Measuring $H_0$ from low-$z$ datasets

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The Hubble constant $H_0$ represents the expansion rate of the Universe at present and is closely related to the age of the Universe. The accurate measurement of Hubble constant is crucial for modern cosmology. However, different cosmological observations give diverse values of Hubble constant in literature. Up to now, there are two methods to measure the Hubble constant. One is to directly measure the Hubble constant based on distance ladder estimates of Cepheids and so on. The other is to globally fit the Hubble constant under the assumption of a cosmological model, for example the “standard” $\Lambda$CDM model. Adopting the low-redshift observational datasets, including the Pantheon sample of Type Ia supernovae, baryon acoustic oscillation measurements, and the tomographic Alcock-Paczynski method, we determine the Hubble constant to be $67.95^{+0.78}_{-0.70}$, $69.81^{+2.22}_{-2.70}$, and $66.75^{+3.42}_{-4.23}$ km s$^{-1}$ Mpc$^{-1}$ at 68% confidence level in the $\Lambda$CDM, $w$CDM and $w_0w_a$CDM models, respectively. Compared to the Hubble constant given by Riess et al. in 2019, we conclude that the new physics beyond the standard $\Lambda$CDM model is needed if all of these datasets are reliable.

Hubble constant, dark energy, equation of state

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1 Introduction

There are a lot of constraints on the Hubble constant $H_0$ in literature. Some results are listed in Table 1 [1-11]. From Table 1, we see that there is an obvious tension between the local measurement on the Hubble constant from SH0ES and the results from globally fitting the cosmic microwave background (CMB), including Wilkinson Microwave Anisotropy Probe (WMAP) and Planck, and baryonic acoustic oscillation (BAO). In particular, the tension between SH0ES [5] and Planck [9] has been at around 4.4$\sigma$ level. And both the combinations of WMAP+BAO datasets [10] and BAO+Alcock-Paczynski (AP) datasets [7] give similar Hubble constant with Planck in the standard $\Lambda$CDM cosmology. On the other hand, recently a new measurement of the Hubble constant, namely H0LiCOW [11], in the $\Lambda$CDM model from a joint analysis of six gravitationally lensed quasars with measured time delays which is completely independent of both supernovae and CMB analyses roughly recovers the Hubble constant from SH0ES.
Even though the tension on the Hubble constant from diverse measurements might arise from the uncertain systematic errors in the datasets, it is still important to propose new methods to measure the Hubble constant. In this article we suggest to determine the Hubble constant by adopting the low-redshift datasets, including BAO, AP and supernovae, in the models beyond the standard ΛCDM model which are supposed to relax the cosmological model dependence.

2 Constraints on the Hubble constant

Here we only adopt the low-redshift datasets, including BAO measurements from Six-degree-Field Galaxy Survey (6dFGS), Main Galaxy Sample (MGS), DR12, DR14 and eBOSS DR14 Lyα, Pantheon sample of Type Ia supernovae (SNe Ia), and AP effect from the BOSS DR12 galaxies.

- The Pantheon sample, as the largest confirmed SNe Ia sample, which includes 1048 SNe Ia and covers the redshift range of 0.01 < z < 2.3 [12].

- The BAO measurements from the 6dFGS at $z_{\text{eff}}=0.106$ [13], the SDSS DR7 MGS at $z_{\text{eff}}=0.15$ [14], the BOSS DR12 sample [15] at $z_{\text{eff}}=0.31, 0.36, 0.40, 0.44, 0.48, 0.52, 0.56, 0.59, 0.64$, the eBOSS DR14 quasar sample at $z_{\text{eff}}=1.52$ [16], the eBOSS DR14 Lyα at $z_{\text{eff}}=2.34$ [17].

- The tomographic AP method to the BOSS DR12 galaxies (0.15 < z < 0.693) [18].

Since the late-time dynamics of the Universe is dominated by dark energy, the properties of dark energy significantly affect the expansion history of the Universe. Therefore, we constrain the Hubble constant in three different dark energy models, including the standard ΛCDM model, $w$CDM and $w_0w_a$CDM models, respectively. We use the CosmoMC software [19] to obtain the Markov Chain Monte Carlo (MCMC) samples. Here we assume a fiducial cosmology, namely $\Omega_m h^2 = 0.02236$ [9]. The changes of $\Omega_m h^2$ within its error bars do not substantially shift our results.

We perform a likelihood analysis to place constraints on the parameters space in the ΛCDM, $w$CDM and $w_0w_a$CDM models from Pantheon+BAO+AP datasets. The total likelihood $\chi^2$ for the datasets can be constructed by

$$\chi^2_{\text{total}} = \chi^2_{\text{Pantheon}} + \chi^2_{\text{BAO}} + \chi^2_{\text{AP}}.$$  

Our main results are illustrated in Figure 1 and Table 2.

