Monitoring of Mira Variable Stars

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Abstract We have begun intensive *V*- and *R*-band CCD monitoring of Mira variable stars since early in 2003. This project was initiated in the hopes of improving the statistics of putative flaring phenomena among these stars. This paper will give an update of the project and describe the strategies being employed.

1. Introduction

Among all the stars of the heavens, there exists a small sub-group called Long Period Variables (also known as *Miras*) which has served as a key to our understanding of stellar evolution through spectroscopic examination. These stars are defined by large visual amplitude changes (>2.5 magnitudes) and are giants at the tip of the asymptotic giant branch, the second and final ascent as a red giant. In this stage, nuclear burning in a shell around the core produces He and C and also other elements that are mixed to the surface, giving rise to a chemical sequence from M (oxygen-rich), to S, to C (carbon-rich). These variables pulsate with periods on the order of one year and their atmospheres are traversed by shock waves.

In the recent literature there are several reports which have examined putative reports of flares or events that alter the brightness of these objects on much smaller time scales (Schaefer 1991, Maffei and Tosti 1995, de Laverny *et al.* 1998). These events may be concentrated near minimum light (de Laverny *et al.* 1998), suggesting that they are not energetic enough to show up in contrast to the star at its brightest and/or that the event involves a travel time over a standard distance at a standard velocity. At least three general classes of explanation have been put forward for these events: (a) they are associated with propagation shocks; (b) they are associated with magnetic, possibly solar-type activity (Stencel 2000); (c) they are associated with the motions of planets through the stellar atmosphere or wind (Struck *et al.* 2002). 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, the statistics of such events can be better defined, and potential flare up episodes can be studied in this spectroscopic region.

2. Background, Results and Discussions

The primary instrument for spectroscopy is a Celestron 14-inch telescope with a Paramount ME system, located near Valley Center, CA. The Santa Barbara Instrument Group (SBIG) Self Guiding Spectrometer (SGS) is linked to the telescope with a focal reducer giving a final f/6 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/mm 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 (http://astrosurf.com/vdesnoux/). Absorption and emission line identifications were also carried out using Vspec.

Photometry was conducted with an Astrophysics 5.1-inch f/6 refractor using an ST-10XME camera and 2×2 binned pixels, and 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 same. Differences arise because of changes in their outer atmosphere chemistries, which can be seen in Figure 1. The prominent TiO molecular bands so prominent in M-types gradually weaken as one proceeds to S-types and essentially disappear in C-types. The Hα line 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-process 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 greater than 1. Finally, the molecular bands of titanium oxide (TiO) observed in the spectra of cooler M-type stars often disappear and are replaced by zirconium oxide (ZrO) and vanadium oxide (VO) bands (zirconium is a slow neutron capture element). (Lattanzio and Wood 2004.)

The lower temperatures of these stars give rise to many metal lines in the spectra, and a typical spectrum of these stars is shown in Figure 2. This shows a medium resolution spectrum of Mira (o 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 types of 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 Miras, it is not uncommon to see the essentially complete disappearance of the blue region of the spectrum due to the very heavy absorption of diatomic carbon (C2). 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 Miras, undergo flare-up episodes with brightenings of several tenths to over one 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 (1995) 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 Miras over a 37-month period indicated what appeared to be 51 flare-up events in 39 M-type Miras. No similar type flare-ups were observed with S- and C-type stars but the sample size was small for these 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 atmospheric depth.

(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 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 Hα or Ca II K, if these could be extensively monitored for microflares (Stencel and Ionson 1979, Stencel 2000).

(3) An interesting speculation involves extending the discovery of extra-solar planets to their role around evolved stars like Mira variables. Struck *et al.* (2002) have suggested that short-lived events could occur when a pulsation-induced shock passes the orbit of a planet or brown dwarf companion. These would then occur

every cycle at the same phase, but only a subset of events would be observable from a given direction. They also point out that the signal would not be seen in the IR but only in the visible, where a modest energy event would be able to be seen in contrast with the stellar flux: in the IR an event needs $L/L_{\odot}$~1000 while in the visible $L/L_{\odot}$~1 is sufficient if the event spectrum peaks in the visible. These are in principle testable constraints, if one or several systems can be identified to show events and these can be followed for repeat occurrences. 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 and monitor a group of program stars. Of the 39 M-type Miras 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 bright enough—especially in the Hα region (6562Å) and higher—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 Miras.

