The Carnegie-Chicago Hubble Program. IV. The Distance to NGC 4424, NGC 4526, and NGC 4536 via the Tip of the Red Giant Branch

Dylan Hatt1, Wendy L. Freedman1, Barry F. Madore1,2, Rachael L. Beaton3,8,9, Taylor J. Hoyt1, In Sung Jang4, Myung Gyoon Lee5, Andrew J. Monson6, Jeffrey A. Rich2, Victoria Scowcroft7, and Mark Seibert7

1 Department of Astronomy & Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637, USA; dhatt@uchicago.edu
2 Department of Astrophysical Sciences, Princeton University, 4 Ivy Lane, Princeton, NJ 08544, USA
3 Leibniz-Institut für Astrophysik Potsdam, D-14482 Potsdam, Germany
5 Department of Physics & Astronomy, Seoul National University, Gwanak-gu, Seoul 151-742, Republic of Korea
6 Department of Astronomy & Astrophysics, Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA
7 Department of Physics, University of Bath, Claverton Down, Bath, BA2 7AY, UK

Abstract

The Carnegie-Chicago Hubble Program is undertaking a re-calibration of the extragalactic distance scale, using SNe Ia that are tied to Tip of the Red Giant Branch (TRGB) distances to local galaxies. We present here deep Hubble Space Telescope ACS/WFC imaging of the resolved stellar populations in the metal-poor halos of the SN Ia-host galaxies NGC 4424, NGC 4526, and NGC 4536. These three Virgo constellation galaxies are prime targets for calibrating the extragalactic distance scale given their relative proximity in the local universe and their low line-of-sight reddenings. Anchoring the TRGB zero-point to the geometric distance to the Large Magellanic Cloud via detached eclipsing binaries, we measure extinction-corrected distance moduli of $31.00 \pm 0.03_{stat} \pm 0.06_{sys}$ mag, $30.98 \pm 0.03_{stat} \pm 0.06_{sys}$ mag, and $30.99 \pm 0.03_{stat} \pm 0.06_{sys}$ mag for NGC 4424, NGC 4526, and NGC 4536, respectively, or $15.8 \pm 0.2_{stat} \pm 0.4_{sys}$ Mpc, $15.7 \pm 0.2_{stat} \pm 0.4_{sys}$ Mpc, and $15.8 \pm 0.2_{stat} \pm 0.4_{sys}$ Mpc. For these three galaxies, the distances are the first that are based on the TRGB, and for NGC 4424 and NGC 4526, they are the highest-precision distances published to date, each measured to 3%. Finally, we report good agreement between our TRGB distances and the available Cepheid distances for NGC 4424 and NGC 4536, demonstrating consistency between the distance scales currently derived from stars of Population I and II.

Key words: distance scale – galaxies: individual (NGC 4424, NGC 4526, NGC 4536) – stars: Population II

1. Introduction

At present, there remains a significant tension in the value of $H_0$ as determined by direct methods (e.g., Freedman et al. 2012; Riess et al. 2016) and by indirect methods, such as modeling of the Cosmic Microwave Background (e.g., Komatsu et al. 2011; Planck Collaboration et al. 2016). The need for improved systematic accuracy in the direct distance ladder has motivated the Carnegie-Chicago Hubble Program (CCHP; Freedman 2014), which is calibrating anew the SN Ia extragalactic distance scale, using Population (Pop) II stars. This route is independent of and parallel to the traditional Pop I, Cepheid-based distance scale, and can, therefore, provide insight into the current divide in the measurement of $H_0$.

Pop II stars have numerous advantages over their Pop I counterparts as distance indicators. In the first instance, Pop II stars are found in the gas- and dust-free, outer halos of galaxies, where source crowding and confusion is also less than that of the disk and where the uncertainty associated with line-of-sight reddening is naturally minimized.

The primary focus of the CCHP is the Tip of the Red Giant Branch (TRGB) Method, which has been well-studied both theoretically (Iben & Renzini 1983; Renzini et al. 1992) and empirically (an overview of recent calibration efforts is given in Bellazzini 2008). In brief, the He-flash marks the point of rapid departure of stars from the high-luminosity (hydrogen shell-burning) TRGB over to bluer colors (higher temperatures, smaller radii) and onto the lower-luminosity (helium core-burning) Horizontal Branch. This phase is initiated by the lifting of degeneracy in the helium cores of red giant branch (RGB) stars having total masses of $\lesssim 1.8 M_\odot$ (Salaris & Cassisi 2005). The peak luminosity in this phase is insensitive to stellar metallicities as high as $[\text{Fe/H}] = -0.3$ (Barker et al. 2004).

This CCHP paper is the second in detailing the measurement of TRGB distances to nine nearby galaxies containing a cumulative 12 SN Ia. Previously, we have published a distance to NGC 1365 (Jang et al. 2018, Paper III), host to the SN Ia SN 2012fr. In addition, we have measured the distance to the Local Group galaxy IC 1613 (Hatt et al. 2017, hereafter, Paper II). IC 1613 and NGC 1365 represent the extremes in distance for galaxies studied in the CCHP, approximately 730 kpc and 18.1 Mpc, respectively. A summary of science goals and expected error budgets, including calibration of the RR Lyrae distance scale, are given in Beaton et al. (2016, Paper I).
In this paper, we present TRGB distances to three SN Ia-host galaxies—NGC 4424, NGC 4526, and NGC 4536—using deep Hubble Space Telescope (HST) imaging of their halos. NGC 4424 is a barred spiral galaxy that was host to the recent SN Ia, SN 2012cg (Cenko et al. 2012). NGC 4526 is an S0/ lenticular galaxy in the Virgo Cluster and was host to SN 1994D (Treffers et al. 1994). Finally, NGC 4536 is a spiral galaxy that was host to SN 1981B (Branch et al. 1983). Earlier work suggests that these galaxies all lie at a similar distance of \( \sim 15 \) Mpc, and they can therefore serve as important calibrators for the SN Ia distance scale in the local universe.

