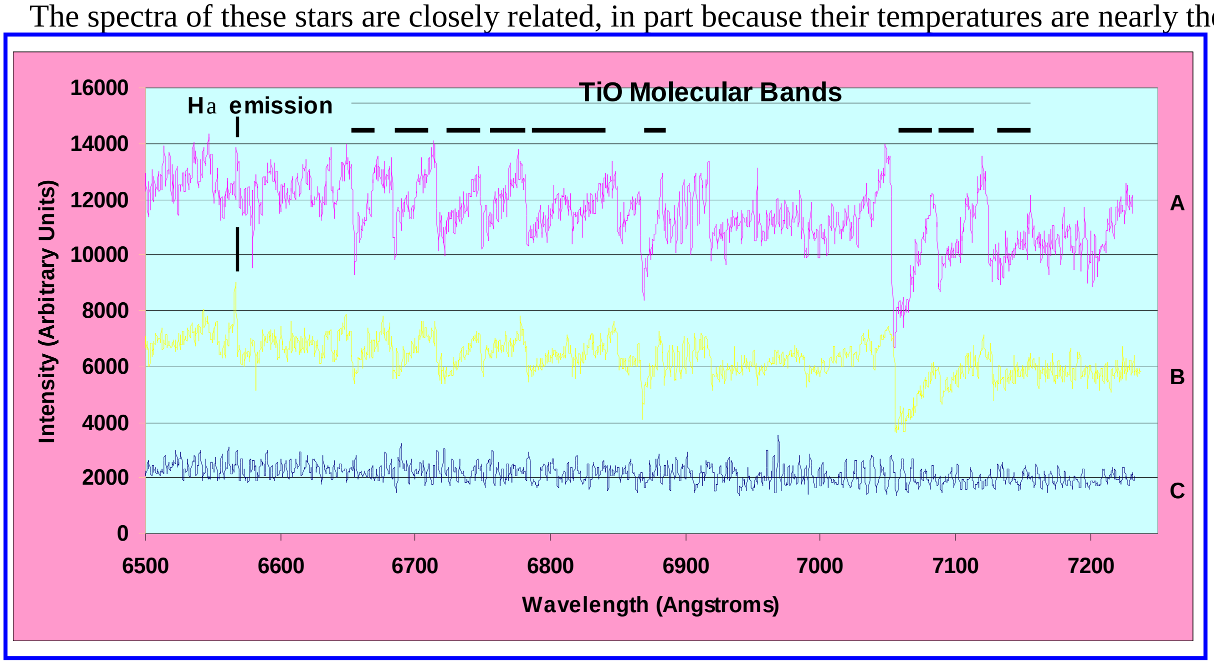

Figure 1. As stars of ~0.8 to 8 solar masses evolve away from the main sequence, they expand and cool and move into the red giant M type stars (A). From here they enter into Mira type long period variability and gradually evolve into S (B) and ultimately C type (C). In the thermally pulsing phase many of heavy elements synthesized deep down are brought to the surface including carbon and zirconium. As a result, there is a gradual increase in the C/O ratio. 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. Hα emission may appear in any of these types and is often variable.

same. Differences arise because of changes in their outer atmosphere chemistries and can be seen in figure 1. The prominent TiO molecular bands so prominent in M types gradually give way as one proceeds to S types and essentially disappear in C types. Hα lines can be in emission for any of these types and is often variable with the phase of the variability. Also, one often observes an enhancement of s-elements (heavy elements) in their atmospheres. These are elements synthesized by the slow neutron capture method in shell regions around the core of these stars. 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).

