Invited Articles

造父變星在觀測宇宙學中的角色

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摘要

造父變星是脈動變星的一種，也在宇宙學中扮演了一定的角色。這是因爲造父變星的週光關係在經過矯正後是一種標準燭光。它可以用來矯正在宇宙測距的階梯上其他可測量距離天體的絕對星等，從而能夠準確地（在10%誤差以内）測量宇宙學内一個非常重要的常數 – 哈伯常數。在這一篇文章裡，我們回顧了近代四個主要測量哈伯常數的計劃 ，以及造父變星在這些計劃内扮演的角色。

The Role of Cepheid Variables in Observational Cosmology

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Abstract

As a class of pulsating variable stars, Cepheids play an important role in comsology via its period-luminosity (P-L) relation. This is because Cepheid P-L relation, after properly calibrated, is a standard candle that can be used to calibrate distances to a number of secondary distance indicators along the cosmic distance scale ladder. This in turn permits the determination of Hubble constant – an important parameter in modern cosmology, to within 10% accuracy. In this paper, we briefly review four recent major projects that determine the Hubble constant, with emphasize given on the role of Cepheid in these projects.

關鍵字(Keywords): 造父變星(Cepheid)、距離測量(distance scale)、哈伯常數(Hubble constant)

1. Introduction

1.1 The Cepheid Variables

Classical Cepheid variables, hereafter Cepheids, are intrinsic pulsating variable stars that crossing the instability strip in the Hertzsprung-Russell (H-R) diagram, with pulsation periods range from ~2 days to ~80 days. Cepheids are important astrophysical tool, as they can be used to derive distances to nearby galaxies, as well as constraining theoretical stellar pulsation and evolution models. The classical Cepheids should not be confused with other types of variable stars that carry similar name, such as Type II Cepheids, β Cephei and dwarf Cepheid.

Cepheids are named after its prototype – δ Cephei in the constellation of Cepheus, discovered in 1784 by John Goodricke. Since then, a number of Cepheids were discovered in our Galaxy, as well as in Small Magellaic Cloud (SMC). Finding of Cepheids in SMC led to the discovery of Cepheid's period-luminosity (P-L) relation – an important relation in modern astronomy, by Henrietta Swan Leavitt in early 20th century (Leavitt 1908; Leavitt & Pickering, 1912). Since all Cepheids in SMC can be considered to be located at the same distance from us, Leavitt found that longer period SMC Cepheids also tend be intrinsically brighter, and follow a simple linear relation. Today, Cepheid's P-L relation is also referred as Leavitt Law, for dedicating the work and contribution of Leavitt.

1.2 Cepheids and Distance Scale

Cepheid is considered as a standard candle via its P-L relation: once the period of a Cepheid is known, its intrinsic brightness can be deduced, and hence the distance can be inferred from its observed brightness. The P-L relation takes the form of

$$M_\lambda = \alpha_\lambda \log(P) + \beta_\lambda, \qquad (1)$$

where P is the pulsation period in days, and M is absolute magnitude in a given broadband filter λ. α and β are slope and intercept of the relation, respectively, and their values will depend on given λ. Once the P-L relation is calibrated, it can be used to derive distance to a galaxy that hosts Cepheids, as illustrated in Figure 1. Note that Cepheid's P-L relation is a statistical relation, and should be apply to Cepheids within a galaxy. This is because the P-L relation exhibits an intrinsic dispersion (in the order of ~0.2mag in optical, and decreases toward longer wavelength) due to the finite width of the instability strip in H-R diagram.

Harlow Shapley saw the opportunity to use Leavitt's P-L relation in SMC to derive distance to globular clusters[1]. He has calibrated the intercept of Leavitt's P-L relation using a small number of Galactic Cepheids (Shapley 1918; Shapley et al. 1925; Shapley 1930). In 1920s, based on the calibrated P-L relation from Shapley, Edwin Hubble has successfully derived the distance to NGC 6822 (Hubble 1925), M33 (Hubble 1926) and M31 (Hubble 1929), using the Cepheids he discovered in those galaxies. Note that the Cepheid distances derived for these galaxies, especially M31, has settled the "Great Debate" between Shapley and Curtis on the extra-galactic nature of spiral galaxies (Code 1999). With Cepheids, Hubble was able to determine distances to only few nearest galaxies. For galaxies in further distances, Hubble use other type of stars – the brightest stars in a galaxy (calibrated with Cepheid distances), to obtain distances to their host galaxy. Together with velocities determined from Slipher and Humason, Hubble has published the famous velocity–distance relation (Hubble 1929; Hubble & Humason 1931):

$$v = H_0\, D. \qquad (2)$$

Today, this relation is also known as the Hubble

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[1] However, he incorrectly applied the P-L relation derived for classical Cepheids to the Type II Cepheids and RR Lyrae in globular clusters.

