Low Resolution Spectroscopy of Miras—X Octantis

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Abstract We present a photometric and spectroscopic study of X Oct and five selected comparison stars. We show that the changes in spectral classification of X Oct over the course of its pulsation cycle can be determined by comparison between its spectra and that of the five comparison stars. In particular, we conclude that the ratio between the counts at the continuum point at 754nm and the TiO absorption line at 719nm is the single most reliable feature for determining spectral type. We suggest that X Oct may cycle between M3 and M7 as it pulsates, rather than the published range of M3 to M6. We also undertook a frequency analysis of CQ Oct and report two significant pulsation periods of 52.9 and 37.4 days, respectively.

1. Introduction

Mira variables have long been a favorite observing target for amateur astronomers because their long periods and large amplitudes meant that they only needed to be observed about once a week and small uncertainties in the estimation of the visual magnitudes did not detract significantly from the quality of the light curves.

Over recent decades CCD photometry with multiple filters has become commonplace among amateur astronomers, with a selection of UBV filters from the Johnson system and RI from the Cousins system being the most common. The collection of multiple color estimates allows the observer to estimate the effective temperature of a variable star, particularly using the B–V index. However, it has long been known that for spectral types K5 through M8, which encompasses most Miras, the B–V index is nearly constant (Smak and Wing 1979) despite the temperature dropping by nearly a factor of two over this range. The presence of large numbers of TiO absorption bands depresses almost the entire spectrum between 4300 Å in the blue and 7500 Å in the infra-red. Kirkpatrick *et al.* (1991) state that in the region 6300 to 9000 Å there are, at best, only six points which could possibly be labelled as continuum points, and they are listed in Table 1.

The problem of trying to determine a spectral class for these stars from purely photometric data has led to the development of some narrow band systems such as the three- and eight-filter systems described in Wing (1992) and White and Wing (1978). Bessel *et al.* (1989) provide an example of the White and Wing (1978) system applied to M giants. Recently, Azizi and Mirtorabi (2015) proposed a modification to some of the filters in the eight-filter system of White and Wing (1978) to overcome known problems with the spectra of the coolest stars.

Table 1. The six possible continuum ponts in spectral class K5 to M9 identifed by Kirkpatrick *et al.* (1991).

Continuum Point	*Wavelength (Å)*
C1	6530
C2	7040
C3	7560
C4	8130
C5	8840
C6	9040

The problems associated with methods of obtaining spectral classification from photometry were discussed in some detail in Wing (2011).

As Wing (1997) notes: "If we think of Miras as variable stars with time-dependent spectra, it is clearly desirable to record both their spectroscopic and photometric behavior." While many Miras pulsate in a stable manner, a number have evolved significantly on time scales considerably less than a human lifespan. Changes can include the shapes of light curves, pulsation period, and pulsation amplitude. Templeton *et al.* (2005) studied the pulsation periods of 547 Miras and reported 57, or slightly more than 10%, of these had changes in period which were significant at the 2σ level, 21 at the 3σ level, and eight at the 6σ level. At least some of these changes are thought to be the result of a helium flash (see Hawkins *et al.* (2001) for example), with potential for the star to change its spectral type (see Uttenthaler et al. (2016) for an example). It is these types of Miras which would benefit most from long-term spectroscopic monitoring, although monitoring of stable Miras is also worthwhile.

With the readily available, low cost, filter-wheel grating spectroscopes it is now possible to routinely observe Mira spectra as part of an CCD photometric observing program. Although the resolution of these types of spectrographs is very low, with typical R (λ/Δλ) values in the range 50–200, the recent introduction of the AAVSO spectroscopic database means these observations can now be combined with similar observations by other observers, increasing their scientific value.

