A Preliminary Calibration of the JAGB Method Using Gaia EDR3

Abigail J. Lee1,2, Wendy L. Freedman1,2, Barry F. Madore1,3, Kayla A. Owens4, and In Sung Jang1,2
1Department of Astronomy & Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
2Kavli Institute for Cosmological Physics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA
3Observatories of the Carnegie Institution for Science 813 Santa Barbara Street, Pasadena, CA–91101, USA

Abstract

The recently developed J-region asymptotic giant branch (JAGB) method has extraordinary potential as an extragalactic standard candle, capable of calibrating the absolute magnitudes of locally accessible Type Ia supernovae, thereby leading to an independent determination of the Hubble constant. Using Gaia Early Data Release 3 (EDR3) parallaxes, we calibrate the zero-point of the JAGB method, based on the mean luminosity of a color-selected subset of carbon-rich AGB stars. We identify Galactic carbon stars from the literature and use their near-infrared photometry and Gaia EDR3 parallaxes to measure their absolute J-band magnitudes. Based on these Milky Way parallaxes we determine the zero-point of the JAGB method to be $M_J = -6.14 \pm 0.05$ (stat) $\pm 0.11$ (sys) mag. This Galactic calibration serves as a consistency check on the JAGB zero-point, agreeing well with previously published, independent JAGB calibrations based on geometric, detached eclipsing binary distances to the LMC and SMC. However, the JAGB stars used in this study suffer from the high parallax uncertainties that afflict the bright and red stars in EDR3, so we are not able to attain the higher precision of previous calibrations, and ultimately will rely on future improved DR4 and DR5 releases.

1. Introduction

Measuring the Hubble constant ($H_0$) precisely and accurately has remained a challenging endeavor for observational cosmologists. $H_0$ parameterizes the current expansion rate of the universe, and together with measurements of the cosmic microwave background (CMB) radiation, it provides a powerful constraint on the standard model of cosmology (e.g., Freedman & Madore 2010; Planck Collaboration et al. 2020). Because of its significance, the value of $H_0$ has undergone intense scrutiny and redetermination over the past few decades. Currently, early universe measurements of $H_0$ (forward modeled to the present day) as inferred from the measurements of the power spectra of the temperature and polarization anisotropies of the CMB appear to differ by 4–6σ from measurements directly measured by late-time universe distance ladders (Verde et al. 2019). Even more perplexing, the two most accurate and precise late-time universe values of $H_0$ measured by the Supernovae and $H_0$ for the Equation of State (SHoES) Group via the Leavitt law (Riess et al. 2016, 2019, 2021) and by the Carnegie–Chicago Hubble Program (CCHP) via the tip of the red giant branch (TRGB) method (Freedman et al. 2019, 2020; Freedman 2021) differ by about 2σ. Clearly, the local universe tension should be reconciled before concluding unambiguously that new physics is required to bridge the gap between early and late-universe measurements of $H_0$.

Recently, a new independent distance indicator was proposed as an alternative Type Ia supernovae calibrator to Cepheids and the TRGB in order to act as a tiebreaker, especially for more distant galaxies where the agreement between the two standard methods begins to break down, and where hidden systematic uncertainties may be revealed. This new method, the J-region asymptotic giant branch (JAGB) method, was introduced by Madore & Freedman (2020), was further applied and tested by Freedman & Madore (2020), and was also independently developed by Ripoche et al. (2020) and Parada et al. (2021).

JAGB stars are thermally pulsating asymptotic giant branch stars that are undergoing dredge-up events: instabilities in the two energy-producing shells in these stars induce episodes of upper-envelope convection that eventually penetrate deep into the helium-fusing shell which can result in freshly produced carbon being brought to the surface. The carbon then gives these stars a much redder appearance than their bluer oxygen-rich counterparts (Habing & Olofsson 2003). In order to distinguish this region of C-rich stars from the O-rich AGB stars to the blue and the extreme carbon stars to the red, Nikolaev & Weinberg (2000) defined color limits of 1.40 $<$ $(J - K_s)$ $<$ 2.00 mag for this class of stars they labeled as Region J in a $K$ versus $(J - K_s)$ color–magnitude diagram. The JAGB stars are also bounded in luminosity. JAGB stars have an upper magnitude limit as more luminous (and thus more massive) stars undergo hot-bottom burning, where as the carbon is being transported to the surface of the star during dredge-up, the star is so hot that the carbon is converted to nitrogen before it can reach the atmosphere. There also exists a lower magnitude limit because the dredge-up events for fainter (and thus less massive) stars are ineffective in transporting carbon to the surface. Therefore, JAGB stars have well-defined color and magnitude limits and can be easily photometrically identified.
Over 15 years ago, the mean absolute $I$-band magnitude of carbon stars was shown to be remarkably stable from galaxy to galaxy and was therefore proposed as a standard candle by Battinelli & Demers (2005). Recently, Lee et al. (2021) compared distances determined by the JAGB method, Cepheid Leavitt law, and TRGB in the Local Group galaxy Wolf–Lundmark–Melotte, finding agreement at the 3% level among the three methods. Lee et al. (2021) also found that the JAGB method had comparable precision to the Cepheid Leavitt law and TRGB, indicating enormous potential for its own future, independent $H_0$ measurement.

