THREE-COLOR NARROW-BAND PHOTOELECTRIC PHOTOMETRY OF RED VARIABLES

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Abstract

A photometric system consisting of three near-infrared interference filters and designed for studies of red variable stars is described. It represents a simplification of the writer's eight-color system of classification photometry and is intended for use with small telescopes and inexpensive instrumentation. The three filters measure an infrared magnitude, a color index, and an index of the TiO band strength, which indicates the spectral type. Measurements on this system should provide a valuable supplement to the visual light curves of red variable stars. A set of standard stars is given which will enable observers to reduce their measurements to a system of absolute fluxes. A procedure is described for deriving an index of TiO strength from the data and calibrating it in terms of spectral type.

1. Introduction

It is certainly not necessary for me to tell members of the AAVSO that long period variables are fascinating objects for a long-term observing program, or that there is great value in making sustained, uninterrupted observations in the same manner as in the past. To the many observers who are persevering with visual observations of Miras, I would like to offer encouragement -- and extend my thanks. At the same time, I feel sympathy for those observers who ask, from time to time, whether there might be other ways of observing Miras which have greater sensitivity or accuracy, or which are more amenable to interpretation. Here I would like to describe a photometric system defined by three relatively narrow near-infrared filters designed specifically for the study of red variable stars. While observations on this system will never eliminate the need for continued visual monitoring, they have the potential for supplementing the visual data in a way that provides scientifically useful additional information.

When considering how to make a light curve more interpretable, we might do well to reflect that a visual magnitude is the sum of many things. First of all it is an integration over a broad spectral region, which in the case of Miras contains numerous emission and absorption lines and molecular bands as well as continuum radiation. It is also an integration over the surface of the star -- a surface that is likely to be spotted or mottled, with different points emitting different spectra. As if that were not enough, a magnitude also represents an integration over all depths in the atmosphere that contribute to the emitted flux; in the case of a Mira variable, the atmosphere is greatly extended and there are layers of very different temperature, opacity, and motion that contribute to the light. As we watch the visual magnitude of a Mira variable go through its more-or-less periodic variations, we might wonder just what it is that is changing: Are we witnessing a change in temperature? Or in the star's diameter? Or in its rate of energy production? Or might changes in emission lines, or opacity sources, be involved? Or changes in the atmospheric structure, or in the degree of spottedness? Or perhaps all of these? How can we tell? If two stars have slightly different light curves (one might, say, show a hump on the rising branch, and the other not), what is it that is different about the two stars? Or if the same star behaves differently in two different cycles, what is it about the star that has changed?

As observers, we cannot control the surface markings or atmospheric structure of the stars we study, but we *can* control the portion of the spectrum that contributes to our measurements of magnitude. This is most easily done with the use of filters. Photoelectric photometrists always use filters because their detectors are sensitive to a broad range of wavelength. In the study of large-amplitude variables, the most important advantage of photoelectric photometry over visual measurements -- yes, more important than its increased accuracy -- is that it frees us to select our bandpasses, to choose what to measure. We can, for example, choose to measure magnitudes in spectral regions that are invisible to the eye, or we can compare spectral regions that are strongly depressed by molecular absorption to regions that are relatively clear. The narrower the bandpasses that we use, the more we can control the types of information that we collect. By exercising this freedom of choice we can begin to answer the questions posed above, to untangle the many factors that contribute to the brightness of a star.

There is, however, such a thing as too much freedom. If every observer made his or her own choice of filters, it would be difficult if not impossible to combine the observations of different people in any meaningful way. What is needed is a well-defined photometric *system,* one that can readily be duplicated and that is simple enough to encourage its widespread use.