The lower temperatures of these stars give rise to many metal lines in the spectra and typical spectra of these stars is shown in Figure 2. This shows a high resolution spectrum of Mira,

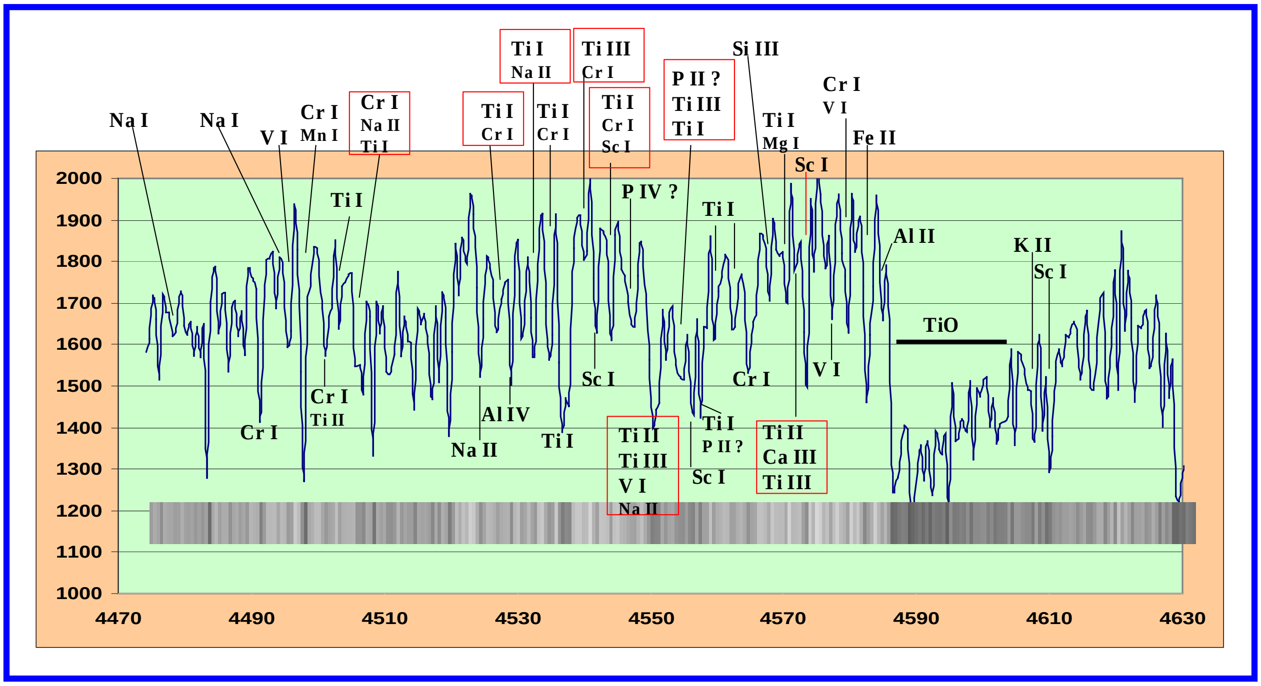

Figure 2. Spectrum of Omicron Ceti (M type Mira) obtained near maximum light in the blue region of the spectrum using a moderate resolution grating (1200 line, ~0.5 A/pixel). The large number of lines, many blended, is typical of these type cooler stars as is the molecular TiO bands (one such seen at ~4590 A). 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.

(omicron Ceti) 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 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 (Figure 1).

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 a year and a half ago 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 Hα region (6562 A) and higher, bright enough such that moderate resolution spectroscopy could be performed as part of the monitoring process. The final breakdown in program stars include 25 M-type, 16-S type and 57 C-type Mira's.

To accomplish this in a semi-automated manner, the telescope, camera and filter wheel are controlled by a single computer with Orchestrate. 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