Moreover, the results presented here are of particular importance to the SN Ia distance scale because (1) they are the first TRGB distances for these galaxies and (2), in the case of NGC 4424 and NGC 4526, these are the first distance estimates achieving high-precision (3\%) errors in distance. An increased level of precision for these distances is made possible, in part, by the recent availability of an improved (2.2\% precision) geometric distance to the Large Magellanic Cloud (LMC) derived from detached eclipsing binaries (Pietrzyński et al. 2013). In the near-term, we anticipate that it will be possible to even more precisely anchor the TRGB distance scale (to 1\% precision) directly within the Milky Way, using \textit{Gaia} parallaxes of RGB stars. At that time, we anticipate that the precision of the results presented here will improve further.

The paper is organized as follows: Section 2 describes the observations and photometry. Section 3 presents the analysis of the TRGB, including the estimation of measurement uncertainties and the determination of distances. Section 4 places the distances measured here in the context of previously published estimates, especially recent Cepheid-based determinations, and Section 5 provides a summary and the immediate impact of the results presented in this study.

2. Data

The image processing and extraction of photometry follow the procedures described in Paper II and employed for the SN Ia-host galaxy NGC 1365 in Paper III. In the following sections, we briefly summarize the observations as well as their reduction and calibration.

2.1. Observations

Imaging in this study made use of the HST Advanced Camera for Surveys with the Wide-Field Channel (ACS/ WFC). Observations were specifically designed to target galaxy halos, where the selection of the fields is described in Paper II. In summary, these fields were chosen: (i) to avoid disks (if any), young (blue) populations and/or tidal structures; (ii) to straddle the \textit{WISE} \textit{W1} 25–26 mag isophote and the \textit{GALEX} NUV 27–28 mag isophote, if applicable; and (iii) to be aligned along the minor axes so as to maximize the number of uncrowded halo stars within each field of view. Figure 1 displays the imaging coverage for this study, and Table 1 provides a summary of the observations.

For each galaxy, six orbits were devoted to three F606W and nine F814W exposures, each of which were approximately 1200 s in length. Exposure time calculations were optimized to achieve an approximate signal-to-noise ratio (S/N) of 10, in F814W, at the anticipated magnitude of the TRGB. The image products used here were FLC data files, obtained from the \textit{Space Telescope Science Institute} website. As received, these images are calibrated, flat-fielded, and CTE-corrected. Each frame was then multiplied by its corresponding Pixel Area Map\textsuperscript{10} to account for flux differences due to ACS/WFC geometric distortions.

2.2. Photometry

We derived instrumental magnitudes from individual images through point-spread-function (PSF) fitting using the DAOPHOT software (Stetson 1987). The PSFs for F606W and F814W were created using synthetic star grids generated using the HST Tiny Tim PSF modeling software (Krist et al. 2011). A direct test of the Tiny Tim PSFs against direct frame-by-frame PSF modeling with isolated, bright stars is described in Paper II and was found to agree to within the quoted photometric uncertainties. Images were aligned from preliminary catalogs using DAOMATCH/DAOMASTER (Stetson 1987) then simultaneously photometered using the ALLFRAME software (Stetson 1994) with a “master source list” from a co-add of all images.

2.3. Calibration of Photometry

Instrumental magnitudes were brought onto the HST Vega magnitude system using Equations (2) and (4) of Sirianni et al. (2005). The photometric zero-points are 26.405 mag for F606W and 25.517 mag for F814W, accessed on 2018-05-12.\textsuperscript{11} We note that there is a systematic uncertainty in the observed flux of Vega, which forms the basis for the ACS zero-point calculation. As per Sirianni et al. (2005), we adopt a conservative 2\% systematic uncertainty in flux (0.02 mag) for these zero-points. The correction from the PSF magnitudes to the 0\%5 aperture magnitudes was calculated for each filter and CCD combination. Due to the small number of bright and isolated stars that are free of cosmic rays (typically \( \sim 3 \) per frame), we have previously adopted a mean value from all frames for each filter and CCD. This approach was shown in Paper II to be indistinguishable from tailoring corrections to a frame-by-frame basis when bright and isolated stars are abundant. In this work, we have found that the frame-by-frame corrections, obtained through an automated selection of bright and isolated stars, yield the same science result as when using the average correction. In the following, all results use the frame-by-frame corrections. In Table 2, we list the averages for brevity, where the standard deviation of values across all frames for a given CCD and filter is typically 0.03 mag. We have found during the study of NGC 1365 in Paper III that independent efforts in the selection of bright, isolated stars resulted in differences at the \( \sim 0.01 \) mag level. In the following, we therefore adopt a 0.01 mag systematic uncertainty in the photometric calibration due to the aperture correction at 0\%5. We plan to investigate the uncertainty of this correction in greater detail in future works.

