COMMISSIONS 27 AND 42 OF THE IAU
INFORMATION BULLETIN ON VARIABLE STARS
Number 4500

Konkoly Observatory
Budapest
23 July 1997
HU ISSN 0374 – 0676

RADIUS AND LUMINOSITY VARIATIONS OF MIRA FROM WING NEAR-IR PHOTOMETRY

Mira (omicron Ceti AB) is the prototype of a class of pulsating red asymptotic giants that undergo large (typically 3 to 7 mag. in V) brightness variations with periods of a few hundred days. Mira itself is more complex as it is a binary system composed of the luminous M4-7IIIe star (o Ceti; Mira A; HD 14386) and a hot accreting component $0\overset{''}{.}6$ distant (Mira B). *AAVSO* visual estimates of Mira A have shown its brightness to vary typically between 3rd and 10th magnitude over a period $P \sim 332$d. Recently Mira's parallax has been re-determined by *Hipparcos* to be $r = 129 \pm 18$pc (van Leeuwen *et al.* 1997). As one of the nearest Mira variables, its brightness has made it a favorite object for spectroscopic, photometric and interferometric measurements.

Of particular interest to the study of Mira, and Mira variables in general, are observations obtained in the infrared. Among the coolest of all stars, their maximum energies lie in the near-infrared, and typical Miras are 6-10 magnitudes brighter in this region than they are in the optical. Also, there are fewer molecular absorption features in the infrared than at optical wavelengths. As discussed by Wing (1992), the interpretation of standard *UBVRI* optical photometry of Miras and other cool variables is compromised chiefly by the presence of strong TiO molecular features that fall within these bandpasses for stars with spectral types of M0 or later. For these reasons, Wing (1992) has developed a simple near-infrared photometric system for use with red stars, including Miras. This photometric system uses three intermediate-band filters that have been carefully chosen to have bandpasses that include a temperature dependent TiO molecular band and two in the near IR that are essentially free of strong absorption features, except in the coolest of stars.

The first filter, designated by Wing as A, is centered around one of the strongest isolated TiO (γ;0,0) bands and has a central wavelength of 719 nm. TiO was chosen because it is an excellent temperature indicator in cool stars and it has been known for a long time that visual maximum corresponds to the time of highest temperature and weakest TiO band strength in Miras (Pettit & Nicholson 1933). Filter B, with a central wavelength of 754 nm, is placed in a region essentially clear of strong absorptions except in the coolest of stars. Both A and B have bandpasses of 11 nm. Filter C is also located at a region essentially free of absorption, but at a much longer wavelength, centered at 1024nm, where it provides a measurement of the infrared apparent magnitude. Its bandpass is larger at 42 nm which compensates for the usual decreased detector sensitivity at this wavelength.