Law. In equation (2), v and D is the recession velocity (in km/s) and distance (in Mpc), respectively, and H_0 is the Hubble constant in unit of km/s/Mpc.

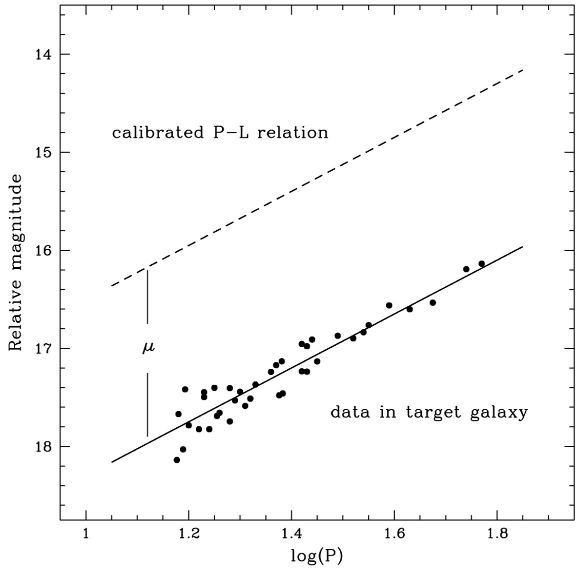

Fig. 1: Illustration of using the calibrated Cepheid P-L relation to derive distance to a target galaxy. A calibrated P-L relation, represented as a dashed line, shifts vertically to fit the Cepheid data in a target galaxy (represent as a solid line). The vertical shift, μ, is the relative distance between the target galaxy and the calibrating (or anchoring) galaxy. Interstellar extinction is ignored in this illustration. Once the distance to the calibrating galaxy is known or adopted, the distance to the target galaxy can be derived in a straight forward manner.

1.3 Hubble Constant and Cosmology

Angular power spectrum anisotropies of the cosmic microwave background (CMB) radiation can be used to determine a number of cosmological parameters. However, degeneracy exists among these cosmological parameters (e.g., see Efstathiou & Bond 1999). An independent and yet accurate determination of Hubble constant (to within few percent error) can be use to break some of these degeneracies. Throughout review on this topic is beyond the scope of this paper, and can be found in, for examples, Hu (2005), Tegmark et al. (2006), Jackson (2007), Olling (2007), Spergel et al. (2007), Grenhill et al. (2009), Freedman & Madore (2010), Komatsu et al. (2011), Larson et al. (2011) and Riess et al. (2011). A promising way to obtain independent measurement of Hubble constant within to few percent accuracy is via the cosmic distance scale ladder pioneered by Shapley and Hubble.

2. Hubble Constant Via Cepheid's Distance Scale Ladder

In this paper, we briefly review four major projects that determine the Hubble constant to ~10% or less using the cosmic distance scale ladder, at which Cepheid's P-L relation plays an important first step, or first rung, in this ladder. In short, distances to a number of nearby galaxies were determined using Cepheid's P-L relation. These galaxies were then used to calibrate a host of secondary distance indicators – the next rungs in the cosmic distance scale ladder. Distances to galaxies determined from Cepheid calibrated secondary distance indicators will be far enough to be located within the Hubble flow (i.e. free from local peculiar velocity field), and hence the Hubble constant can be accurately derived.

