# Crowd-Sourced Spectroscopy of Long Period Mira-Type Variables

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## Abstract

Crowd-sourced observing campaigns provide frequent temporal sampling over long durations at lower cost than can be achieved with exclusively professional efforts. They have been used very successfully to construct well-sampled light curves for variable stars and inform the timing of professional observing efforts. Until recently, spectroscopy has not been a tool commonly available for use in crowd-sourced campaigns. But advances in commercial equipment and educational efforts have removed many of the traditional barriers to low-resolution spectroscopy with small telescopes. One type of target that could benefit from a crowd-sourced photometry and spectroscopy campaign is Mira-type variables with long periods (over 500 days). We report the preliminary results from a pilot study testing the efficacy of crowd-sourcing spectroscopic observations of those stars using small telescopes and filter wheel gratings.

## 1. Introduction

Mira-type variables are pulsating stars found on the HR-diagram near the asymptotic giant branch (AGB). They have amplitudes larger than 2.5 magnitudes at visual wavelengths and periods ranging from hundreds to thousands of days (Garrison, 1972). The stars probably range in mass from less than one to several stellar masses, making them highly evolved giants with significant mass-loss rates close to the transition to a planetary nebula (Willson, 2000). These objects are relevant to understanding the late stages of evolution for a vast majority of stars. Their mass loss also contributes significantly to the chemical enrichment of CNO and formation of dust in the interstellar medium.

Several Mira-type variables have changed their period, amplitude and/or spectral characteristics (i.e. LX Cyg, TT Cen, BH Cru). These changes are probably driven by the evolution of the star itself. Caught in the act, a transitioning Mira is a rare opportunity to directly observe rapid underrepresented stages of stellar evolution at key points in low-mass star evolution. These instances provide critical insight and data to refine stellar models. But often the changes have been noted after the fact and detailed observation has not been conducted during the transition (Uttenthaler, 2016).

The high subscription rate for national and university observatories makes it difficult to devote a substantial amount of professional telescope time to monitoring Miras. That effort is more efficiently conducted through crowd-sourcing involving skilled non-professionals. For more than a century the American Association of Variable Star Observers (AAVSO) have successfully crowd-sourced brightness monitoring of many long period variables including Miras. Advances over the last two decades in camera technology and low cost spectroscopy equipment for 6- to 10-inch telescopes make it possible to add spectroscopic monitoring to the existing crowd-sourcing capability.

Over the last year we have conducted a pilot study with small telescopes using CCD imaging and filter-wheel gratings to monitor Mira-type variables with the aim of determining what non-professionals may be able to contribute to long-term spectroscopic monitoring. In particular we are interested in knowing what spectroscopic changes can be detected in a typical Mira over the course of its period as well as what the potential is for detecting the onset of key evolutionary changes in a Mira-type variable.

## 2. Expected Variations in Mira Spectra

The cool temperatures of the atmospheres of Mira variables (1500 – 3200 K) give rise to a spectrum similar to other late-type stars dominated by strong metal lines and molecular absorption bands (i.e. TiO). In all stars, the strength of the TiO bands typically increases at lower temperatures. As noted by Merrill (1962) the TiO bands in hotter Miras' are somewhat weaker than would be expected in normal stars of the same spectral type. The average range of temperature variation for a Mira variable is about 500K over the course of its period (Garrison, 1972) so as they pulsate the bands are strongest at maximum brightness and weakest at minimum brightness. *[REVISON: This is in error. As stated at the start of this paragraph, bands to be strongest when the photosphere is coolest. Therefore, <u>TiO is strongest at MINIMUM brightness</u>.]*

Changes in mass loss rate will also cause some spectral variation over the star's period (Willson, 2000). As a result, emission lines (particularly hydrogen) may be present at some times during the cycle (Garrison, 1972). "Line weakening" of metal lines such as Ca, Fe, and Cr (Merrill, et al. 1962) and variation of AlO absorption bands (Keenan, et al. 1969) may also occur as a result of emission driven by mass loss. *[REVISION: This confusing and in error. Keenan hypothesized that emission may fill in these bands and cause them to weaken.]*