To accomplish this in a semi-automated manner, the telescope, camera, and filter wheel are controlled by a single computer with Orchestrate software (http:\\www.bisque.com). 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 (http:\\www.bisque.com). The images obtained in this manner are stamped both with the name of the variable star, 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 since early 2003 and involves a total of 98 stars. As of November 2004 ~75,000 individual photometric measurements have been obtained. While there are certainly many more of these type stars, only those that had a significant part of their light curve brighter than 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 the *I* and *R* regions of the spectrum. Many of the stars have now completed a complete cycle of variation during our observations, and some interesting features can be discerned in their light curves as will be discussed below. The photometric analysis involves using two 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 0.01 magnitude level. Thus any flare-ups in the range of 0.1 and above should be readily discerned.

The light curves of Miras have been classified into different types, mainly based on their shapes, not their lengths. In most cases for these stars the curve shapes are smooth and sinusoidal in shape while for a sub-type of Miras, 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 of the type of Mira. These bump Miras are of longer period and higher luminosity, but beyond that not much is known as to the physics producing these phenomenon.

A typical light curve of RT Boo, an M-type Mira, in both the *V* and *R* bands, is shown in the top part of Figure 5; R Cam, an S-type is shown in the bottom section. Note the non-recurring bump on the ascending part of the light curve as indicated by the arrow for RT Boo. Subsections of the light curve are best fitted with a polynomial fit; using these results, residuals are calculated in order to monitor potential flare events. Using this paradigm, changes on the order of 0.1 magnitude can easily be detected in the subsection curve fitting. To date however there has been no compelling evidence for flare-ups for any of the stars observed at the 0.1 magnitude level or more. This is consistent with the report by Wozniak *et al.* (2004) who analyzed 105,425 *I* band measurements of 485 Mira-type variables appearing in the OGLE-II survey, and deduced a maximum flare rate of no more than one flare per object per 26 years. Our result places additional constraints on any frequencies of putative flare-like events. We intend to continue the observations to cover at least several complete light curves, potentially adding other filters.

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. As an example, within two hours the images of 40 stars in duplicate in *V* and *R* bands were obtained, reduced, and the results tallied.

3. Summary

We have described the initiation of a program to follow Mira-type long period variables to attempt confirmation of reported flare-up episodes. If flare-ups are observed, we are prepared to follow up with spectroscopic observations of moderate resolution. A group of 98 stars constitute the program stars, 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. After nearly two years of monitoring, there have been no observed flare up episodes among these stars at the 0.1 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.

References

de Laverny, P., *et al.* 1998, *Astron. Astrophys.*, **330**, 169.

Lattanzio, J., and Wood, P. 2003, in *Asymptotic Giant Branch Stars*, ed. H. J. Habing and H. Olofsson, Springer-Verlag, New York, 23.

Maffei, P., and Tosti, G. 1995, *Astron. J.*, **109**, 6.

Melikian, N., 1999, *Astrophysics*, **42**, 408.

Schaefer, B. 1991, *Astrophys. J. Lett.*, **366**, L39.

Stencel, R., 2000, in *Asymmetrical Planetary Nebulae II: From Origins to Microstructures*, ASP Conference Series, 199, 99, J. H. Kastner, N. Soker, and S. Rappaport, eds.

Stencel, R., and Ionson, J. 1979, *Publ. Astron. Soc. Pacific*, **91**, 452.

Struck, C., Cohanim, B., and Willson, L. 2002, *Astrophys. J.*, **572**, L83.

Wozniak, P., McGowan, K., and Vestrand, W. 2004, *Astrophys. J.*, **610**, 1038.