2.1 The HST H_0 Key Project

The main goal of the Hubble Space Telescope (HST) Key Project on the Extragalactic Distance Scale (from 1990 to 2001), abbreviated as HST H_0 Key Project, is to determine the Hubble constant with ~10% error (Aaronson & Mould 1986; Freedman et al. 2001 and reference therein). Using the second generation instruments on board of HST, the Wide Field and Planetary Camera 2 (WFPC2)[2], HST H_0 Key Project team has observed ~1000 Cepheids in 18 spiral galaxies, and many of them are new discoveries. Together with HST and ground-based archival data, Cepheids in total of 31 galaxies have been collected, with furthest galaxies that reach to ~31.7Mpc. A majority of these Cepheids have period longer than 10 days due to two reasons: (a) only the bright Cepheids, hence long periods according to P-L relation, can be detected at these distant galaxies using HST; (b) the sampling strategy adopted by HST H_0 Key Project is very effective finding long period Cepheids (Madore & Freedman 2005). HST observations of these Cepheids include 12 and 4 data points per light curves in V and I band, respectively. The combined V and I band P-L relations can be used to eliminate the extinction. These P-L relations were based on the Large Magellanic Cloud (LMC) Cepheids (Udalski et al. 1999), with an adopted LMC distance modulus of 18.50mag. A metallicity correction that account for difference metallicity between LMC, the calibration or anchoring galaxy, and other target galaxies was included when obtaining the Cepheid distance to these galaxies, which in turns were used to calibrate a host of secondary distance indicators (including Tully-Fisher relation, surface brightness fluctuation, type Ia and type II supernova, and fundamental plane). The final resulted Hubble constant is $H_0 = 72$ km/s/Mpc, with a ±10% total error of 8 km/s/Mpc (Freedman et al. 2001). The dominant sources of systematic errors include the errors in adopted LMC distance modulus (which is the largest systematic error), the difference in metallicity between LMC and target galaxies, extinction corrections, and the calibration and transformation of photometry between ground-based and HST data (Freedman & Madore 2010).

2.2 The SN Ia HST Calibration Program

In parallel to HST H_0 Key Project, a team of astronomers, led by Allan Sandage, Gustav Tammann and Abhijit Saha, has initiated a program (referred as SN Ia HST Calibration Program, though no official name has been given for this project) to calibrate the peak brightness of type Ia supernova via Cepheid distances, and hence derive the Hubble constant based on these calibrations (Saha et al. 2001; Saha et al. 2006 and reference therein; Sandage et al. 2006; Tammann et al. 2008). Same as the HST H_0 Key Project, their observations were mainly carried out with HST using the same instruments (WF/PC and WFPC2). Therefore, both team share some of the same systematic errors in Hubble constant. In contrast to HST H_0 Key Project, this team only use Cepheids to calibrate the type Ia supernova peak brightness based on 10 nearby galaxies that have both Cepheids and the type Ia supernova, but not other secondary distance indicators. The samples of distant type Ia supernova used to

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[2] Only two galaxies were observed with HST's first generation instrument, the Wide Field/ Planetary Camera (WF/PC).

derive the Hubble constant are also slightly different between the two teams[3].

Besides the type Ia supernova samples, one of the major difference between these two teams is the calibration of Cepheid's P-L relations, and hence the derived Cepheid distances to the type Ia supernova host galaxies. In HST H_0 Key Project, the Cepheid's P-L relation is assumed to be universal and defined by LMC Cepheid samples (Udalski et al. 1999; Freedman et al. 2001), and calibrated with an adopted LMC distance modulus. For SNIa HST Calibration Program, the assumption of universality of P-L relation is relaxed. This team derived two sets of P-L relations: one set of the P-L relations were based on Galacitc Cepheids (Tammann et al. 2003; representing metal rich sample), and one set of P-L relations were based on LMC Cepheids with a break period at 10 days (Sandage et al. 2004; representing metal poor sample). Both sets of P-L relations have different calibration of their respected intercepts. Hence, for a given galaxy two sets of Cepheid distances were derived from these two sets of P-L relation, and interpolated (or extrapolated) to the metallicity of the targeted galaxy as the final adopted Cepheid distance. This lead to, on average, further Cepheid distances for the same calibrating galaxies as in HST H_0 Key Project (Saha et al. 2006). Therefore, the final Hubble constant derived from SNIa HST Calibration Program is smaller:

62.3±1.3(statistical)±5.0(systematic) km/s/Mpc (Sandage et al. 2006).

