# NARROW-BAND PHOTOMETRY OF MIRA VARIABLES

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## Abstract

The spectra of Mira variables are extremely complex, with atomic lines in absorption and emission and strong molecular bands, all varying with phase. Magnitudes measured by eye or with wide-band photometry represent averages over so much information that they are hard to interpret. Here narrow-band photometry can help, since filters can be chosen both to avoid absorption bands and to measure some of the strongest ones. Some surprising results that have been obtained for Miras by this method are discussed. A simple three-color system measuring two near-infrared continuum points and a TiO (titanium oxide) band can be used to obtain a magnitude, a color index, and a spectral type for normal M-type Miras. The light curves obtained with such a system can be interpreted in terms of variations in luminosity, temperature, and diameter.

## 1. Introduction

What is a Mira variable? As any of us attending this special session can surely appreciate, there are a great many answers to this question. Some of us, like Fabricius 400 years ago, think of Miras as wonderful red stars in certain constellations that are sometimes visible, sometimes not. As AAVSO members, we may think of them as points at the centers of charts on which neighboring dots have names like "96" and "132." Or we may think in terms of the results of many years of visual observing—the mean light curves, no two of which are quite the same. But active observers may be more conscious of a Mira's light curve from recent cycles, as plotted by Headquarters with all individual observations shown, since they know that some of the points are their own. Observers of Miras are acutely aware that their work is never finished, since the changes in brightness are never exactly predictable.

There are, of course, many other completely different ways to think of Miras. We might imagine a huge physical object, large enough to engulf the orbit of Mars, its surface pulsating and changing color. Or we might think of a dense swarm of carbon nuclei, stripped of all electrons at a temperature of a hundred million degrees, surrounded by a shell where helium nuclei are combining to form more carbon and a flood of energy, deep below the pulsating atmosphere. To others, a Mira is a point on an H-R diagram, or more specifically a star that has reached the low-effective-temperature extreme of the asymptotic giant branch.

Now I must tell you that my own orientation is not any of the above. To me, a Mira is an incredible *spectrum*, full of both absorption and emission lines, some appearing individually as atomic lines and some grouped into molecular bands which can be strong enough to dominate the appearance of the spectrum completely. It is these spectra, of course, that reveal the chemical and physical properties of a star's atmosphere and lead to deductions about its interior and evolutionary state.

There are many ways to visualize the spectra of Mira variables, but I always think first of the marvelously illustrated paper by Merrill, Deutsch, and Keenan (1962). Here we see a wealth of spectral detail, primarily in the blue region where a "window" in the blanketing by molecular bands permits the study of weaker features. Their photographic spectra were mostly taken with the Mount Wilson 100-inch telescope in the days when the world's largest telescopes were used for stellar spectroscopy. My introduction to Miras, as a graduate student, occurred quite abruptly when one of my professors placed a large collection of such spectra at my disposal and challenged me to identify and explain some of the weak emission lines that come and go at different points of the light cycle. The result (Wing 1964) was the identification of a number of fluorescence mechanisms that operate only because of the extreme conditions (very low density, and the presence of strong emission lines produced by shock phenomena) in the atmospheres of these stars.

Classical spectroscopists like Paul Merrill and his colleagues were concerned with the resolution of spectral detail, usually in very narrow segments of the spectrum. By adjusting the exposure in each segment for optimum visibility of spectral lines, information about the photometric characteristics of the star—its magnitude and color—was lost. There are, however, representations of stellar spectra that retain the photometric information (i.e., calibrated spectra), although these usually have low resolution. The energy distribution of a typical Mira variable, extending from the near ultraviolet to the far infrared, shows a peak in the near infrared and a series of great waves caused by strong absorption bands of water vapor which are interspersed throughout the infrared.

If we think of Miras as variable stars with time-dependent spectra, it is clearly desirable to record both their spectroscopic and their photometric behavior. Since spectroscopic and photometric observations are usually carried out by different observers with different equipment, the coordination of such programs has been difficult, especially for variables of long period. Narrow-band photometry, however, is a single technique that can provide both kinds of information. Here I will discuss the application of this technique to Mira variables and some of the surprising results that have been obtained. Finally, I will mention how observers with modest equipment can participate in collecting this important kind of information.

