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APPLICATION OF CEPHEIDS TO DISTANCE SCALE: EXTENDING TO ULTRA-LONG PERIOD CEPHEIDS

Chow-Choong Ngeow
Graduate Institute of Astronomy, National Central University, Jhongli 32001, Taiwan
E-mail: cngeow@astro.ncu.edu.tw
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ABSTRACT

Classical Cepheids (hereafter Cepheids) belong to a class of important variable stars that can be used to determine distances to nearby galaxies via the famous period-luminosity (PL) relations, i.e. the Leavitt Law. In turn, these distances can then be used to calibrate a host of secondary distance indicators located well within the Hubble flow, and ultimately determine the Hubble constant in a manner independent of the Cosmic Microwave Background (CMB) measurements. Some recent progress in determining the Hubble constant to within ∼ 3% level via the Cepheid-based distance scale ladder (the SH0ES and the Carnegie Hubble Program) were first summarized in this Proceeding, followed by a brief discussion on the prospect of using ultra-long period Cepheids (ULPC) in future distance scale work. ULPC are those Cepheids with periods longer than 80 days, which seem to follow a different PL relation than their shorter period Cepheids. It has been suggested that ULPC can be used to determine the Hubble constant in "one-step". However, based on the two ULPCs found in M31, it was found that the large dispersion in derived distance moduli leads to a less accurate distance modulus to M31 compared to the classical Cepheids. This finding might raise an alert regarding the use of ULPCs in future distance scale work.

Key words: stars: variables: Cepheids — distance scale

1. INTRODUCTION

For the local expansion rate of the Universe, the Hubble constant H_0, is an important parameter in the era of precision cosmology. Since E. Hubble (Hubble, 1929; Hubble & Humason, 1931), many efforts have been made to measure H_0 precisely using various observational techniques – see, for examples, Jackson (2007), Tammann et al. (2008) and Freedman & Madore (2010) for recent reviews. These different observational techniques and methods constitute the extra-galactic distance scale ladder[1], with ultimate goal of measuring the H_0 and its associated error to within a few percent. Note that properly and accurately calibrating the distance indicators in each rung of the ladder is crucial and important for climbing up the ladder. This allows the connection between local and cosmological distance indicators for the H_0 measurement. The main reason for measuring the H_0 to within a few percent accuracy, or even down to ∼ 1%, via the extra-galactic distance scale ladder is to constrain and/or break the degeneracy in cosmological parameters when combined with other cosmological measurements such as the CMB anisotropies (for examples, see Efstathiou & Bond, 1999; Hu, 2005; Freedman & Madore, 2010; Freedman et al., 2011; Riess et al., 2011; Weinberg et al., 2013). Furthermore, comparison of the H_0 from extra-galactic distance scale ladder with measurements from CMB anisotropies (for examples, Verde et al., 2013a,b; Gao & Gong, 2014; Planck Collaboration XIV, 2014) could hint towards new physics, such as the need of an additional sterile neutrino species (Wyman et al., 2014), or for the cosmological parameters to be refined (Li et al., 2014). In this Proceeding, we summarized some of the recent progress on measuring H_0 via the Cepheid-based distance scale ladder (Section 2), and we briefly discussed the prospect of using the so-called ultra-long period Cepheids (ULPC) in future distance scale work (Section 3).

[1] The latest version of the extra-galactic distance scale ladder can be found in de Grijs (2011), or in `http://kiaa.pku.edu.cn/∼grijs/distanceladder.pdf`

2. RECENT PROGRESS ON THE CEPHEID-BASED DISTANCE SCALE LADDER

Cepheids are radially pulsating yellow supergiants that cross the instability strip on the color-magnitude diagram. The pulsation periods for Cepheids range from ∼ 2 days to ∼ 100 days, and their periods are well correlated with the intrinsic luminosity of these variable stars – this is the famous period-luminosity relation, also known as the Leavitt Law. After proper calibration, the Leavitt Law can be serve as a standard candle and is a crucial rung in the extra-galactic distance scale ladder. The Cepheid-based distance ladder is an important route to accurately measure H_0 independent of the CMB measurements (either from Plank or WMAP), as well as providing a cross-check to other methods along the ladder. In short, Cepheids are used to determine distances to galaxies in the local universe (i.e. within ~ 40 Mpc), and these galaxies serve as calibrating galaxies for a host of secondary distance indicators, including the Tully-Fisher relation and the peak brightness of type Ia supernovae, that are located well within the Hubble flow.

