Determining $H_0$ with the Latest H II Galaxy Measurements

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Abstract

We use the latest H II galaxy measurements to determine the value of $H_0$ by adopting a combination of model-dependent and model-independent methods. By constraining five cosmological models, we find that the obtained values of $H_0$ are more consistent with the recent local measurement by Riess et al. at the $1\sigma$ confidence level. For the first time, we implement the model-independent Gaussian processes using the H II galaxy measurements, and confirm the correctness of $H_0$ values obtained by the model-dependent method at the $1\sigma$ confidence level.

Key words: cosmological parameters – dark energy

1. Introduction

Determining the Hubble constant ($H_0$) accurately is one of the most important challenges in modern cosmology, since it sets the scale for all cosmological times and distances and reveals for human beings the present cosmic expansion rate, the size, and age of the universe and its cosmic components. Based on the early determination by Hubble (1929), the value of $H_0$ was believed to lie in the large range $[50, 100]\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ (Kaiser 2003). Utilizing improved control of systematics and different calibration techniques, the first precise value, $H_0 = 72 \pm 8\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ (Freedman 2001), was given by the local measurements from the Hubble Space Telescope (HST) in 2001. Ten years later, Riess et al. (2011, hereafter R11) calibrated the Type Ia supernovae (SNe Ia) and obtained $H_0 = 73.8 \pm 2.4\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ using four indicators, i.e., the distance to NGC 4258 from a mega-maser measurement, the trigonometric parallax measurements to the Milky Way (MW) Cepheids, Cepheid observations, and a modified distance to the Large Magellanic Cloud (LMC). In 2012, there were three groups that measured the Hubble constant: Riess et al. (2012) obtained $H_0 = 75.4 \pm 2.9\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ utilizing the Cepheids in M31; Freedman (2012) obtained $H_0 = 74.3 \pm 2.1\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ using a mid-infrared calibration for the Cepheids; and Chávez et al. (2012) obtained $H_0 = 74.3 \pm 3.1(\text{random}) \pm 2.9(\text{syst.})\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ by adopting H II regions and H II galaxies as distance indicators. Subsequently, in 2013, $H_0 = 67.3 \pm 1.2\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ derived by Planck Collaboration et al. (2014) from the anisotropies of the cosmic microwave background (CMB) gave a strong tension with the local measurement from R11’s result at 2.4$\sigma$ confidence level. In order to resolve or alleviate the tension, several groups carried out the measurements utilizing different techniques and methods: Bennett et al. (2013) and Hinshaw et al. (2013) gave a 3% determination, i.e., $H_0 = 70.0 \pm 2.2\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ using the nine-year Wilkinson Microwave Anisotropy Probe (WMAP-9) measurements; Spergel et al. (2015) found $H_0 = 68.0 \pm 1.1\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ by removing the $217 \times 217\,\text{GHz}$ detector set spectrum used in the Planck analysis; and Fiorentino et al. (2013) obtained $H_0 = 76.0 \pm 1.9\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ utilizing 8 new classical Cepheids observed in galaxies hosting SNe Ia. Different from the calibration method exhibited by R11, Tammann & Reindl (2013) obtained a lower value of $H_0 = 63.7 \pm 2.3\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ by calibrating the SN Ia with the tip of red-giant branch (TRGB); Efstathiou (2014) obtained $H_0 = 70.6 \pm 3.3\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ by revising the geometric maser distance to NGC 4258 from Humphreys et al. (2013) and using this indicator to calibrate the R11’s measurements; and Rigault et al. (2015) gave $H_0 = 70.6 \pm 2.6\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ by considering predominately star-forming environments.