The main problem with determining the range of spectral classifications for a Mira over the course of its cycle is that spectroscopy is usually done differentially. That is, the spectrum of a star to be classified is compared with the spectra of known standards and a best fit is obtained. Sometimes the best fit involves statistical testing of the goodness-of-fit (see Kirkpatrick *et al.* (1991) for an example). Gray and Corbally (2009) provide considerable detail on spectra of a wide range of spectral types.

For Miras we would usually require red giant stars of spectral class M for spectral comparison but all such stars are variable to a greater or lesser extent. Hence there are no true standards to work with. Nevertheless, with a filter wheel grating spectroscope an amateur can obtain both photometric and spectroscopic data for target Miras and a range of suitable comparison stars so that the photometric and spectroscopic variability in the comparisons can be quantified.

The present paper presents some results from an on-going pilot study on the feasibility and potential contributions to the study of Miras through the addition of low-resolution spectroscopy to a photometric observing program. Some previous results can be found in Martin *et al.* (2016a) and Martin *et al.* (2016b).

The research question addressed here is: can the spectral type of an M-type Mira be reliably determined for M2-M6 over the course of its pulsation cycle.

The remainder of this paper is structured as follows: section 2 describes the target stars, observing equipment and methods, section 3 presents the results, section 4 contains the discussion, and section 5 explains our conclusions and gives some indication of future directions.

2. Target stars, observing equipment and methods

2.1. Target stars

Table 2 presents a list of stars observed in the current phase of this project. All stars chosen are close to the south celestial pole to enable year-round observation so that no part of the cycle will be lost through being below the horizon and hence unobservable.

2.2. Observing equipment

Three telescopes have participated in this study. They are:

1. I operated an 80-mm f/6 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 2.77 arcseconds / pixel. I used a Paton Hawksley Star Analyzer 100 grating yielding a first order spectrum with a dispersion of 1.488 nm / pixel.

2. BSM_South of the AAVSOnet's Bright Star Monitors. It is an AstroTech-72ED, a 72-mm, f/6 apochromatic refractor with an SBIG ST8-XME CCD camera located at Ellinbank Observatory in Victoria, Australia. The filter wheel contains Astrodon filters of which the B and V filters were used in this study. (Note that recently BSM_South has recently had an upgrade and these details no longer accurately reflect the camera and filters available.)

3. BSM_Berry is located in Perth, Australia. It also is an AstroTech-72ED with an SBIG ST8-XME CCD camera. Of the filters available we used the B and V for photometry and the grating spectrograph.

The published spectral range of the Mira, X Oct, was M3 to M6. This guided the selection of the five comparison stars listed in Table 2 to cover the same range of spectral types using stars with low variability.

In both the three- and eight-filter systems of Wing (1992) and White and Wing (1978), as well as the modified system of Azizi and Mirtorabi (2015), the deep TiO absorption line at 719 nm was used to establish an estimate of the stellar temperature and spectral classification of M-type Miras. While these systems involved narrow band filters, with spectroscopy, even the low resolution spectroscopy presented here, there is no question where the lowest point of the absorption line and the peak of the nearby continuum point are (754 nm in the Wing system and 704 nm in the Azizi system). Accordingly, in the remainder of this paper we will refer to the ratio of counts at 754 nm / 719 nm as the Wing ratio and 704 nm / 719 nm as the Azizi ratio.

The spectra obtained with the gratings were measured with SAOImage DS9 and analyzed with custom write R code (R Foundation 2015).

3. Results

A total of 69 spectra of X Oct were collected between 20 October 2015 and 25 September 2018 and cover approximately four pulsation cycles.

Spectra for the five comparison stars were collected between 9 April 2017 and 25 September 2018. Spectra for the comparison stars only began after the early part of this study indicated that something like comparison stars, long used in photometry, were also required for spectroscopy.

The final two columns in Table 2 presents the mean Wing and Azizi ratios (described in section 2) for each of the comparisons together with the standard deviations in brackets.