Today, measurements of H_0 can reach $\sim 3\%$ accuracy from two programs, with measurements based on the Cepheid-based distance scale ladder. This result supersedes the H_0 measurement made by the *Hubble Space Telescope (HST)* Key Project about a decade ago, which had a state-of-the art accuracy of $\sim 10\%$ (Freedman et al., 2001). The two highlighted programs are the "Supernova and H_0 for the Equation of State" Program (SH0ES, Riess et al., 2009b, 2011) and the Carnegie Hubble Program (CHP, Freedman et al., 2011, 2012). These two programs will be briefly described in the following sub-sections. Further details of the programs and the resulting H_0 can be found in respective papers.

2.1. The SH0ES Program

The result from the *HST* Key Project still possesses several large systematic errors that lead to a total error of $\sim 10\%$ in H_0. One of the largest systematic errors is the distance to Large Magellanic Cloud (LMC) used to calibrate the Leavitt law. Other systematic errors such as extinction uncertainties and metallicity corrections also contributed a considerable fraction to the total error budget of H_0. Hence the SH0ES Program is designed to reduce the total error H_0 to within few percent by reducing, or even eliminating, the errors along the distance scale ladder. The SH0ES Program employed two major rungs in the ladder – well calibrated Cepheid distances to nearby type Ia supernovae host galaxies and a large number of type Ia supernovae located in the Hubble flow. Here we focus on the first rung (Cepheids) of the SH0ES' distance scale ladder. The major improvements of the SH0ES Program (Riess et al., 2009a,b) for the calibration of Cepheid distances are as follows.

1. Using anchoring galaxies that have direct and/or geometric distances: Instead of using LMC as an anchoring galaxy to calibrate the Cepheid's Leavitt Law, the SH0ES Program used the famous water maser galaxy, NGC 4258, as the anchoring galaxy in their distance scale ladder. Detections of water masers in the central region of NGC 4258 permit the derivation of an accurate geometric distance to this galaxy by tracing their Keplerian rotation. The distance of NGC 4258 was found to be 7.3 Mpc with an error of $\sim 3\%$ (Humphreys et al., 2008). Furthermore, the metallicity of NGC 4258 is closer to type Ia supernovae hosting galaxies than the LMC, hence the need for metallicity correction is minimized. Later, the SH0ES Program (Riess et al., 2011) included another two anchoring galaxies – the LMC now with accurate geometrical distance from a number of detached eclipsing binaries and the Milky Way for which 10 Galactic Cepheids possess accurate parallax measurements from *HST* (Benedict et al., 2007).
2. Homogenizing the data and samples: The SH0ES Program observed their targeted galaxies (including NGC 4258) using the same instruments on board of *HST*, including the Advanced Camera for Surveys (ACS) and the newest Wide Field Camera 3 (WFC3) for optical data, and the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) for near infrared data. Homogenized data taken from the same instrument can eliminate the zero-point differences that arise from using different instruments and the cross calibration processes, and hence reduce the overall systematic errors. The SH0ES Program also observed Cepheids in the targeted galaxies with similar period range and metallicity, homogenizing the Cepheid samples to further reduce the systematic errors.

2.2. The CHP

The CHP took another approach to improve the measurement of H_0 by moving to the mid-infrared (MIR, from $\sim 3\mu$m to $\sim 8\mu$m) and constructing the MIR extra-galactic distance scale ladder. MIR observation of Cepheids, which will be discussed here, build up the first rung on this MIR distance scale ladder, while the second rung that reaches to the Hubble flow consists of type Ia supernova and the Tully-Fisher relation observed in the MIR (Sorce et al., 2012). The goal of CHP is to measure H_0 with $\sim 2\%$ error with the current *Spitzer Space Telescope* (or simply *Spitzer*) and future *James Webb Space Telescope* in the MIR (Freedman et al., 2011). In a similar spirit to the SH0ES Program, observations in CHP will be made with the same instrument on-board of *Spitzer* – the Infrared Array Camera (IRAC) in 3.6μm and 4.5μm, to minimize the impact of cross calibration and zero-points errors in the total error budget. Cepheids that are being observed or will be observed in CHP include the Galactic Cepheids and extra-galactic Cepheids in Magellanic Clouds and nearby Local Group galaxies that are suitable to be observed with *Spitzer*.

