Period-Magnitude relation of Mira-like variables in the Large Magellanic Cloud as a tool to understand circumstellar extinction

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ABSTRACT
Near- to mid-infrared period-magnitude relations and also the period-bolometric luminosity relation of OGLE-III Mira-like variables in the LMC are derived. The relations have a kink, and the period at which the break occurs is quantitatively obtained. There are many Mira-like variables whose fluxes at the optical and the near-infrared wavebands are fainter than the ones predicted by the period-magnitude relations. The deviation is due to the circumstellar extinction, and the amount of the deviation is found to be strongly correlated with near-infrared colors. The empirical formulae relating the amount of the deviation and the near-infrared colors are derived. These relations are useful to accurately calculate the distances to the dusty Mira-like variables, because the dimmed fluxes due to the circumstellar extinction can be estimated. In a manner analogous to the interstellar extinction law, the ratios of deviations at any two different wavebands are calculated. The ratios are found to change with the pulsation period, indicating that the dust properties are subject to change as Mira-like variables evolve.

Key words: Stars: AGB and post-AGB – Infrared: stars – Galaxies: Magellanic Clouds

1 INTRODUCTION
One of the most astronomically profitable aspects to study radially pulsating variable stars is that some groups of them have their individual period-luminosity relations that can be used as cosmic distance scales. Mira-like variables are one of such group of variable stars that evolved from low- to intermediate mass (∼0.8 < M/M⊙ < ∼8) stars, and they are in the late stage of stellar evolution (e.g., Iben & Renzini 1983). Since the discovery of the period-magnitude relation of Mira-like variables (Glass & Lloyd Evans 1981), many astronomers observed them to refine the relation and to study its metallicity dependency. From late 90’s to early 00’s, there was a major progress on the study of the period-luminosity relations of variable stars due to the advent of the optical large survey projects looking for the gravitational lensing events with robotic telescopes (e.g., MACHO, OGLE, EROS, MOA). The discovery of parallel sequences of period-magnitude relations of red giant variables in the Large Magellanic Cloud (Wood 2000) is an especially important result, because it told us that each group of variables has different period-luminosity relations, and also, different relation is assigned to different pulsation mode within a group (see also, for example, Kiss & Bedding 2003, Ita et al. 2004, Groenewegen et al. 2004, Fraser et al. 2005, Derekas et al. 2006, Glass et al. 2009, Soszyński et al. 2009, and Tabur et al. 2010).

The aim of this paper is to study the near- to mid-infrared period-magnitude relations of Mira-like variables in the LMC, using the combined data of recently published OGLE-III data (Soszyński et al. 2009) and the Spitzer SAGE catalog (Meixner et al. 2006). Infrared data is imperative because Mira-like variables are usually associated with the circumstellar dust shell, which is formed by the mass-loss phenomenon.

2 THE DATA
Recently, the OGLE project (Udalski 2003) released its third phase (OGLE-III; 12th June, 2001 – 3rd May, 2009) survey data. They provided catalogs of several types of variable stars in the Magellanic Clouds. Using their on-line database[1] stars with variable star type of ”Mira” were chosen by querying their catalog of long-period variables in the LMC (Soszyński et al. 2009). The query yielded a catalog of 1,663 Mira-like variables in the LMC. Soszyński et al. (2009) used the I−band pulsation amplitude to distinguish Miras and Semi-regular variables. They defined Miras as having I−band pulsation amplitude greater than 0.8 mag. In this paper, we follow their classification and call these Mira-like variables as just Miras or OGLE-III Miras. The OGLE-III catalog lists not only coordinates, but also pulsation periods, amplitudes, surface...
chemistries (Oxygen-rich / Carbon-rich) inferred by photometric colors, time averaged $V$- and $I$-band magnitudes, and other useful parameters.