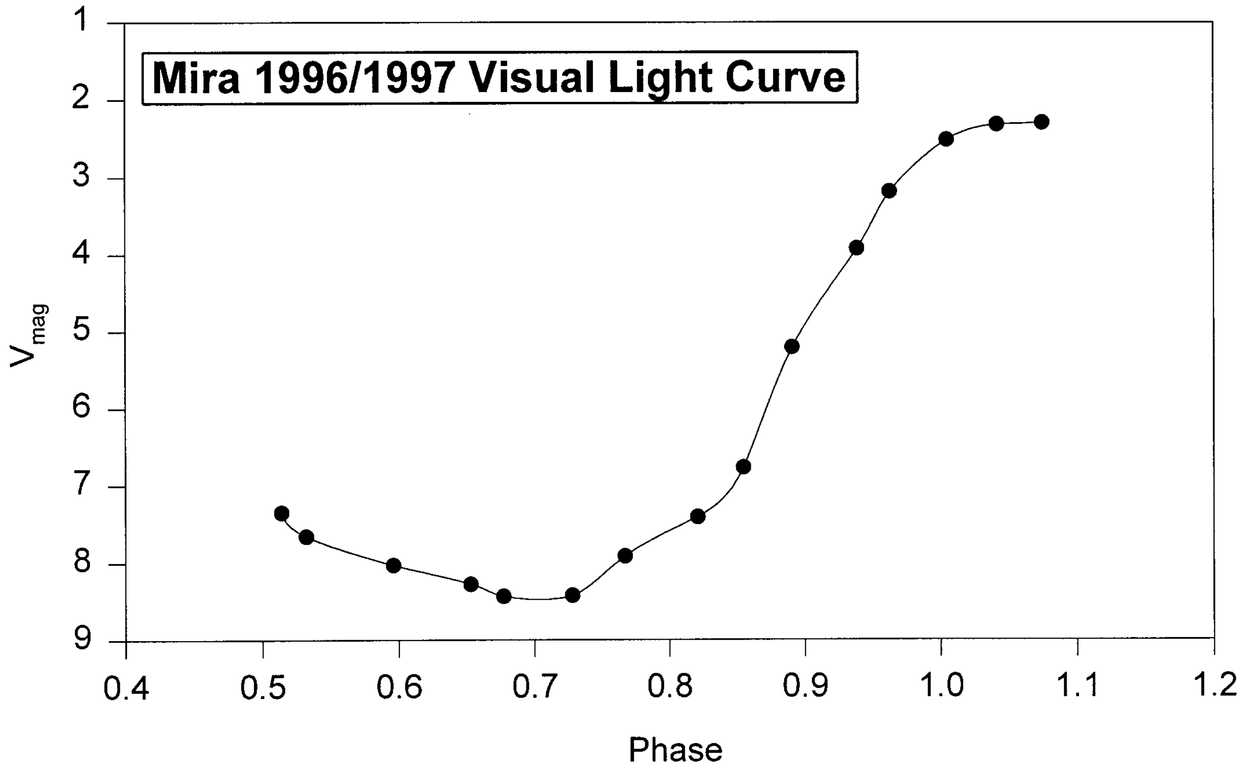

Figure 1. V light curve of Mira covering half of its pulsation period

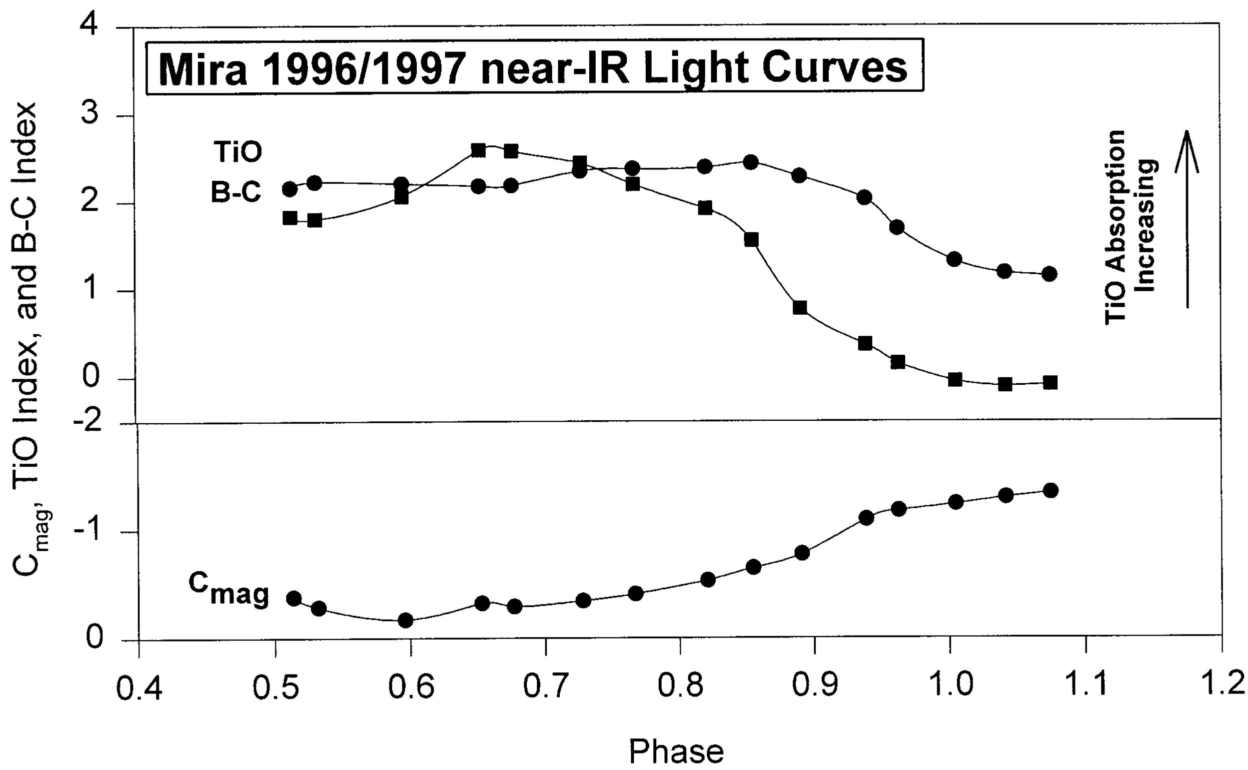

Figure 2. Light curves of Mira's TiO Index, B−C Index, and $C(1024)_{mag}$

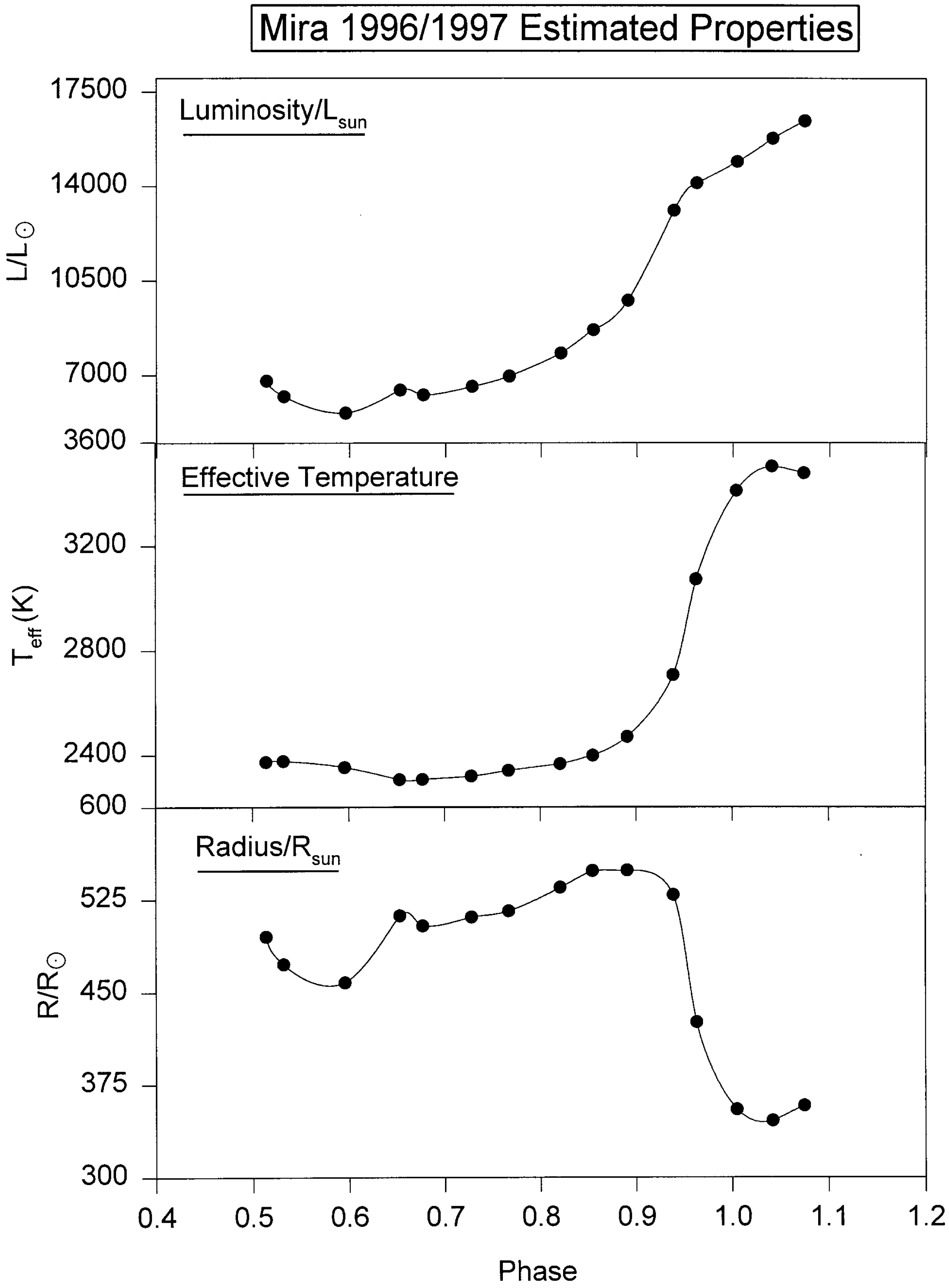

Figure 3. Luminosity, effective temperature and radius of Mira. The properties were estimated using the near-IR B−C Color Index to obtain an effective temperature, and the transformed $C(1024)_{mag}$ as an approximation of m_{bol}

As discussed by Wing (1992), filter C can also be used as a short-cut to measuring the star's total energy output as the light curves of Mira variables, measured at near infrared continuum points, are similar to bolometric light curves in shape, amplitude, and phasing (Lockwood & Wing 1971; Wing 1986). Filters B and C are used together to obtain a color index defined by:

$$\text{near-IR Color Index} = B - C$$

Because this color index measures the slope of the continuum and is affected little by spectral lines and bands, it is primarily an indicator of temperature. Finally a TiO index can be obtained by using the magnitudes of all three filters in the formula:

$$\text{TiO Index} = A - B - 0.13 \times (B - C)$$

With this method, the continuum level is extrapolated to the TiO wavelength band and the observed magnitude at this band is compared to the magnitude the star would have if no TiO band were present. The numerical coefficient is determined by the spacing of the filters in wavelength. The TiO Index is the measure of the relative strength of the TiO bandhead near 719nm and, as defined, the index becomes numerically larger as the TiO absorption increases.

Starting in 1996, photometric observations of Mira covering half of its pulsation period (from light maximum to past light minimum) have been carried out by Wasatonic using the Wing near-infrared ABC bands just described, as well the V-band. With a 20-cm Schmidt-Cassegrain (SCT) coupled to an uncooled Optec photometer, the photometry was carried out relative to nearby and check stars, following the usual observing sequence of sky-comp.-var.-comp.-sky-check-comp.-sky. The comparison star was HD 16400 (V = +5.65, B−V = +1.02, G5 III) and HD 16160 (V = +5.82, B−V = +1.04, K3 V) was the primary check star. In addition, several Wing standard stars ranging from M1 to M7 were observed most nights and their TiO and B−C indices were obtained. The photometric observations of Mira are provided in Table 1.

Table 1. Photometric data

JD2450000+	V	A	B	C
314.0	7.351	3.842	1.452	−0.377
320.0	7.656	3.971	1.515	−0.282
341.0	8.030	4.360	1.891	−0.169
360.0	8.277	4.773	2.262	−0.322
368.0	8.434	4.800	2.284	−0.290
385.0	8.425	4.757	2.095	−0.343
398.0	7.916	4.445	1.790	−0.405
416.0	7.410	4.023	1.387	−0.530
427.0	6.767	3.550	0.911	−0.644
439.0	5.210	2.384	0.002	−0.772
455.0	3.922	1.355	−0.723	−1.090
463.0	3.187	0.689	−1.020	−1.172
477.0	2.516	0.034	−1.280	−1.232
489.0	2.320	−0.226	−1.396	−1.293
500.0	2.297	−0.287	−1.425	−1.337

Figure 1 shows the visual-band light curve. Phasing was done using a t_{max} of JD 2447823 and a period of 331.9 days (Quirrenbach *et al.* 1992).