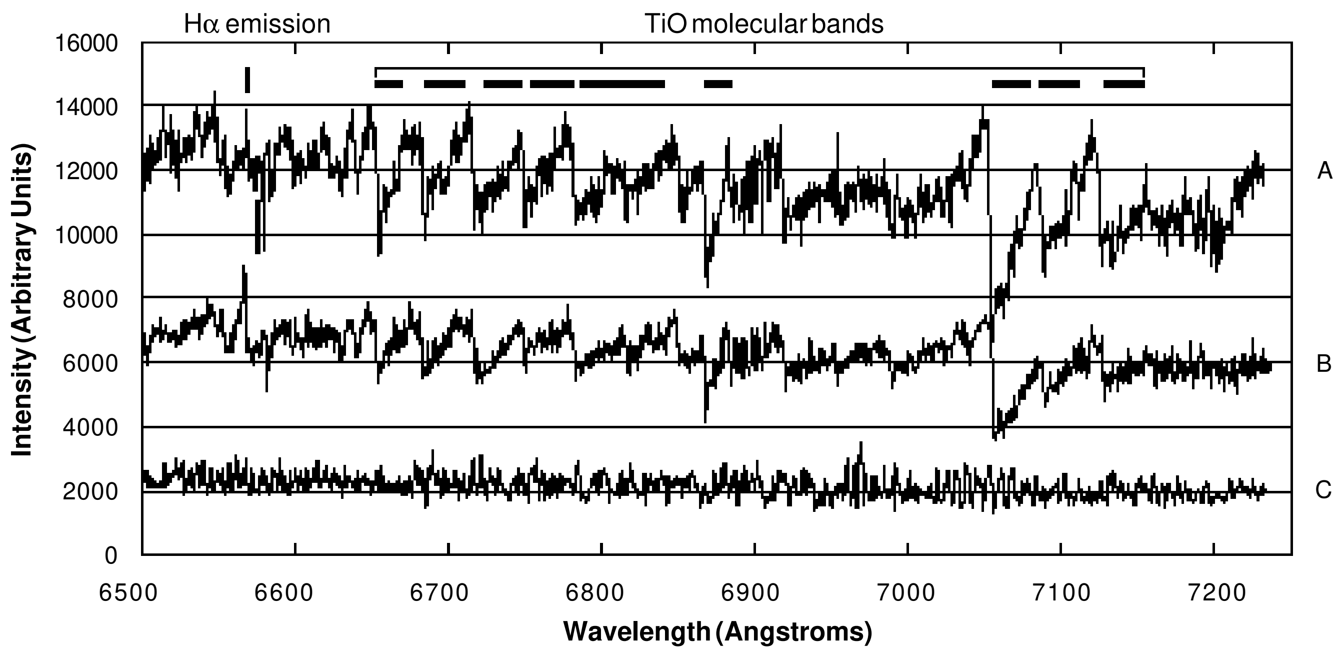


Figure 1. For a selected group of Mira-type stars we can obtain modest resolution spectra showing a number of interesting spectral features, particularly for the M stars, as indicated above. (A) indicates an M-type, (B) an S-type and (C) a C-type Mira.

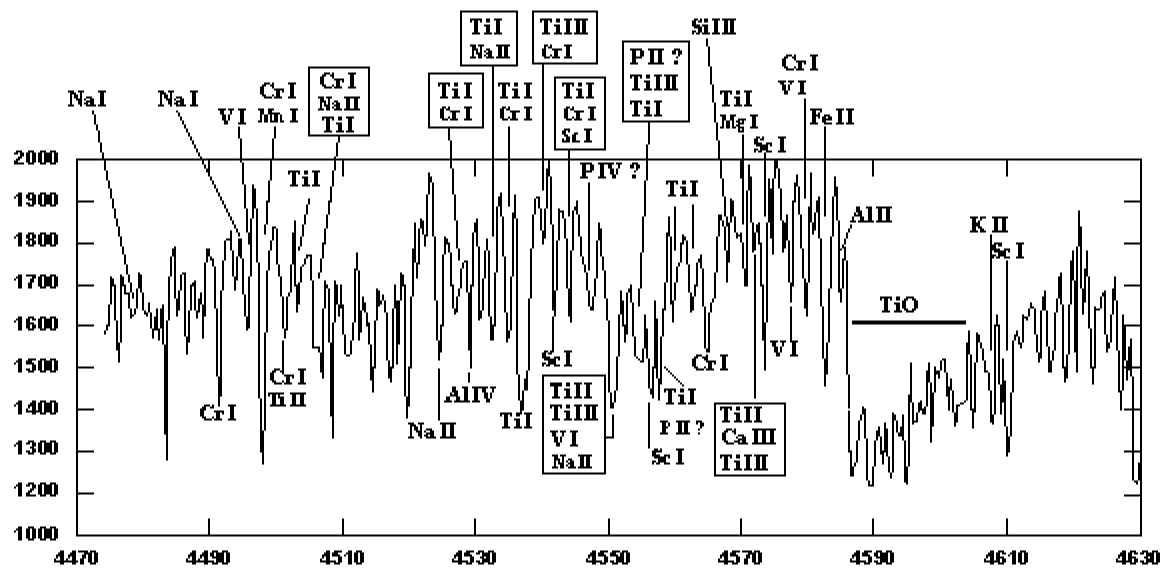


Figure 2. Spectrum of o Ceti (M-type Mira) obtained near maximum light in the blue region of the spectrum using a moderate resolution grating (1200 line, ~0.5 A/pixel). The large number of lines, many blended, is typical of these type cooler stars as is the molecular TiO bands (one such seen at ~4590 A). These bands give way to ZrO bands in S stars and finally molecular C2 bands in the C types as the evolution of these long period variables proceed.