Madore & Freedman (2002) were the first to calibrate the JAGB method in the LMC and SMC via detached eclipsing binary (DEB) distances (Pietrzyński et al. 2019; Graczyk et al. 2014). In this paper, we provide an independent consistency check on that calibration using the Gaia Early Data Release 3 (EDR3) parallaxes. Gaia is a European Space Agency satellite that recently provided accurate astrometry for over 1.8 billion nearby sources in their EDR3 (Gaia Collaboration et al. 2016, 2021). However, limits in the accuracy of the Gaia parallaxes are still present, especially for bright and red stars, which we discuss in Section 4. Hence, our Gaia calibration remains preliminary only, and we expect that it will be superseded by future Gaia releases.

The outline of this paper is as follows. In Section 2, we discuss the photometry of our sample of Galactic JAGB stars. In Section 3, we give an overview of the Gaia distance measurements used in this study. In Section 4, we present an absolute calibration of the JAGB method zero-point via Gaia parallaxes, and discuss the limitations of the Gaia parallaxes for bright and red stars. In Section 5, we compare our absolute calibration with previous calibrations. Finally, in Section 6, we present a summary of this paper and the future direction of the JAGB method.

2. Photometry

In this section, we describe the Milky Way carbon stars used in this study. We identified two robust catalogs of Galactic carbon stars from Whitelock et al. (2006) and Chen & Yang (2012).

In Appendix, we also describe our attempts to identify JAGB stars solely on the basis of their color from the Two Micron All Sky Survey (2MASS) Point-source Catalog (Skrutskie et al. 2006). Unfortunately, stars in the 2MASS catalog with $m_J < 5.5$ mag, a magnitude limit that many Galactic JAGB stars are brighter than, have large photometric uncertainties on the order of 0.25 mag (Skrutskie et al. 2006). Gaia also reported potential large systematic parallax uncertainties for both bright and red stars, of which JAGB stars are both (Lindegren et al. 2021). In conclusion, we found that the large photometric and parallax uncertainties of bright JAGB stars made it difficult to discern them solely on the basis of color.

2.1. The Milky Way Carbon Star Sample

Whitelock et al. (2006) identified 239 Galactic carbon-rich variable stars from the IRAS Point-source Catalog (Beichman et al. 1988), the Aaronson et al. (1989) carbon star catalog, and their own observations of C stars, for which they measured $JHK_L$ photometry, defined on the South African Astronomical Observatory magnitude system (Carter 1990), which we converted to the 2MASS magnitude system using transformations from Koen et al. (2007). These carbon stars were selected on the basis of their color, $K$-band variability, carbon star SiC emission feature at $11.2 \mu m$, 25-to-12 $\mu m$ flux ratio, and $12 \mu m$ flux. The goal of their study was to identify Galactic carbon stars with accurate distances and radial velocities in order to gain insight into the ages and masses of the local carbon star population.\(^5\)

Chen & Yang (2012) compiled a sample of 972\(^6\) Galactic carbon stars from the literature, with 2MASS $JHK_s$ photometry. These stars were selected by their color, carbon star SiC emission feature at $11.2 \mu m$, flux ratios, and HCN + $C_2H_2$ feature in absorption spectra at $3.1 \mu m$. The goal of this study was to investigate carbon-rich AGB stars in the late stages of evolution.

Both Chen & Yang (2012) and Whitelock et al. (2006) applied Galactic interstellar extinction corrections to their photometry, using the Drimmel et al. (2003) three-dimensional Galactic extinction model, and following the reddening law from Glass (1999).