2. The Three-Color System

The characteristics of the three-color system discussed here were developed at a meeting of three people -- Russell M. Genet, Gerald Persha, and the writer -- in my office at the Ohio State University during the Spring of 1984. Genet, as one of the organizers of the International Amateur-Professional Photoelectric Photometry (I.A.P.P.P.), was interested in defining projects for amateur observers with photoelectric photometers; Persha, as owner of a company (Optec, Inc.) that manufactures photoelectric photometers for small telescopes, was interested in finding new applications for his photometers; I was interested in directing the energies of amateur photometrists to the Mira variables and helping them to make their observations as useful as possible. Our idea was to design a set of filters that could be used easily and inexpensively by owners of small telescopes, and yet was capable of providing useful data on red variables to supplement their visual light curves. The result was the set of three filters given in Table 1; a brief description of their characteristics has been given previously by the writer (Wing 1986).

Table 1. The Three-Color Filter Set

Filter	*Region Measured*	*Central Wavelength*	*Bandpass (FWHM)*
A	TiO band	7190 Å	110 Å
B	Continuum	7540	110
C	Continuum	10240	420

By choosing wavelengths in the near-infrared spectral region, we take advantage of both the brightness of cool stars and the good sensitivity of certain solid-state detectors in this region. A number of sets of these filters have been distributed to owners of Optec SSP-3 photometers, which use silicon diode detectors with peak sensitivity near 8000 A. The filters distributed by Optec, Inc. have been marked with the names MA, MB, MI; I rather prefer the simpler names A, B, C (which, surprisingly, appear not to have been used previously for an astronomical filter set).

The three filters are intended to measure three basic properties of red variables: their infrared magnitude, their color, and their spectral type (as indicated by their TiO strength). The positions and widths of the filters have been carefully chosen so that these three pieces of information can be determined separately with only three filters. Filters A and B are narrow because they serve to measure an index of TiO strength, and wider filters would have less sensitivity to this quantity; filter A is centered on one of the strongest TiO bands, and filter B is placed in a nearby region that is clear of serious absorption except in the coolest stars. Filter C is a second continuum point at a much longer wavelength; since the clear region around 10200 A is quite broad, this filter could be made wider than the others without degrading its function, and its greater width compensates for the decreased detector sensitivity at this wavelength (in fact, filter C is hardly "narrow"; it would more accurately be described as an "intermediate" bandwidth filter).

Any filter can be used to measure an apparent magnitude, but one placed in the infrared continuum, away from bands of TiO and other molecules, provides important information that cannot be obtained from the visual magnitude (which is strongly affected by TiO absorption). One of the functions of filter C, then, is to measure the infrared apparent magnitude. It has been known for some time (Lockwood and Wing 1971; Wing 1986) that light curves of Mira variables measured at near-infrared continuum points, near their energy maxima, are similar to bolometric light curves as regards their shape, amplitude, and phasing. In other words, measuring the magnitude with filter C is a short-cut to measuring the star's total energy output.

To measure a color index that is sensitive to the star's temperature, we need two well-separated filters, preferably clear of molecular absorption. Filters B and C serve this purpose: the color index B-C (where B and C are the magnitudes in the respective filters) is primarily an indicator of temperature because it measures the slope of the continuum and is affected very little by the presence of spectral lines and bands.

In choosing filters for the three-color system, I have been guided by experience with my eight-color system of classification photometry (see, e.g., White and Wing 1978), which uses somewhat narrower filters in order to better define the continuum and additional filters to measure CN and VO as well as TiO. What information do we lose by using only three filters instead of eight? Actually surprisingly little, if our intention is to study M-type Mira variables. Without a measure of CN strength we lose the ability to distinguish luminosity classes, or to recognize carbon stars, but I presume that users of the three-color system will be observing stars that are already known to be M-type Miras. Without a VO index we do lose some ability to classify the coolest stars, i.e., those whose types are later than M8, but these stars can still be recognized as such by their extremely red B-C colors.