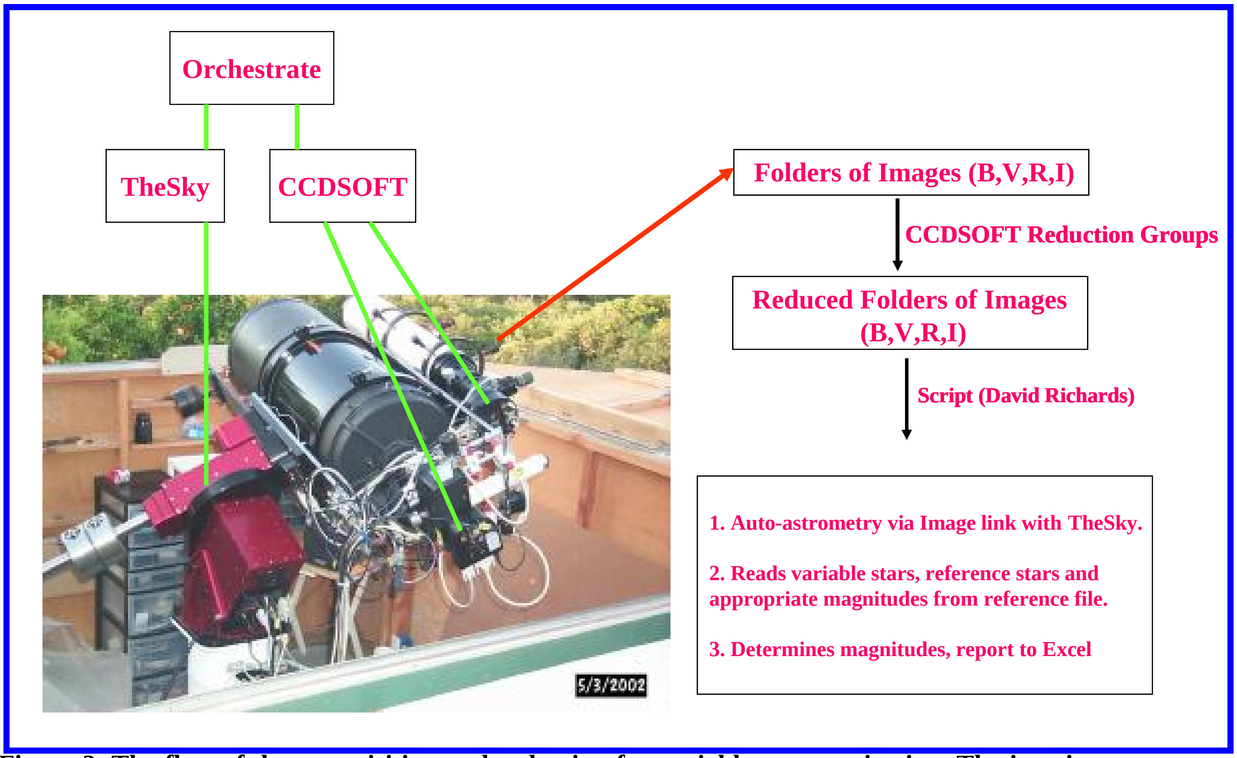

Figure 3. The flow of data acquisition and reduction for variable star monitoring. The imaging camera and filter wheel are controlled by CCDSOFT while the Paramount ME is controlled by TheSky. All of this is under the umbrella of Orchestrate which allows for non-intervention in acquiring images of varying 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.

since this was how Orchestrate 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. Figure 3 shows the flow scheme for data acquisition. Once the astrometric solution is accomplished, the program reads through a reference file with the pertinent data such as reference star name and magnitudes along with variable star of interest. 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. Figure 4 shows the script page that carries out these reductions.

The project has been underway now for only about 1.5 years and involves a total of 98 stars. 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. Many of the stars have now completed a complete cycle of variation and some interesting features can be discerned in their light curves as will be discussed below. 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 sub 0.01 magnitude level. Thus any flare-ups in the range of 0.1 and above should be readily discerned.