### 2.1 Cross-identification with existing catalogs

The OGLE-III Mira catalog is cross-identified with the following existing catalogs using a positional tolerance of 3 arcsec. If more than one stars are present within the tolerance radius, the closest one is adopted and discard the others. The result is used for discussion in the rest of this paper.

- The Large Magellanic Cloud Photometric Survey catalog (Zaritsky et al. 2004): The catalog lists $U$, $B$, $V$, and $I$ stellar photometry of the central 64 deg$^2$ area of the LMC. It must be noted that we preferentially used the time-averaged $V$- and $I$-band data in the OGLE-III survey catalog whenever available, 1,412 out of a total of 1,663 Miras have counterparts in this catalog.

- The Two Micron All Sky Survey (2MASS) catalog (Skrutskie et al. 2006): The catalog provides uniform $J$, $H$, and $K_s$ photometry for sources all over the sky. The 2MASS catalog is complete down to $K_s < 14.3$ mag in the absence of confusion. The 2MASS magnitudes are used for the bright sources without IRSF measurements (The IRSF survey did not detect bright sources due to the saturation limit of about 10 mag at $K_s$ band. See below). 1,639 out of a total of 1,663 Miras have counterparts in this catalog.

- The IRSF Magellanic Clouds Point Source Catalog (IRSF catalog) (Kato et al. 2007): The IRSF catalog lists $J$, $H$, and $K_s$ photometry of over $1.4 \times 10^5$ sources in the 40 deg$^2$ area of the LMC. Compared to the contemporary DENIS (Cioni et al. 2000) and 2MASS (Skrutskie et al. 2006) catalogs, the IRSF catalog is more than two magnitudes deeper at $K_s$ band and about four times finer in spatial resolution. The IRSF system magnitudes were converted into the 2MASS system ones by using the conversion equations given in (Kato et al. 2007) and (Kućinskas et al. 2008). We preferentially used IRSF photometry whenever available. 1,557 out of a total of 1,663 Miras have counterparts in this catalog.

- The Spitzer SAGE-LMC survey catalog (Meixner et al. 2006): The catalog lists near- ($[3.6]$, $[4.5]$, $[5.8]$, and $[8.0]$) to mid-infrared ($[24]$ and $[70]$) photometry of sources in the central 40 deg$^2$ area of the LMC. It must be noted that we preferentially used the time-averaged $V$- and $I$-band data (The IRSF survey did not detect bright sources due to the saturation limit of about 10 mag at $K_s$ band. See below). 1,639 out of a total of 1,663 Miras have counterparts in this catalog.

### 2.2 Corrections for the interstellar reddening

In this paper, the optical ($U$, $B$, $V$, and $I$) and the near-infrared ($J$, $H$, and $K_s$) photometry are corrected for the interstellar reddening based on the relations in Cardelli, Clayton, & Mathis (1989), assuming $A_V/E(B-V) = 3.2$. We uniformly adopt ($A_U$, $A_B$, $A_V$, $A_J$, $A_H$, $A_K$) = (0.407, 0.345, 0.272, 0.159, 0.078, 0.048, 0.032) mag, corresponding to the mean foreground reddening of $E(B-V) = 0.085$ mag toward the LMC (Larsen, Clausen, & Storm 2000). Fluxes in any other longer wavelengths (i.e., photometry in the Spitzer wavebands) are not corrected for the interstellar extinction, which we assume negligible. We also ignore the reddening inside the LMC.

### 2.3 Calculation of the bolometric luminosity

We calculate the bolometric luminosity of all OGLE-III Miras by using a cubic spline to interpolate the spectral energy distribution and integrate it from the shortest available wavelength to 8 or 24 $\mu$m. We used zero-magnitude fluxes tabulated in Table 1 to convert magnitude into Jansky. Color-correction is not applied to the flux density, due to the lack of information of the incident spectrum. For some of the very red sources, the calculated luminosities can be underestimated to a large extent because the fluxes longward of 24 $\mu$m are not included. Therefore the calculated luminosities should be only lower limits for the very red sources. Also, we have to note that the calculated luminosities are rather uncertain, because they are sensitive to changes of degree of interstellar reddening, color correction, and also to time variation of light, which is significant especially for Mira-like variables discussed here.