Figure 1 presents the V-band light curves for the five comparison stars listed in Table 2. The data were obtained largely from the AAVSOnet telescopes described in section 2; some were from other observers who contributed to the AAVSO International Database. The light curve for each comparison was created by subtracting the mean observed magnitude from each observation and then stacking the resulting curves at one-magnitude intervals. Vertical error bars have been added to the points in Figure 1 but in most cases the uncertainty in magnitude

Table 2. The details of the published variability in spectral type and magnitude of the primary target and a selection of five comparison stars.

Star	*Spectral Class*	*Variable Type*	*Brightness Range (V mag)*	*Period (days)*	*Wing Ratio*	*Azizi Ratio*
X Oct	M3/M6IIIe	Mira	6.8-10.9	200		
CV Oct	M3	LB	8.92-9.19	—	2.63 (0.37)	2.27 (0.25)
BQ Oct	M4III	LB	6.8	—	2.21 (0.15)	2.05 (0.15)
CQ Oct	M4/M5III	SRB	8.12-8.59	50.8	3.82 (0.30)	2.76 (0.19)
eps Oct	M5III	SRB	4.58-5.3	55	4.08 (0.29)	2.81 (0.19)
BW Oct	M5-M7III	LB	7.9-9.1	—	5.85 (0.41)	3.26 (0.20)

Note: The comparison stars are ordered in decreasing expected temperature. Magnitude ranges are for the V band. The data in first five columns of this table were obtained from the AAVSO Variable Star Index (VSX). The final two columns are the mean and standard deviation, in brackets, of the Wing and Azizi ratios and are results from this study. They are discussed in more detail in sections 3 and 4 below.

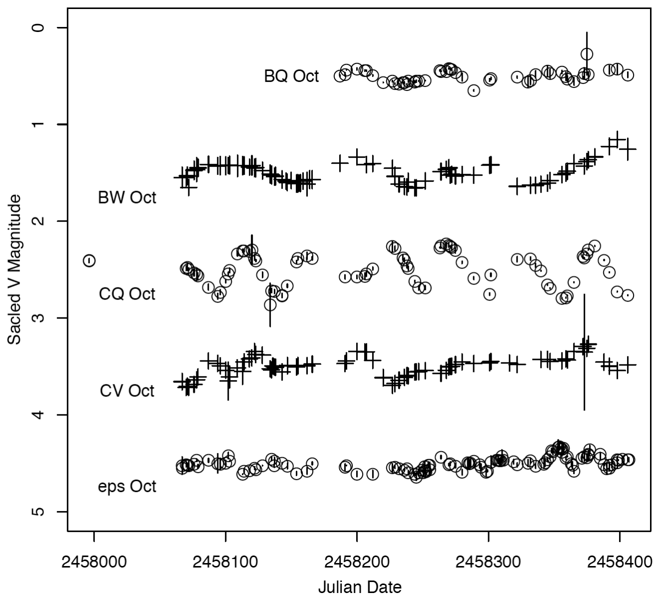

Figure 1. The V-band light curves for the five comparison stars over the course of the study period. Each light curve has had the mean magnitude subtracted from the observed magnitude and the resulting light curves have been stacked at one magnitude intervals. Details of their published magnitude ranges, variable type, and spectral classification can be found in Table 2.