3. Gaia EDR3 Distances

To obtain distance estimates for each source, we chose not to perform a simple cone search between our carbon star catalog and the Gaia EDR3 catalog, as generally the most probable match is often not necessarily the nearest neighbor. Instead, the Gaia team has already matched the Gaia EDR3 catalog with the 2MASS catalog, calculating the most probable neighbor based on positional and source density properties (Marsee et al. 2017, 2019). This catalog is publicly available\(^7\) and can be queried at https://gaia.aip.de/query/. To find each carbon star’s corresponding 2MASS identifier, we located its SIMBAD entry using its R.A./decl. coordinates and name. Every star in the Whitelock et al. (2006) catalog had a corresponding 2MASS identifier. Of the 972 stars in the Chen & Yang (2012) catalog 14 lacked 2MASS identifiers, and were removed.

Using the tmass_psc_xsc_best_neighbor catalog, we then determined the unique Gaia EDR3 source id for each star from its corresponding 2MASS identifier. There were several sources in both catalogs that lacked Gaia counterparts: 2 in the Whitelock et al. (2006) catalog and 85 in the Chen & Yang (2012) catalog. This may occur because as carbon stars are moderately dusty, they may be too faint in the optical for Gaia to detect. This is one reason why it was beneficial to use this procedure instead of a simple cone search; while a cone search will always result in a nearest neighbor, utilizing the Gaia team’s best-neighbor match catalog revealed whether a given source had a genuine Gaia counterpart.

We then combined the two catalogs, finding 108 sources in common between them. This brought the total number of unique sources in our list to 970. If a source overlapped in both lists, we averaged its flux.

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\(^5\) We also removed 32 stars from the Whitelock et al. (2006) catalog that were missing $J$-band photometry.

\(^6\) There were two objects, IRAS 03291 +4116 and IRAS 20204 +2914, for which there were duplicate entries. However, neither star resided in the JAGB star color range, so they ended up being inconsequential to the final calculation.

\(^7\) Find the documentation at https://gea.esac.esa.int/archive/documentation/GEDR3/Gaia_archive/chap_datamodel/sec_dm_crossmatches/sec_dm_tmass_psc_xsc_best_neighbour.html.
Then, using each star’s Gaia EDR3 source id, we acquired a distance to each star from the Bailer-Jones et al. (2021) catalog of stellar distances, which was derived from the Gaia EDR3 information. Of the 970 stars, 30 did not have Bailer-Jones et al. (2021) distances available and were removed. The catalog gives two types of distance estimates for a given source: the geometric and photogeometric distance. The geometric distances were calculated from the star’s parallax, parallax uncertainty, and Galactic latitude and longitude. The photogeometric distances were calculated from the aforementioned parameters, as well as the star’s apparent $G$-band magnitude and $BP - RP$ color. Bailer-Jones et al. (2021) noted that their model for calculating photogeometric distances failed for stars at the bluest and reddest ends of the color range ($BP - RP \lesssim 0$ or $BP - RP \gtrsim 4$ mag, respectively; see Figures 4 and 5 of their paper). As carbon stars are extremely red stars, we found a fraction (7%) of our carbon star sample had $(BP - RP > 4)$ mag, and thus lacked photogeometric distances. Therefore, we opted to use the geometric distances. A common way of selecting sources with reliable astrometry from Gaia is to only use parallaxes much larger than their estimated uncertainties (Fabricius et al. 2021). We eliminated sources with $\sigma_\pi/\pi > 0.20$, where $\pi$ is the measured parallax by Gaia and $\sigma_\pi$ is the uncertainty on the parallax. The Gaia team also recommends cutting on the parameter ruwe, the primary indicator for the quality of a given astrometric solution (Fabricius et al. 2021). We used a cut of $ruwe < 2.0$, determined by Maíz Apellániz et al. (2021) likely to be a safe cut for determining high-quality parallaxes. After making these two data cuts, 579 carbon stars remained in our final catalog. We have made this catalog publicly available and show a sample of it in Table 1. Finally, we calculated the absolute $J$-band magnitude $M_J$ for each star, using its apparent $J$-band magnitude and distance from the Bailer-Jones et al. (2021) catalog.