There are several advantages to observing Cepheids in the MIR, such as a much reduced extinction (by $\sim 1/40$ compared to optical bands), minimal metallicity effect at these wavelengths and a MIR Leavitt Law which shows a reduction in the intrinsic dispersion (Freedman et al., 2008; Freedman & Madore, 2010; Freedman et al., 2011; Madore et al., 2009; Ngeow & Kanbur, 2008; Ngeow et al., 2009). In contrast to optical bands, the derivation and calibration of the MIR Leavitt Law only commenced a few years ago (Freedman et al., 2008; Ngeow & Kanbur, 2008), with subsequent analysis and improvements (including theoretical work) that can be found in Madore et al. (2009), Marengo et al. (2010), Monson et al. (2012), Ngeow et al. (2009), Ngeow & Kanbur (2010), Ngeow et al. (2012), and Scowcroft et al. (2011). In contrast to these previous studies, the latest calibration of the MIR Leavitt Law, as presented in Majaess et al. (2013), suggests that the MIR Leavitt Law follows a quadratic relation (based on the MIR period-color relation). Nevertheless, the CHP team calibrated the MIR Leavitt Law using the 10 Galactic Cepheids that have *HST* parallax measurements, and refined the distance to the LMC. Together with several other improvements when using *Spitzer's* MIR data, the CHP team reduced the error for H_0 by a factor of ~ 3 compared to the *HST* Key Project result.

3. MOVING TO ULPC – A PROMISING PATH?

It has been known that Cepheids with very long pulsation periods, say > 70 days, appear to be outliers in the period-luminosity diagram and follow a flatter Leavitt Law (for example, see Figure 7 in Freedman, 1988, as an illustration). In addition, the observing strategy of the *HST* Key Project (see Freedman et al., 2001, and reference therein) primarily focused on extra-galactic Cepheids with periods in the range of 10 to ~ 80 days (Madore & Freedman, 2005). Therefore, these long period Cepheids were excluded from extra-galactic distance scale applications. However, Bird et al. (2009) proposed Cepheids with period longer than 80 days follow a different Leavitt Law, and called them the ultra-long period Cepheids (ULPCs). ULPCs are indeed Cepheids with higher masses than their shorter period Cepheids, with masses in the range of ~ 12 to $\sim 20\ M_\odot$ (Bird et al., 2009; Fiorentino et al., 2012). ULPCs are also intrinsically ~ 1 to ~ 3 magnitudes brighter than the shorter period Cepheids (as targeted by *HST* Key Project) suggesting that it is possible to probe the distance to galaxies in the Hubble flow (> 100 Mpc) by using ULPCs[2], and hence deriving the H_0 in a "single-step" without the calibration of secondary distance indicators (Bird et al., 2009; Fiorentino et al., 2012).

To date, about 37 ULPCs have been identified in the Magellanic Clouds, nearby dwarf galaxies and spiral galaxies (Fiorentino et al., 2012). Surprisingly, no ULPC has been identified in M31 – the nearest spiral galaxy with the potential to be an anchoring galaxy in future extra-galactic distance scale work. Since the angular size of M31 is $\sim 3^o$ on the sky, long term time series observations that cover the entire M31 are needed to find ULPCs in M31. Past time-series surveys or projects that targeted M31 either only covered small patches of M31 or the observing windows were shorter than 80 days. In contrast, data taken from Palomar Transients Factory (PTF) is ideal to search for ULPCs in M31, as the large field-of-view mosaic CCD used by PTF can cover the entire M31 and PTF has been regularly monitoring M31 for a few years.

The PTF R-band images used in the search for M31's ULPCs were downloaded from the PTF data archive, in which the data has been processed with a dedicated reduction pipeline (Laher et al., 2014). The imaging data includes ~ 170 frames spanned from 2010 to 2012, with observing cadence from 1 to few days. We applied image subtraction techniques to search for possible candidates, and found $\sim 10^5$ candidates initially. Various selection criteria (including restricting the range of periods and R-magnitudes appropriate for ULPCs at the distance of M31) and eye inspection were applied to filter out non-ULPC candidates, and finally we were left with 8 ULPC candidates. Details of this work can be found in Lee et al. (2013) and will not be repeated here. We then performed time series follow-up observations on these 8 candidates in VI-band using the Lulin 1-meter Telescope (LOT, located in Lulin Observatory, Taiwan) and the Palomar 1.5-meter Telescope (P60, located in Palomar Observatory, USA). Based on the VI-band light curves of these 8 candidates, we classified 2 of them as being *bona fide* ULPC, and the other 6 candidates most likely belong to other types of long period variables. Further details on the follow-up observations and results can be found in Ngeow et al (2014 – submitted).