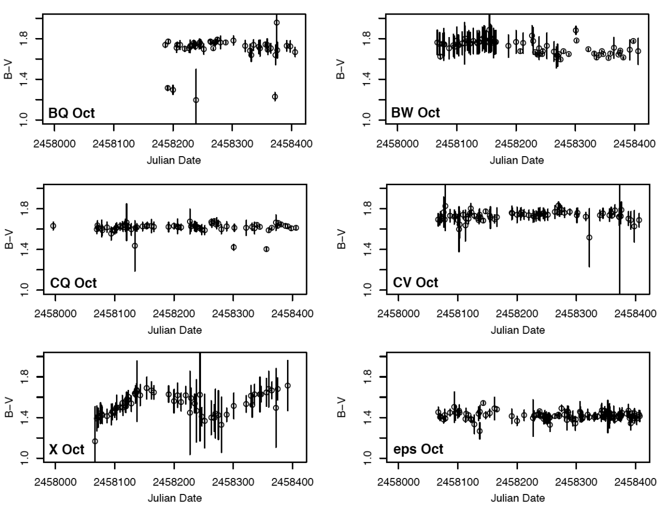

Figure 2. The B–V index for all six stars. All parts of the figure have common scales on their horizontal and vertical axes and so are directly comparable. The uncertainties in the B–V index are plotted as vertical lines on each data point. Details of the stars' spectral classification and variable type are in Table 2.

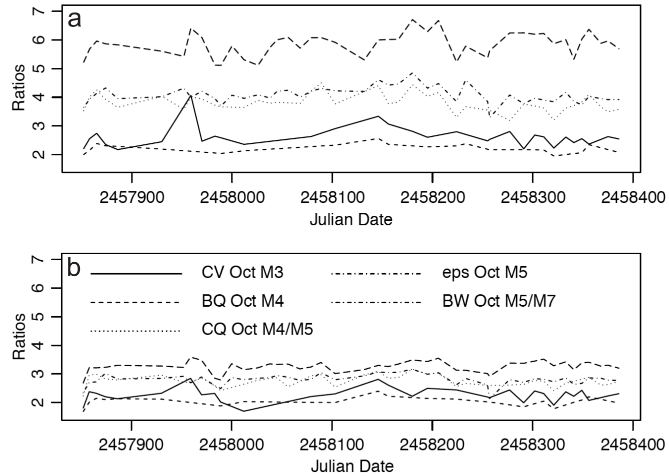

Figure 3. Panel (a) presents the Wing ratios for the five comparison stars over the course of the study period while panel (b) presents the Azizi ratios for the same stars and period. The use of a common scale for the vertical axes allows direct comparison between the two ratios for the same set of stars. The legend in panel (b) is common to both panels. Details of their spectral classification and variable type are in Table 2.

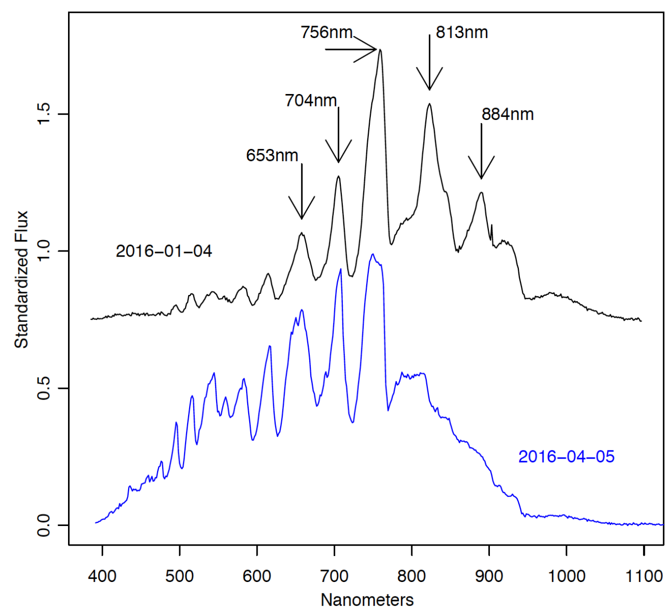

Figure 4. The spectra of X Oct at close to maximum (2016-04-05) and minimum (2016-01-04) light. Each spectrum has been scaled so that it has a range of one and the spectrum from the minimum light has been offset by 0.75 unit so that the two spectra do not overlap. Five of the six possible continuum points discussed in Kirkpatrick *et al.* (1991) and listed in Table 1 are marked on the upper spectrum.

estimates were sufficiently small that they were less than the size of the plotting symbol used and hence appear to be dots inside the circles for BQ Oct, CQ Oct, and ε Oct while for BW Oct and CV Oct the use of the plus symbols usually does not allow the error bars to be seen.