Some consideration should be given as to the best way to extract an index of TiO strength from the data. If we simply compare the magnitudes in filters A and B, the resulting index A-B would be sensitive to TiO strength but would also have some sensitivity to the slope of the energy distribution (and hence also to the interstellar reddening) because the two filters are at different wavelengths. We can remove this dependence on color by taking account of the star's brightness in filter C; by extrapolating the continuum level to the wavelength of the TiO band we can compare the observed magnitude in the band to the magnitude the star would have if no band were present. On my eight-color system this extrapolation is done by fitting a blackbody curve to the best continuum points; for the three-color system, with its emphasis on simplicity, a linear extrapolation seems more appropriate. Hence I would recommend defining our reddening-free TiO index as

$$TiO = A - B - 0.13(B-C), \quad (1)$$

where A, B, and C are the magnitudes in those filters (reduced to the standard system: see below). The value of the numerical coefficient is determined by the spacings of the filters in wavelength. This definition can be visualized with the help of Figure 1. As the TiO absorption is increased, the magnitude in filter A gets larger (fainter), and the index increases. Note that the TiO index depends primarily upon the values of A and B; the magnitude in filter C has a relatively low weight.

To determine spectral types, it is necessary to calibrate the TiO index by observing stars of known spectral type. I have done this for my eight-color system (White and Wing 1978) but not for the three-color system; the calibration will be somewhat different because of the different filter widths. I would be happy to provide lists of M stars with accurately-known spectral types to any observer interested in undertaking this calibration.

3. Standard Stars and Reductions

A photometric system is defined by the adopted magnitudes of a set of standard stars, some of which are observed along with the variables on each night of work. By comparing the instrumental magnitudes (i.e., the raw readings, corrected for sky background and converted to the magnitude scale) of standard stars to the adopted standard values, we obtain the zero point at each filter which must be applied to all instrumental magnitudes to "reduce" them to the standard system. Corrections for atmospheric extinction must be determined and applied unless the observations have been programmed in such a way as to make them unnecessary. In addition, photometric observers often find that their filters are not at quite the same wavelengths as the ones used to define the standard values, and in that case color terms will be present in the transformations to the standard system (i.e., the zero points will show a dependence on color). The reader will find good general advice on the reductions of photoelectric photometry in articles that have appeared in the I.A.P.P.P. *Communications*.

In the case of the three-color system, the reductions should be straight-forward. Atmospheric extinction is substantially less in filters A, B, and C than in the visual region, so that it will often be sufficient to use mean coefficients instead of determining them every night. Also, as long as observers make certain that they are using filters consistent with the ones described in Table 1 (for example by obtaining them from Optec, Inc.), they should not have to worry about color terms in their reductions.

A set of 15 standard stars for the three-color system is given in Table 2. Although it is a small set, leaving some parts of the sky far from any standard, it is at least a start. Observers contemplating extensive work with the three-color system will no doubt wish to set up a longer list of secondary standards, or local standards close to variable stars of interest; any non-variable star that has been compared repeatedly to the standards of Table 2 can serve this purpose. Most of the standards given lie close enough to the equator to be accessible from both hemispheres. Observers who find these standards inconveniently bright for their telescopes may wish to establish fainter secondary standards by stopping down their telescopes until some of the original standards are brought into range.

Table 2. Standard Stars for Three-Color System

Star	*α* (2000) h m	*δ*	*Sp. Type*	*A*	*B*	*C*
αAri	02 07.2	+23° 28'	K2 IIIab	-0.014	-0.001	0.383
εEri	03 32.9	-09 28	K2 V	1.825	1.889	2.442
εTau	04 28.6	+19 11	K0 III	1.645	1.672	2.167
αCMi	07 39.3	+05 14	F5 IV	-1.201	-1.086	-0.336
αLeo	10 08.4	+11 58	B7 V	0.255	0.446	1.445
ΨUMa	11 09.7	+44 30	K1 III	1.014	1.014	1.416
εVir	13 02.2	+10 58	G8 IIIab	0.997	1.041	1.560
βCom	13 11.9	+27 53	G0 V	2.580	2.680	3.376
109 Vir	14 46.2	+01 54	A0 V	2.546	2.730	3.616
αSer	15 44.3	+06 26	K2 III	0.667	0.660	1.061
αLyr	18 36.9	+38 47	A0 V	-1.145	-0.950	-0.064
110 Her	18 45.7	+20 33	F6 V	2.603	2.720	3.459
βAql	19 55.3	+06 24	G8 IV	1.871	1.930	2.462
εCyg	20 46.2	+33 58	K0- III	0.539	0.567	1.020
αPsA	22 57.7	-29 37	A3 V	-0.098	0.074	0.953

