Astrophysical Distance Scale: The AGB J-band Method. I. Calibration and a First Application

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Abstract

A near-infrared, color-selected subset of carbon-rich asymptotic giant branch (C-AGB) stars is found to have tightly constrained luminosities in the near-infrared J band. Based on JK photometry of some 3300 C-AGB stars in the bar of the Large Magellanic Cloud (LMC) we find that these stars have a constant absolute magnitude of \( M_J = -6.22 \) mag, adopting the detached eclipsing binary (DEB) distance to the LMC of 18.477 ± 0.004 (stat) ± 0.026 (sys). Undertaking a second, independent calibration in the Small Magellanic Cloud, which also has a DEB geometric distance, we find \( M_J = -6.18 \pm 0.01 \) (stat) ± 0.05 (sys) mag. For the LMC the scatter is ± 0.27 mag for single-epoch observations, (falling to ± 0.15 mag for multiple observations averaged over a window of more than one year). We provisionally adopt \( M_J = -6.20 \) ± 0.01 (stat) ± 0.04 (sys) mag for the mean absolute magnitude of these stars. Applying this calibration to stars recently observed in the galaxy NGC 253, we determine a distance modulus of 27.66 ± 0.01(stat) ± 0.04 (syst), corresponding to a distance of 3.40 ± 0.06 Mpc (stat). This is in excellent agreement with the average tip of the red giant branch (TRGB) distance modulus of 27.68 ± 0.05 mag, assuming \( M_I = -4.05 \) mag for the TRGB zero-point.

Unified Astronomy Thesaurus concepts: Distance indicators (394); Galaxy distances (590); Galactic and extragalactic astronomy (563); Asymptotic giant branch stars (2100); Red giant branch (1368)

1. Introduction

Examining near-infrared (NIR) color–magnitude diagrams (CMDs) of the Large Magellanic Cloud (LMC) based on the Two Micron All Sky Survey (2MASS) JHK survey, Nikolaev & Weinberg (2000) separated out and labeled various stellar populations, including two very red, high-luminosity regions (labeled F and J) that were populated by oxygen-rich and carbon-rich asymptotic giant branch (AGB) stars, respectively. These populations were followed by an even redder but more sparsely populated group (labeled K) which are also thought to be carbon stars, but in a short-lived phase, involving the development of strong winds and in situ dust production (e.g., Boyer et al. 2015; Pastorelli et al. 2019). In the same year, a complementary study conducted by van der Marel & Cioni (2001) was published using the same general techniques and similar goals, but using different survey data and slightly different color-selection criteria. Both studies successfully used NIR color-selected AGB stars (in the J branch of Weinberg & Nikolaev 2001, hereafter WN01) to measure the differential back-to-front geometry of the LMC. Figure 1 reproduces the K versus (J − K) CMD in WN01, defining their 11 distinct sequences of stars, based on 2MASS data for the LMC. The stars in Region J are high-luminosity AGB stars, whose colors are very red and whose intrinsic luminosities are well defined, and by construction, restricted to a narrow color range. This population of stars is made up of “carbon-rich” AGB stars of intermediate age and mass (e.g., Boyer et al. 2015; Ruffé et al. 2015; Jones et al. 2017). The stars in Region J also overlap with a subset of Mira variables in specific, and with long-period variables (LPV) more generally, with those stars being subclassified as such by their variability, amplitudes, colors, and periods (see Riebel et al. 2010). Within the context of this work on the extragalactic distance scale and within the following series of papers, the C-AGB stars found in Region J are being defined and selected in terms of purely single-eclipse, NIR photometric criteria. We emphasize from the outset that we rely neither on spectral data, nor on time-domain information to make efficient use of these stars as potentially high-precision and accurate extragalactic distance indicators.

In a companion paper (Freedman & Madore 2020) we discuss the historical context and empirical evidence for C-AGB stars being high-precision distance indicators. Based exclusively on previously published NIR data, we extend our application of this method to a sample of 14 galaxies, both within the Local Group and out to a distance of 4 Mpc. With that sample, we can assess the accuracy and current precision of the J-region Asymptotic Giant Branch (JAGB) method making a comparison with published distances that are based on the tip of the red giant branch (TRGB) method.

In this contribution, we use three galaxies to build, calibrate, and then test this new parallel path in the establishing the extragalactic distance scale. The LMC and Small Magellanic Cloud (SMC) are used to establish the zero-point of the JAGB method, and the galaxy NGC 253 is used as an extreme-case system, having been observed at the current distance limit, for ground-based telescopes, of about 4 Mpc. Published, NIR CMDs show that C-AGB stars have been found in abundance and easily measured in all three galaxies.