### 2.4 Evaluation of the color-classified surface chemistry in the OGLE-III catalog

Soszynski et al. (2009) used $W_V$ vs. $W_K$ diagram to classify O-rich and C-rich surface chemistry of Mira variables in the LMC, where...
W$_I$ and W$_{JK}$ are Wesenheit indices defined as $W_I = I - 1.55(V - I)$ and $W_{JK} = K_s - 0.686(J - K_s)$, respectively. The validity of their classification should be checked before use, and its evaluation is done in the following way. We make the same $W_I$ vs. $W_{JK}$ diagram as in Soszyński et al. (2009), using only 1,663 OGLE-III Miras. The diagram is shown in Figure 1. Then, those with spectroscopically known surface chemistry (based on Kontizas et al. 2001 and Groenewegen et al. 2009) are highlighted to see their distribution on the employed Wesenheit index plane. It is clear that the distribution of Miras with spectroscopically known chemistry is fairly reproduced by the OGLE’s color-classification criteria, that were defined by Soszyński et al. (2009). We do not see any color-classified O-rich stars that correspond to the infrared O-rich red supergiants (blue pluses in Figure 1). This is due to the lack of their V-band data, probably because of the circumstellar extinction. Presumably, they get fainter than the detection limit of the OGLE-III V-band observations. We use their color-classified chemistry throughout this paper unless otherwise noticed.

3 RESULTS AND DISCUSSIONS

3.1 Period-magnitude relations

Glass et al. (2009) used the combined data of the MACHO survey (e.g., Alcock et al. 2000) and the previous version of the Spitzer SAGE catalog (Meixner et al. 2006) to discuss the mid-infrared period-magnitude relations (PMR) of variable red giants. They compared the PMRs of variable red giants in the LMC and the NGC6522, showing that there is little difference in their PMRs despite the differences in ages and metallicities between the two galaxies. Very recently, Riebel et al. (2010) discussed the infrared PLRs and showed that the wavelength dependence of the slope of the period-luminosity relationship is different for different classes of variable red giants.

Here we use the combined data of the OGLE-III Mira catalog and the new version of the Spitzer SAGE catalog (DR3), focusing on the PMRs of Miras in the LMC. In Figure 2 the PMRs of the OGLE-III Miras are shown. The abscissa is the common logarithm of the primary pulsation period in days. We use the primary period only. Note that the OGLE-III catalog provides not only the primary period, but also the secondary, and the tertiary periods. The left ordinate of each panel is in reddening-corrected apparent magnitude. Its corresponding waveband is indicated at the top left of each panel. The unit of the left ordinate can be scaled to the absolute one by subtracting a certain constant (i.e., distance modulus of the LMC). The colors of the marks in Figure 2 are different for different classes of variable red giants. By comparing these two figures, one can understand where each of the three groups is located in the period-magnitude plane.
Figure 2. Period-magnitude relations for OGLE-III Miras in the LMC. The color of the marks represents the differences in the color-classified surface chemistries (Soszyński et al. 2009); black for O-rich and red for C-rich stars. The cyan vertical lines show the mean magnitudes of O-rich Miras in 0.05 mag bins and their corresponding standard deviations. The thick solid and thick dashed blue lines are least-square fit to the mean magnitudes (see text and table 3).
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Table 2. Results of Student’s t-test to test a hypothesis that “the O-rich and C-rich Miras obey the same period-luminosity relation”. The A and R means accept and reject the hypothesis, respectively.