The 0\%5 to infinite aperture correction values are 0.095 and 0.098 mag for the F606W and F814W filters, respectively (Bohlin 2016), which were computed from the provided Encircled-Energy (EE) tables. Bohlin (2016) quotes a 4\% uncertainty in EE for cool, late-type stars (i.e., RGB stars) that are used to compute these 0\%5 to infinite aperture corrections. Table 6 of Sirianni et al. (2005), however, shows that the total variation in EE due to changes in effective wavelength via

\textsuperscript{10} \url{http://www.stsci.edu/hst/acs/analysis/PAMS}  
\textsuperscript{11} \url{https://acszeropoints.stsci.edu/}
spectral type is < 0.01 mag for WFC at 0°5, implying that the EE for these cooler stars are consistent with hotter stars that are constrained at the 1% level. In this study, we adopt half of the Bohlin (2016) estimate, or 2% error in flux (0.02 mag) as another systematic uncertainty due to the scatter in the measured EE for the RGB stars that are the focus of this work. In total, we have adopted a combined 0.03 mag systematic uncertainty attributed to the Vegamag zero-points, measured aperture corrections, and the EE of late-type stars.

2.4. Color–Magnitude Diagrams

The calibrated photometry is presented in the form of color–magnitude diagrams (CMDs) in Figure 2. In each plot, median uncertainties in measured F814W and F606W–F814W are shown for a variety of magnitudes. Each CMD shows a “pure halo” component, i.e., only an RGB, mixed with likely thermally pulsating Asymptotic Giant Branch (TP-AGB) stars above the RGB and early-type AGB (E-AGB) in the same magnitude range as the RGB. In the following, we often refer to the two AGB classes as a single “AGB” component. The small color range for the RGB in each CMD reflects the metal-poor nature of the halos surrounding these galaxies. In a later section, we quantify the effect of contamination by AGB sources as well as assess the level of photometric completeness and crowding/blending through extensive artificial star tests and population models.

Figure 2(a) displays the CMD for NGC 4424. This field has the second-most notable AGB/blended RGB component of the three galaxies in this study, although the TRGB is still readily detected as demonstrated later in this work. The contamination by AGB/blends, or blurring of the TRGB, is partly attributable to crowding and source confusion given the relative proximity of the observations to the galaxy center.

Figure 2(b) is the CMD of NGC 4526, which has the most-populated RGB, and consequently, the most-populated TRGB. It is apparent that there is less of an AGB/blended RGB component compared to NGC 4424. Given the favorable

### Table 1
ACS/WFC Observation Summary

| Target   | Dates       | Filters [no. obs. × exposure time (s)] | α (2000)   | δ (2000)   | Field Size      |
|----------|-------------|----------------------------------------|------------|------------|-----------------|
| NGC 4424 | 2015 May 18 | F606W [3 × 1200], F814W [9 × 1200]     | 12°27′12″  | +09°27′32″ | 3°37′ × 3°37′   |
| NGC 4526 | 2015 Jun 13 | F606W [3 × 1200], F814W [9 × 1200]     | 12°34′04″  | +07°45′11″ | 3°37′ × 3°37′   |
| NGC 4536 | 2015 Dec 14–15 | F606W [3 × 1200], F814W [9 × 1200] | 12°34′21″  | +02°08′41″ | 3°37′ × 3°37′   |

**Note.** See also Figure 1 for imaging coverage.

### Table 2
Measured Aperture Corrections at 0°5

| Target   | Chip 1 | Chip 2 |
|----------|--------|--------|
|          | F606W (No.) | F814W (No.) | F606W (No.) | F814W (No.) |
| NGC 4424 | −0.12 (26) | −0.13 (121) | −0.12 (24) | −0.12 (100) |
| NGC 4526 | −0.12 (33) | −0.10 (111) | −0.12 (37) | −0.12 (99)  |
| NGC 4536 | −0.08 (29) | −0.06 (90)  | −0.10 (45) | −0.07 (142) |

**Note.** Number of bright, isolated stars used in the average is given in parentheses.
number of stars defining the tip, the major contribution to the uncertainty in measuring the TRGB is then expected to be photometric errors.

Figure 2(c) shows the CMD of NGC 4536, which has the most prominent AGB/blended RGB component of the three galaxies studied here. Although the TRGB of NGC 4536 is more visually obscured in comparison to the previous two cases, the jump in the star counts in the luminosity function (LF) at the TRGB is nonetheless readily detectable, as demonstrated in the following section.

As a special note for NGC 4536, we identified a luminous stellar component that spans part the highest star density region of the imaging for chip 2. The feature appears visually consistent with a spiral arm or other stellar feature. This possible spiral arm suggests that the CMD for NGC 4536 is not a "pure" halo. The impact of the blue sources is quantified later in Section 3.5.

3. The Tip of the Red Giant Branch

3.1. Background

The TRGB is a discontinuity in the RGB LF for low-mass stars as they rapidly drop in luminosity while evolving over and down onto the Horizontal Branch. This process is triggered by the Helium-flash at a critical core mass, where an electron degenerate equation-of-state simultaneously fixes the star’s bolometric luminosity. In the I-band (or in the HST equivalent, F814W filter), the TRGB is remarkably fixed in brightness for observations of metal-poor stars, such as those presented here (although corrections for the higher-metallicity extension have recently been calibrated empirically for ACS/WFC filters by Jang & Lee 2017). A detailed physical description of the TRGB and its measurement is given in Paper II, Paper III, and the references therein. In the following, we revisit only major points.

In making our measurements of the brightness of the TRGB, we have used bins of 0.01 mag in width to measure the relative star abundance in the F814W LF. This finely binned LF has then been smoothed using GLOESS (Gaussian-windowed, Locally Weighted Scatterplot Smoothing), which is an interpolating technique first used in an astrophysical context for Cepheid light curves by Persson et al. (2004). A further example of GLOESS can also be found in Monson et al. (2017) in the discussion of RR Lyrae light curves.