Figure 2 presents the B–V index for X Oct and each of the five comparison stars. As indicated in the caption to the figure, they all have a common scale on both horizontal and vertical axes and error bars have been included on each observation.

Panel (a) of Figure 3 presents the Wing ratios (754/719 nm) for the five comparison stars while panel (b) presents the Azizi ratios (702/719 nm) for the same stars during the study period. The two parts of the figure have common horizontal (date) and vertical axes. The common axes allows a direct comparison between the two ratios for the same set of stars.

Figure 4 presents two representative spectra from near minimum and maximum light for X Oct during the study period. Significant changes in the spectrum can be seen. There is much less output in the 400 to 600 nm region in the 2016-01-04 spectrum, when X Oct is cooler, than in the 2016-04-05 spectrum near maximum light. The relative strengths of the continuum points C1 through C5 have changed. While the C3 point (754nm) is the maximum in both spectra, in the 2016-04-05 spectrum the C1 and C2 points are stronger and the C4 and C5 points weaker than they are in the 2016-01-04 spectrum.

Figure 5 presents the light curve of X Oct over the study period together with both the Wing and Azizi ratios from the spectra. The common vertical axis is in magnitudes when examining the light curve and in ratios of counts at 754/719 nm and 704/719 nm, respectively, for the Wing and Azizi ratios.

Figure 6 presents the Wing ratios and the V band light curve of CQ Oct where the light curve has been shifted up by 5.5 magnitudes to fit on the common vertical axis. Details of CQ Oct can be found in Table 2.

A frequency analysis of the CQ Oct light curves was undertaken with FAMIAS (Zima 2008) because its main pulsation period appeared to be modulated. We found two significant pulsation periods; the stronger of the two was 52.9 days and closely matches the 50.8-day period reported in VSX. A second, lower amplitude pulsation period of 37.4 days was also found. Two relatively closely spaced pulsation periods would account for the observed beating seen in the light curve. There was a third peak in the Fourier periodogram at 67.1 days, but with only 76 observations spread over 409 days it was not possible to either rule in or rule out this periodicity in the pulsations.

4. Discussion

Figure 4 presents two spectra of X Oct, one taken near maximum light and labelled 2016-04-05, and the other near minimum light and labelled 2016-01-04. The differences in the two spectra are visually obvious. To the extent that the continuum can be determined, it is clear that when X Oct is at its coolest, at or near minimum light, the peak energy output has shifted deeper into the infrared and there is significantly less output in the 400 to 750 nm region than when it is warmer. The cooling between maximum and minimum has resulted in a considerable strengthening of the TiO absorption line at 719 nm. In addition, the strength of the C4 and C5 continuum points have increased significantly as well. In the 2016-04-05 spectrum the C4 continuum point is nothing more than a flattened "bump" in the spectrum, whereas the C5 point gives no discernable peak. By contrast, both points are clearly evident as peaks in the 2016-01-04 spectrum.

When we examine Figure 5 we see that the Wing and Azizi ratios move in a common direction to the light curve. As X Oct dims, it cools, and the TiO absorption line at 719 nm strengthens, giving rise to an increasing ratio between the counts at the continuum point (C2 or C3 as appropriate) and the minimum of the absorption line. Although both the Wing and Azizi ratios show the same pattern the Wing ratio provides a much better picture of the temperature changes in the photosphere for this star.