Mira-type variable stars can be sorted by their spectra into three types: M-type, C-type, and S-type. Each type is characterized by enhancements of specific elements, which imply different evolutionary states. As nuclear burning progresses in the star's core different elements may be mixed with the surface material through "dredge-ups." Those "dredge-ups" occur when the structure of the star is temporarily disrupted by a transition from one form of nuclear burning to another. A star that has transitioned from carbon fusion to oxygen fusion may exhibit a larger proportion of carbon and carbon-like molecules in its atmosphere. M-types are characterized by oxygen enhancement relative to carbon. C-types are more abundant in carbon than oxygen. S-types have about equal amounts of both carbon and oxygen and stronger ZrO, YO, and ScO molecular absorption (Merrill, et al. 1962).

## 3. Filter Wheel Gratings

Filter wheel gratings are diffraction gratings cut to a shape and size to fit into a standard slot in a filter wheel for a CCD imaging camera. They produce a slit-less first order spectrum of every star in the field. The spectral resolution depends on the line spacing ruled in the grating as well as the distance between the grating and the imaging plane. For most small telescope setups, the resulting spectral resolution is on the order of R ~ 50 – 100. To accurately map the wavelengths to the spectrum both the zero-order image and the first-order spectrum must simultaneously fit on the CCD chip. This provides a practical upper limit around R ~ 200 for most systems.

The throughput for these gratings is very good. Generally speaking, a usable spectrum can be obtained for any star that could be imaged with a S/N of 50 or better through a standard broad-band filter with the same telescope and CCD. Cost is likely not a barrier for most non-professionals who are already invested in CCD imaging. The cost of these gratings is typically a few hundred dollars, a small investment relative to the cost of a CCD camera and filters. They are also easy to operate because the images are taken the same as through any standard filter and only need a dark/bias calibration. Wavelength calibration takes some additional effort but only has to be done once if the distance between the filter wheel and imaging plane remains unchanged.

## 4. Observations

Stars for the study were selected from the AAVSO Long Period Variable (LPV) program. They were selected considering a convenient sky position for the observers, periods on the order of a few hundred days, and a minimum brightness that could be observed by small telescopes. See Table 1.

Two telescopes participated in this pilot study:

- In Pleasant Plains, Illinois the University of Illinois Springfield (UIS) Barber Observatory 20-inch reflecting telescope with Apogee U42 CCD camera using a back-illuminated E2V CCD42-40 chip. The plate scale for the imaging plane is 0.62 arcseconds/pixel. This setup used a Paton Hawksley Star Analyzer 200 grating yielding a first order spectrum with a dispersion of 1.328 nm/pixel in the imaging plane.

- Bill Rea operated an 80-mm Explore Scientific apochromatic refractor in Christchurch, New Zealand with an Atik 414E Mono CCD camera using a SONY ICX424AL front-illuminated chip. The plate scale in the imaging plane is 2.7 arcseconds/pixel. He used a Paton Hawksley Star Analyzer 100 grating yielding a first order spectrum with a dispersion of 1.488 nm/pixel.