4. Absolute Calibration of the JAGB Zero-point

We present our final $J$ versus $(J-K_s)$ color–magnitude diagram and $J$-band luminosity function for our sample of 579 carbon stars in Figure 1. This is a carbon star sample, not all carbon stars are JAGB stars. Extreme carbon stars with $(J-K_s) > 2.0$ mag do not have a constant $J$ magnitude, but decrease in magnitude with increasing $(J-K_s)$ color. These extreme carbon stars are heavily affected by dust obscuration and strong winds (Boyer et al. 2011), and have been excluded from our JAGB star sample after making the color cuts of $1.40 < (J-K_s) < 2.00$ mag following Nikolaev & Weinberg (2000). Based on the 153 remaining JAGB stars, we measured the median absolute $J$-band magnitude for the JAGB stars to be $M_J = -6.14$ mag. We chose not to utilize the mean as has been used in previous papers (Freedman & Madore 2020; Madore & Freedman 2020; Lee et al. 2021), as there were three outliers $> -4$ mag that significantly biased the mean $M_J$ to $-6.03$ mag (eliminating these three outliers gave a mean of $M_J = -6.15$ mag). We plan to explore the merits of using the mean, the median, and other methods for determining the JAGB magnitude in a future program aimed at obtaining high-precision $JHK$ photometry for several nearby galaxies. Finally, we discuss the statistical and systematic uncertainties associated with this measurement in Section 4.1 below.

4.1. Gaia Parallax Uncertainties for Bright and Red Stars

Weinberg & Nikolaev (2001) were the first to utilize carbon stars as a distance indicator in the broadband near-infrared filters. For their region-$J$ stars they measured the scatter to be $\pm 0.38$ mag about their $K_s$ versus $(J-K_s)$ relation, using single-epoch data. In comparison, the observed scatter on our JAGB star sample’s median $M_J$ (excluding the three outliers $>-4$ mag) was measured to be $\pm 0.60$ mag, yielding an error on the mean of $0.60/\sqrt{150} = 0.05$ mag, which we adopt as a statistical uncertainty on our measurement.

We note that the scatter in the observed luminosity function must include contributions from the intrinsic variability of the JAGB stars ($\sim 0.2$ mag), the variance due to extinction, parallax uncertainties, and photometric uncertainties (Weinberg & Nikolaev 2001). The Whitelock et al. (2006) $J$-band photometry has a precision better than $\pm 0.03$ mag and the median photometric uncertainty of the Chen & Yang (2012) $J$-band photometry is $\pm 0.026$ mag, indicating that the photometric uncertainties contribute little to the observed scatter.

Next, we estimated the uncertainty introduced from the extinction corrections applied to our photometry. Whitelock et al. (2006) provided $A_J$ values determined by their models for 144 C-rich Miras. We found that 17 of these Miras were also JAGB stars and passed our data cleaning cuts ($ruwe > 2.0$ and $\sigma_\pi/\pi < 0.20$), with a median extinction value in the $J$ band of $A_J = 0.16$ mag. The CCHP procedure is to adopt half of the

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### Table 1

**Carbon Star Catalog**

| Gaia EDR3 Source_id | 2MASS ID | $J$ (mag) | $(J-K_s)$ (mag) | Parallax (mas) | Distance$^a$ (pc) |
|---------------------|----------|-----------|----------------|----------------|------------------|
| 511851187421484544  | 02291531 – 2605559 | 4.074 | 2.536 | 1.807 | 540.0 |
| 3314192240947040    | 04312193 – 1739103 | 6.337 | 2.715 | 0.671 | 1454.6 |
| 29013199762449536   | 05434305 – 3223287 | 9.402 | 3.573 | 0.571 | 1573.3 |
| 34000177428534784   | 05453941 – 2041420 | 2.031 | 1.705 | 1.501 | 649.7 |
| 3304248194120411776 | 05453669 + 1216152 | 6.277 | 2.261 | 0.318 | 2728.1 |
| 337377664738495744  | 06114782 + 1908200 | 8.225 | 3.342 | 0.577 | 1536.4 |
| 3325351357754529152 | 06215800 + 0720576 | 4.413 | 2.068 | 0.662 | 1442.4 |

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*Note. Table 1 is published in its entirety in the machine-readable format. A portion is shown here for guidance regarding its form and content.*

$^a$ Geometric distance from Bailer-Jones et al. (2021). This table is available in its entirety in machine-readable form.
reddening value as its systematic uncertainty, which in this case would then be 0.08 mag (e.g., Jang et al. 2021). However, even adopting the full median extinction value of $A_J = 0.16$ mag as an uncertainty would still not be enough to explain the large observed scatter in the absolute $J$-band luminosity function.