Comparing the range of the Wing ratio for X Oct (2.02 to 7.09) with the Wing ratios of the five comparison stars in Figure 3 which range from 1.95 for BQ Oct to 6.71 for BW Oct, we see that the comparisons cover the range well. The mean Wing and Azizi ratios for the five comparisons presented in the final two columns of Table 2 are well separated and, apart

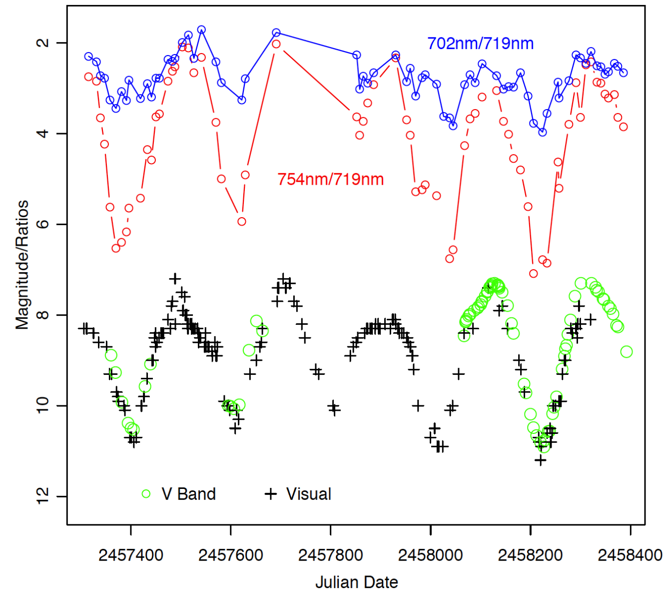

Figure 5. The upper part of the figure presents the Wing and Azizi ratios calculated from the spectra obtained during the study period. On a common set of axes the light curve of X Oct from visual and V band CCD observations over the study period is presented in the lower part of the figure. These data were obtained from the AAVSOnet BSM telescopes described in section 2 and also contain observations by other observers contributed to the AAVSO International Database.

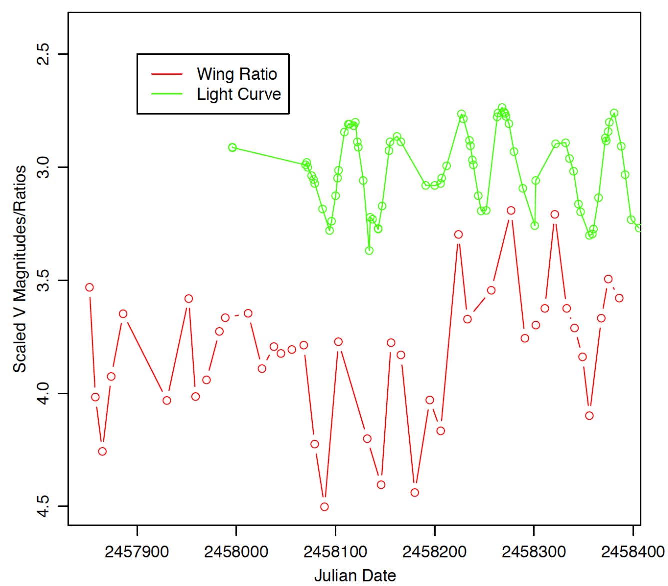

Figure 6. The lower part of the figure presents the Wing ratios calculated from the spectra obtained during the study period. On a common set of axes the light curve of CQ Oct from V band CCD observations from the BSM telescopes is presented in the upper part of the figure where the magnitudes have been scaled up by 5.5 magnitudes to fit on the common vertical axis.

from the obvious discrepancy between BQ Oct and CV Oct, are ordered according to the published spectral types. The minimum value of the Wing ratio for CQ Oct (3.19), which should reflect an M4 spectral type, does not overlap the maximum value for BQ Oct (2.56). However, the range of BQ Oct has a significant overlap with CV Oct. It is reasonable to conclude that both CV Oct and BQ Oct are M3 but with BQ Oct being, on average, the warmer of the two stars.

At maximum light X Oct has a spectral type close to that of BQ Oct. Although the published type is M4 the evidence in Figure 2 suggests that BQ Oct has an earlier spectral type than CV Oct, which has a published estimate of M3. As indicated in the previous paragraph, it would be reasonable to conclude that both CV Oct and BQ Oct have an M3 spectral type and hence so does X Oct at maximum light. This agrees well with the published data for X Oct.

