Mid-infrared Period–Luminosity Relations of Gaia DR3 Long Period Variables Postprint

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Abstract

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Full Text

Preamble

Mid-infrared Period–Luminosity Relations of Gaia DR3 Long Period Variables

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Abstract

Long period variable (LPV) stars are very promising distance indicators in the infrared bands. We selected asymptotic giant branch (AGB) stars in the Large and Small Magellanic Cloud (LMC and SMC) from the Gaia Data Release 3 LPV catalog, and classified them into oxygen-rich (O-rich) and carbon-rich (C-rich) AGB stars. Using the Wide-field Infrared Survey Explorer database, we determined the W1- and W2-band period–luminosity relations (PLRs) for each pulsation-mode sequence of AGB stars. The dispersion of the PLRs of O-rich AGB stars in sequences C and C is relatively small, around 0.14 mag. The PLRs of LMC and SMC are consistent in each sequence. In the W2 band, the PLR of large-amplitude C-rich AGB stars is steeper than that of small-amplitude C-rich AGB stars, due to their more circumstellar dust. By two methods, we find that some PLR sequences of O-rich AGB stars in the LMC are dependent on metallicity. The coefficients of the metallicity effect are $\beta = -0.533 \pm 0.213$ mag dex^{-1} and $\beta = -0.767 \pm 0.158$ mag dex^{-1} for sequence C in W1 and W2 bands, respectively. The significance of the metallicity effect in W1 band for the four sequences is $2.2-3.5\sigma$. Both of these imply that distance measurements using O-rich Mira may need to take the metallicity effect into account.

Key words: stars: variables: general – stars: distances – infrared: stars

1. Introduction

Long period variables (LPVs) represent the asymptotic giant branch (AGB) and red giant branch (RGB) phases in the evolution of low- and intermediate-mass stars. Due to their large amplitude variations in the optical bands and pulsation periods of about 10–1000 days, LPVs are easily detectable and have therefore received considerable attention. In recent years, LPVs in the Milky Way, Large Magellanic Cloud (LMC), Small Magellanic Cloud (SMC), and other galaxies have been extensively searched for and studied using different databases \citep{Menzies_{{{etal}}{{2019}}}, Chen{{{etal}}{{2020}}}, Saremi{{{etal}}{{2020}}}, Groenewegen{2022}, Suh_{2022}}. The study of period–luminosity relations (PLRs) of LPVs has developed rapidly as large microlensing surveys have published long-term photometry for numerous stars. \citet{Cook_{{{etal}}{{1996}}}} *first pointed out that variable stars in the Massive Compact Halo Object experiment database for the LMC present five parallel sequences in the period–luminosity (PL) diagram.* \citet{Wood{{{etal}}{{1999}}}} *and* \citet{Wood{2000}} classified them into five sequences (labeled A, B, C, D, and E). Subsequent studies identified additional sequences: \citet{Ita_{{{etal}}{{2004}}}} *denoted an additional sequence close to sequence B as C , while* \citet{Wood{2015}} defined sequence A . In evolutionary models, stars entering the AGB phase are oxygen-rich (O-rich), and they can transform into carbon-rich (C-rich) objects after dredge-up episodes. Therefore, AGB stars can be classified as O-rich or C-rich based on the relative abundance of oxygen to carbon in their surface composition.

\citet{Soszynski_{{{etal}}{{2004}}}} *divided AGB stars in the LMC and SMC into O-rich and C-rich categories, and* \citet{Soszynski{{{etal}}{{2005}}}} *further classified Mira variables (Miras) and semi-regular variables (SRVs) in the LMC into O-rich and C-rich subtypes. LPV sequences consist of Miras, SRVs, OGLE small-amplitude red giants, and long secondary period (LSP) variables. Their pulsations are caused by radial and non-radial modes* \citep{Wood{2015}}, and consequently they follow several distinct PLRs, which make them potential distance indicators \citep{Soszynski_{{{etal}}{{2007}}}}. *In addition, different PLR sequences are associated with different pulsation models, which can serve as an important tool for constraining stellar evolution* \citep{Trabucchi{{{etal}}_{{2017}}}}.