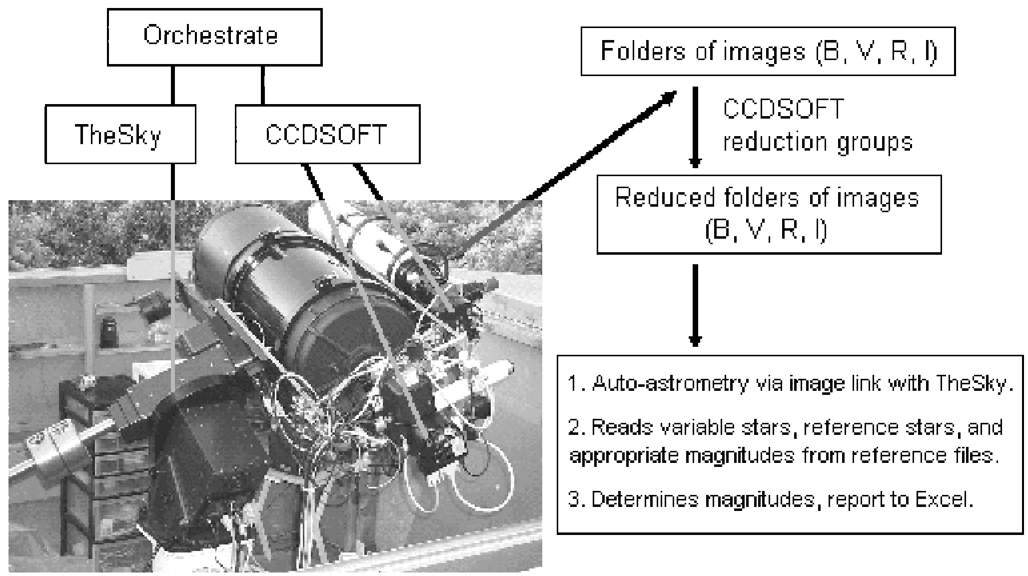


Figure 3. The flow of data acquisition and reduction for variable star monitoring. The imaging camera and filter wheel are controlled by CCDSOFT [www.bisque.com] while the Paramount ME is controlled by TheSky. All of this is under the umbrella of Orchestrate, which allows for non-intervention in acquiring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