2.3 The SH0ES Program

To improve the measurement of Hubble constant with errors smaller than 5% via the cosmic distance ladder, a team of astronomers, led by Adam Riess, has initiated the SH0ES (Supernova and H_0 for the Equation of State; Riess et al. 2009a, 2009b, 2011) Program. Similar to the SN Ia HST Calibration Program, the SH0ES Program also uses type Ia supernova as secondary calibrator, at which their peak brightness were calibrated using Cepheid distances.

The improvements of SH0ES Program over the HST H_0 Key Project and the SN Ia HST Calibration Program are the reduction or elimination of various systematic errors along the calibration and distance scale ladder. Some of these improvements include:

(a) *Replacing the LMC as anchoring galaxy with NGC 4258* – Systematic error of the LMC distance modulus, hence the calibration of the intercept of Cepheid's P-L relation, was at ~10% level, which could contribute ~5% error to the error budget of Hubble constant. The SH0ES Program replaces NGC 4258 – the famous water maser galaxy, with LMC as the anchoring galaxy in cosmic distance scale ladder. This is because motion of the water maser sources at the center of NGC 4258 permit the derivation of accurate geometric distance via Keplerian rotation, which is found to be 7.2 Mpc with a ~3% error (Humphreys et al. 2008, and reference

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[3] Details discussion of the different samples, as well as their treatment of extinction etc., is beyond the scope of this paper.

therein). Another advantage of using NGC 4258 over LMC is the metallicity of NGC 4258 is similar, or close to, the metallicity for targeted calibrating galaxies, hence the metallicity correction is much reduced. In contrast, the metallicity of LMC is much lower than these galaxies, which contributing about 3% to 5% errors for the overall error budget for Hubble constant via the metallicity correction.

(b) *Using the "ideal" type Ia supernovae with modern observations for calibration* – The SH0ES Program has identified 8 nearby type Ia supernovae that are suitable to calibrate their peak brightness, at which the selection criteria have been given in Riess et al. (2005, 2009a, 2009b, 2011). By using HST, relatively large numbers of Cepheids have been found in the host galaxies of these supernovae, in turns these Cepheids were used to derive the distance of the host galaxies, hence the peak brightness of the supernovae can be well calibrated.

(c) *Observing with the same HST instruments* – In contrast to previous programs, SH0ES use the latest and the same instruments on board of HST to observe the Cepheids in the anchoring galaxy, NGC 4258 (Macri et al. 2006), and target galaxies that host the "ideal" type Ia supernovae. This approach can eliminate the systematic errors arise from cross calibration of the photometry and instrumental zero-points when different instruments were used (e.g., HST vs ground-based observations), as well as the anomaly photometric errors inherent from WFPC2 (see Riess et al. 2009b and reference therein). In early phase of the SH0ES Program the Advanced Camera for Surveys (ACS) was used (Riess et al. 2005, 2009a; Macri et al. 2006), and later it was switched to the newest Wide Field Camera 3 (WFC3) on board of HST (Riess et al. 2011). This is same for the near infrared observations by using the Near-Infrared Camera and Multi-Object Spectrometer (NICMOS). Note that in their latest paper, Riess et al. (2011) has calibrated all of the optical data to WFC3 to remove zero-points errors from using different instruments.

(d) *Using homogeneous Cepheid data and including H band data* – The SH0ES Program only use Cepheids with similar period ranges and metallicity. Together with the observations based on the same instruments, this built up a homogeneous Cepheid data that further eliminate systematic errors arose from using in-homogeneous data. In addition to optical data, the SH0ES Program also includes H-band observation using HST. Including the near infrared data further reduce the extinction errors by five times, at the same time minimize the effect of metallicity (Riess et al. 2009b).

In Riess et al. (2011), the reported determination of Hubble constant is 73.8±2.4 km/s/Mpc, representing a total error of 3.3%. Note that this final result is based on the calibration using three calibrators with accurate geometrical distances: NGC 4258 with water maser distance, 13 Galactic Cepheids with parallaxes, and LMC revised distances based on the measurements from detached eclipsing binaries (see Riess et al. 2011 for further details).