In the infrared bands, LPVs are as bright as or brighter than Cepheids. The PLRs of LPVs have little dependence on metallicity \citep{Goldman_{{{etal}}{{2019}}}} *and can be used as independent distance indicators. PLRs in the near-infrared and mid-infrared (MIR) bands are tighter than those in the optical bands due to reduced sensitivity to effective temperature and extinction* \citep{Iwanek{{{etal}}{{2021a}}}}. *In recent years, PLRs of LPV subtypes in the Milky Way and other galaxies have been studied across a wide range of wavelengths using different databases* \citep{Bhardwaj{{{etal}}{{2019}}}, Kudashkina{2019}, Trabucchi_{{{etal}}{{2021}}}}. *Particularly for Miras, their tight PLRs enable them to serve as reliable distance indicators for measuring and calibrating Galactic and extragalactic distances* \citep{Matsunaga{{{etal}}{{2005}}}, Whitelock{{{etal}}{{2008}}}, Yuan{{{etal}}{{2017}}}, Huang{{{etal}}{{2018}}}, Qin{{{etal}}{{2018}}}, Molina{{{etal}}{{2019}}}, Urago{{{etal}}{{2020}}}, Iwanek{{{etal}}{{2021b}}}}. *Accurate distances play a crucial role not only in understanding the formation, evolution, and structure of galaxies* \citep{Iwanek{{{etal}}{{2023}}}, Parto{{{etal}}{{2023}}}}, *but also in measuring the Hubble constant* \citep{Huang{{{etal}}_{{2020}}}}.

The longer and deeper photometry of Gaia Data Release 3 (DR3) provides a larger sample of LPVs. This work aims to study the MIR PLRs of LMC and SMC LPVs in Gaia DR3 using data from the Wide-field Infrared Survey Explorer (WISE). In Section 2, we describe the data used in this work for LPVs. In Section 3, we present our methods, including obtaining mean magnitudes in the MIR by fitting light curves, distinguishing AGB stars from LPV candidates through color–magnitude diagrams (CMDs), classifying AGB stars into O-rich and C-rich subtypes, and determining PLRs. We compare the PLRs of the two galaxies and discuss the dependence of PLR zero-points on metallicity in Section 4. This work concludes in Section 5.

2. Data

Gaia DR3's latest database covers 34 months of multi-epoch photometry, providing deeper and broader coverage for identifying LPVs. We selected samples from the "gaiadr3.vari_{{{long}}*{{period}}}*{variable}" catalog, which contains basic information such as pulsation frequency and amplitude for 1,720,588 LPVs, as described in detail by \citet{Lebzelter_{{{etal}}*{{2022}}}}. We then matched these sources to the Gaia DR3 main catalog "gaiadr3.gaia_{source}" using the source*{id} to obtain additional parameters such as parallax and mean magnitudes. To investigate PLRs, we removed LPVs with null frequency values, leaving 392,240 candidates. The frequency range is 0.00098–0.0285 day^{-1} (35–1020 days), with upper and lower limits determined by the time span and sampling mode of each LPV's observations.

In this work, we studied LPVs in the LMC and SMC separately. The Gaia database provides optical photometry, and we obtained samples of LMC and SMC LPVs through simple selection based on their spatial positions. There are 11,047 and 3,045 LPVs with associated periods in the LMC (67°.5 < R.A. < 97°.5, –70° < decl. < –62°) and SMC (0° < R.A. < 30°, –76° < decl. < –70°), respectively.

The MIR PLRs of AGB stars have smaller dispersion compared to optical PLRs. Here we used the WISE database, which provides multi-epoch MIR photometry. The main mission of WISE (AllWISE) observed the entire sky in four bands (W1, W2, W3, W4). After this mission ended in 2010, observations in the W1 and W2 bands resumed in 2011 as part of the Near Earth Object WISE Reactivation Mission (NEOWISE-R). To combine AllWISE and NEOWISE-R data to create a longer time baseline, we used only the W1 and W2 bands in this work.