The light curves of Mira's have been classified into different types, mainly based on their shapes, not their lengths. The top of figure 5 shows 2 different periods of M type Mira's. In addition, this figure shows 2 different types of curves based on the curve shape. In most cases for

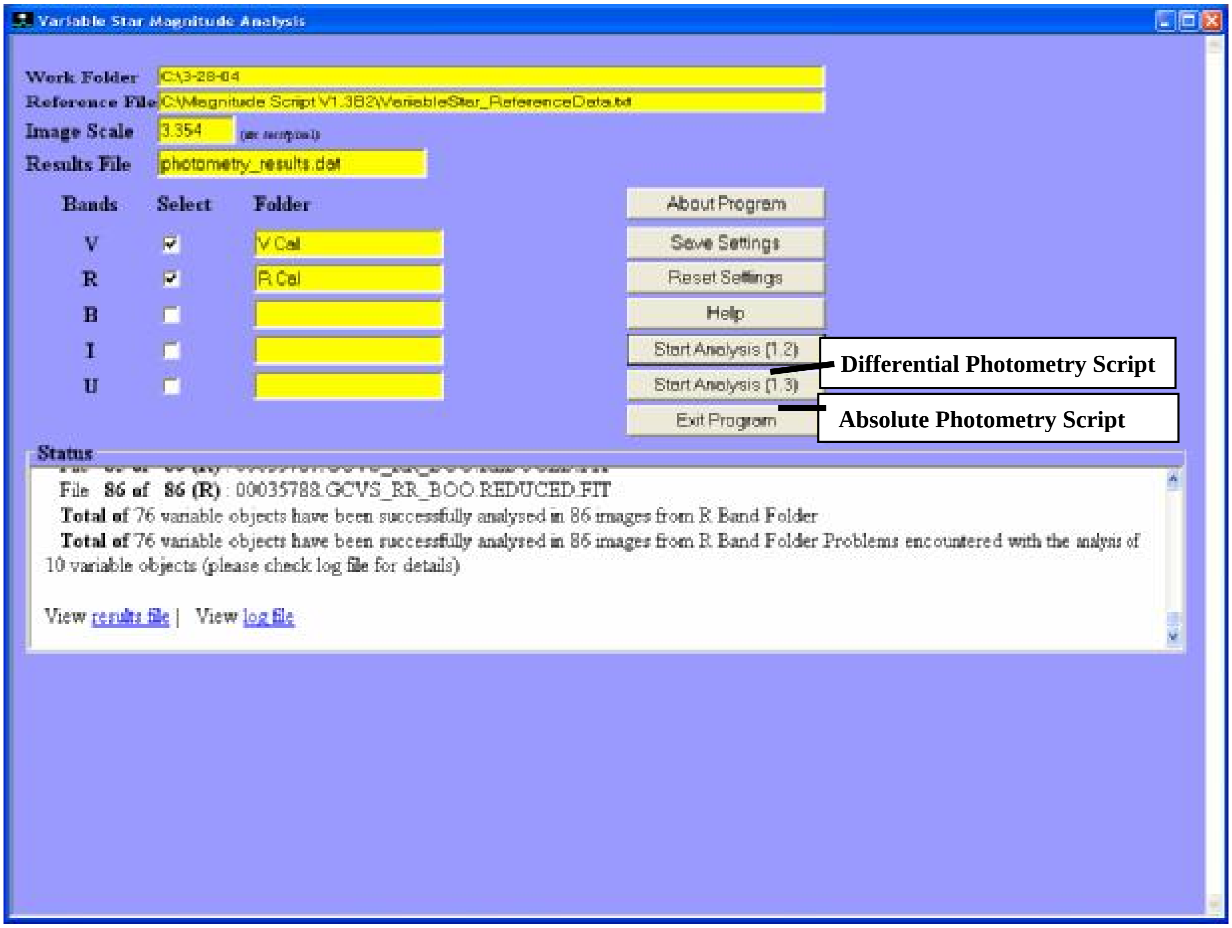

Figure 4. The window which appears when initiating the Variable Star Magnitude Analysis script. Several options are available such as which filters were used with the image sets to be analyzed. All that is required is that a reference file be created, just once, with the reference stars name and corresponding 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. Two tools are available for analysis, differential and absolute photometry. The later utilizes Landolt field stars.

these stars the curve shapes are smooth and sinusoidal in shape while for a sub-type of Mira's, they possess a "Cepheid bump like" phenomenon as indicated by the arrows. These have been described before (Melikian, 1999). We see these bumps on about 20% of the light curves for the program stars, irrespective as to the type of Mira. These bump Mira's are of longer period and higher luminosities but beyond that not much is known as to the physics producing these phenomenon.