**Table 1: Stars Observed in This Study**

| Star | Spectral Class | Mira Type | Brightness Range (Vmag) | Period (days) | Phases Observed |
|---|---|---|---|---|---|
| Observed by UIS Barber Observatory in Pleasant Plains, IL | | | | | |
| V Cam | M7 | M | 7.7 – 16.0 | 522 | 0.10 - 0.28 and 0.80 - 0.84 |
| RW Lyr | M7e | M | 9.8 – 16.7 | 503 | 0.20 – 0.52 |
| V Del | M6e | M | 8.1 – 17.0 | 527 | 0.93 – 0.13 |
| RZ Peg | SC-9/9-e | S | 7.6 – 13.6 | 436 | 0.43 – 0.69 |
| RU Tau | M3.5e | M | 10.0 – 17.4 | 611 | 0.54 – 0.71 and 0.14 – 0.17 |
| Observed by Bill Rea in Christchurch, NZ | | | | | |
| R Cen | M4-8e | M | 5.3 – 11.8 | 502 | 0.24 – 0.77 |
| TT Cen | CSe | S | 9.0 – 15.2 | 462 | 0.99 – 0.05 |
| BH Cru | SC4.5/8-e | C | 6.6 – 9.8 | 530 | 0.83 – 0.94 |

For slit-less spectroscopy the image FWHM has a direct impact on the effective resolution of the spectrum. Assuming typical 3 arcsecond seeing, the effective spectral resolution unit for the UIS 20-inch was 6.4 nm. Rea's 80-mm was 1.7 nm, almost four times better than the UIS setup.

The spectra in our study were extracted from bias-corrected and dark-subtracted images using the "projection" tool in SAOimage DS9. To correct for scattered light, a "sky background" strip extracted immediately next to the spectrum was subtracted from the target spectrum. Wavelength calibration was performed by applying a dispersion per pixel computed from observations of sharp emission lines in unresolved planetary nebula.

For more information, including a tutorial on wavelength calibration, see the web site: http://go.uis.edu/gratingspectra/.

The counts recorded in each spectrum varied depending on the telescope, exposure time, and brightness of the target. To aid comparison between spectra, their fluxes are normalized between 915 — 920 nm. These wavelengths are mostly continuum and relatively uninfluenced by telluric absorption or absorption normally present in Mira spectra. The normalization did not correct for the different spectral responses of the CCD chips.

## 5. Potential Issues with Crowd-Sourcing Spectral Monitoring of Mira's

There are several issues that may present obstacles to successfully crowd-sourcing spectral monitoring on Mira-type variables with filter-wheel gratings. Those include: field crowding, spectral response of different CCDs, different spectra resolutions with different setups, focus of the images, and the practical faint limit for small telescopes. Foresight and planning may be able to overcome several of these.

### 5.1 Overlap in Crowded Fields

Field crowding presents a challenge to all forms of slit-less spectroscopy. Without a slit the spectrum of the target can overlap the zero-order images or first-order spectra of other stars in the field. This presents a particular challenge to targets like Mira variables that are predominantly found in the galactic plane. When the target is much brighter than the other stars in the field this becomes less of an issue. The exposure time can be shortened for a brighter star so that the other stars in the field, which are much fainter, barely register in the image. However, a Mira variable near minimum can be faint, requiring deeper exposures that have greater potential for field crowding problems. Rotating the grating in the filter holder can change the orientation of the spectrum for the target but in very crowded fields this is not a practical solution. We encountered this issue with several potential targets, which were removed from the pilot study.

One solution could be to mask the grating in the filter wheel. A mask before the grating darkens the part of the field that the target's spectrum falls in, eliminating any issue with overlap. Fast optical systems with the grating further from the imaging plane need to carefully account for the converging beam and the position of the grating when introducing a mask. For those systems, masking too much area around the target will cause a significant drop in the throughput for the first order spectrum. We suggest a mask that covers half the field, allowing the target to be positioned in the unmasked half of the field and the first order spectrum to fall in the masked portion.

## 5.2 Different Telescope/CCD/Grating Setups

One of the challenges of any crowd-sourcing effort is the difference in the equipment used by individuals who are contributing to the project. Rules and expectations can enforce uniformity, however too many regulations will discourage more people from joining the effort. Any successful crowd-sourcing endeavor needs to balance these competing factors.

It is unrealistic and burdensome to require all participants in a crowd-sourced spectroscopy project to have exactly the same telescope/camera/grating setup. We sought to gather information and suggest techniques and tools that can be used to overcome differences in the spectra contributed by different systems. The largest contributing factors to consider are differences in CCD response, differences in spectral resolution, and good focus of the images.