| log_{10} P | I | J | H | Ks | 3.6 | 4.5 | 5.8 | 8.0 | 24 | m_{bol} |
|------------|---|---|---|----|-----|-----|-----|-----|----|--------|
| 2.125      | A | - | - | A  | A   | A   | A   | A   | -  | -      |
| 2.175      | A | A | A | A  | A   | A   | A   | A   | -  | -      |
| 2.225      | A | A | A | A  | A   | A   | A   | A   | -  | -      |
| 2.275      | A | A | A | A  | R   | A   | R   | A   | -  | A      |
| 2.325      | R | R | A | R  | R   | R   | R   | A   | A  | A      |
| 2.375      | R | R | R | A  | R   | R   | R   | R   | A  | R      |
| 2.425      | R | R | R | A  | R   | R   | R   | R   | R  | R      |
| 2.475      | R | R | R | A  | R   | R   | R   | R   | R  | R      |
| 2.525      | R | R | R | A  | R   | R   | R   | R   | R  | R      |
| 2.575      | R | R | R | R  | R   | R   | R   | R   | R  | R      |
| 2.625      | R | R | R | R  | R   | R   | R   | R   | R  | R      |
| 2.675      | R | R | R | R  | R   | R   | R   | R   | R  | R      |

There are several interesting features in Figures 2 and 3. It seems that Miras with shorter primary pulsation periods fall on a relatively tight PMR regardless of their surface chemistry. We conducted a two-tailed Student’s t-test to test a hypothesis that “the O-rich and C-rich Miras obey the same period-luminosity relation”. A 95 % confidence level was chosen. Specifically, the mean magnitudes and variances of O-rich and C-rich Miras in the log_{10} P(days) = 0.05 bins are calculated and then compared. The results are summarized in Table 2. The test suggests that Miras with periods shorter than about 200 days (log_{10} P > 2.3) obey the same PMR regardless of their surface chemistry and also of employed waveband. For the easy explanation, we call the PMRs of these shorter period Miras as standard PMRs, and use them for comparison.

The PMRs become complex for Miras with pulsation periods longer than about 320 days. C-rich Miras with longer periods locate below the extension of the standard PMRs in the optical and near-infrared wavebands, although they locate above the standard PMRs in the Spitzer wavebands. This can be understood as the extinction by the circumstellar dust, and also as the intrinsic redness of C-rich Miras. On the other hand, O-rich Miras with longer periods locate above the reference PMR in all wavebands. Some O-rich Miras with very long period (log_{10} P > 3.0) locate below the reference PMR, due probably to the extinction by circumstellar dust, just like the C-rich Miras. Indeed, some of them are spectroscopically confirmed to have circumstellar dust (Groenewegen et al. 2009). These dusty O-rich Miras with very long period may be counterparts to the Galactic OH/IR stars.

To derive the PMRs, we concentrate on the O-rich Miras (i.e., black dots in Figure 2). The scatter about the PMR is related to differences in the color, error in the photometry, difference in the observed pulsation phase, and its intrinsic error. Mira-like variables discussed here are bright especially in the infrared, and their photometric errors should be small. Meanwhile, they are large-amplitude variables, and the difference in the observed pulsation phase (recall that we use single-epoch photometric data) can produce significant scatter. With the present data, we can not estimate the attributable fraction of scatter for each possible cause. Then we assume that the primary cause of the scatter about the PMR is due to the difference in the observed pulsation phase, and derive the PMRs in the following way. As a first step, we calculate the mean apparent magnitude (< m_i >) of O-rich Miras in the log_{10} P (days) = 0.05 bin and its corresponding standard deviation (σ_{m_i}), where the suffix i stands for the i-th bin. The cyan points with error bars in Figure 2 show the calculated < m_i > and σ_{m_i}. Because the cyan points obviously do not lie on a line, we fit two lines in the form of m_i = a_i log_{10} P + b_i to the cyan points by using least-square algorithm. We gave a relative statistical weight for each data point, which is proportional to 1/σ_{m_i}^2. Apparently, the break seems to occur at around log_{10} P (days) = 2.6. In the following section, we estimate the break periods quantitatively. The calculated PMRs are shown as the blue thick solid and dashed lines in Figure 2. The values of the a_i and b_i with their errors and the log_{10} P range used for the fitting are summarized in Table 3. Also, we calculated the residuals r from the derived PMRs for all O-rich Miras, which is defined as r = a_i × log P + b_i - m_{observed}. The standard deviation of r is then calculated after 10 times iterations of 3 sigma clipping. The standard deviation of r and the number of O-rich Miras used to calculate it are also tabulated in Table 3. The PMRs of C-rich Miras are not derived because most of them (except optical ones with periods shorter than about 400 days) do not obey a relation in the optical and near-infrared wavebands. In addition, their PMRs in the Spitzer wavebands have very large scatter, probably due to the broad range in the amount of circumstellar extinction and/or in the amplitude of light variation.