## 2. Narrow-band photometry

The light from a Mira variable carries an incredible amount of information, mostly in the form of spectral lines. When magnitudes are measured by eye or photoelectrically with wide-bandpass filters, most of this information is lost; only a weighted sum of all the intensities in the given spectral interval is preserved. On the other hand, magnitudes measured through narrow-band filters (by which we usually mean less than about 100Å in width) can be sensitive to the presence of individual (strong) spectral features. Narrow filters can also be chosen to avoid spectral features, to provide a measurement of the stellar continuum.

Narrow-band "systems" (usually filter sets) are most useful if they include two or more filters located at clean continuum points, as well as one or more filters chosen to measure specific spectral features. The continuum points serve two important functions: they determine the slope of the stellar continuum, which can be calibrated in terms of the star's photospheric temperature, and they provide a reference level with respect to which the strengths of spectral features can be measured. Without some indication of the position of the continuum (i.e., the star's energy distribution in the absence of spectral features), the measurement of a star's brightness in a filter containing a spectral feature would be uninterpretable.

Cool stars such as Mira variables contain numerous spectral features that are strong enough to measure by narrow-band photometry; most of these are molecular in origin. In normal M-type stars, the visible and near-infrared spectra are dominated by bands of TiO, the strengths of which are customarily used in assigning the spectral type, and bands of water vapor appear prominently in the infrared spectra of the coolest stars. In measuring the strengths of these bands, the main difficulty is in locating the continuum. Calibrated spectral scans of Mira and non-Mira stars of types M0 to M9, when compared to blackbody energy distributions, show that TiO produces significant absorption throughout the visible spectrum, from 4500 to 7500Å without a break, in all stars later than about type M3 (Smak and Wing 1979).

In the near infrared, however, the situation is more favorable. Although TiO is still prominent, it is not as overpowering as in the visible region, and there are windows between the TiO bands that allow the measurement of continuum points and bands of other molecules such as CN (cyanogen) and VO (vanadium oxide). In Figure 1, spectral scans of 6 representative M-type stars are shown. These data were obtained with a single-channel spectrum scanner at Lick Observatory many years ago, and they have been reduced to a scale of absolute fluxes through comparisons with standard stars of known energy distribution. The 26 data points, obtained through a fixed bandpass of 30Å, are not uniformly distributed in wavelength because measurements were made only at wavelengths that were thought to be useful in some kind of star. Here we have examples of narrow-band photometry on a 26-color system, presented in a way that clearly shows its spectroscopic information. Some of the more easily-recognizable bands of TiO, CN, and VO are labeled.

One of the stars shown in Figure 1 is a Mira variable: the lower spectrum in the right panel is that of Mira itself, at minimum light. Its strong bands of TiO and VO indicate a spectral type of M9.0. Some Miras display even stronger bands at minimum, and the spectrum of R Cas at minimum has been used as the definition of type M10 (Wing and Lockwood 1973).

## 3. Some surprising results

I was fortunate to be able to use the spectrum scanner on Lick Observatory's Crossley telescope on 75 nights spread over a little more than two years. Many of the stars observed were Miras. What can be learned from such data? I was hoping, first of all, that they would help with the interpretation of light curves. When the magnitude of a Mira variable changes, are we witnessing primarily a change in the continuum, caused by changes in the size and temperature of the star's surface layers? Or are we seeing the effects of changes in the strengths of molecular absorption bands or atomic emission lines? I was surprised to find that the light curves of Miras at infrared continuum points have a character quite similar to that of the visual light curves, although maximum light occurs later in the infrared continuum. In particular, the continuum light curves often show humps on the rising branch, and successive maxima are often of unequal brightness. These features thus pertain to changes in the star's radius and temperature and are not simply the superficial effects of changing spectral features (Lockwood and Wing 1971).