The “J” in JAGB method emphasizes the fact that this method is wholly dependent upon using J-band NIR photometry to minimize the dependence of the C-AGB stars’ luminosities on color.
We conclude that the JAGB method is a promising technique for determining distance to galaxies that can in principle be applied out to distances where the Leavitt Law for Cepheids and the TRGB method red giant stars have reached their practical limits. Taken as a whole, we refer to this tripartite ensemble of stellar distance indicators as forming the basis of the Astrophysical Distance Scale.

2. The LMC

NIR \textit{JHK} data used here for the LMC calibration of the JAGB method were taken from Macri et al. (2015). These observations are preferred over previously available 2MASS data (as used by WN01) for a number of reasons: the Macri photometry has higher precision and better spatial resolution (alleviating crowding), and, most importantly, these data are temporally averaged. The Macri data, which are all on the 2MASS photometric system, were collected over 13 months, resulting in an average of 16 epochs being obtained for each star in the survey. The cadence and window over which the observations were made were chosen so as to be able to identify known Cepheids and to discover new LPVs in order to determine their periods, amplitudes phases, and mean magnitudes in the NIR. The Cepheids are treated in Macri et al. (2015), while the Miras are discussed in Yuan et al. (2017).

It is also important to note that the Macri sample is confined to the bar of the LMC. This region is colocated with the detached eclipsing binary (DEB) stars, used for a geometric determination of the distance to the LMC, were observed by Pietrzynski et al. (2019). Having the DEBs and C-AGB stars located cospatially minimizes the concern that the two populations might be at different mean distances due to inclination effects and/or the generic back-to-front geometry of the LMC (e.g., Welch et al. 1987; Scowcroft et al. 2011; WN01). For the LMC bar and for our C-AGB stars, we adopt a true distance modulus of $\mu_o = 18.477$ mag, carrying a systematic error of $\pm0.026$ mag, as attributed to the DEB population by Pietrzynski et al.

Figure 2 shows the $J - (J - K)$ time-averaged, NIR CMD for the 3.5 million LMC stars published in Macri et al. (2015). The dominant population of red stars, rising vertically from $J \sim 14.5$ mag at around $(J - K) = 1.0$ mag consists of the...
Population II red giant branch (RGB), continuing up to its “tip” at $J \sim 13.5$ mag (Hoyt et al. 2018). This is followed (almost without interruption in this high-density plot) by the “oxygen-rich” AGB plume (marked midway at $J \sim 12.5$ mag). This feature continues up another several magnitudes to $J \sim 10.5$ mag in this diagram. It is important to note that both of these red populations, and almost all of the other dominant stellar populations in the NIR CMD, are confined to colors that are bluer than $(J - K) \sim 1.3$ mag. Redward of this limit there is only two remaining populations, one of them being the object of this study, i.e., the population of C-AGB stars. Operationally, we simply define C-AGB stars to have NIR colors between $1.30 < (J - K) < 2.00$ mag. The red limit eliminates the possibility of low-level contamination from extreme carbon stars that fall in magnitude and continue out to $(J - K) > 4.5$ mag, constituting what WN01 have independently designated as being a separate population, the “K Branch” (see Figure 1).

3. Absolute Calibration

As we proceed in the calibration of the absolute magnitude of the JAGB method, we begin by reviewing the conclusions reached earlier by WN01. They found a tight correlation between the $(J - K)$ color and the $K$-band luminosity of the “J-branch” stars as delimited and separated out in Figure 1. A luminosity-color fit to their 2MASS data in the $J$ Branch gave $K = D_o - 0.99 (J - K)$, where $D_o$ is the $K$-band zero-point of this particular “color–magnitude” relation. What Weinberg & Nikolaev did not comment on was that, by (not unreasonably) adopting a unit slope for the color term, their relation becomes

$$K = D_o - (J - K)$$

which, upon transposing the color term, becomes

$$J = K + (J - K) = D_o$$

Figure 2. Left side: the $J$ vs. $(J - K)$ CMD of the LMC based on data from Macri et al. (2015). The AGB population, as marked, is seen to be constant in luminosity as a function of color within the color range $1.30 \leq (J - K) \leq 2.00$ mag. The right-hand side of the figure shows the smoothed luminosity function of stars within that same color range.
or, more to the point

\[ J = \text{constant}. \]