The medium redshift data can also act as a complementary and effective tool to determine $H_0$. Combining them with the high-redshift CMB data, the uncertainties of $H_0$ can be reduced significantly. For instance, utilizing the CMB and medium redshift baryon acoustic oscillations (BAO) data, and assuming the six-parameter standard cosmology, Bennett et al. (2014) got a substantially accurate result of $H_0 = 69.6 \pm 0.7\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ with a 1% determination, which is one of the most accurate results found to date. By making the best of BAOs data, Cheng & Huang (2015) found $H_0 = 68.0 \pm 1.1\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ for the standard cosmological model. Subsequently, using other mid-redshift data including the BAO peak at $z = 0.35$ (Eisenstein et al. 2005), 18 H(z) data points (Simon et al. 2005; Gaztañaga et al. 2009; Stern et al. 2010), 11 ages of old high-redshift galaxies (Longhetti et al. 2007; Ferreras et al. 2009), and the angular diameter distance data from the Bonamente et al. (2006) galaxy cluster sample, Lima & Cunha (2014) obtained $H_0 = 74.1 \pm 2.2\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ in a $\Lambda$CDM model. Furthermore, replacing the Bonamente et al. (2006) galaxy cluster sample with the De Filippis et al. (2005) one, Holanda et al. (2014) gave $H_0 = 70 \pm 4\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. This indicates that different mid-redshift data can provide different values of $H_0$. Moreover, based on the fact that different observations should provide the same luminosity distance at some certain redshift, Wu et al. (2017) proposed a model-independent method to determine $H_0$. They found $H_0 = 74.1 \pm 2.2\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ by combining the Union 2.1 SNe Ia data with galaxy cluster data (Suzuki et al. 2012). Recently, the improved local measurement $H_0 = 73.24 \pm 1.74\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ from Riess et al. (2016) has more tension with the Planck 2016 release $H_0 = 66.93 \pm 0.62\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$ (Planck Collaboration et al. 2016b, hereafter P16) at the 3.4$\sigma$ confidence level. The improvements that differ from R11’s result are summarized in the following manner:

1. adopting new, near-infrared observations of Cepheid variables in 11 SNe Ia hosts;
2. increasing the sample size of ideal SNe Ia calibrators from 8 to 19;
3. giving the calibration for a magnitude-redshift relation based on 300 SNe Ia at $z < 0.15$;
4. a 33% reduction of the systematic uncertainty in the maser distance to the NGC 4258;
5. increasing the sample size of Cepheids in the LMC;
6. HST observations of Cepheids in M31;
7. using new HST-based trigonometric parallaxes for the MW Cepheids;
8. and a more robust distance to the LMC based on the late-type detached eclipsing binaries (DEBs).

Considering the higher tension than before between the local and global measurements of $H_0$, we use the latest HII galaxy data to determine the Hubble constant. We find that the $H_0$ values are more consistent with the results of Riess et al. (2016, hereafter R16) at the 1σ confidence level utilizing a combination of model-dependent and model-independent methods, and also find that the data prefers a higher underlying value of $H_0$ than R16’s result.

The rest of this paper is outlined as follows. In the Section 2, we describe the data and review the basic formula. In Section 3, we constrain five cosmological models. In Section 4, we use the model-independent GP reconstructions to check the correctness of the $H_0$ values from the model-dependent method. The discussion and conclusion are presented in Section 5.

### 2. The Data and Basic Formula

The values for the data used in this paper are given by Erb et al. (2006), Masters et al. (2014), Maseda et al. (2014), Terlevich et al. (2015), and Chávez et al. (2012, 2014, 2016). For details on the selection criteria, measurement techniques, and error determinations, we refer the reader to the original Chávez and Terlevich papers.

Chávez et al. (2016) have pointed out that, for Giant Extragalactic H II Regions (GEHR) and H II galaxies, the $L(H/β) - σ$ relation can be applied in measuring the distance and can be expressed as

$$\log L(H/β) = (5.05 \pm 0.097) \log σ(H/β) + (33.11 \pm 0.145),$$  \(1\)

where $L(H/β)$ and $σ(H/β)$ denote the Balmer emission line luminosity for these objects and the velocity dispersion of the young star-forming cluster from the measurements of the line width, respectively. Then the corresponding observational distance modulus is shown as

$$μ_{obs} = 2.5 \log L(H/β) - 2.5 \log f(H/β) - 100.95,$$  \(2\)

where $f(H/β)$ is the measured flux in the H/β line. The theoretical distance modulus $μ_{th}$ for a GEHR or H II galaxy can be written as

$$μ_{th} = 5 \log_10 d_L(z) + 25.$$  \(3\)