Therefore, the large scatter may be explained, in part, by the fact that the astrometric precision of the Gaia parallaxes in EDR3 has strong color and magnitude dependencies, relying heavily on accurate point-spread function (PSF) fitting and calibration (Rowell et al. 2021). While we found the median parallax uncertainty of our sample of JAGB stars to be only $\pm 0.027$ mas, recent publications have found the Gaia EDR3 parallax uncertainties to be underestimated for brighter stars (El-Badry et al. 2021). For stars brighter than $G = 13$ mag, the instrument switches its main CCD sampling scheme to mitigate saturation effects. However, this secondary mode is more sensitive to PSF modeling deficiencies, leading to larger uncertainties (Rowell et al. 2021). These uncertainties are relevant for not only the bright JAGB stars, as all of the JAGB stars used in this study were brighter than $G = 13$ mag, but other local distance indicators as well. Fortunately, as detailed by Rowell et al. (2021), improvements in the PSF modeling, particularly for bright stars ($G < 13$ mag), are already being implemented for DR4. Advancements in the PSF modeling for Gaia DR4 will benefit the astrometry for several distance indicators including the JAGB stars and Cepheids.

In addition to the large statistical uncertainties, the Gaia parallaxes for the JAGB stars also likely suffer from systematic offsets. Although in theory Gaia should be able to measure absolute parallaxes, that is, for sufficiently distant sources such as quasars, the measured parallax by Gaia should be zero. However, the accuracy of Gaia’s astrometry has been shown to be subject to various instrumental effects that cause a global systematic offset in the parallaxes with respect to the International Celestial Reference System (Lindegren et al. 2018), referred to as the parallax zero-point offset. For their EDR3 in 2020 December, Gaia reported a median zero-point offset of $-17 \mu$as, with systematic variations on the order of $10 \mu$as, defined by over 1.6 million background quasars (Lindegren et al. 2021). However, this parallax zero-point offset was derived from quasars in the magnitude and color ranges of $G > 16$ mag and $(GP−RP) < 1.6$ mag (Lindegren et al. 2021), respectively, ranges within which none of our bright and red JAGB stars fall. Lindegren et al. (2021) speculated that sources outside of the region of parameter space well populated by quasars could have additional systematic uncertainties ranging from a few microarcseconds to several tens of microarcseconds.

Several recent publications have attempted to also quantify additional parallax offsets in the Gaia EDR3 data. Using first-ascent red giant branch stars with asteroseismic parallaxes,
Zinn (2021) derived an offset of $-15 \pm 3 \mu\text{as}$. Huang et al. (2021) found a global offset of $-9.8 \pm 1.0 \mu\text{as}$ for the <10.8 mag Large Sky Area Multi-Object Fibre Spectroscopic Telescope (LAMOST) primary red clump (PRC) stellar sample. Stassun & Torres (2021) compared the EDR3 parallaxes with distances derived from eclipsing binaries and found a maximum additional offset of $+33 \mu\text{as}$. Using globular clusters, Maťa Apellániz et al. (2021) measured an offset of $+6.9 \pm 2.2 \mu\text{as}$ for stars in the range of $9.3 < G < 11$ mag. Finally, Riess et al. (2021) derived a $-14 \pm 6 \mu\text{as}$ offset by comparing the EDR3 parallaxes with Hubble Space Telescope (HST) photometrically predicted parallaxes. Thus, due to the lack of consensus on a parallax offset value, we conservatively adopt $\pm 30 \mu\text{as}$ as the systematic uncertainty on the parallax measurements. We propagated this uncertainty on the parallax estimates into an error on $M_J$, which amounted to $\pm 0.11$ mag. We thus adopt $-0.11$ mag as a systematic uncertainty on the absolute calibration.

We look forward to the Gaia DR4, which promises better astrometry and self-calibration of the global parallax zero-point, especially for brighter and redder stars (Lindemgren et al. 2021). In conclusion, we report our final value for the JAGB zero-point to be $M_J = -6.14 \pm 0.05$ (stat) $\pm 0.11$ (sys) mag.