For LMC and SMC LPVs, we searched for counterparts within 1 of the Gaia coordinates and downloaded photometry in the W1 and W2 bands from the AllWISE multi-epoch photometry table and the NEOWISE-R single exposure source table using the NASA/IPAC Infrared Science Archive. Since the angular resolution of WISE (6 in W1) is worse than that of Gaia, we estimated a blending factor to exclude LPVs contaminated by bright neighbors. We obtained counterparts within a 6 radius around each LPV in the 2MASS database and used the ratio (1.05) of the total K-band flux of all sources within 6 to the

LPV's K-band flux as a blending factor. Using a blending factor of 1.1 would increase the sample size by only about 2%, which has little effect on the PLR fit, so we adopted the more stringent criterion of 1.05. For these remaining sources, we added an error blending factor to the absolute magnitude error. Finally, 9,774 and 2,778 LPVs remained from the LMC and SMC, respectively.

3. Methods

3.1. Mean Magnitudes in MIR

In Section 2, we obtained WISE W1- and W2-band photometric data for LPVs in the LMC and SMC. To optimize the MIR PLRs, we fitted the light curves using a nonlinear least squares method to measure the mean magnitude and amplitude of each LPV. First, we converted the Modified Julian Date of each WISE photometric measurement into phase based on the LPV's period from Gaia DR3. We then performed the fit using a sinusoidal function, where x is the phase, a_0 is the mean magnitude, and a_1 is the amplitude. Considering the photometric accuracy and sampling pattern of WISE, we did not use high-order functions to avoid overfitting.

The number of photometric measurements from NEOWISE-R is eight times greater than that from AllWISE. To obtain better mean magnitudes, we removed LMC and SMC LPVs with fewer than 200 and 50 NEOWISE-R measurements, respectively. We finally obtained MIR mean magnitudes for 9,365 LMC and 2,682 SMC LPVs.

3.2. Period–Luminosity Diagrams

LPVs can be divided into AGB stars, red supergiant (RSG) stars, and RGB stars according to their locations on CMDs. The CMDs of LPVs in the LMC and SMC are shown in Figure 1 [Figure 1: see original paper], where we used GBP – GRP and the Wesenheit indices WG,BP,RP = GRP – 1.3(GBP – GRP) as the color and magnitude, respectively. Among LPVs, RGB stars are the faintest members, and the tip of the RGB (TRGB) marks their boundary with AGB stars in absolute magnitude \citep{Freedman_{{{etal}}*{{2019}}}}.* *\citet{Boyer*{{{etal}}}_{{{2011}}}} determined the TRGB apparent magnitudes in the Spitzer [3.6] band to be 11.9 mag and 12.6 mag in the LMC and SMC, respectively. In this work, we used apparent TRGB Wesenheit magnitudes of 11.7 mag and 12.1 mag for the LMC and SMC, respectively, determined by visual inspection. We verified that a small adjustment in TRGB magnitude has little effect on the final PLR. For example, an increase of 0.1 mag increases the number of LMC O-rich AGB stars by only 4%, and the bias in the PLR zero-point is around or less than 0.01 mag for each sequence. We selected RGB stars in the LMC and SMC using the criteria WG,BP,RP $\geq$ 11.7 and (GBP – GRP) $\leq$ 2.9, and WG,BP,RP $\geq$ 12.1 and (GBP – GRP) $\leq$ 2.3, respectively. For both the LMC and SMC, the parallaxes of the samples conform to a Gaussian distribution, with about 1% and 2% of samples having parallaxes larger than

0.2 mas. Therefore, foreground star contamination is negligible. After selecting RGB and RSG stars, the remaining LPVs are AGB stars, which include both O-rich and C-rich AGB stars. We focused primarily on the PLRs of AGB stars in this work.

AGB stars are classified into O-rich and C-rich subtypes based on their chemical abundances. As with Gaia DR2 \citep{Mowlavi_{{{etal}}{{2018}}}}, the Gaia DR3 LPV catalog provides the parameter "medin_{{{delta}}{{wl}}}{rp}" to classify C-rich and O-rich (M-type) AGB stars. This parameter represents the median value of the pseudo-wavelength difference between the two highest peaks in the RP spectrum of each LPV. LPVs with medin{{{delta}}{{wl}}}{rp} > 7 and < 7 are classified as C-rich and O-rich stars, respectively. Notably, S-type stars are significantly enhanced in ^{12}C and s-process elements due to third dredge-up episodes. Although their optical spectra are still dominated by TiO, they are identified by the presence of ZrO bands in that wavelength range \citep{VanEck_{{{etal}}{{2017}}}}. S-type stars form a continuum from M- to C-type with subtypes MS, S, SC, and CS. In the Gaia catalog, O-rich stars include the majority of S-type stars, while a few S-type stars are included among C-rich stars \citep{Lebzelter{{{etal}}{{2022}}}}. In LMC LPVs, about 48.7% are O-rich AGB stars and 33.5% are C-rich AGB stars. The ratio of C- to O-rich AGB stars is 0.69, consistent with the value of 0.61 obtained by \citet{Spano{{{etal}}{{2011}}}} and the range of 0.63–0.72 obtained by \citet{Wisniewski{{{etal}}{{2011}}}}. In SMC LPVs, 34.2% are O-rich AGB stars and 52.0% are C-rich AGB stars. These proportions are consistent with \citet{Mowlavi{{{etal}}{{2019}}}}, and the different proportions in the LMC and SMC primarily reflect their different metallicities. As metallicity increases, the efficiency of the third dredge-up decreases, leading to higher oxygen abundance in the envelopes of AGB stars \citep{Mowlavi{{{etal}}_{{2019}}}}.