Another surprise came from plotting bandstrength-color diagrams. Since the strengths of all TiO and VO bands vary with temperature, as does the continuum color, most cool stars (namely unreddened non-Mira stars of normal composition) show a well-defined relation between bandstrength and color. It was expected that Mira variables would move back and forth along this relation, as their temperature varies with phase in the light cycle. But in fact, Miras often show large, open *loops* in such diagrams. That is, a given star does not always show the same bandstrength at phases of equal temperature. A given star does not even follow the same loop in consecutive cycles! Both clockwise and counter-clockwise loops were observed (Spinrad and Wing 1969).

To understand how such loops can come about, we must remember that the

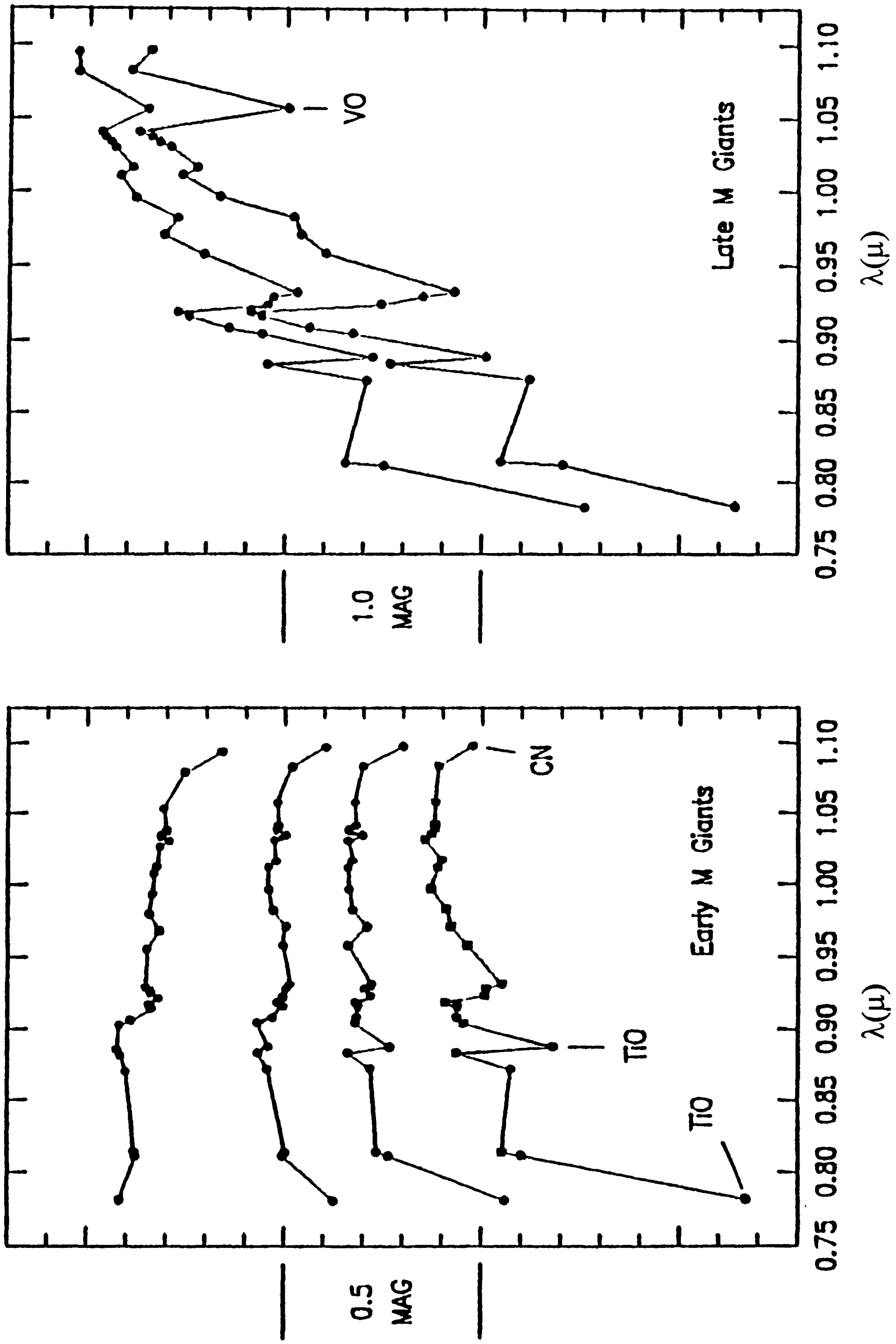


Figure 1. Narrow-band 26-color photometry of 6 M-type stars obtained with a spectrum scanner and 30Å bandpass. Left panel, top to bottom: giant stars of types M0.5, M2.5, M4, and M5. Right panel, top to bottom: the semiregular variable RX Boo (M8.0), and the Mira variable o Cet (M9.0). Absolute fluxes, expressed on a magnitude scale with an arbitrary vertical displacement for each star, are plotted against wavelength in microns.