A typical light curve of S Cam, an S type Mira, is shown in the bottom part of figure 5 in both the V and R bands. Again, note the bump on the ascending part of the light curve as indicated by the arrow. The analysis of the light curve is shown in figure 6. The best fit of the growing light curve is determined and with this best fit equation, residuals between calculated and observed magnitudes can be found. A plot of these residuals for the V band is shown along with residuals for one of the standard stars. Clearly, there is more scatter in the variable residuals than for the standard. Perhaps what is being observed here are micro-flares in the variable or even the presence of large star spots on the surface of the variable resulting in greater scatter. To date however there has been no compelling evidence for flare-ups for any of the stars observed at the 0.15 magnitude level or more. Observations will continue to complete at least several complete light curves.

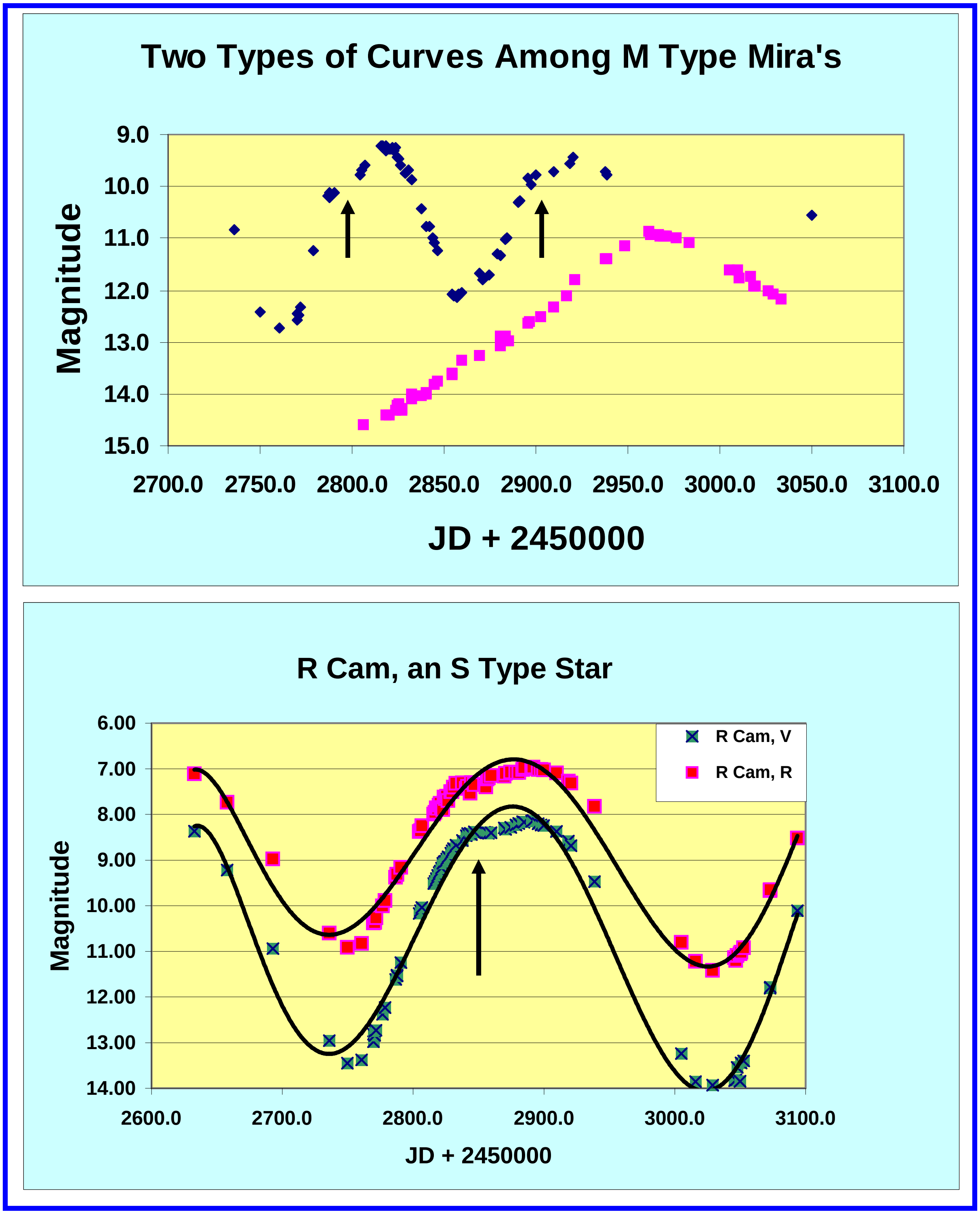

Figure 5. Typical light curves obtained for the first several months of the project. Shown above are 2 typical M type Mira, displaying 2 different types of curves both in period and in