3.2 A kink in the period-magnitude relation

It is clear that the cyan points do not fall on a single straight line. There is a break at a certain pulsation period, and the PMR becomes steep from there. This feature is seen regardless of the wavebands. We determined the break period by calculating α_i = (< m_{i+1} > - < m_i >)/0.05, where the α_i should remain constant (equals to the slope) for a straight line without a kink. Although the calculated α_i is a bit noisy, we found a significant leap of α_i at a certain pulsation period. The corresponding periods (log_{10} P) for the leap are, 2.7 for < J >, 1.8 for < I >, J, H, Ks, and m_{bol}, 2.65 for [3.6], 4.5, [5.8], and [8.0], and 2.6 for [24], respectively.

Feast (1982) first pointed out the existence of O-rich Miras in the LMC with periods longer than 420 days (log_{10} P ~ 2.6) that locate above the extrapolations of the period-K magnitude relation derived with Miras with periods shorter than 420 days. Then Hughes & Wood (1990) and Whitelock et al. (2003) increased the number of samples, showing that the period-m_{bol} relation also have a break at around that period. Our results are very consistent with these previous works. A possible explanation for the excess luminosity of O-rich Miras with longer periods is the “hot bottom burning” (HBB) process (e.g., Whitelock et al. 2003, Feast 2009) that occurs in stars with masses greater than about 3 M_{⊙}, with the metallicity of the LMC (e.g., García-Hernández et al. 2006). Note that the lower mass limit to activate the HBB depends on the metallicity (see, for example, Boothroyd, Sackmann, & Ahenk 1993). Very interestingly, all but one spectroscopically-known infrared C-rich Miras have periods longer than the break period. Pulsation period of a Mira variable is related to its mass and radius (e.g., Wood 1990). Assuming that the radii of O-rich and C-rich Miras with about the same pulsation period are more or less the same, the longer period one should have larger mass. On the condition that the kink in the PMR is due to the HBB, one can speculate that the C-rich Miras with periods longer than the break period are undergoing the HBB process now. If so, the high mass-loss rate (> 10^{-5} M_{⊙}/yr, see next section) of infrared C-rich Miras can be due to the excess luminosity emerged from the HBB process that should create additional ra-
and Table 6. Employed near-infrared color in magnitude. The fitting results are summarized in Table 4.

As stated above, the amount of deviation is independent of pulsation period and amplitude. However, it would be of great interest if we can correlate the deviation with the other observables (and especially distance-independent ones), because such relation would be useful, for example, to correctly estimate the distances to Mira-like variables through PMR after considering the reduction in their apparent magnitude by the circumstellar extinction. Figure 4 is a plot to show that there is a strong correlation between the observed near-infrared color and the deviation. This result suggests that the near-infrared color can be a good indicator to probe the circumstellar extinction of Mira. To formulate the relation between the near-infrared colors and the deviation, we calculate the mean deviation ($<d_{i}>$) of Mira in the $s = 0.05$ mag bin and its corresponding standard deviation ($\sigma_{d_{i}}$), where the suffix $i$ stands for the $i$-th bin and $x$ represents the employed color in magnitude. The cyan points with error bars in Figure 4 show the calculated $<d_{i}>$ and $\sigma_{d_{i}}$. Then we fit a quadratic function to the cyan points in the form of $d = ax^2 + bx + c$ by using Levenberg-Marquardt algorithm with giving statistical weights proportional to $1/\sigma_{d_{i}}^2$. The fitting results are shown in the solid line in Figure 4 and the calculated coefficients are summarized in Table 4b.