2.4 The Carnegie Hubble Project

Besides the approach taken by the SH0ES Project, another way to improve the determination of Hubble constant via the cosmic distance scale ladder is moving to the mid-infrared (MIR, from ~3 micron to ~8 micron). This is because MIR observation of Cepheids offer several advantages over their optical counterparts (Freedman et al. 2008; Ngeow & Kanbur 2008; Madore et al. 2009; Ngeow et al. 2009; Freedman & Madore 2010; Ngeow et al. 2010; Freedman et al. 2011): (a) extinction in MIR is almost negligible; (b) metallicity effect is minimal at MIR; (c) amplitude in these wavelengths is smaller and hence the mean magnitudes can be accurately determined[4]; and (d) the MIR P-L relations exhibit a smaller dispersion.

The Carnegie Hubble Program (CHP, Freedman & Madore 2010; Freedman et al. 2011; Scowcroft et al. 2011; Freedman et al. 2012; Monson et al. 2012) is designed to leverage these advantages to improve the determination of Hubble Constant to ~3% level, with ultimate goal of bringing down the systematic errors to ~2% with future James Webb Space Telescope (JWST). Similar to SH0ES Program, CHP utilizes the same instrument on board of Spitzer Space Telescope (SST), the Infrared Array Camera (IRAC), to observe Cepheids in both of the anchoring galaxies and galaxies that used to calibrate the secondary distance indicators. This will eliminate any additional calibration and zero-point errors arise from using different instruments. The major secondary distance indicators employed by CHP includes Tully-Fisher relation and type Ia supernovae.

CHP focused on the MIR observations, in 3.6 micron and 4.5 micron, based on the post-cryogenic Spitzer mission. Cepheids in the Milky Way[5], LMC, SMC and a number of nearby galaxies that are suitable to calibrate the Tully-Fisher relation and type Ia supernovae (see Table 1 in Freedman et al. 2011) are targeted in CHP. Calibration of the MIR Tully-Fisher relation with Cepheid distance is still an on-going progress within the CHP. However, using the MIR P-L relation derived from ~80 LMC Cepheids (Scowcroft et al. 2011), at which the intercept of this P-L relation was calibrated using the 10 Galactic Cepheids (Monson et al. 2012) that possess accurate HST parallax measurements, the distance to LMC has been updated. Using this updated LMC distance, CHP revised the Hubble constant from HST H_0 Key Project (Section 2.1), at which it was based on canonical LMC distance modulus of 18.50mag (with a 10% error). The improved measurement of LMC distance, together with the calibration of P-L relation with Galactic Cepheids[6] that minimize the metallicity correction, has reduced the systematic error of Hubble constant by

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[4] The smaller amplitudes in MIR also imply that Cepheids need to be discovered in optical bands based on their larger amplitudes.

[5] Only for those Galactic Cepheids that are close enough to have accurate parallax measurements from Gaia.

[6] The Galactic Cepheids have metallicity, on average, closer to the calibrating galaxies in HST H_0 Key Project, than LMC, hence reducing the systematic errors based on metallicity correction.

factor of three. The Hubble constant reported in latest CHP paper, Freedman et al. (2012), is 74.3±1.5(statistical)±2.1(systematic) km/s/Mpc.

3. Conclusion

In this paper, we review the role of Cepheid in modern cosmology, in particular its importance in the cosmic distance scale ladder that permit accurately determine the Hubble constant. We highlight four recent projects that utilize Cepheid distances to derive Hubble constant to within 10% accuracy, they are the HST H_0 Key Project, the SN Ia HST Calibration Program, the SH0ES Project and the Carnegie Hubble Project. The last two projects have demonstrated that reaching a ~3% error in Hubble constant is possible with current space-based telescopes – the HST and the SST. In near future, a 2% (or less) error in Hubble constant can be obtained with Gaia and JWST (Riess et al. 2009b; Freedman & Madore 2010; Riess et al. 2011). Again, Cepheids will be important to provide a firm rung in the cosmic distance scale ladder, via the calibration of the P-L relation. Cepheid-based systematic errors will directly propagate to the accuracy of the final determined Hubble constant. Therefore, further understanding of Cepheids and improvement of the usage of Cepheids, through various empirical properties and relations, in cosmic distance scale ladder will be important (this is similar to the understanding of type Ia supernova in modern cosmology). Even after almost 100 years of development in Cepheid's P-L relation since its discovery by Leavitt, there are still remained some unsolved problems related to the P-L relation (see, for example, Szabados & Klagyivik 2012, and reference therein) that need to be investigated and refined further.

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