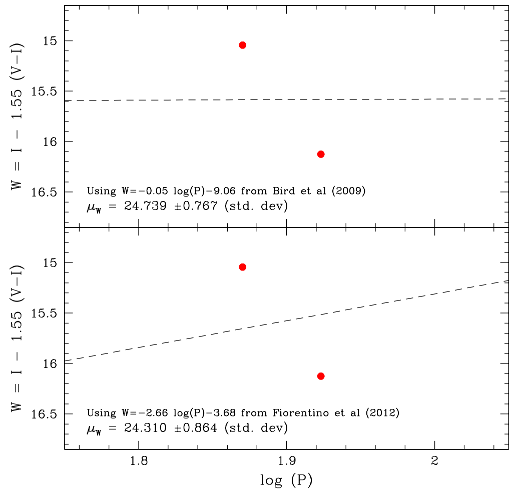

Figure 1. Fitting of the extinction-free Wesenheit W magnitudes for the two confirmed ULPCs in M31 with publicly available period-Wesenheit relation. The derived distance modulus, and the associated standard deviation, is also given in the lower left corners in each panels.

Figure 1 presents the fitting of these two ULPCs in M31 with two period-Wesenheit functions available from Bird et al. (2009) and Fiorentino et al. (2012), at which can be used to determine the distance modulus to M31. The derived distance moduli as shown in Figure 1, albeit with large standard deviations, are consistent with the recommended value of 24.46 ± 0.10 given in de Grijs & Bono (2014). However, the large standard deviations of the derived distance moduli suggest ULPC may not be suitable to be serve as a standard candle. Hence, the idea of using ULPC to probe distances out to ~ 100 Mpc may need to be evaluated. Further discussion on this issue can be found in Ngeow et al (2014 – submitted).

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[2]In contrast, the shorter period Cepheids can only probe to a distance of ~ 40 Mpc using *HST*.

REFERENCES

Benedict, G. F., McArthur, B. E., & Feast, M. W., et al., 2007, Hubble Space Telescope Fine Guidance Sensor Parallaxes of Galactic Cepheid Variable Stars: Period-Luminosity Relations, AJ, 133, 1810

Bird, J. C., Stanek, K. Z., & Prieto, J. L., 2009, Using Ultra Long Period Cepheids to Extend the Cosmic Distance Ladder to 100 Mpc and Beyond, ApJ, 695, 874

de Grijs, R., 2011, An Introduction to Distance Measurement in Astronomy, John Wiley & Sons Ltd, 1st-edition

de Grijs, R. & Bono, G., 2014, Clustering of Local Group Distances: Publication Bias or Correlated Measurements? II. M31 and Beyond, AJ, 148, 17

Efstathiou, G. & Bond, J. R., 1999, Cosmic Confusion: Degeneracies Among Cosmological Parameters Derived from Measurements of Microwave Background Anisotropies, MNRAS, 304, 75

Fiorentino, G., Clementini, G., & Marconi, M., et al., 2012, Ultra Long Period Cepheids: a Primary Standard Candle out to the Hubble Flow, Ap&SS, 341, 143

Freedman, W. L., 1988, New Cepheid Distances to Nearby Galaxies Based on BVRI CCD Photometry. I - IC 1613, ApJ, 326, 691

Freedman, W. L., Madore, B. F., & Gibson, B. K., et al., 2001, Final Results from the Hubble Space Telescope Key Project to Measure the Hubble Constant, ApJ, 553, 47

Freedman, W. L., Madore, B. F., Rigby, J., Persson, S. E., & Sturch, L., 2008, The Cepheid Period-Luminosity Relation at Mid-Infrared Wavelengths. I. First-Epoch LMC Data, ApJ, 679, 71

Freedman, W. L. & Madore, B. F., 2010, The Hubble Constant, ARA&A, 48, 673

Freedman, W. L., Madore, B. F., & Scowcroft, V., et al., 2011, The Carnegie Hubble Program, AJ, 142, 192

Freedman, W. L., Madore, B. F., & Scowcroft, V., et al., 2012, Carnegie Hubble Program: A Mid-infrared Calibration of the Hubble Constant, ApJ, 758, 24

Gao, Q. & Gong, Y., 2014, The Tension on the Cosmological Parameters from Different Observational Data, Classical and Quantum Gravity, 31, 105007

Hu, W., 2005, Dark Energy Probes in Light of the CMB, ASP Conference Series, 339, 215

Hubble, E., 1929, A Relation between Distance and Radial Velocity among Extra-Galactic Nebulae, Contributions from the Mount Wilson Observatory, 3, 23

Hubble, E., & Humason, M. L., 1931, The Velocity-Distance Relation among Extra-Galactic Nebulae, ApJ, 74, 43

Humphreys, E. M. L., Reid, M. J., Greenhill, L. J., Moran, J. M., & Argon, A. L., 2008, Toward a New Geometric Distance to the Active Galaxy NGC 4258. II. Centripetal Accelerations and Investigation of Spiral Structure, ApJ, 672, 800