The two systems in our pilot study had some significant differences in those areas (see Section 4). We did not observe a common target with both telescopes, so we compare the images taken with either system of two M-type Mira variables with similar surface temperatures at about the same phase in their cycles.

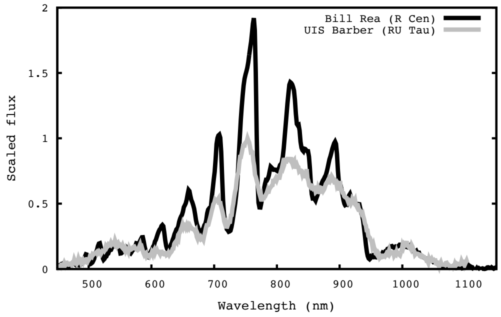

**Figure 1. A comparison of spectra that should appear similar taken with the two systems used in this study.**

The differences in the appearance of the spectra in Figure 1 are due almost entirely to the differences in setup. We note that there is not a large difference between front-illuminated (UIS Barber) and back-illuminated CCDs (Bill Rea). Mira variables are very red. So even though the two CCDs have different blue response, their relative red response is similar (dictated by the atomic properties of silicon in the detector), so it is not a factor for comparing Mira variable spectra. We have also normalized the spectrum to continuum at 920 nm (see Section 4) where the relative response from both CCDs is similar.

There is a clear difference in Figure 1 due to spectral resolution. The Rea system has a higher effective spectra resolution (see Section 4) so the peaks and dips are sharper. Normal practice for comparing spectra of different resolutions is to blur the sharper spectrum to the lower resolution. Because that blurring degrades the better spectrum, we suggest that users of any archive generated by crowd-sourcing be made aware of the effects of differing resolution and provided with tools to degrade the higher resolution contributions as needed to make comparisons with lower resolution spectra.

It should be noted that neither setup has a high enough resolution to detect sharp emission features. Any analysis of Mira spectrum at this spectral resolution is restricted to focusing on the strength of absorption bands and not individual transitions.

It is important to encourage crowd-sourcing participants to get the best focus for their spectra and work under the best seeing conditions. Any problems with the focus will degrade the spectral resolution of their observations. Seeing and focus of the stellar images also contribute to the effective resolution. So contributors should be encouraged to avoid bad seeing conditions and frequently check their focus.

We also suggest that crowd-sourcing be restricted to only reflecting telescopes and apochromatic refractors. Rea’s own experience attempting to observe spectra with a two-element refractor showed that systems which have chromatic aberration will not be able to focus all parts of the spectrum to the same sharpness. This leads to a constant change in effective resolution across the spectrum and presents very significant challenges to comparing spectra from different telescopes.

## 5.3 Faint Limits

A successful crowd-sourced program should consider the ability of participants to observe the faintest targets. The light-curves of variables in the AAVSO database usually have many more observations of a variable at its brightest than when it is faintest. This can create problematic biases in analysis of the database if they are not recognized.

Our experience shows it is possible to get a spectrum with a filter-wheel grating for almost any star which can be imaged with a signal to noise acceptable for AAVSO CCD photometry. Field confusion and spectrum overlapping will be a greater concern in deeper exposures. But our suggestions for masking the grating in Section 5.1 potentially alleviate that issue.

## 6. What Was Detected

The resolution of spectra obtained with filter-wheel gratings is low. The spectra do not resolve or detect narrow emission or absorption features. The strong molecular absorption bands in Mira variables are detected as blends. The motivation for this pilot project was to determine if changes could be detected between different Mira types and also in a single Mira variable as it progresses through its cycle.

### 6.1 Differences in Type

Figure 2 shows that the differences between M, C, and S type Mira variables are easily detected at this resolution. The M type is dominated by TiO molecular bands. The C type shows almost no TiO but strong CN bands instead. The S type appears transitional between the M and C types including both TiO and CN bands.