The underlying principle behind GLOESS smoothing is the sequential moving and fitting of a second-order polynomial to the entire data set of points weighted by their Gaussian distance to a given reference point. This polynomial is swept across the interval of interest at arbitrarily small, but user-controlled, steps. The degree of smoothing is controlled by the width of the Gaussian window, which we define as $\sigma_s$. On the smoothed LF, we then apply a Sobel filter $[-1, 0, +1]$ (as first introduced for this application by Lee et al. 1993), which is the finite-difference version of the first-derivative for a discrete function. This Sobel kernel is an effective "edge detector", given that it produces the maximum response when the local change in the LF is greatest, i.e., at discontinuities, such as those encountered at the TRGB.

Paper II describes a procedure using artificial star tests to empirically derive the value for $\sigma_s$ that minimizes the the associated statistical (random) and systematic uncertainties in the measurement of the TRGB, which are expected to be unique for a given data set. In the following section, we create similar artificial star LFs that are tailored to the observations in this study.

Figure 2. Color–magnitude diagrams of the galaxies NGC 4424, NGC 4526, and NGC 4536. Likely TP-AGB stars are mixed with Red Giant Branch stars, though a steep jump in the luminosity function of each CMD still marks the location of the TRGB as seen later in this work. Median uncertainties in magnitude and color are shown alongside each CMD.
3.2. Artificial Star LFs

In order to effectively model the RGB and AGB populations as seen in our observations, we first created an artificial star LF for each galaxy in order to better understand the natural blurring of the TRGB discontinuity due to factors including photometric errors, crowding, and contamination by AGB stars.

As described in Paper II, we adopted the RGB and AGB LF slopes of 0.3 dex mag\(^{-1}\) and 0.1 dex mag\(^{-1}\), respectively. For each galaxy, 2000 stars were placed into each of our ACS/WFC CCD frames at pixel coordinates chosen by randomly sampling from a uniform distribution in \(X\) and \(Y\) in order to avoid over-crowding in any given realization. Stellar magnitudes were drawn from the RGB and AGB LFs as described above. The RGB LF was chosen to begin at F814W = 26.9 mag, and was then sampled 1 mag fainter. The AGB LF was started 1 mag brighter than the input TRGB and extended 1 mag downward through the TRGB, down to faint end of the RGB LF. The color for each star was drawn from a uniform distribution 1.0 \(\leq (F606W - F814W) \leq 1.5\) mag to adequately model the natural breadth of the TRGB due to metallicity, though still within the anticipated metal-poor range where “tip rectification” or metallicity correction tools are unnecessary. Finally, we set the relative number of RGB to AGB stars below and above the tip to have a population ratio of 4:1. This ratio is a lower limit on the RGB-AGB contrast based on recently published statistics for these populations in local galaxies (e.g., Rosenfield et al. 2014). The simulation was repeated 500 times for each CCD, producing \(500 \times 2 \times 2000 = 2,000,000\) artificial stars per field/galaxy (see Figure 3(a)).

3.3. Photometric Completeness and Crowding

Based on the photometry of artificial stars, we find that the fraction of recovered stars is primarily dependent on the S/N of the input star rather than the physical location the star in the imaging; moreover, the completeness of stars across our sample of galaxies is fairly stable in the simulated magnitude range. The recovery rate of stars at the faint limit of the artificial star simulations is 96%, 98%, and 91% for NGC 4424, NGC 4526, and NGC 4536, respectively. In the TRGB magnitude range, the recovery of artificial stars stands at the 98%–99% level. We conclude that source crowding is not a significant factor in recovering stars within our data sets.

Regarding blends, we have performed an estimation of possible blends through surface brightness arguments via Renzini (1998) as follows: we divide our imaging into sections, aligned along the minor axes of each galaxy so that we take into account that the surface brightness of the imaging trends with distance from the central galaxy. We compute the total counts in F606W (the V-band is used by Renzini 1998), correct to V-band magnitudes using Table 22 of Sirianni et al. (2005), then transform them into absolute magnitudes using the approximate distance moduli that we measure via the TRGB (distances are derived later in Section 3.5).

Using units of solar luminosities per pixel, we scale the population counts in the Renzini (1998) Table 1 from their \(10^5 L_\odot\). The probability of a blend (when the predicted numbers are less than unity) is simply the product of the predicted abundances. We compute the probability of a blend for each region in each galaxy by considering all likely pair combinations of RGBT, E-AGB, and TP-AGB stars (RGBT is defined as an RGB stars within 1 mag of the TRGB in
Renzini 1998). We assume that the photometry in the region at hand is likely compromised, making a measurement of the TRGB difficult, if the probability of a blend exceeds 0.05 (5%).

We find that the cumulative probability exceeds our defined blend threshold in the 10% of the footprint that is closest to the disk of only NGC 4424, especially in the case of chip 2. In the following analysis, we exclude this region.

3.4. Optimizing the TRGB Edge Detection

With artificial star LFs in hand that probe the properties of the images used in this study, we now investigate how a randomly generated LF subset—comparable in number counts and slope to the observed data—affects the measurement of the TRGB as a function of the adopted GLOESS-smoothing scale.

In order to ensure that our artificial star LFs are reflective of the observed LFs, the relative number of RGB to AGB stars was adjusted so that the slope of the artificial LF at the TRGB mirrored that of the observed LF. This alteration is permissible because our method relies only on the total shape of the LF, i.e., it does not differentiate between the shapes of the individual stellar components. Consequently, the exact slopes or number counts of AGB and RGB components is unimportant.