### 5. Comparison with Previous Calibrations

Previous JAGB calibrations are compiled in Table 2. This is the first study to date that has utilized the Gaia EDR3 parallaxes as the geometric anchor for the JAGB method. Two previous studies, Madore & Freedman (2020) and Ripoche et al. (2020), both anchored the JAGB method to the LMC and SMC. Ripoche et al. (2020) also measured a JAGB zero-point based on Gaia DR2 parallaxes.

For the LMC-based calibrations, Madore & Freedman (2020) found $M_J = -6.22 \pm 0.01$ (stat) $\pm 0.03$ (sys) mag, based on a DEB distance to the LMC (Pietrzyński et al. 2019). Using the same LMC DEB distance, Ripoche et al. (2020) measured $M_J = -6.28 \pm 0.004$ mag.

For the SMC-based calibrations, Madore & Freedman (2020) found $-6.18 \pm 0.01$ (stat) $\pm 0.05$ (sys) mag based on the SMC DEB distance from Graczyk et al. (2014). Ripoche et al. (2020) found $-6.16 \pm 0.015$ mag based on the Scowcroft et al. (2016) Leavitt law SMC distance.

Finally, Ripoche et al. (2020) measured an $M_J = -5.60 \pm 0.026$ mag based on Galactic carbon stars. This calibration was measured using Gaia DR2 parallaxes. They attributed their considerably fainter calibration to the high parallax uncertainties from Gaia DR2.

### 6. Summary and Conclusions

The JAGB method is a geometrically calibrated and simply applied stellar distance indicator that capitalizes on the fact that JAGB stars are easily identified in the near-infrared. We have identified a sample of 153 JAGB stars from Milky Way carbon star catalogs, for which we derived distances using Gaia EDR3 parallaxes. We present an absolute calibration of the JAGB method, $M_J = -6.14 \pm 0.05$ (stat) $\pm 0.11$ (sys) mag for this Galactic sample.

Our Milky Way JAGB calibration is completely independent of and agrees well with the Madore & Freedman (2020) LMC and SMC DEB-based calibrations of $M_J(LMC) = -6.22 \pm 0.01$ (stat) $\pm 0.03$ (sys) mag and $M_J(SMC) = -6.18 \pm 0.01$ (stat) $\pm 0.05$ (sys) mag. Averaging these three calibrations yields an updated JAGB zero-point of $M_J = -6.18 \pm 0.02$ (stat) $\pm 0.04$ (sys) mag. Moreover, no statistically significant trend with increasing host-galaxy metallicity is found here, with the SMC ($M_J = -6.18$ mag, $[\text{Fe/H}] \sim -0.8$ dex), LMC ($M_J = -6.22$ mag, $[\text{Fe/H}] \sim -0.5$ dex), and Milky Way ($M_J = -6.14$ mag, $[\text{Fe/H}] \sim 0$ dex) already spanning a large range in present-day metallicity. We also note that our calibration is also in excellent agreement with the independent Ripoche et al. (2020) SMC calibration of $-6.16 \pm 0.015$ mag, and consistent to within $1.2\sigma$ of their LMC calibration of $-6.28 \pm 0.004$ mag.

We have demonstrated that the JAGB method’s absolute J-band calibration is consistent across three independent zero-point calibrators. With this increasing accuracy, the stage is being set for the JAGB method to be more widely applied as a primary extragalactic distance indicator. We look forward to the release of Gaia DR4 in 2022, which will bring with it several improvements in its astrometry.

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This research made use of the cross-match service and SIMBAD database (Wenger et al. 2000), provided by and operated at CDS, Strasbourg. This research has made use of NASA’s Astrophysics Data System Bibliographic Services.

**Software:** Astropy (Astropy Collaboration et al. 2013, 2018), TOPCAT (Taylor 2005), NumPy (van der Walt et al. 2011).

### Table 2

| Study                  | $M_J$ (mag) | Anchor                          |
|------------------------|-------------|---------------------------------|
| Madore & Freedman (2020)| $-6.22 \pm 0.01$ (stat) $\pm 0.03$ (sys) | LMC DEB (Pietrzyński et al. 2019) |
| Madore & Freedman (2020)| $-6.18 \pm 0.01$ (stat) $\pm 0.05$ (sys) | SMC DEB (Graczyk et al. 2014) |
| Ripoche et al. (2020)  | $-6.28 \pm 0.004$                          | LMC DEB (Pietrzyński et al. 2019) |
| Ripoche et al. (2020)  | $-6.16 \pm 0.015$                          | SMC Leavitt Law (Scowcroft et al. 2016) |
| Ripoche et al. (2020)  | $-5.60 \pm 0.026$                          | Gaia DR2 Galactic Parallaxes |
| This Work              | $-6.14 \pm 0.05$ (stat) $\pm 0.11$ (sys)  | Gaia EDR3 Galactic Parallaxes |
Appendix