The Hubble luminosity distance in a Friedmann–Robertson–Walker (FRW) universe is

$$d_L(z) = \frac{1 + z}{H_0 \sqrt{Ω_0}} \sin^{-1} \left(\sqrt{Ω_0} \int_0^z \frac{dz'}{E(z'; θ)}\right).$$  \(4\)

where $θ$ denotes the model parameters, $H_0$ is the Hubble constant, the dimensionless Hubble parameter is $E(z; θ) = H(z; θ)/H_0$, the present-day cosmic curvature is $Ω_{k0} = -K/(a_0 H_0^2)$, and for

$$\sin n(x) = \sin(x), x, \sinh(x), K = 1, 0, -1,$$ which corresponds to a closed, flat, and open universe, respectively.

In order to constrain a specific cosmological model, we adopt the maximum likelihood method and the corresponding $χ^2$ function to be minimized for the GEHR, and the H II galaxy data is

$$χ^2 = \sum_{i=1}^{156} \left[ \frac{μ_{obs}(z_i) - μ_{th}(z_i; θ)}{σ_i} \right]^2,$$  \(5\)

where $σ_i$ and $μ_{obs}(z_i)$ are the 1σ statistical error and the observed value of distance modulus at a given redshift $z_i$ for every object, respectively.

### 3. The Constraints

In this section, to explore the values of $H_0$, we place constraints on five cosmological models using the latest H II galaxy measurements.

In modern cosmology, the simplest and most elegant cosmological model is the so-called $Λ$-cold-dark-matter ($Λ$CDM) model, which has proved to be very successful in describing many aspects of the observed universe, such as the spectrum of anisotropies of the cosmic microwave background radiation, the large-scale structure of matter distribution at the linear level, and the expansion phenomena. The Hubble parameter for the spatially flat $Λ$CDM model is

$$H(z) = H_0 \sqrt{Ω_{m0}(1 + z)^3 + 1 - Ω_m},$$  \(6\)

while for the non-flat $Λ$CDM model, it can be expressed as

$$H(z) = H_0 \sqrt{Ω_{m0}(1 + z)^3 + Ω_{k0}(1 + z)^2 + 1 - Ω_m - Ω_k},$$  \(7\)

where $Ω_{m0}$ and $Ω_{k0}$ denote the dimensionless matter density ratio parameter and the dimensionless curvature density ratio parameter today, respectively.

We consider the simplest parametrization of the dark energy equation of state (EoS) $ω(z) = ω = constant$, namely the $ω$CDM model, which regards the dark energy as a single negative pressure fluid, and the corresponding Hubble parameter for the spatially flat $ω$CDM model can be written as

$$H(z) = H_0 \sqrt{Ω_{m0}(1 + z)^3 + (1 - Ω_{m0})(1 + z)^{3(1+ω)}}.$$  \(8\)

Another consideration is the so-called decaying vacuum (DV) cosmology, which is aimed at resolving the well-known fine-tuning problem by assuming the cosmological constant to be dynamical. In general, to obtain a definite DV model, one should specify a vacuum decay law. However, Wang & Meng (2005) proposed an interesting model based on a simple assumption of the form of the modified matter expansion rate. The Hubble parameter for this DV model is

$$H(z) = H_0 \sqrt{\frac{3Ω_{m0}}{3 - ϵ}(1 + z)^{3-ϵ} + 1 - \frac{3Ω_{m0}}{3 - ϵ}},$$  \(9\)

where $ϵ$ is a small positive constant describing the deviation from the standard matter expansion rate.