Combining the mean magnitudes in the W1 and W2 bands with pulsation periods from the Gaia database, we plotted MIR PLR diagrams for O-rich and C-rich AGB stars in the LMC and SMC. In the LMC PLR diagram (left panel of Figure 2 [Figure 2: see original paper]), four sequences (B , C , C , D) of O-rich AGB stars and three sequences (C _c, C_c, D_c) of C-rich AGB stars are clearly visible. The subscripts c and o indicate membership in C-rich and O-rich AGB stars, respectively. Similarly, in the SMC PLR diagram (Figure 2, right panel), there are three sequences (C , C , D , C _c, C_c, D_c) for both O-rich and C-rich AGB stars. The PLR diagram in the W2 band exhibits the same multiple sequences as in the W1 band, and we determined the PLRs in the W2 band in the next subsection. In the MIR-band PLR diagrams, we found that C- and O-rich AGB stars in the same sequence (e.g., C and C_c of LMC AGB stars in the C sequence in the left panel of Figure 2) appear to follow a consistent PLR. However, for Wesenheit indices WG,BP,RP, C- and O-rich AGB stars show quite different PLRs for each sequence. Therefore, we discuss the PLRs of C- and O-rich AGB stars separately.

3.3. MIR Period–Luminosity Relations

We obtained a linear PLR for each sequence in Figure 2 through the following steps, where logP$_0$ is the mean logarithmic period of samples for each sequence. First, based on the PLR density maps of O-rich or C-rich AGB stars in the LMC and SMC in the W1 band (Figure 3 [Figure 3: see original paper]), we determined the approximate period boundaries for each sequence (considering only the dense region of each sequence). We list the period ranges used for each sequence in Tables 1 and 2. In particular, sequences B and C of LMC O-rich AGB stars are too close to be separated based on their period distributions, so we roughly divided them using a line (the red line K boundary in the M_{W1} versus logP diagram, connecting two saddle points in Figure 3). The raw samples for each sequence in the W2 band are the same as those in the W1 band. We then performed a linear fit to each trimmed sequence using the weighted least squares method with a sigma-clipping procedure. The weights are estimated by the inverse of σ_M^2, where σ_M represents the absolute magnitude uncertainty that includes contributions from the mean magnitude error in fitting light curves (σ_m), the uncertainty from the period (σ_p, where we assumed a period error of 10%), and the uncertainty from blending (σb). *The period error broadens the x-axis, and we converted it to an error in absolute magnitude using the PLR slope, which contributes errors of around 0.15 mag.* σ{int} is the intrinsic PLR scatter; we adopted 0.10 mag because even PLRs as tight as those of Cepheids have an intrinsic dispersion of 0.06–0.10 mag. Errors in the period and intrinsic PLR dispersion are the main contributions. We performed multiple sigma-clipping iterations until the PLR converged. Due to the small and scattered sample (see Figure 3), we used a 2σ-clipping procedure for O-rich AGB stars in the SMC, while a 2.5σ-clipping procedure was applied to the other AGB stars.