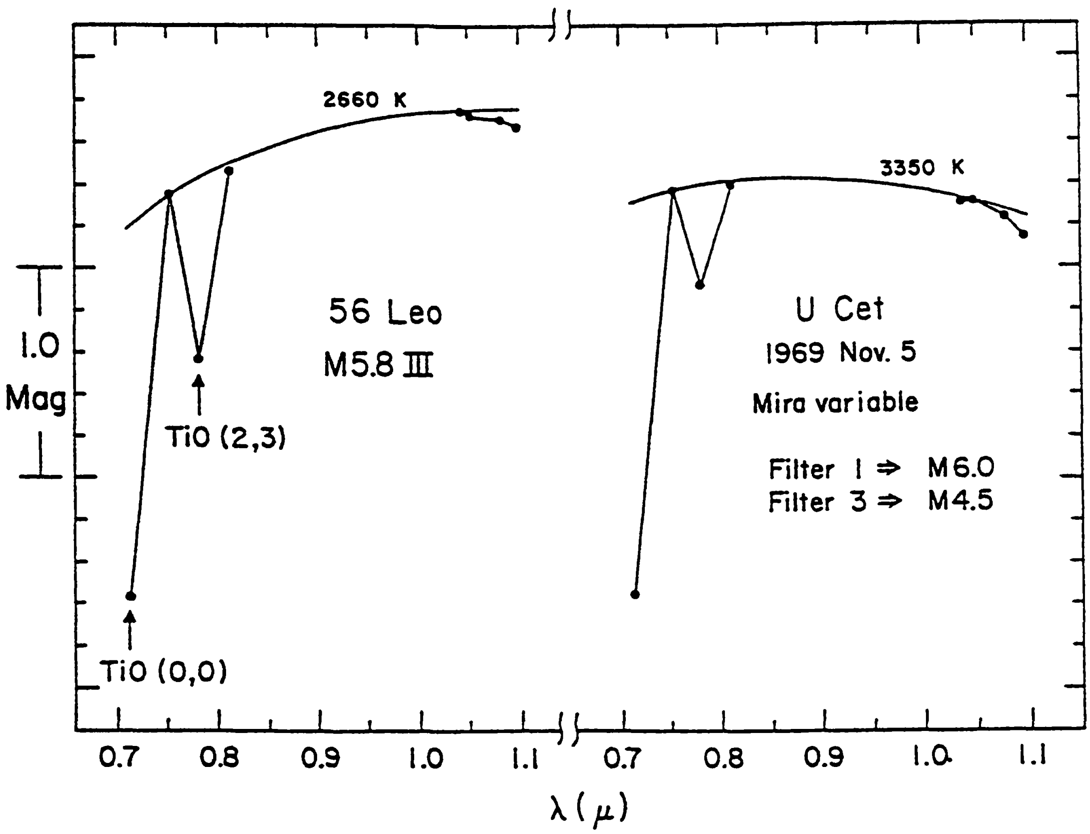


Figure 2. Calibrated eight-color narrow-band photometry of the small-range variable 56 Leo (left) and the Mira variable U Cet (right). The eight measurements of each star are connected by straight lines, while the smooth curve is a blackbody curve fitted to the measurements and taken to represent the stellar continuum. In the case of the Mira, the two TiO bands and the continuum color all suggest different spectral types.

atmospheres of Mira variables are highly stratified. That is, there are atmospheric regions of very different temperature that contribute to the observed spectrum. Since the formation of TiO and VO molecules is favored by the coolest temperatures, these molecules exist primarily in the coolest, outermost layers, and the observed band strengths reflect the physical conditions there. The continuum points, on the other hand, contain radiation coming from much deeper, and hotter, layers. Evidently these layers, in Mira variables, are so far apart that their behavior is not well coordinated (Wing 1980).