We first estimate the number of stars that contribute to the TRGB measurement. We count 2852 (1147), 2054 (2133), and 1121 (3285) stars in chip 1 (chip 2) within a ±0.25 mag interval centered on the estimated TRGB magnitude for NGC 4424, NGC 4526, and NGC 4536, respectively. We then model the true locations of sources by their Cumulative Distribution Functions (CDFs). Although we do not expect crowding to play a significant role in our TRGB measurement as discussed above, we nonetheless model the locations of sources as closely as possible to embody all possible known and unknown properties of the images. We then apply inverse transform sampling of these CDFs, locating the artificial stars that lie closest in X and Y, until the number of artificial stars for each CCD matches the observed count. For a fixed GLOESS \( \sigma_r \), we run our Sobel edge detector and record the location of the greatest change in the LF. This process was repeated 10000 times (enough for the TRGB simulations to converge across all three galaxies) for smoothing scales of 0.01 \( \leq \sigma_r \leq 0.18 \) mag.

Figure 3(b) presents the uncertainties associated with edge detection in our data sets as a function of smoothing scales, \( \sigma_r \). Squares represent average systematic differences between the measured and input tip magnitude; plusses represent the dispersion of measured tip magnitudes, or a measure of the statistical (random) uncertainty; and circles represent these uncertainties added in quadrature. We find that the location of the TRGB is well-recovered at a \( \leq 0.02 \) mag level of precision. This result is not entirely surprising: simulations by Madore et al. (2009) have shown that 0.1 mag precision in tip detection can be achieved with \(~400\) stars in the first magnitude of the RGB. For the galaxies studied here, we have enormous statistical samples of 22224, 15439, and 15069 stars in the first magnitude below the anticipated TRGB. The high precision in the measurement of the TRGB then suggests that the driving source of uncertainty for the galaxies being studied here is photometric errors. Finally, Figure 3(c) shows the distribution of measurements for the simulated TRGBs relative to their input values.

These modeled measurement uncertainties, combined with the adopted calibration errors, show that the galaxies studied here are found to have roughly the same overall uncertainties (±0.04–0.05 mag) in the measured magnitudes of their tip discontinuities. This fact translates into almost identical uncertainties in their distances (±0.5 Mpc), scaled to a common TRGB zero-point, as calculated in the following section.

3.5. TRGB Measurements and Distances

On the topic of line-of-sight reddening, the targets of this study were chosen, in part, because of their estimated low foreground extinction (i.e., \( E(B-V) \leq 0.02 \); Schlafly & Finkbeiner 2011 obtained via the NASA/IPAC Extragalactic Database, NED). Adopting a Cardelli et al. (1989) reddening law, the predicted foreground reddening is \( A_{F814W} = 0.03 \) mag in all three cases. The uncertainty in \( E(B-V) \) is estimated to be ±0.03 mag (Schlegel et al. 1998), which suggests that the foreground extinctions for each of these galaxies are statistically consistent with zero. We conservatively include half of the value of the predicted extinction as an additional systematic error in the distance moduli derived below.

Although the foreground reddening is predicted to be very low, it is not yet possible to assess whether there is extinction intrinsic to the halos themselves. One possible test for the presence of halo dust, however, is to observe whether or not the apparent TRGB magnitude changes with increasing projected distance from the galaxy. We tested for this possibility by dividing the images into two distinct regions of stars having equal numbers. We re-ran our TRGB simulations with the adjusted star counts for this new test to find the appropriate level of GLOESS smoothing to minimize the combined measurement uncertainties. We found that even with the reduced statistics, the required level of smoothing is comparable to its original value with the full stellar catalogs. In each of the three galaxies, we found that the region closest to the disk was in fact brighter than further away, ranging between 0.05 and 0.10 mag. This observation is the opposite expectation to a reddening effect, and we note that the previous two targets in the CCHP series, IC 1613 and NGC 1365, had no discernible difference in the measured TRGB across different regions of the imaging. Instead, it suggests that the edge detector may be triggering off bright stars or AGB stars—a known systematic when the number of TRGB stars is limited—or other stellar populations near the TRGB that are not resolved in color–magnitude space due to signal-to-noise considerations and the proximity of the imaging to their respective bodies.

In Section 3.3, we identified blends as probably being present for the 10% of the footprint for NGC 4424 closest to its disk, which is likely to be the source of the brighter TRGB measurement for that galaxy. We plan to undertake a more comprehensive, consistent review of the photometry for all galaxies that are part of the CCHP in a future work in order to make an informed decision of when regions of a CCD are compromised and, if so, how they can be accounted for. At present, we take the entire photometry sample for NGC 4526 and NGC 4536 as is for the basis of our science result. As stated in Section 3.3, we exclude the region of NGC 4424 whose photometry is likely compromised by blends.

We turn now to the question of metallicity. At high-metallicity, a downward sloping TRGB is observed in color–magnitude space for the reddest stars at optical wavelengths. However, the observations used in this study were specifically crafted to target the metal-poor halos of these galaxies. As a result, the TRGBs in...
our sample of galaxy halos do not show any discernible color–magnitude dependence and are not red enough to necessitate the application of TRGB “rectification tools” (for ACS filters see Jang & Lee 2017); in other words, there is negligible slope to correct.

Figure 4 displays the results of the TRGB measurement using the optimally selected GLOESS-smoothing scales for each galaxy. We find the following F814W (I-band equivalent) TRGB magnitudes: For NGC 4424, $I_{\text{TRGB}} = 27.03$ mag, for NGC 4526, $I_{\text{TRGB}} = 27.01$ mag, and for NGC 4536, $I_{\text{TRGB}} = 27.02$ mag. The targeting of the galaxy halos minimizes the need for the isolation of RGB stars via a color–magnitude selection cut. We note only a 0.01 mag difference in the aforementioned measurement for NGC 4424 when removing the bluest of sources F606W – F814W ≤ 0.6 within the CMD. As with the study of NGC 1365 in Paper III, all three galaxies have little to no difference in measured TRGB magnitudes.
value at the 0.01 mag level with or without a color–magnitude selection cut.