At minimum light the Wing ratio for X Oct of 7.09 is larger than the maximum attained by BW Oct at 6.71, suggesting that at minimum light X Oct is cooler than BW Oct. The published range for BW Oct is M5 to M7. A visual inspection of the spectra of both X Oct and BW Oct at their largest Wing ratios shows that VO molecules are starting to form in the atmosphere and hence beginning to affect the reliability of the 754 nm continuum point (C3). Were either star to cool much more than they do, an alternative method of spectral classification would be needed; see future directions in section 5 below.

Small differences in spectral type can be detected. In Figure 5 the minimum light near Julian date 2457800 is brighter than the other four minima for which we have spectra. The Wing ratio line of the same figure shows that it was the highest of the four minima for which we have data.

For five of the six stars, the B–V index in Figure 2 exhibits low variability, the exception being X Oct, which exhibits a clear color change over the course of its pulsation cycle. It is clearly redder when dimmer and bluer when brighter. The clear pulsation cycle of CQ Oct evident in the light curve in Figure 1 and in the Wing ratio in Figure 6 is not discernable in its B–V index values. When CQ Oct was selected as a comparison star, VSX classified it as an SRB, a semi-regular, late-type giant with poorly defined periodicity. Figures 1 and 6 show that it has quite a regular pulsation and that this is matched by the changes in strength of the TiO absorption line as measured by the Wing ratio. Although this study was aimed at Miras because of their long periods, large pulsation amplitudes, and corresponding large changes in their spectra, an unexpected result is that it appears that the Wing ratio is sufficiently sensitive to changes in the stellar temperatures that lower amplitude variables, such as the semi-regular CQ Oct, can be usefully studied with small, BSM-type, telescopes equipped with filter wheel grating spectrographs.

5. Conclusions and future directions

5.1. Conclusions

For spectral types M2-M6 where there is no contamination of the C3 continuum point by the VO molecule, the Wing ratio of counts at 754/719 nm provides a superior guide to the spectral class than the Azizi ratio of 702/719 nm. Even if there are some uncertainties with the wavelength calibration of the spectrograph, or non-linearities in the first-order spectra, or other factors which affect the conversion of pixels to nanometers, these were sufficiently small that the spectral peaks at the continuum points and the troughs of the absorption lines can easily be determined. If masking is not used (see Martin *et al.* (2016a) and Martin *et al.* (2016b) for details) there is an ever-present problem of potential contamination of the first-order spectra by dim field stars or other luminous sources. Consequently, the spectra should always be visually inspected before measurements are made.

We conclude that over the course of the pulsation cycles we observed that X Oct changes between M3 and somewhere between M6 and M7.

The evidence in Figure 3 suggests that BQ Oct is actually warmer than CV Oct, though the difference is small, and so the assignment of spectral classifications of M4 and M3, respectively, in VSX seems unlikely to be correct; both appear to be M3.

The method of determining spectral type which we present here requires calibration because of differences in the quantum efficiency of among CCD detectors at different wavelengths. However, the use of comparison stars in CCD photometry is routine and should also be used in spectroscopy.

The evidence from the CQ Oct observations indicates that lower amplitude pulsating variables, such as semi-regulars, can be usefully studied with low resolution spectrographs. For CQ Oct, owing to its shorter period, a higher cadence of spectral observation than was used in this study would be beneficial.

5.2. Future directions

We are currently working on more closely identifying the spectral classification of M-type Miras for those which are cooler than M6. For these stars the presence of the VO molecule renders the C3 (754 nm) continuum point unreliable and hence the Wing ratio should not be used to estimate spectral type. This work will primarily feature observations of R Oct and will be presented at a later date.

6. Acknowledgements

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