The Miras surprised me again when I compared the strengths of two different bands of the same molecule. If one measures the strengths of two bands, A and B, both due to the TiO molecule, one would expect that either band could be used as a basis for spectral classification (that is, that one could obtain the same spectral subtype from either band, assuming that its bandstrength had been calibrated in terms of spectral type through observations of standard stars). This would be the case if there existed a well-defined relation between the bandstrength of A and the bandstrength of B. This expectation is met by non-Miras, but not by Miras! At least, not when the two bands arise from different states of excitation.

This last phenomenon is illustrated in Figure 2, where data for a small-amplitude variable (56 Leonis) and a Mira variable (U Ceti) are compared. These observations were made on my eight-color system, which is defined by interference filters of about

50Å width (MacConnell *et al.* 1992). Since this system includes measurements of continuum points and bands of TiO, VO, and CN, it provides most of the same information as the scanner observations described earlier. Two different bands of the γ-system of TiO are measured: filter 1 at the left measures the (0,0) band, which arises from the ground state, and filter 3 measures the (2,3) band, which arises from a vibrationally excited state. In the comparison, the two stars have almost the same bandstrength at filter 1 and would be assigned nearly the same spectral type on that basis, but their bandstrengths at filter 3 are very different. Since the slope of the continuum should be a good indicator of the temperature, we have fitted blackbody curves to the best continuum points in each case, and the temperatures of these blackbodies are shown above the curves in Figure 2. By this criterion, U Cet was much warmer than 56 Leo on this date. This figure illustrates a fundamental problem in assigning spectral classifications to Mira variables. The spectrum of U Cet would be classified M6.0 on the basis of filter 1, and M4.5 on the basis of filter 3, while its continuum color corresponds to a star of type M3! Here again we are evidently seeing the effects of stratification. The cool layers where the TiO bands are formed do not yet know how hot it is down in the deeper layers where the continuum is formed. The discrepancy between the two TiO bands may be the result of a cool circumstellar shell which contributes absorption in the (0,0) band, but not in the excited band.

## 4. Suggested observations

At a meeting of the AAVSO a few years ago, I described a three-color system of narrow-band photometry suitable for the study of M-type variables (Wing 1992). This system is a simplification of the eight-color system employed in Figure 2, the three filters being somewhat wider versions of filters 1, 2, and 5 of the eight-color system. These filters can be purchased from Optec, Inc. for use in their SSP-3 photometer, which is light enough to be mounted comfortably on a small telescope.

Now that I've had a chance to discuss with you some of the results of narrow-band photometry of Miras, I would like to appeal again for observations of Miras on the three-color system. It would be particularly valuable to follow a number of the brighter variables throughout their cycle, for several cycles. Professional astronomers are usually in a poor position to carry out a monitoring program like that, but the results could be important. What can be learned from such data? The three-color system measures two continuum points and a TiO band, all in the near infrared; it therefore provides a magnitude in the infrared continuum, a continuum color index, and the spectral type. We can expect that the continuum color will soon be calibrated in terms of effective temperature, since work on calculating synthetic spectra from model atmospheres of Miras is progressing rapidly at several institutions. Similarly, we should soon have the calibrations needed to derive bolometric magnitudes from the monochromatic infrared magnitude, continuum color, and TiO strength, all of which are provided by the photometry. Observations on the three-color system thus will immediately provide a magnitude, color, and spectral type, and will ultimately provide the bolometric magnitude and effective temperature. Furthermore, from the changes in bolometric magnitude and effective temperature, the changes in the star's diameter can be directly calculated. These quantities have proved very difficult to derive by spectroscopic analysis or other more complicated methods, but they are within the reach of photometric observers with suitable filters.

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