Figures 4 and 5 present the fitting results for each sequence of AGB stars in the LMC and SMC. Through the sigma-clipping procedure, for most sequences (e.g., sequence C in Figure 4 [Figure 4: see original paper] and Figure 5 [Figure 5: see original paper]), the rejected points are distributed on both sides of the high-density region used to fit the PLR and show parallel sequences. Inspection revealed that most of these points were samples from other sequences. Specifically, sequences B and C of LMC O-rich AGB stars were divided by a given line (K in Figure 3). This explains why the rejected points appear on one side (top two rows of Figure 4(a)). Linear PLRs with uncertainties for LMC and SMC sequences are listed in Tables 1 and 2, respectively. We also list the period range for each sequence in these tables. Among these PLRs, the PLRs of O-rich AGB stars have smaller dispersion, particularly for sequences C and C. This suggests that these O-rich AGB stars are suitable for distance measurements. The period of sequence D corresponds to the LSP of AGB stars, and the PLR scatter of sequence D is larger than for other sequences.

The histogram of magnitude residuals relative to the PLR fit line for each sequence is shown in Figure 6 [Figure 6: see original paper]. We used the

Kolmogorov–Smirnov test to check the distribution and found that most sequences satisfy a Gaussian distribution (with p-value > 0.05). Sequences B and C of LMC O-rich AGB stars were divided by a given line (K in Figure 3), so the stars with positive residuals in sequence B and negative residuals in sequence C have distinct truncations (top two panels (a) in Figure 6). As a result, these two sequences do not well satisfy a Gaussian distribution. Additionally, due to small and more scattered samples, the symmetric distribution of SMC O-rich AGB star sequences is weak.

4. Discussion

4.1. PLR Comparison

In Section 3.3, we determined the PLRs of each sequence for O-rich and C-rich AGB stars in the LMC and SMC. In this section, we compare these PLRs in both W1 and W2 bands (see Figure 7 [Figure 7: see original paper]). We find that for each sequence, the PLRs of the LMC and SMC are consistent with each other. The period of sequence D corresponds to the LSP of AGB stars, and the PLR dispersion of sequence D is larger than for other sequences. This is understandable because the measurement precision is lower for the LSP. \citet{Soszynski_{{{etal}}*{{2021}}}} detected secondary eclipses in MIR light curves and argued that an eclipsing binary is a reasonable explanation for the origin of the LSP. In the LMC and SMC, \citet{Soszynski*{{{etal}}*{{2007}}}} obtained the PLR of sequence D and found it to be a continuation of the PLR of sequence E at the bright end. Sequence E is predominantly composed of binary systems of red giants. For contact binaries, there is a tight relationship between radius and orbital period due to the Roche lobe constraint, which allows the derivation of an infrared PLR. The infrared PLR has been found for main sequence stars \citep{Chen*{{{etal}}*{{2018}}}} and red giants \citep{Muraveva*{{{etal}}_{{2014}}}} as components of contact binaries. Due to the consistency of the D and E sequences, a PLR also exists for AGB contact binaries. When an AGB contact binary has not yet filled both Roche lobes (detached or semi-detached binary), the orbital period is slightly larger, but the change in PLR still roughly holds. For AGB binaries with orbital periods twice as large, Gaia DR3 is unable to detect them. These factors lead to the D sequence being a PLR with large dispersion.

Mira is a subtype of AGB stars with large amplitude in sequence C \citep{Wood_{2015}}. \citet{Iwanek_{{{etal}}*{{2021b}}}} determined PLRs in the MIR bands based on Miras in the LMC. We compared the PLRs of sequence C of AGB stars in the LMC with the PLRs of Miras in Figure 8 [Figure 8: see original paper]. For O-rich AGB stars and Miras, the PLRs are consistent. However, the PLR of C-rich AGB stars in the W2 band differs from that of Miras. Miras show a brighter PLR with a steeper slope. Upon inspection, we found that the PLR of C-rich AGB stars with larger amplitudes in sequence C differs from that of stars with smaller amplitudes. In contrast, this difference is negligible in the W1 band. We suspect that the difference* *in the W2-band PLR arises because large-amplitude C-rich AGB stars have more circumstellar dust, which enhances dust emission in the W2 band. \citet{Trabucchi*{{etal}}_{{2021}}}} also found these PLR features in SRVs. They found that fundamental-mode SRVs are split into two branches, and those with relatively larger amplitudes follow the same distribution as Miras in the period–amplitude and PL diagrams.