We also consider the holographic dark energy (HDE) model inspired by the extraordinary thermodynamics of black holes. Based on the maximal entropy postulation of a black hole by Bekenstein, Li (2004) proposed the HDE model, in which the future event horizon is chosen as the characteristic length scale,
to apply the holographic principle to the dark energy problem. This model can successfully give the late-time acceleration of the universe. For details, we refer the reader to the recent review article by Wang et al. (2016). The corresponding Hubble parameter of the HDE model can be shown as

\[ H(z) = H_0 \sqrt{\Omega_{m0}(1 + z)^3 + (1 - \Omega_{m0})(1 + z)^{2(1 + \omega_m)}} \tag{10} \]

where the parameter \( c \) plays a main role in the HDE model. Moreover, researchers find that this model is compatible with current observations (Huang & Gong 2004; Zhang 2007).

We exhibit the minimal values of the derived \( \chi^2 \) in Table 1. Furthermore, the limits on cosmological parameters shown in Table 1 are derived from the corresponding one-dimensional likelihood function that results from the marginalization over all of the other parameters. We also exhibit the 1σ and 2σ contour plots in Figure 1. One can easily find that, using the latest H\( \alpha \) galaxy data, the \( H_0 \) values for these five cosmological models are consistent with R16’s local measurement at the 1σ confidence level.

### Table 1

| Parameter | \( \Lambda \)CDM | Non-flat \( \Lambda \)CDM | \( \omega \)CDM | DV | HDE |
|-----------|-----------------|-----------------|-----------|-----|-----|
| \( H_0 \) | 76.12±3.47 | 75.74±3.45 | 75.67±3.32 | 76.10±3.36 | 75.65±3.86 |
| \( \Omega_{m0} \) | 0.265±0.176 | 0.263±0.177 | 0.251±0.174 | 0.266±0.120 | 0.271±0.117 |
| \( \omega \) | \( \cdots \) | \( \cdots \) | \( -0.844±0.953 \) | \( \cdots \) | \( \cdots \) |
| \( \epsilon \) | \( \cdots \) | \( \cdots \) | \( 0.010±0.005 \) | \( \cdots \) | \( \cdots \) |
| \( \epsilon \) | \( \cdots \) | \( \cdots \) | \( 1.466±0.318 \) | \( \cdots \) | \( \cdots \) |
| \( \chi^2 \) | 222.228 | 222.217 | 222.003 | 222.222 | 221.757 |

**Figure 1.** 1σ and 2σ confidence ranges for parameter pairs \((H_0, \Omega_{m0})\) of the \( \Lambda \)CDM model, \((H_0, \omega_m)\) of the non-flat \( \Lambda \)CDM model, \((H_0, \omega)\) of the \( \omega \)CDM model, \((H_0, \Omega_{m0})\) of the DV model, and \((H_0, \epsilon)\) of the HDE model, respectively. The blue symbol, ×, represents the best-fit points.

As in previous works (Seikel et al. 2012; Wang & Meng 2016, 2017), using Equation (3) and the expression of the normalized comoving distance \( D(z) = H_0(1 + z)^{-1} d_L(z) \), we transform the theoretical distance modulus \( \mu_{th} \) to \( D(z) \) in the following manner:

\[ D(z) = \frac{H_0}{1 + z} 10^{\frac{\mu_{th} - 25}{5}}, \tag{12} \]

and the dark energy EoS can be expressed as

\[ \omega(z) = \frac{2(1 + z)(1 + \Omega_{m0})d'' - [(1 + z)^2\Omega_{m0}D'^2 - 3(1 + \Omega_{m0}D^2) + 2(1 + z)\Omega_{m0}DD'']D'}{3D'[1 + z]^{2}[1 + z]^{2}\Omega_{m0}D^2 - (1 + \Omega_{m0}D^2)}, \tag{13} \]
where the prime represents the derivative with respect to the redshift $z$. As noted by Seikel et al. (2012), we set the initial conditions $D(z) = 0$ and $D'(z) = 1$ throughout the reconstruction processes. Note that the $H_0$ value obviously affects the reconstruction results by affecting the transformed $D(z)$. Additionally, we have assumed $\Omega_{\Lambda 0} = 0$ and $\Omega_m 0 = 0.308 \pm 0.012$ (Planck Collaboration et al. 2016a) in our GP reconstructions.