shape. Note the "Cepheid bump like" phenomenon near maximum light, seen for many of these variables at phase 0.6-0.8 (arrow). Below is shown the curves of R Cam, an S-type star in both V and R bands along with a polynomial best fit to the data.

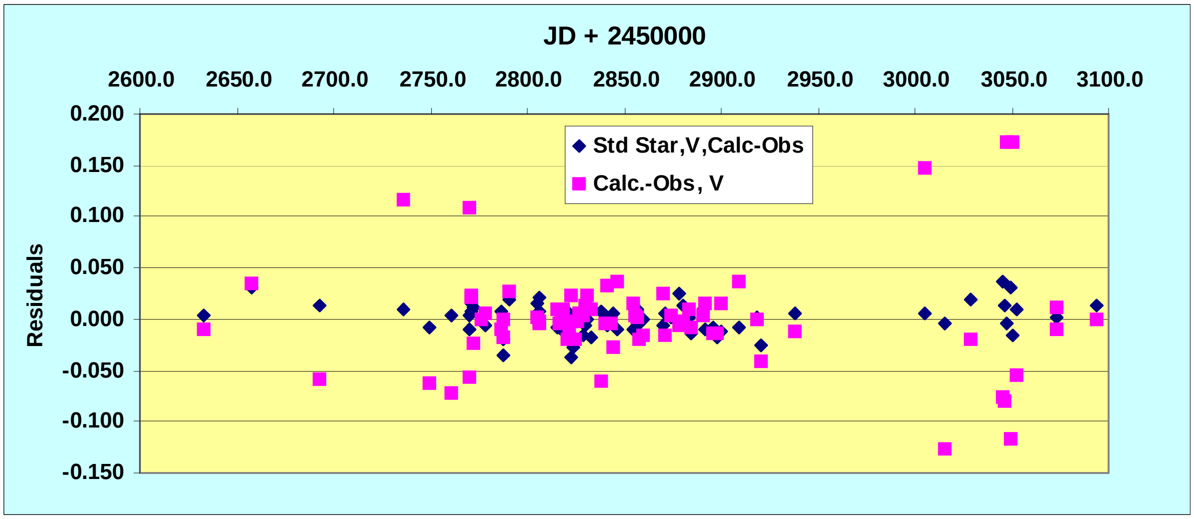

Figure 6. Analysis of the growing light curves are, in part, demonstrated here. Analysis of residuals for the growing light curves are plotted in real time. In this case we use a 6th order polynomial fit to sections of the growing light curve and plot the residuals for the variable (purple squares) along with residuals for a standard star in the field (blue diamonds)

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.

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 flare-ups are observed, to follow up with spectroscopic observations of moderate resolution. A group of 98 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 extend using software aimed at control of telescope-camera-filter wheel for image acquisition and image reduction. To date there have been no observed flare up episodes among these stars at the 0.15 magnitude or greater level. 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.