The Hubble constant can be precisely determined by the low-redshift observational data in the ΛCDM model in which the late-time evolution of our Universe is determined by two parameters, i.e. $\Omega_m$ and $H_0$. Here we find

$$\Omega_m = 0.292^{+0.011}_{-0.015},$$  

and present a 1.3% precision measurement on the Hubble constant:

$$H_0 = 67.95^{+0.78}_{-1.03},$$  

which has a tension with the Hubble constant given by Riess et al. [5] at the 3.75σ level.

In the $w$CDM model, we have one more parameter, i.e. $w \equiv p_d/c/\rho_d$ which is a constant describing the equation of state of dark energy with energy density $\rho_d$ and $p_d$. The constraints on $w$ and $\Omega_m$ is illustrated in Figure 2. It indicates that the mean values of $\Omega_m$ and $w$ as well as the 68% limits are

$$\Omega_m = 0.305^{+0.019}_{-0.021},$$  

$$w = -1.05 \pm 0.06.$$  

The constraint on the Hubble constant in $w$CDM model reads

$$H_0 = 69.81^{+2.22}_{-2.70} (3.5\% \text{ precision}).$$
Finally, we consider a more general dark energy model, namely $w_0w_a$CDM model in which the equation of state of dark energy is given by

$$w_{de} = w_0 + w_a(1 - a) = w_0 + w_a \frac{z}{1 + z} \quad (7)$$

Table 2  Parameter 68% intervals and $\chi^2$ for the $\Lambda$CDM, wCDM and $w_0w_a$CDM models from Pantheon+BAO+AP datasets

| Parameter | $\Lambda$CDM | wCDM | $w_0w_a$CDM |
|-----------|-------------|------|-------------|
| $w_0$     | -1         | -1.05 $\pm$ 0.06 | -1.05 $\pm$ 0.07 |
| $w_a$     | -          | -    | 0.59$^{+0.52}_{-0.51}$ |
| $\Omega_m$| 0.292$^{+0.011}_{-0.015}$ | 0.305$^{+0.009}_{-0.012}$ | 0.265$^{+0.045}_{-0.040}$ |
| $H_0$     | 67.95$^{+0.78}_{-1.03}$ | 69.81$^{+2.22}_{-2.70}$ | 66.75$^{+3.42}_{-4.23}$ |
| $\chi^2_{\text{Pantheon}}$ | 1036.42 | 1036.68 | 1036.77 |
| $\chi^2_{\text{BAO}}$ | 17.34 | 18.19 | 17.10 |
| $\chi^2_{\text{AP}}$ | 73.41 | 72.91 | 72.16 |
| $\chi^2_{\text{Total}}$ | 1127.17 | 1127.79 | 1126.03 |

Figure 2  (Color online) The marginalized contour (68% CL and 95% CL) of parameters $\Omega_m$ and $w$ for the wCDM model from Pantheon+BAO+AP datasets.

In this model, the equation of state of dark energy also evolves with time. The constraints on the parameters $w_0$ and $w_a$ are given by

$$w_0 = -1.05 \pm 0.07, \quad (8)$$

$$w_a = 0.59^{+0.52}_{-0.51}. \quad (9)$$

See the contour plot in Figure 3. The constraint on the Hubble constant in this model is

$$H_0 = 66.75^{+3.42}_{-4.23} \ (5.7\% \ precision). \quad (10)$$

Even though the mean value of the Hubble constant becomes lower, the error bar is significantly enlarged and then alleviates the tension with $H_0$ obtained by Riess et al. [5].
To summarize, we combine the low-redshift observational datasets from the Pantheon sample of SNe Ia sample, the BAO measurements (including the 6dFGS, the SDSS DR7 MGS, the BOSS DR12, the eBOSS DR14 quasar, and the eBOSS DR14 Lyα), and the tomographic Alcock-Paczynski method to the BOSS DR12 galaxies, and globally determine the Hubble constant in three cosmological models. For the standard $\Lambda$CDM model, the Hubble constant is $H_0 = 67.95^{+0.78}_{-1.03} \text{ km s}^{-1} \text{ Mpc}^{-1}$ which is nicely consistent compared with the measurement from CMB data, but has a $3.75\sigma$ tension with that given by Riess et al. [5]. Such a tension can be significantly relaxed in the $w$CDM model and $w_0\Lambda$CDM model. In fact, a dynamical dark energy model can also relax the tension between the local measurement on the Hubble constant and the global fitting from CMB and BAO data [20].

Even though the true value of the Hubble constant is still unknown, we conclude that the tension between the local measurement and the global fitting from CMB and other low-redshift cosmological data strongly implies that we need new physics beyond the standard $\Lambda$CDM cosmology. It may imply something about the $w$CDM model and $w_0\Lambda$CDM model.

In a word, more study on the Hubble constant is needed in the future.

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