The amount of deviation itself has important physical meanings. It can be used to roughly estimate the mass-loss rate by making a further assumption that the standard interstellar extinction law can be equally applied to Mira’s circumstellar environment. This assumption should be inappropriate especially for C-rich Miras, because the interstellar environment is O-rich in the first place. Also, the extinction law in the circumstellar environment looks indeed different from that in the interstellar environment, to the extent that the Figures 5 shows (see next). At the level of order of magnitude estimate, however, we suppose the assumption is valid. The observed $K_s$ band magnitude of most of the infrared Miras are more...
than 2 magnitude fainter than the one predicted by the period–K∗ magnitude relation. There are some extreme infrared Miras that are more than 4 magnitude fainter than the prediction. Using the standard interstellar extinction law, the 2(4) magnitude extinction in K∗ band correspond to AV of about 17(34) mag, and the optical depth at visual wavelength of about 15.7(31.3). van Loon (2007) related the total mass loss rate and the optical extinction as, \( M_{\odot}yr^{-1} = 1.5 \times 10^{-6} \left( \frac{Z}{Z_{\odot}} \right)^{0.55} \left( \frac{L/L_{\odot}}{0.8} \right)^{0.75} \). Substituting typical LMC values of \( Z = 0.4Z_{\odot} \) and \( L = 8000L_{\odot} \), the circumstellar extinction of \( AV = 15.7(31.3) \) mag gives \( M \sim 1.6(2.7) \times 10^{-5} M_{\odot}yr^{-1} \). If we take \( L = 4000L_{\odot} \), instead of \( L = 8000L_{\odot} \), the mass loss rate is reduced by a factor of \( (4000/8000)^{0.75} \sim 0.6 \). At any rate, it is likely that many of the infrared Miras in the LMC are losing mass of the order of about \( 10^{-5} M_{\odot}yr^{-1} \), comparable to the Galactic (i.e., presumably more metal-rich) Miras. Interestingly, this rather rough estimation of mass-loss rate is consistent with Groenewegen et al. (2009), who fit model spectral energy distribution to the observed mid-infrared spectra to calculate mass-loss rates of the same stars.

The ratios of deviations in any two different wavebands also give us insights on the properties (e.g., grain size and composition) of the circumstellar dust. The basic idea is like the interstellar extinction law that varies with the properties of interstellar dust. Figure 5 is a plot to show the relation between the ratios of deviations and pulsation period of Miras. For comparison purpose, the ratio of standard interstellar extinction law (Cardelli, Clayton, & Mathis 1989) is also shown by the horizontal line. It is clear that the extinction law in the interstellar and circumstellar environment is different. It is also clear that the ratio of deviations (hence dust properties) changes with increasing pulsation period of C-rich Miras. Interestingly enough, the interstellar and circumstellar extinction laws differ considerably for shorter period Miras, but the difference is little for longer period ones. It would be valuable to compare this observational results with the dust extinction models to quantitatively constrain the circumstellar dust properties.

4 CONCLUSIONS

We derived the near- to mid-infrared period-magnitude and also period-bolometric luminosity relations of OGLE-III Mira-like variables in the LMC. Mass-losing Mira-like variables do not fall on the derived relations, due to the circumstellar extinction. We showed that this fact can be used as an proxy to study the properties of the circumstellar dust, and also to estimate mass-loss rate. We found that the dust properties change with increasing pulsation period. A comparison between the observational facts and dust extinction model would reveal how dust grain evolves during the Mira phase.

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