Jackson, N., 2007, The Hubble Constant, Living Reviews in Relativity, 10, 4

Laher, R. R., Surace, J., & Grillmair, C. J., et al., 2014, IPAC Image Processing and Data Archiving for the Palomar Transient Factory, PASP, 126, 674

Lee, C. -H., Ngeow, C. -C., Yang T. -C., & Ip, W. -H., et al., 2013, Using the Palomar Transient Factory to Search for Ultra-Long-Period Cepheid Candidates in M31, Proc. of the 2013 IEEE International Conference on Space Science and Communication (IconSpace2013), 1

Li, Z., Wu, P., & Yu, H., et al., 2014, A Possible Resolution of Tension Between Planck and Type Ia Supernova Observations, Science China Physics, Mechanics and Astronomy, 57, 381

Madore, B. F., & Freedman, W. L., 2005, Nonuniform Sampling and Periodic Signal Detection, ApJ, 630, 1054

Madore, B. F., Freedman, W. L., & Rigby, J., et al., 2009, The Cepheid Period-Luminosity Relation (The Leavitt Law) at Mid-Infrared Wavelengths. II. Second-Epoch LMC Data, ApJ, 695, 988

Majaess, D., Turner, D. G., & Gieren, W., 2013, On the Form of the Spitzer Leavitt Law and Its Dependence on Metallicity, ApJ, 772, 130

Marengo, M., Evans, N. R., & Barmby, P., et al., 2010, Galactic Cepheids with Spitzer. I. Leavitt Law and Colors, ApJ, 709, 120

Monson, A. J., Freedman, W. L.,& Madore, B. F., et al., 2012, The Carnegie Hubble Program: The Leavitt Law at 3.6 and 4.5 μum in the Milky Way, ApJ, 759, 146

Ngeow, C. & Kanbur, S. M., 2008, The Period-Luminosity Relation for the Large Magellanic Cloud Cepheids Derived from Spitzer Archival Data, ApJ, 679, 76

Ngeow, C. -C., Kanbur, S. M., Neilson, H. R., Nanthakumar, A., & Buonaccorsi, J., 2009, Period-Luminosity Relations Derived From the OGLE-III Fundamental Mode Cepheids, ApJ, 693, 691

Ngeow, C. -C. & Kanbur, S. M., 2010, The Mid-infrared Period-Luminosity Relations for the Small Magellanic Cloud Cepheids Derived from Spitzer Archival Data, ApJ, 720, 626

Ngeow, C. -C., Marconi, M., Musella, I., Cignoni, M., & Kanbur, S. M., 2012, Theoretical Cepheid Period-Luminosity and Period-Color Relations in Spitzer IRAC Bands, ApJ, 745, 104

Planck Collaboration XIV, 2014, Planck 2013 Results. XVI. Cosmological Parameters, A&A, 571, A16

Riess, A. G., Macri, L., & Li, W., et al., 2009a, Cepheid Calibrations of Modern Type Ia Supernovae: Implications for the Hubble Constant, ApJS, 183, 109

Riess, A. G., Macri, L., & Casertano, S., et al., 2009b, A Redetermination of the Hubble Constant with the Hubble Space Telescope from a Differential Distance Ladder, ApJ, 699, 539

Riess, A. G., Macri, L., & Casertano, S., et al., 2011, A 3% Solution: Determination of the Hubble Constant with the Hubble Space Telescope and Wide Field Camera 3, ApJ, 730, 119

Scowcroft, V., Freedman, W. L., & Madore, B. F., et al., 2011, The Carnegie Hubble Program: The Leavitt Law at 3.6 μm and 4.5 μm in the Large Magellanic Cloud, ApJ, 743, 76

Sorce, J. G., Courtois, H. M., & Tully, R. B., 2012, The Mid-infrared Tully-Fisher Relation: Spitzer Surface Photometry, AJ, 144, 133

Tammann, G. A., Sandage, A., & Reindl, B., 2008, The Expansion Field: the Value of H_0, A&ARv, 15, 289

Verde, L., Jimenez, R., & Feeney, S., 2013, The Importance of Local Measurements for Cosmology, PDU, 2, 65

Verde, L., Protopapas, P., & Jimenez, R., 2013, Planck and the Local Universe: Quantifying the Tension, PDU, 2, 166

Weinberg, D. H., Mortonson, M. J., & Eisenstein, D. J., et al., 2013, Observational Probes of Cosmic Acceleration, PhR, 530, 87

Wyman, M., Rudd, D. H., Vanderveld, R. A., & Hu, W., 2014, Neutrinos Help Reconcile Planck Measurements with the Local Universe, PhRvL, 112, 051302