Simply stated, in the NIR J band, C-AGB stars have a constant mean magnitude, independent of color.\(^4\)

Nikolaev & Weinberg (2000) measured the scatter in their single-epoch data to be on the order of \( \sigma_{\text{C-AGB}} = \pm 0.33 \) mag. However, in the presence of known variability in the C-AGB star population, the question naturally arises as to what the intrinsic (i.e., the time-averaged) scatter is for these stars. If we assume that the average amplitude of these stars is 0.7 mag (which corresponds to an equivalent sigma of \( \pm 0.22 \) mag) then subtracting this in quadrature from the observed (single-epoch) scatter \( \pm 0.33 \) mag gives an upper limit of \( \sigma_o = \pm 0.25 \) mag for the intrinsic scatter of the JAGB method. The observed, time-averaged scatter seen in the C-AGB LMC-bar sample (Macri et al. is found to be \( \pm 0.15 \) mag. Given the possibility of additional, currently unaccounted for, sources of scatter (residual depth effects, crowding, and photometric errors, etc.) we take this, already small, value for the intrinsic dispersion to still be an upper limit on the method.\(^5\)

3.1. The LMC

By adopting a true distance modulus to the LMC bar of \( \mu_o = 18.477 \) mag, and an apparent mean magnitude of \( J = 12.31 \pm 0.01 \) mag for the 3341 C-AGB stars studied here (also in the bar), we find that the mean absolute J band zero-point of the JAGB method (corrected for \( A_J = 0.053 \) mag of foreground extinction, NED) is \( M_J(\text{LMC}) = -6.22 \) mag \( \pm 0.01 \) (stat) \( \pm 0.03 \) (syst).\(^6\)

3.2. The SMC

The SMC may not seem to be an ideal object for testing the JAGB method, given that it is well known to be highly disturbed and tidally extended on the sky (e.g., Scowcroft et al. 2016 and references therein), presumably because of interactions with both the LMC and the Milky Way. But, one can select a subsample of C-AGB stars found in a one-degree-radius circular region centered on the main body of the SMC, which may arguably be less dispersed along that particular line of sight, when compared to the tidal tails, far from the main body (see Scowcroft et al. 2016). The JHK photometry for that subset of 116,298 SMC stars was extracted from the 2MASS on-line version of that survey, available through IRSA.

The CMD and luminosity function for the C-AGB stars in the SMC are each shown in Figure 3. 3405 C-AGB stars contributed to the color-selected luminosity function, yielding a mean apparent magnitude of \( J = 12.81 \pm 0.01 \) mag. The DEB distance modulus to the SMC is \( \mu_o = 18.965 \) mag, as published by Graczyk et al. (2014). Those DEB stars are centered on this same region of the SMC, making it not unreasonable to assume that their mean distance is the same as the average distance of the selected C-AGB stars. Applying a foreground Galactic extinction correction of \( A_J = 0.026 \) mag to the apparent magnitude of the C-AGB stars, and correcting for distance yields \( M_J(\text{SMC}) = -6.18 \) mag \( \pm 0.01 \) (stat) \( \pm 0.05 \) (syst).\(^6\)

4. A Provisionally Adopted Zero-point

Taking the two geometrically calibrated zero-points, based on DEB distances to the LMC and SMC, we arrive at our first estimate of the J band zero-point of the C-AGB distance scale: \( M_J(\text{nph}) = -6.20 \) mag \( \pm 0.01 \) (stat) \( \pm 0.04 \) (syst), where the systematic error is dominated by appropriately averaged the systematic errors on the DEB distances to the LMC (0.026 mag) and SMC (0.048 mag), respectively.

For single-epoch observations, the scatter in the JAGB method is found by \( \text{WN01} = 0.27 \) mag. For time-averaged observations, the scatter reduces to \( \pm 0.15 \) mag (Macri et al. 2015). In conservatively adopting the larger dispersion, a sample of 200 C-AGB stars can deliver a distance that is statistically good to a precision of 1%. To put that sample size in perspective, even in the restricted bar region of the LMC (itself a relatively low-mass, low-luminosity galaxy) there are over 3000 of these stars cataloged.

All galaxies with intermediate-age populations are now candidates for having high-precision distances determined by the JAGB method. In what follows, we make the first application of this method to the galaxy NGC 253 at 3.5 Mpc, some 70 times more distant than the LMC.