We noted in Section 2.4 that NGC 4536 has an apparent spiral arm or other stellar feature that passes through the imaging. In order to ensure that we are largely, if not exclusively, measuring the TRGB for Pop II stars, we manually select the physical region in the imaging that encompasses what appears to be the arm. We then compare the difference in the TRGB measurement with and without the contribution of stars in this region. We find that the TRGB is only 0.01 mag fainter without the arm than with it, or in other words, a difference that is negligibly small compared to the other uncertainties we have quoted thus far in the analysis.

We conclude this section by making explicit our adopted zero-point for the TRGB. The F814W filter is a "broad I" filter, and the observed transformation from F814W to the I-band is a negligible 0.002 ± 0.017 mag effect for a common color of V − I ≈ 1.0 for bright RGB stars (see Table 22 of Sirianni et al. 2005). We therefore adopt a provisional zero-point in the I-band, using three recent determinations of the I-band discontinuity of the TRGB in the LMC as follows: (1) Romaniello et al. (2000) give a reddening-corrected value of $I_0 = 14.50 ± 0.25$ mag. (2) Sakai et al. (2000) find $I_0 = 14.54 ± 0.04$ mag. (3) Cioni et al. (2000) also find $I_0 = 14.54 ± 0.04$ mag. The weighted mean of $I_{0,MC} = 14.54$ mag compares favorably with the reddetermination of Jang & Lee (2017), who obtain $I_0 = 14.524 ± 0.042$ from the mean of eight fields covering the eclipsing binaries with known geometric distances. We adopt $E(B−V) = 0.03 ± 0.03$ mag for the reddening of the LMC TRGB stars (see Hoyt et al. 2018). Combining this corrected, weighted mean with our adopted LMC distance modulus of 18.49 mag, we arrive at $M_I = −4.00$ mag ± 0.03stat ± 0.05sys for the I-band TRGB absolute zero-point calibration. At present, we have adopted the systematic uncertainty for the LMC distance following Pietrzyński et al. (2013), based on their study of detached eclipsing binaries in the LMC bar. Applying the corresponding foreground reddening correction and provisional TRGB zero-point, we present the LMC moduli and true distances in Table 3.

Table 3
Summary of TRGB Distances to NGC 4424, NGC 4526, and NGC 4536

| Galaxy     | $m_{TRGB}$ | $σ_{stat}$ | $σ_{sys}$ | $m − M$ | $σ_{stat}$ | $σ_{sys}$ | $D$ (Mpc) | $σ_{stat}$ | $σ_{sys}$ |
|------------|------------|------------|------------|----------|------------|------------|-----------|------------|------------|
| NGC 4424   | 27.03      | 0.03       | 0.03       | 31.00    | 0.03       | 0.06       | 15.8      | 0.2        | 0.4        |
| NGC 4526   | 27.01      | 0.03       | 0.03       | 30.98    | 0.03       | 0.06       | 15.7      | 0.2        | 0.4        |
| NGC 4536   | 27.02      | 0.03       | 0.03       | 30.99    | 0.03       | 0.06       | 15.8      | 0.2        | 0.4        |

Notes.

a F814W.
b Combined statistical and systematic uncertainties from the edge-detection method and calibration to the HST flight magnitude system.
c $M_I^{TRGB} = −4.00 ± 0.03 ± 0.05$ mag.

d The interested reader is referred to the following four papers for detailed discussions of the intricacies of calibrating the zero-point of the I-band TRGB, (a) through the galactic globular cluster ω Cen (Bellazzini et al. 2001), (b) using scaled theoretical models (Bellazzini 2008), (c) setting the zero-point at the LMC (Jang & Lee 2017, who derive a totally consistent zero-point $M_I = −3.970 ± 0.102$ mag to the value derived here, albeit with a significantly larger uncertainty), and finally (d) iterating distance determinations to nearby galaxies (Rizzi et al. 2007). In the latter paper, we note that their Figure 13 indicates that the maser NGC 4258 (which has a truly independent, geometric distance determination) gives an I-band TRGB zero-point of $−3.94$ mag. Their preferred value is, however, $−4.05 ± 0.02$ at $(V − I) = 1.6$ mag.

4. Distance Comparisons

The following are comparisons of the TRGB distances determined here against previously published, independent measurements, which are visualized in Figure 5.

4.1. NGC 4424

At the time of this writing, there are four publications reporting distances to this galaxy. Two of these estimates are based on the Tully–Fisher relation, though only the more recent analysis by Cortés et al. (2008) is based on a direct measurement of NGC 4424. Their distance of 30.90 ± 0.30 mag, obtained using synthetic $H_β$ rotation curves, is considerably more uncertain compared to our 31.00 ± 0.03stat ± 0.06sys mag, but there is mutual agreement in the estimates to within their reported errors.

The third of four publications on the distance to NGC 4424 is based on observations of SN 2012cg itself (Munari et al. 2013). They find an average distance of 30.95 mag (no quoted uncertainty and using only VRI observations), which, though consistent with our estimate, is not a truly independent comparison given the SN Ia calibration objectives of the CCHP.

The fourth and most recent estimate is based on just three Cepheids published in Riess et al. (2016). That paper finds an “approximate” distance modulus of 31.08 ± 0.29 mag. To within 1σ in the combined uncertainties, that distance determination for NGC 4424 is formally consistent with our more precise value.

The compilation of independent estimates (Tully–Fisher and Cepheids), obtained via NED (excluding Munari et al. 2013), yields a mean distance of 31.00 ± 0.21 mag. This value is only a slight improvement over the two original estimates alone, but it is still consistent with the value determined here.