4.2. The Dependence of PLRs on Metallicity

To examine the correlation between PLR zero-points and metallicity, we used metallicity ([M/H]) from Apache Point Observatory Galactic Evolution Experiment (APOGEE) DR17. The metallicity was determined by the APOGEE Stellar Parameters and Abundances Pipeline (ASPCAP). In the LMC, there are 87, 34, 30, and 98 O-rich AGB stars with metallicities in sequences B, C , C, and D, respectively, and 11, 39, and 5 C-rich AGB stars with metallicities in sequences C , C, and D, respectively. For the SMC, sequence C contains only 5 O-rich and 6 C-rich AGB stars with metallicities, and sequence C contains 4 O-rich and 17 C-rich AGB stars with metallicities.

Figure 9 [Figure 9: see original paper] shows the distributions of carbon abundance and metallicity of AGB stars in the LMC and SMC. There is a clear boundary between C-rich and O-rich AGB stars in carbon abundance, indicating that the classification of AGB stars using colors is appropriate. The metallicities of O-rich AGB stars in the SMC (red dots) are overall 0.2 dex lower than those in the LMC (green dots). This difference reflects the overall metallicity difference between the LMC and SMC. These results imply that ASPCAP metallicities are suitable for internal comparison and statistical analysis. The metallicity of O-rich AGB stars in the LMC ranges from –1.2 to –0.3 dex, while in the SMC it ranges from –1.5 to –0.6 dex. Compared to O-rich AGB stars, the metallicity of C-rich AGB stars is much lower ([M/H]   –2.0 dex), and metal-poor C-rich AGB stars are older stars with lower initial masses.

Considering the small sample sizes of C-rich AGB stars in the LMC and both O-rich and C-rich AGB stars in the SMC, we focused only on the metallicity effect for O-rich AGB stars in the LMC. We obtained the relations between the residuals and metallicity. This method is more accurate than three-parameter regression in cases where metallicity and period are not independent. Figure 10 [Figure 10: see original paper] shows the correlation between metallicities and the W1- and W2-band magnitude zero-point residuals of PLRs for sequences of LMC O-rich AGB stars. The residuals are the observed absolute magnitudes minus the absolute magnitudes estimated by the PLRs in Table 1. We found that for O-rich AGB stars in the LMC, there is a correlation between PLR residuals and metallicities in each sequence. We fitted them with a linear relationship (ΔM_W $= \alpha + \beta \times$ [M/H]) using the weighted least squares method, where the weights are represented by σ^{-2}. The metallicity effect for each sequence is listed in Table 3 . The metallicity effect is similar between the W1 and W2 bands, with sequence C having the lowest metallicity dependence while sequences C and D have the largest dependence. In particular, the metallicity dependence of sequence C in the W2 band is only about 0.8σ, indicating no obvious metallicity effect. However, based on the non-zero coefficient of the metallicity effect ($\beta =$ –0.746   –0.296 mag dex^{-1}) and significance of 2.2–3.5σ for sequences in the W1 band and 4.9σ for sequence C in the W2 band, we suggest that the metallicity effect may need to be taken into account in distance measurements using either O-rich AGB stars or Miras. At a fixed period, the luminosity of O-rich AGB stars becomes brighter in the infrared bands as metallicity increases. This trend is similar to that of classical Cepheids, for which luminosity also brightens with increasing metallicity at a given period \citep{Riess_{{{etal}}_{{2021}}}}.

To double-check the metallicity effect based on the same sample, we determined the period–luminosity–metallicity relation (PLMR), which includes metallicity as an independent parameter. For O-rich AGB stars in the LMC, we performed the fit and tested the metallicity effect with a T-test. A smaller p-value of coefficient c_1 (p_c_1) indicates a more significant metallicity effect. The PLMRs and p_c_1 for each sequence in both W1 and W2 bands are listed in Table 4 . Similarly, the metallicity effect is significant (2σ) except for sequence C in the W1 band and sequences B and C in the W2 band.

In addition, we obtained the PLR $\log P_0$ for the same sample and found that the PLR scatter of each sequence is larger than that of the PLMR by 1%–20%. Considering that the main components of PLR dispersion (0.1–0.2 mag) come from period errors and intrinsic PLR dispersion, which are not reduced by including the metallicity term, the optimization of the other dispersion components is greater than 1%–20% with the inclusion of the metallicity term. The results are shown in Table 4. Both methods suggest that for O-rich AGB stars, the metallicity effect in the PLR may need to be considered.