5. NGC 253: A First Test of the JAGB Method outside of the Local Group

For NGC 253, there are four modern Hubble Space Telescope detections of TRGB stars outside of the main disk of this nearby edge-on galaxy. Each determination has been standardized to an absolute I-band magnitude for tip of \( M_I = -4.05 \) mag and uniformly corrected for the same foreground extinction of \( A_I = 0.136 \) mag (NED). The homogenized distance moduli are 27.53 mag (Mouchine et al. 2005), 27.68 mag (Dalcanton et al. 2009), 27.67 mag (Rayburn-Smith et al. 2011), and 27.82 mag (Jacobs et al. 2009). The averaged TRGB distance modulus is found to be \( \langle M_I(\text{TRGB}) \rangle = 27.68 \) mag \( \pm 0.06 \) (scatter on the mean).

Ground-based Z and J-band data, used for the C-AGB detection, were published by Greggio et al. (2014) based on observations made as part of the VISTA science verification process. The CMD is shown in Figure 4. 3169 C-AGB stars in NGC 253 give an apparent distance modulus of \( \mu_J(C-\text{AGB}) = 27.67 \pm 0.006 \) mag.

\(^4\) While this paper was under review, it came to our attention that Ripoche et al. (2020) had revisited the very question of the color dependence of the carbon star luminosities as a function \((J - K)\) color. For their LMC sample they find a color term of \( \alpha = -0.039 \pm 0.038 \) mag/mag, and for their SMC sample they find a solution of the opposite slope, that being \( \alpha = +0.100 \pm 0.098 \) mag/mag. Neither solution is statistically significant.\(^5\)

Indeed, some Mira are known to have amplitudes up to 10 mag (peak-to-peak) in the blue. However, most of what is (residually) seen in the NIR is the sinusoidal variation of the radius, giving K-band amplitudes of less than 0.5 mag according to Weinberg & Nikolaev. Similarly, Smith et al. (2002) cite average J-band amplitudes of 0.5 mag. On the other hand, Huang et al. (2018) find H-band amplitudes of LMC Miras typically fall in the range of 0.4–1.3 mag, with an average amplitude of about 0.8 mag. Here we have adopted a provisional value of 0.7 mag for the average J-band amplitude). Nikolaev & Weinberg (2000) give a detailed break down of the various additional terms contributing to their single-phase observed scatter of \( \pm 0.33 \) mag. Those factors include back-to-front depth, photometric errors, differential extinction, and intrinsic scatter in their J Branch mean stellar magnitudes, and in their own words, they conclude that “This is direct evidence that our color-selected sources are standard candles at least as good as \( \sigma = 0.2 \) mag. In fact, they are even better.”

\(^6\) At the request of the referee, we checked our Macri/LMC solution using the Zaritskys merged UBVJHK catalog (https://www.as.arizona.edu/~denis/mcsurvey/Home.html), and then a one-degree sample of 2MASS stars centered on the LMC, obtained from the IRSA website (http://irsa.ipac.caltech.edu/cgi-bin/Gator/nph-scan). We obtained \( \langle J \rangle = 12.304 \pm 0.011 \) (stat) mag from Zaritsky, which gives \( MJ = 18.477 - (12.304 - 0.053) = 6.226 \) mag, and \( J = 12.317 \pm 0.016 \) (stat) mag which gives \( MJ = 18.477 - (12.317 - 0.053) = 6.213 \) mag. from the 2MASS/IRSA download.
Correcting for a foreground extinction of $A_J = 0.013$ mag (NED), the true C-AGB distance modulus to NGC 253 then becomes $\mu_o (\text{C-AGB}) = 27.66 \pm 0.01$ mag (stat).\footnote{As can be seen from Figure 4, the $(Z - J)$ color index used in this study is certainly capable of segregating out the red C-AGB stars from the bluer oxygen-rich population, but this color index is not the same as the $(J - K)$ color used by WN01 in defining the J Branch. We adopted a blue color cut $(Z - J) = 1.6$ mag. The effect of moving that color cut by $\pm 0.05$ mag results in a change of the mean $J$ magnitude of the total C-AGB population in NGC 253 amounting to $\pm 0.008$ mag.}

The agreement of these two determinations, made at the current limit of ground-based observing, is very encouraging, and foreshadows the confirming results of an inter-comparison of a significantly larger sample of C-AGB and TRGB distances to nearby galaxies, given in Freedman & Madore (2020). But what can be said here is that the low-metallicity calibration made using the LMC $[Z] = 8.50$ and SMC $[Z] = 7.98$ applies to apply equally well to the high-metallicity galaxy NGC 253 $[Z] = 8.99$, (Zaritsky et al. 2000, which is almost identical to the metallicity of M31, at $Z = 8.98$) whose C-AGB distance is in exact agreement with its independently determined TRGB distance.