4.2. NGC 4526

There are over 20 published distance moduli for this galaxy, but the span in those estimates is large, ranging from 29.23 to 31.47 mag. Some of the most precise measurements for NGC 4526 come from Globular Cluster Luminosity Functions (GCLFs) that were derived as part of the the ACS Virgo Cluster Survey (Jordán et al. 2007; Villegas et al. 2010). The most recent estimates presented in Villegas et al. (2010) give 30.89 ± 0.10 mag and 31.03 ± 0.09 mag for the g- and z-bands, respectively, or an average 30.97 ± 0.07 mag. Individually or combined, the GCLFs and our estimate 30.98 ± 0.03stat ± 0.06sys mag are in mutual agreement.

Additional distances to NGC 4526 are available based on its SN Ia, SN 1994D. Of the 14 publications that report a SN Ia distance, 2 report measurements with sub-0.1 mag uncertainties:

12 The interested reader is referred to the following four papers for detailed discussions of the intricacies of calibrating the zero-point of the I-band TRGB, (a) through the galactic globular cluster ω Cen (Bellazzini et al. 2001), (b) using scaled theoretical models (Bellazzini 2008), (c) setting the zero-point at the LMC (Jang & Lee 2017, who derive a totally consistent zero-point $M_I = −3.970 ± 0.102$ mag to the value derived here, albeit with a significantly larger uncertainty), and finally (d) iterating distance determinations to nearby galaxies (Rizzi et al. 2007). In the latter paper, we note that their Figure 13 indicates that the maser NGC 4258 (which has a truly independent, geometric distance determination) gives an I-band TRGB zero-point of $−3.94$ mag. Their preferred value is, however, $−4.05 ± 0.02$ at $(V − I) = 1.6$ mag.
Parodi et al. (2000) and Jha et al. (2007). The average of these is $31.18 \pm 0.03$, nearly 0.2 mag fainter than our result and that of the GCLFs (as well as several standard deviations apart). A direct comparison to SN Ia distances here is not very informative given the goal of the CCHP to independently calibrate them, but we note the possibility of a large systematic in their SN Ia zero-points due to underlying assumptions regarding the value of $H_0$.

Finally, the remaining distance indicators with “modern” (since the year 2000) publications include Tully–Fisher (31.02 ± 0.40 mag, Courtois & Tully 2012) and Surface Brightness Fluctuations (average 30.98 ± 0.07 mag, Ferrarese et al. 2000; Ajhar et al. 2001; Tonry et al. 2001; Tully et al. 2013). Thus, there appears to be excellent consistency between all distance indicators for NGC 4526 (excluding SN Ia distances). The mean of the methods listed above gives a precise 30.98 ± 0.05 mag that is consistent with our distance. Importantly, the TRGB distance given here represents an order-of-magnitude improvement in precision over most previously published, individual estimates.

4.3. NGC 4536

Aside from its SN Ia, distance determinations for NGC 4536 have focused on Cepheids and the Tully–Fisher relation. For Cepheids, the measured distance moduli have varied greatly with bounds of 30.61–31.24 mag. Those with reported measurement uncertainties produce an average of $30.88 \pm 0.01$ mag, where the uncertainty (the error on the mean) is minuscule due to the fact that NED lists 45 estimates from 36 unique publications. We note that we have not adjusted these estimates to a common zero-point or reddening and have simply used the values “as published.” For the purposes of this work, we note them here merely to establish a reference point for the historical efforts to determine the distance to NGC 4536. The most recent Cepheid publication reported an “approximate” distance of $30.91 \pm 0.05$ mag (Riess et al. 2016), which is consistent with the historical average. These Cepheids-based distances are to be compared to the value determined here using the TRGB, $30.99 \pm 0.3_{\text{stat}} \pm 0.06_{\text{sys}}$ mag. Our distance for NGC 4536 is approximately 1.2 standard deviations from the recent Riess et al. (2016) estimate, and roughly 1.6 standard deviations from the average of historical Cepheid distances.

In contrast to the Cepheids, the Tully–Fisher relation has produced a notably smaller distance modulus. Its average is $30.83 \pm 0.04$ mag from nine publications that report uncertainties (since the year 2000), though it is only approximately one standard deviation from the historical Cepheid average. When combined with the Cepheid distances, the literature again produces an average $30.88 \pm 0.01$ mag, which is dominated by the large number of Cepheid estimates and their small reported uncertainties. Despite the small uncertainty on
the averages, we again caution that the values are simply used “as is” without altering their zero-point or reddening assumptions, which may not be possible depending on the level of detail given in each publication. Thus, it would be safe to assume that the uncertainties on the Cepheid and NED averages are underestimated and could be as large as the standard deviations of their values, 0.13 mag and 0.39 mag, respectively. In this scenario, our reported distance for NGC 4536 is consistent with the literature.

5. Conclusion

We have determined the first TRGB distances to three SN Ia-host galaxies—NGC 4424, NGC 4526, and NGC 4536—which are an integral part of an on-going effort by the CCHP to independently set the SN Ia absolute zero-point using (Population II) TRGB distances. We find good agreement between these latest results (with independent systematics) in comparison to a number of previously published distances for each of these galaxies. In particular, we find consistency between the distances derived from Pop I and II stars in NGC 4424 and NGC 4536, where the comparisons were possible.

The TRGB distances determined here are of relatively high precision at 3% uncertainty in distance; and in the cases of NGC 4424 and NGC 4526, they represent a substantial improvement over previously published estimates. For this reason, the results presented here will serve as valuable calibrators for the SN Ia extragalactic distance scale. With future Gaia data releases, the CCHP will be refining the TRGB distance scale locally using Milky Way RGB stars, thereby improving the zero-point accuracy of the TRGB method as a whole and further improving upon the distances estimates reported here. Longer-term, with the pending launch of JWST, it will be possible to extend the TRGB method, as demonstrated here using HST, to samples of galaxies at even greater distances.