The standard values given in Table 2 must be considered preliminary in that they were determined not from observations with the three-color filter set itself, but from data on other, related, photometric systems. The values for filters A and B are, in fact, standard values for filters 1 and 2 of my eight-color system (Wing 1979), which have very similar central wavelengths (7120 and 7540 A, respectively). Since all 15 standards have spectral types earlier than K3, they have smooth spectra (free of TiO) in the region of the filters, and it will matter very little that the filters of the three-color system are approximately twice as wide as the eight-color filters. Filter C is intended to serve the same purpose as filter 5 (10400 A) of the eight-color system, but since in this case the central wavelengths are significantly different, the values in Table 2 have been derived from unpublished spectrophotometry obtained by the writer many years ago at Lick Observatory. The magnitudes on these various systems can be combined in this way because they are actually all on the same system -- a system of absolute fluxes defined by a theoretical energy distribution chosen to represent the star Vega (αLyr). Consequently, the magnitudes A, B, and C for variable stars obtained by reducing the observations relative to the standards of Table 2 will also be absolute fluxes.

I hope that the information given in this paper will make it possible for observers to use the three-color system in the manner intended. I would be happy to consult with anyone making such observations, especially anyone undertaking to extend or improve the set of standard stars.

References

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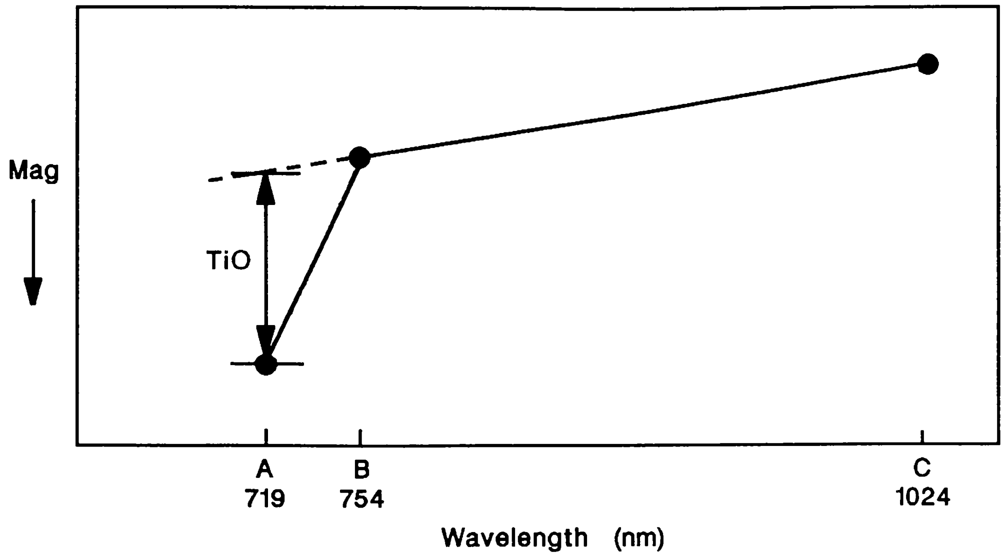

Figure 1. Definition of TiO index. The sketch shows the reduced magnitudes of a typical M star in filters A, B, and C plotted against the filter wavelength; filter A is depressed by TiO absorption. The index is defined as the difference (in magnitude units) between the measured flux in filter A and the value predicted from linear extrapolation from the continuum points B and C.