Before concluding this paper, we next give a short description of the physics behind the JAGB method, showing that current models can justifiably claim to describe most of the salient aspects of this promising, new distance indicator.

6. A Very Brief Introduction to Stellar Evolution Models

Stellar evolution models have become sufficiently sophisticated of late that they can accommodate many of the details leading up to and including the transition producing carbon-rich AGB stars from their thermally pulsing (TP) oxygen-rich precursors (see Habing & Olofsson (2004) for extensive reviews, and especially Marigo et al. (2008, 2017) for more recent updates.) The intermediate-age, intermediate-metallicity TP-AGB stars, that are of interest to us here, as a whole have a narrowly defined range of masses, going from 2 to 5 $M_\odot$. As Marigo et al. (2008) show (in their Figure 1), these same stars (that have ages between 300 Myr and 1 Gyr) are tightly constrained in luminosity in their carbon-rich phase whose total range is only $\Delta \log (L/L_\odot) = 0.5$ (i.e., $\sigma = \pm 0.31$ mag) at $Z = 0.008$, for example.

It should be noted that the stellar interior physics, predicting the narrowly confined luminosities of carbon stars has been part of stellar evolution theory for nearly half a century. As for the reaction of the atmospheres, that situation is succinctly summarized by Marigo et al. (2008) wherein “... the main physical effects driving the appearance of the red tail of C stars,
are the cool effective temperatures, caused by changes in molecular opacities, as the third dredge-up events increase the C/O ratio.

The reasons for the upper and lower cutoffs to the oxygen-rich AGB evolution toward the red have also been known and understood for decades. The sole reason for these advanced-evolutionary-phase stars becoming as red as some of them do is because of carbon being transferred from the interior out into the envelope (and then into the atmosphere). The “dredge-up” episodes (number 3 and beyond), that penetrate deep enough into the interior to reach the carbon-rich, helium-burning shell, are only effective in bringing carbon to the surface for masses in excess of $1.2 \sim 1.3 M_\odot$ (Groenewegen & Marigo 2004). Below that critical mass AGB stars cannot, and do not, develop carbon-rich atmospheres. This leads to a lower bound on carbon star luminosities (Iben & Renzini 1983). At the other extreme, an upper limit on carbon star masses (and luminosities) comes from the destruction of carbon at the base of the convective zone. This occurs when the temperature in the carbon-rich interior region becomes so hot that carbon itself burns, leaving none of it left to be convected to the surface.

This phase transition to “Hot-Bottom Burning” turns on for AGB stellar masses in excess of $3.5 M_\odot$ (Iben 1973; Sackmann et al. 1974), and it may be cutting in at $2 M_\odot$ for very low-metallicity stars (Seiss et al. 2002).

The AGB phase of stellar evolution is still not fully understood, especially regarding the metallicity dependence of AGB evolution (e.g., Marigo et al. 2017; Pastorelli et al. 2019 and references therein.) In addition, the carbon star luminosity function is known to vary with age and metallicity in the $K$ band and in bolometric magnitude, but that their work suggests that the $J$ band may be more stable, as observations are indicating. Clearly, much work remains to be done from both the theoretical and the observational sides of this program; but, we are optimistic that the interaction will inform and benefit both sides.

7. Conclusions

C-AGB stars are easily identified in the NIR by their extremely red colors. They are also very luminous and have a well-defined mean magnitude in the $J$ band that is constant with color. Based on a sample of 3300 C-AGB stars in the bar of the NGC 253.
LMC, and a similar number of C-AGB stars in the main body of the SMC, we have calibrated the mean absolute magnitude of C-AGB stars in the NIR $J$ band. Using the DEB distance modulus of 18.477 mag to the LMC and an SMC DEB distance modulus of 18.965 mag, we provisionally find the mean $J$-band absolute magnitude of the C-AGB stars to be $M_J = -6.20 \pm 0.01$ (stat) $\pm 0.04$ (sys) mag. Applying this calibration to NGC 253, we derive a C-AGB distance modulus of $27.68 \pm 0.01$ (stat) $\pm 0.04$ (sys) mag, which corresponds to a metric distance of $3.44 \pm 0.06$ Mpc.

A more extensive application of the JAGB method to galaxies within and beyond the Local Group, extending out to 4 Mpc is presented in a companion paper (Freedman & Madore 2020).

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