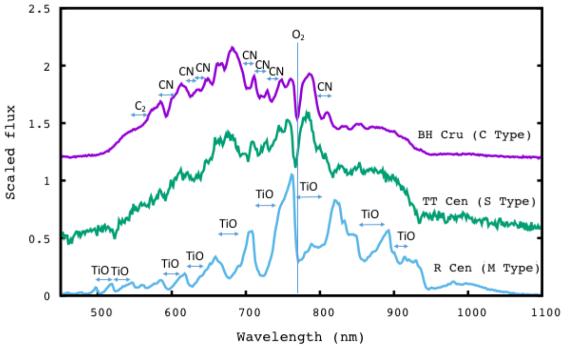

**Figure 2. Comparison of the spectra of three types of Mira variable.**

Crowd-sourced Mira variable observations can monitor a large number of targets with regularity. Several Mira variables have changed type, but none has been caught in the act of changing. LX Cyg is an excellent illustrative example. Uttenthaler et al. (2016) report that sometime between 1975 and 2008 LX Cyg changed from type S to type C. Observations of the light curve in broad band filters did not immediately indicate the change and because of the sparse sampling of spectral observations its transition was not well recorded and only recognized after the fact. Crowd-sourced monitoring of the spectra has a greater chance of catching these transitions as they happen and providing a record of the changes and/or alerting professional astronomers to bring to bear additional resources.

### 6.2 Differences in Surface Temperature

Figure 3 shows the spectra of two M type Mira variables both at a similar phase in their cycle but with different spectral classifications (due to different surface temperature). Not only is there relatively more flux at bluer wavelength for the hotter star, but there are also, as expected, clear differences in the relative strengths of the different TiO molecular bands. It is difficult to flux calibrate spectra of this type so the difference in molecular bands is probably a more reliable indicator when considering data from several different telescopes.

### 6.3 Spectral Changes Through the Cycle

R Cen was observed continuously at regular intervals over more than half its cycle (2015 July 11 = phase 0.25 to 2016 April 5 = phase 0.77). The AAVSO light curve (Figure 4) shows that during that time it went through a local maximum at about 2015 Dec 01 = phase 0.53 as well as its minimum at about 2016 March 25 = phase 0.76.

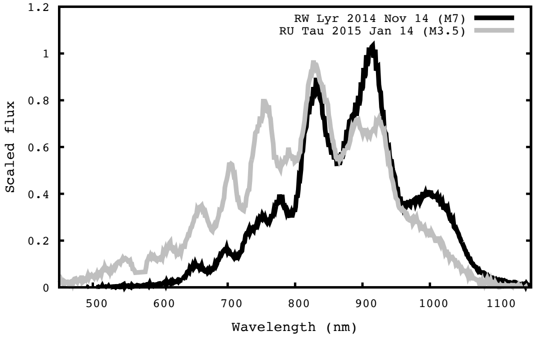

**Figure 3. A comparison of the spectra of two M type Mira variables at a similar phase in their cycle but with different spectral classes (surface temperatures).**