Using the formula previously described, the TiO index was calculated for each observation. Figure 2 shows the TiO Index, B−C Index, and the C_{mag} light curve versus phase. From the data, it can be seen that the bolometric magnitude, which is computed from C_{mag} (see below), reaches its faintest value near Mira's minimum phase at 0.6 - 0.7P. As would be expected, the B−C color index also reaches its greatest value at this phase indicating the lowest temperature. The TiO index becomes unreliable as a temperature indicator at Mira's minimum because the continuum regions of the spectrum become contaminated by lines of VO and other molecular species at $T_{eff} < 2400$K (Wing 1992). This is noted in Figure 2 as the TiO index is nearly constant from phases 0.5 - 0.9P.

To test the accuracy of using the $C(1024)_{mag}$ as an approximation of the apparent bolometric magnitude m_{bol}, a calibration was carried out using a large number of Wing standard stars whose $C(1024)_{mag}$ or comparable $I(1040)_{mag}$ are given by Wing (1978), and whose V magnitudes and spectral type are known (Wing 1978). By calculating m_{bol} for each of these stars by the standard formula:

$$m_{bol} = V_{mag} + BC$$

and comparing the results to the given $C(1024)_{mag}$, it was found that the $C(1024)_{mag}$ was fainter by an average difference of ~ 1.04 mag with a standard deviation of ± 0.31 mag. Therefore, this difference was added to each C filter reading to obtain a good estimate of the apparent bolometric magnitude. The bolometric correction (BC) values were obtained from Novotny (1973).

Using this adjusted value of m_{bol}, and the distance to Mira, the absolute bolometric magnitudes (M_{bol}) were calculated for each observation phase. Mira s luminosity was then calculated relative to the sun s and is shown in the upper panel of Figure 3.

An estimate of Mira's temperature at each observation phase was determined by applying a set of standard stars whose effective temperatures are known, and whose B−C color indices were obtained by Wasatonic. The middle panel of Figure 3 shows the variations of Mira's temperature with phase.

With estimates of both Mira's luminosity and temperature at each observation phase, a radius can be determined from the standard formula:

$$L = 4\pi\sigma R^2 T^4$$

The bottom panel of Figure 3 shows Mira's radius versus phase. Large scale radius changes from an $R_{min} = 345 R_{\odot}$(1.6 AU), to an $R_{max} = 548 R_{\odot}$(2.5 AU) can be seen in the plot. To place Mira s size in better perspective, if the star were placed at the center of our solar system, it would extend from just beyond the orbit of Mars (1.5 AU) to half way the distance of Jupiter (5.2 AU). The following table summarizes the extremes of the properties of Mira found during the 1996/97 epoch.

Table 2. Mira's Estimated Properties

V_{mag}	B-C Index	T_{eff}	Spec. Type	$L/L_{\odot}$	$R/R_{\odot}$	Radius (AU)
+2.29	−0.103	3520	~M0 III	1.6×10^4	345	1.6
+8.43	+2.584	2350	~M9 III	5.6×10^3	548	2.5

This work represents the first time the radius of Mira has been estimated using its proper distance and intermediate-band near-infrared photometric techniques. The values obtained for the radius compare well with previous interferometric measurements, such as those of Labeyrie *et al.* (1977) who found a radius of $\sim 645R_{\odot}$ at 1040nm at light maximum (Phase $\sim$ 0.0). Also, the mean radius of $464R_{\odot}$ recently reported by van Leeuwen *et al.* (1997) is in excellent agreement with our mean radius of $474R_{\odot}$. However, interferometric observations at 775nm by Karovska *et al.* (1991), when corrected for Mira's recently determined distance, yield an average radius of $\sim 1100R_{\odot}$ at nearly light maximum (Phase $\sim$ 0.97). Again, it should be noted that our estimates of radius and luminosity are based upon a transformation of the $C(1024)_{mag}$ to m_{bol}. Relative changes obtained for the radius of Mira, however, are not dependent on this approximation and should be of particular interest. Further near-IR observations of Mira over its entire pulsation period and the results of radius estimates will be reported in the future.

The authors wish to thank Robert Wing and the SIMBAD database for their assistance in this work. This research is supported by NSF grants AST-9315365 to Villanova University and AST-9528506 to the Four College Consortium.

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