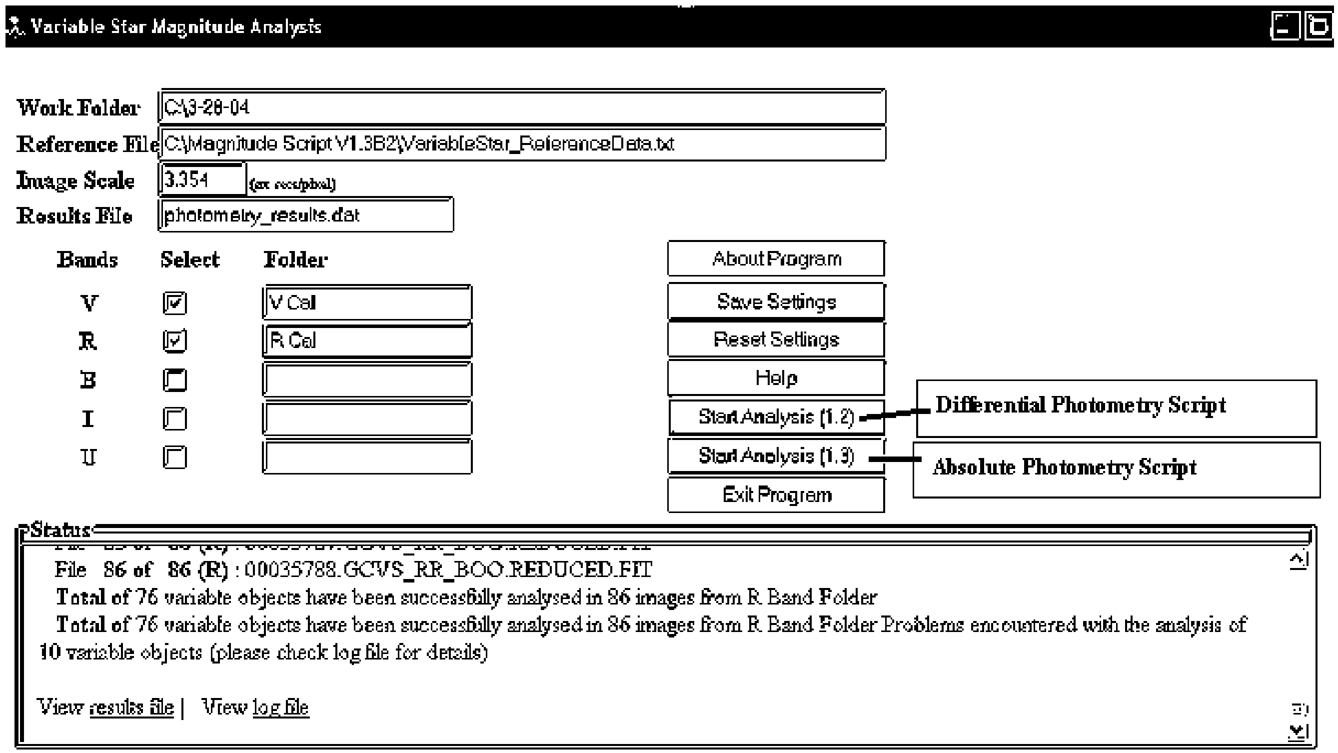
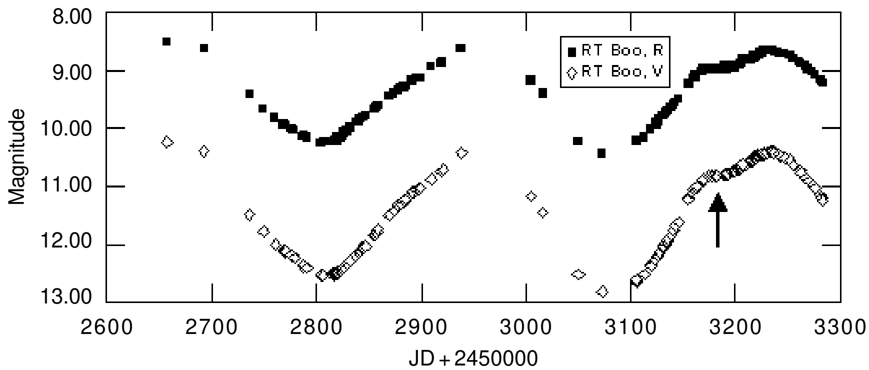


Figure 4. The window which appears when initiating the Variable Star Magnitude Analysis script. Several options are available such as which filters were used with the image sets to be analyzed. All that is required is that a reference file be created, just once, with the reference stars name and corresponding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



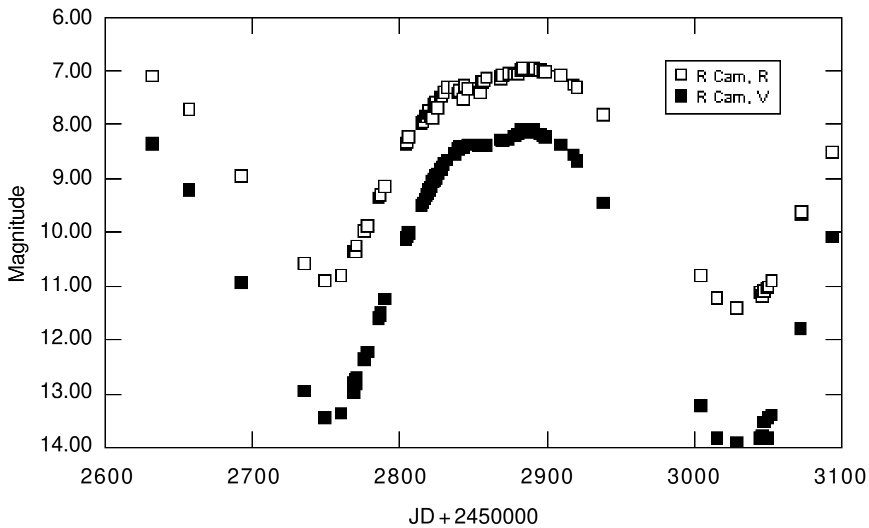


Figure 5. Typical light curves obtained over the project's first year-and-a-half. Top panel: RT Boo, an M-type Mira; bottom panel: R Cam, an S-type Mira.