In Figure 2, we consider the effects of three different $H_0$ values on the reconstructions of $D(z)$, $D'(z)$, $D''(z)$, and dark energy EoS, i.e., $\text{R16}$’s result $H_0 = 73.24 \pm 1.74 \, \text{km s}^{-1} \text{Mpc}^{-1}$, $\text{P16}$’s result $H_0 = 66.93 \pm 0.62 \, \text{km s}^{-1} \text{Mpc}^{-1}$, and the prediction of the $\Lambda$CDM model $H_0 = 76.12^{+3.47}_{-3.44} \, \text{km s}^{-1} \text{Mpc}^{-1}$ using the H II galaxy data. From the upper panels of Figure 2, one can easily find that when $H_0 = 76.12^{+3.47}_{-3.44} \, \text{km s}^{-1} \text{Mpc}^{-1}$, the reconstructions of $D(z)$, $D'(z)$, and $D''(z)$ are better than of the other two cases. In the lower left and middle panels of Figure 2, when $H_0 = 66.93 \pm 0.62 \, \text{km s}^{-1} \text{Mpc}^{-1}$ and $73.24 \pm 1.74 \, \text{km s}^{-1} \text{Mpc}^{-1}$, we find that the underlying true model is consistent with the $\Lambda$CDM model in the low-redshift range at the 2$\sigma$ confidence level. However, when $H_0 = 76.12^{+3.47}_{-3.44} \, \text{km s}^{-1} \text{Mpc}^{-1}$, this occurs in the low-redshift range at the 1$\sigma$ confidence level. Hence, we conclude that the GP reconstructions may prefer a higher best-fit $H_0$ value at the 1$\sigma$ confidence level over that of the measurements in previous works (e.g., $\text{R16}$ and $\text{P16}$), and also conclude that the model-independent method has verified the correctness of $H_0$ values that were obtained by the model-dependent method. It is worth noting that, because the current H II galaxy data points are mainly located at low redshifts (low-$z$ and GEHR samples) and there is a lack of medium and high redshift data, we cannot provide an accurate constraint on $D(z)$, $D'(z)$, $D''(z)$, and the dark energy EoS.

5. Conclusions

The precise measurement of $H_0$ is one of the most important and intriguing tasks. The recent local measurement implemented by Riess et al. exhibits high tension with the Planck’s result from CMB anisotropy data at the 3.4$\sigma$ confidence level. Our motivation is to use the latest H II galaxy measurements to determine the value of $H_0$.

We explore the value of $H_0$ using a combination of model-dependent and model-independent methods. First of all, we constrain five cosmological models using the newest compilation of H II galaxy measurements and obtain the corresponding values of $H_0$. We find that the $H_0$ values for these five cosmological models are all consistent with $\text{R16}$’s local measurement at the 1$\sigma$ confidence level (see Table 1 and Figure 1). In light of this, to check the correctness of $H_0$ values obtained by the model-dependent method, we first implement the GP reconstructions using the H II galaxy data in the literature. We find that when $H_0 = 76.12^{+3.47}_{-3.44} \, \text{km s}^{-1} \text{Mpc}^{-1}$ (see Table 1), the reconstructed dark energy EoS is more consistent with the $\Lambda$CDM model in the relatively low redshift range at the 1$\sigma$ confidence level than with the cases of $H_0 = 73.24 \pm 1.74$ and $66.93 \pm 0.62 \, \text{km s}^{-1} \text{Mpc}^{-1}$ (see the lower panels of Figure 2). Hence, we have verified the correctness of $H_0$ values obtained by the model-dependent method at the 1$\sigma$ confidence level.

Using 69 nearby H II galaxies and 23 GEHR in 9 galaxies, Chávez et al. (2012) have obtained a value of $H_0 = 74.3 \pm 3.1$ (statistical) $\pm 2.9$ (systematic), which is also consistent with our results at the 1$\sigma$ confidence level.

The tendency of high best-fit values of $H_0$ may be attributed to different data systematics, a lack of medium and high
redshift data, or underlying new physics. In the future, we expect that additional high-precision data can provide more useful information for us and help us better distinguish different cosmological models.

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