Identifying JAGB Stars with 2MASS Photometry

In addition to identifying JAGB stars from spectroscopically selected carbon star catalogs in the literature, we also attempted to photometrically select JAGB stars solely on the basis of their color. This approach follows that of Madore & Freedman (2020), who photometrically selected JAGB stars without using carbon star catalogs for their LMC and SMC DEB-based calibrations.

A.1. 2MASS Sample

To build a Galactic near-infrared color–magnitude diagram, $JHK_s$ data for Galactic stars were obtained from the 2MASS All Sky Point-source Catalog and the Gaia EDR3 best-neighbor cross-match catalog (tmass_psc_xsc_best_neighbor) using a Galactic latitude constraint of $|l| > 30$. We chose to limit our catalog to sources with high Galactic latitude in order to avoid high line-of-sight contamination from Galactic dust and source crowding (Skrutskie et al. 2006). We also applied more stringent data cuts ($ruwe < 1.4$ and $\sigma_\pi/\pi < 0.10$) than in Section 3 to obtain the highest-quality parallaxes.

A.2. Issues in the Astrometry and Photometry

In Figure A1, we show in a color–magnitude Hess diagram that the JAGB stars at $1.4 < (J−K_s) < 2.0$ mag were heavily contaminated by bluer O-rich AGB stars. In this section, we explore several potential explanations for why the photometry and astrometry of the 2MASS sample was too inaccurate to distinguish between the O-rich AGB stars and JAGB stars using the standard color cuts. First, as discussed in Section 4.1, bright ($G < 13$ mag) and red stars in the Gaia catalog suffer from high parallax errors resulting from their parallax zero-point offset measurement and uncertainties in the PSF fitting routines. Second, reddening could also be a source of error. In the future, we will explore applying the Wesenheit function (Madore 1982) as a means of correcting the reddening. Third, Skrutskie et al. (2006) reported large photometric uncertainties on the order of ~0.25 mag for bright stars with $m_J < 5.5$ mag. Removing stars with $m_J < 5.5$ mag or $G < 13$ mag was not a viable solution because it would have removed many of the brighter JAGB stars and introduced a systematic bias in $M_J$.

 Attempts to clean our photometry with cuts on the distance ($d < 1$ kpc) and fractional parallax uncertainty ($\sigma_\pi/\pi < 0.05$), shown in Figure A2, also proved unsuccessful. In both cases, a large fraction of the O-rich AGB stars remained post-cleaning, continuing to make it impossible to distinguish between the O-rich AGB stars and the JAGB stars. Therefore, we found that photometrically selecting a sample of Galactic JAGB stars was not a viable option at this time, and for the time being, chose to select JAGB stars from Galactic carbon star catalogs instead.

![Figure A1](image1.png)

Figure A1. $J$ vs. $(J−K_s)$ color–magnitude Hess diagram for the full 2MASS-selected sample. The JAGB stars are obscured by O-rich AGB stars likely because of large errors from reddening, Gaia parallax uncertainties, and 2MASS photometric uncertainties.

![Figure A2](image2.png)

Figure A2. Cleaned $J$ vs. $(J−K_s)$ color–magnitude Hess diagrams for the 2MASS-selected sample, filtered by distance (left) and fractional parallax uncertainty (right). We determined that attempts to clean the 2MASS photometry using aggressive cuts on distance and fractional parallax uncertainty were still ineffective in isolating the JAGB stars, particularly at the blue end.
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ORCID iDs

Abigail J. Lee https://orcid.org/0000-0002-5865-0220
Wendy L. Freedman https://orcid.org/0000-0003-3431-9135
Barry F. Madore https://orcid.org/0000-0002-1576-1676
Kayla A. Owens https://orcid.org/0000-0003-3339-8820
In Sung Jang https://orcid.org/0000-0002-2502-0070

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