After APOGEE DR16, the accuracy and consistency of stellar parameters for cool stars (T_{eff} < 3500 K) were improved due to the use of MARCS model atmospheres in spherical symmetry \citep{Schultheis_{{{etal}}*{{2020}}}}. To verify the reliability of ASPCAP metallicities for AGB stars, we compared them with those obtained from the Brussels Automatic Code for Characterizing High-accUracy Spectra (BACCHUS). The BACCHUS Analysis of Weak Lines in APOGEE Spectra (BAWLAS, \citealt{Hayes*{{{etal}}_{{2022}}}}) catalog includes chemical abundances for about 120,000 giants with APOGEE DR17 spectra. We cross-matched our AGB stars with objects from the BAWLAS catalog using a 1 radius and obtained 1,869 AGB stars with both ASPCAP and BAWLAS metallicities. The comparison of metallicities for these AGB stars is shown in Figure 11 [Figure 11: see original paper]. We found that 94.7% of AGB stars have a metallicity difference smaller than 0.05 dex, with an overall bias of $\Delta[M/H] = 0.007 \pm 0.033$ dex. This indicates that ASPCAP metallicities are reliable for AGB stars, at least suitable for internal comparisons and statistical analysis.

5. Conclusion

We analyzed the MIR PLRs of LPVs in the LMC and SMC using Gaia DR3 LPVs and the WISE database. For both galaxies, LPV candidates were selected based on their sky positions. Meanwhile, we excluded LPVs affected by blending from other sources using a blending factor threshold of 1.05 in the K band. We cross-matched them with the AllWISE and NEOWISE databases to obtain their MIR photometric data. Based on light curve fitting, we determined the mean magnitudes of these objects. The LPVs were classified into AGB, RGB, and RSG stars according to their positions on CMDs (W_G,BP,RP versus GBP − GRP). In this work we focused on AGB stars, which constitute the majority of LPVs. AGB stars were further classified as C-rich and O-rich subtypes based on the parameter in the Gaia DR3 LPV catalog. In the PL diagrams (M_{W1} versus logP), O-rich and C-rich AGB stars in the LMC show four and three distinct sequences, respectively. For the SMC, there are three sequences for both O-rich and C-rich AGB stars. We used the weighted least squares method to obtain the best-fit linear PLR for each sequence in both galaxies along with its uncertainty.

We compared the PLRs in the W1 and W2 bands for each sequence of LMC and SMC AGB stars. The PLRs of O-rich AGB stars in sequences C and C have smaller dispersion, making them more suitable as distance indicators. The dispersion of the D-sequence PLR is larger due to less accurate measurement of the LSP. The PLRs of LMC and SMC AGB stars in each sequence are very consistent, especially for sequence C. We compared the PLRs of C-sequence AGB stars in the LMC with PLRs of Miras from the literature and found that the PLRs of O-rich AGB stars and O-rich Miras are consistent. However, the PLRs of C-rich AGB stars and C-rich Miras in sequence C show significant differences in the W2 band. The W2-band PLR of C-rich Miras is brighter and has a steeper slope. This is because large-amplitude C-rich AGB stars have more circumstellar dust, leading to excess emission in the MIR bands.

We investigated the dependence of PLRs on metallicity ([M/H]) for LMC O-rich AGB stars and found linear relations ($\sigma = 2.3$–4.9) between PLR zero-point residuals and metallicities for sequences B, C, and D in the W1 band and sequences C and D in the W2 band. The coefficients of the metallicity effect are $\beta = -0.533 \pm 0.213$ mag dex^{-1} and $\beta = -0.767 \pm 0.158$ mag dex^{-1} for sequence C in the W1 and W2 bands, respectively. We also found that the scatter in PLMR is smaller than in PLR based on the same sample, and the p-value indicates a significant relationship with metallicity ($\sigma = 2.3$–4.6) for PLMR in sequences B, C, and D in the W1 band and sequences C and D in the W2 band. We suggest that the metallicity effect may need to be taken into account when measuring distances using O-rich Miras or O-rich AGB stars. Based on future APOGEE data, the coefficient error of the metallicity effect will be optimized to a level of 0.05–0.10 mag dex^{-1}.

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