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Facility: HST (ACS/WFC).
Software: DAOPHOT (Stetson 1987), ALLFRAME (Stetson 1994), TinyTim (Krist et al. 2011).

References

Ajhar, E. A., Tonry, J. L., Blakeslee, J. P., Riess, A. G., & Schmidt, B. P. 2001, ApJ, 559, 584
Barker, M. K., Sarajedini, A., & Harris, J. 2004, ApJ, 606, 869
Beaton, R. L., Freedman, W. L., Madore, B. F., et al. 2016, ApJ, 832, 210
Bellazzini, M. 2008, MmSAI, 79, 440
Bellazzini, M., Ferraro, F. R., & Pancino, E. 2001, ApJ, 556, 635
Bohlin, R. C. 2016, AJ, 152, 60
Branch, D., Lacy, C. H., McCalm, M. L., et al. 1983, ApJ, 270, 123
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Cenko, S. B., Filippenko, A. V., Silverman, J. M., et al. 2012, ATel, 4115, 1
Cioni, M.-R. L., van der Marel, R. P., Loup, C., & Habing, H. J. 2000, A&A, 359, 601
Cortés, J. R., Kenney, J. D. P., & Hardy, E. 2008, ApJ, 683, 78
Courtois, H. M., & Tully, R. B. 2012, ApJ, 749, 174
Ferrarese, L., Mould, J. R., Kennicutt, R. C., Jr., et al. 2000, ApJ, 529, 745
Freedman, W. 2014, CHP-II: The Carnegie Hubble Program to Measure Ho to 3% Using Population II, HST Proposal, 13691
Freedman, W. L., Madore, B. F., Scowcroft, V., et al. 2012, ApJ, 758, 24
Hatt, D., Beaton, R. L., Freedman, W. L., et al. 2017, ApJ, 845, 146
Hoyt, T. J., Freedman, W. L., Madore, B. F., et al. 2018, ApJ, 858, 12
Iben, I., Jr., & Renzini, A. 1983, ARA&A, 21, 271
Jang, I. S., Hatt, D., Beaton, R. L., et al. 2018, ApJ, 852, 60
Jang, I. S., & Lee, M. G. 2017, ApJ, 835, 28
Jha, S., Riess, A. G., & Kirshner, R. P. 2007, ApJ, 659, 122
Jordán, A., McLaughlin, D. E., Côté, P., et al. 2007, ApJS, 171, 101
Komatsu, E., Smith, K. M., Dunkley, J., et al. 2011, ApJS, 192, 18
Krist, E. J., Hook, R. N., & Stoehr, F. 2011, Proc. SPIE, 8127, 81270I
Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, ApJ, 417, 553
Madore, B. F., Mager, V., & Freedman, W. L. 2009, ApJ, 690, 389
Monson, A. J., Beaton, R. L., Scowcroft, V., et al. 2017, ApJ, 153, 96
Munari, U., Henden, A., Belligoli, R., et al. 2013, NewA, 20, 30
Parodi, B. R., Saha, A., Sandage, A., & Tammann, G. A. 2000, ApJ, 540, 634
Persson, S. E., Madore, B. F., Krzeminski, W., et al. 2004, AJ, 128, 2239
Pietrzyński, G., Graczyk, D., Gieren, W., et al. 2013, Natur, 495, 76
Planck Collaboration, Ade, P. A. R., Aghanim, N., et al. 2016, A&A, 594, A13
Renzini, A. 1998, AJ, 115, 2459
Renzini, A., Greggio, L., Ritossa, C., & Ferrario, L. 1992, ApJ, 400, 280
Riess, A. G., Macri, L. M., Hoffmann, S. L., et al. 2016, ApJ, 826, 56
Rizzi, L., Tully, R. B., Makarov, D., et al. 2007, ApJ, 661, 815
Romanelli, M., Salaris, M., Cassisi, S., & Panagia, N. 2000, ApJ, 530, 738
Rosenfield, P., Marigo, P., Girardi, L., et al. 2014, ApJ, 790, 22
Sakai, S., Zaritsky, D., & Kennicutt, R. C., Jr. 2000, AJ, 119, 1197
Salaris, M., & Cassisi, S. 2005, Evolution of Stars and Stellar Populations (1st ed.; New York: Wiley)
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Sirianni, M., Lee, M. G., & Benitez, N., et al. 2005, PASP, 117, 1049
Stetson, P. B. 1987, PASP, 99, 191
Stetson, P. B. 1994, PASP, 106, 250
Tonry, J. L., Dressler, A., Blakeslee, J. P., et al. 2001, ApJ, 546, 681
Treffers, R. R., Filippenko, A. V., van Dyk, S. D., et al. 1994, IAU Circ., 5946, 2
Tully, R. B., Courtois, H. M., Dolphin, A. E., et al. 2013, AJ, 146, 86
Villegas, D., Jordán, A., Peng, E. W., et al. 2010, ApJ, 717, 603

ORCID iDs

Dylan Hatt @ https://orcid.org/0000-0003-2767-2379
Barry F. Madore @ https://orcid.org/0000-0002-1576-1676
Taylor J. Hoyt @ https://orcid.org/0000-0001-9664-0560
In Sung Jang @ https://orcid.org/0000-0002-2502-0070
Myung Gyoon Lee @ https://orcid.org/0000-0003-2713-6744
Victoria Scowcroft @ https://orcid.org/0000-0001-8829-4653
Mark Seibert @ https://orcid.org/0000-0002-1143-5515