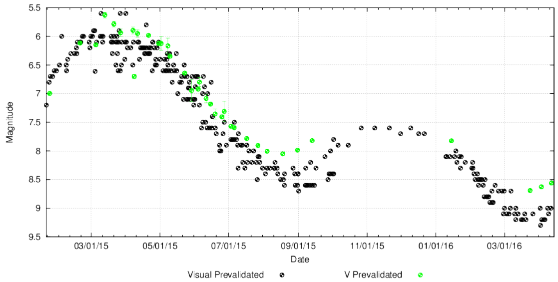

**Figure 4. Light curve for R Cen from the AAVSO (https://www.aavso.org/data/lcg)**

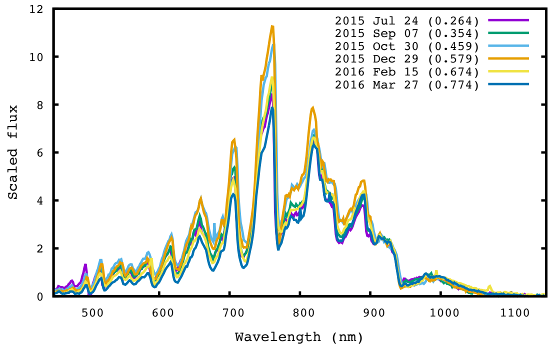

**Figure 5. Regularly sampled spectra of R Cen over the interval of phase 0.25 to phase 0.77 with flux normalized at 920 nm.**

Figure 5 shows the normalized spectra of R Cen sampled at regular intervals during that time. The differences in relative flux are not dramatic but under careful examination they appear to correlate with the ups and downs of the R Cen light curve. An animation of these spectra is at: http://go.uis.edu/BarberObservatory/miras/.

We also have spectra of RZ Peg (S type Mira) and V Cam (M type Mira) near their maximum brightness and minimum brightness (Figure 6 & 7). Both show clear differences in their spectra but the differences in the spectrum of V Cam are more dramatic.

Because spectra at this resolution are sensitive to changes within a typical cycle it will be important to establish what is "normal" to differentiate them from evolutionary changes. The spectra around the cycle can also place limits on the mass loss and surface temperature fluctuations that are typical for each star.

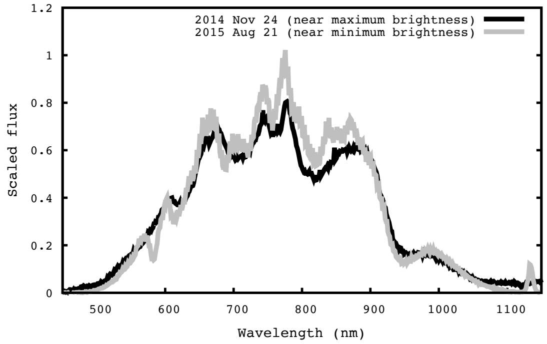

**Figure 6. Spectra of RZ Peg at maximum and minimum brightness**

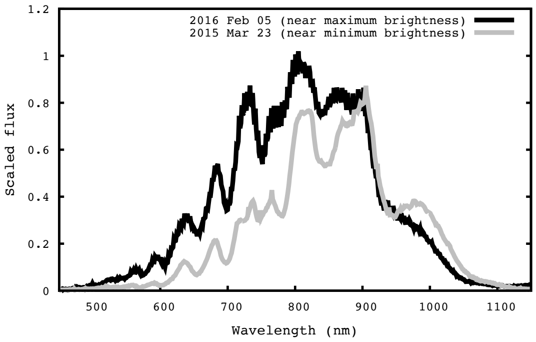

**Figure 7. Spectra of V Cam at maximum and minimum brightness.**

## 7. Conclusions

As a result of our pilot study, we suggest the following guidelines for any crowd-sourced Mira variable spectroscopy project:

- Filter wheel grating spectra are sensitive to changes in:
    - Spectral class / Surface Temperature
    - Differences in Mira type
    - Different phases in a Mira variable's cycle.
- Emission due to mass loss is difficult to detect at this spectral resolution.
- Pick targets that are not too faint for the telescopes used by your target audience.
- For Mira variables there is no significant concern about the difference in sensitivity between front-illuminated and back illuminated CCDs.
- Restrict crowd-sourcing efforts to reflectors and apochromatic refractors.
- Keep in mind the factors that influence effective spectral resolution. Encourage observing under good seeing and good focus.
- Archives of crowd-sourced spectra should provide tools to facilitate comparison of spectra with different resolutions.
- The continuum at 920 nm is a good point to normalize the flux of most Mira variables for comparison.
- We recommend masking half of the grating in order to get better results in crowded fields.

## 8. References

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