A possible resolution of tension between Planck and Type Ia supernova observations

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Abstract

There is an apparent tension between cosmological parameters obtained from Planck cosmic microwave background radiation observations and that derived from the observed magnitude-redshift relation for the type Ia supernova (SNe Ia). Here, we show that the tension can be alleviated, if we first calibrate, with the help of the distance-duality relation, the light-curve fitting parameters in the distance estimation in SNe Ia observations with the angular diameter distance data of the galaxy clusters and then re-estimate the distances for the SNe Ia with the corrected fitting parameters. This was used to explore their cosmological implications in the context of the spatially flat cosmology. We find a higher value for the matter density parameter, \(\Omega_m\), as compared to that from the original SNLS3, which is in agreement with Planck observations at 68.3\% confidence. Therefore, the tension between Planck measurements and SNe Ia observations regarding \(\Omega_m\) can be effectively alleviated without invoking new physics or resorting to extensions for the standard concordance model. Moreover, with the absolute magnitude of a fiducial SNe Ia, \(M\), determined first, we obtained a constraint on the Hubble constant with SNLS3 alone, which is also consistent with Planck.

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I. INTRODUCTION

The cosmic microwave background radiation (CMBR) measurements play a crucial and irreplaceable role in establishing the favored cosmological model, that is, a flat cosmological constant-dominated, cold dark matter model ($\Lambda$CDM), and constraining the cosmological parameters. It is important, however, to bear in mind that CMBR observations predominantly probe the early universe at high redshift ($z \sim 1100$). As a result, a projection within a given cosmological model is needed when we interpret these observations in terms of the standard cosmological parameters defined at $z = 0$, for instance, the Hubble constant, $H_0$, and the matter density parameter, $\Omega_m$, which provide basic information and are key parameters of the universe. Recently, one of the most exciting events is the release of scientific findings based on data from the first 15.5 months of Planck operations [1]. Because of the high precision, the new Planck data could constrain several cosmological parameters at few percent level [2]. Within the context of the spatially flat $\Lambda$CDM cosmology, a low value of the Hubble constant, $H_0 = 67.4 \pm 1.4 \, \text{km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$, and a high value of the matter density parameter, $\Omega_m = 0.314 \pm 0.020$, are obtained. These are seemingly in tension with the measurements of the magnitude-redshift relation for Type Ia Supernova (SNe Ia) [3–5], but are entirely consistent with geometrical constraints from baryonic acoustic oscillation (BAO) surveys [6, 7]. This inconsistency between fundamental cosmological parameters constrained from the high redshift CMBR measurements and those from the observations at relatively low redshifts may indicate the existence of defects in the cosmological model where we project constraints on the standard cosmological parameters from these observations to $z = 0$, since projected parameters should presumably be the same from measurements at all $z$ in a given model. Thus, after Planck, attempts have been made to resolve this tension [8–15]. For instance, the cosmic variance has been suggested to account for the discrepancy in $H_0$ [8] and an extension of the Friedmann-Lemaître-Robertson-Walker (FLRW) metric to the reputed “Swiss-cheese” model for the background has been proposed to alleviate the tension of $\Omega_m$ [12].

Here, we take a different approach to the issue. We show that if we first calibrate,
with the help of the distance-duality relation, the light-curve fitting parameters in the distance estimation of the SNe Ia using the data on angular diameter distance of the galaxy clusters so as to eliminate the cosmological model-dependence that exists in the global fit to the Hubble diagram where the light-curve fitting parameters are treated free on the same footing as cosmological parameters, then a higher value of the matter density parameter $\Omega_m$ can be obtained from SNLS3. This is consistent with the Planck at the 68.3% confidence, thereby alleviating the tension. Furthermore, with the light-curve fitting parameters and the absolute magnitude of a fiducial SNe Ia calibrated first, a low value of the Hubble constant $H_0$ which is consistent with Planck can also be obtained.

Note that in parallel with CMBR measurements at high redshift, accurate distance estimation to celestial objects at relatively low redshift is another key tool in observational cosmology. Some fundamental changes in our understanding of the universe have resulted from such distance measurements. For example, Brahe’s supernova and Hubble’s Cepheids completely reconstructed our understanding of the cosmos [16]. Almost five years after the SNe Ia were shown to be accurate standard candles, distance measurements for them have directly led to the discovery of the cosmic acceleration [17, 18]. After several decades of intensive study, SNe Ia remain, at present, the most direct and mature portal to explore the essence of the accelerated expansion [19]. In the past decade or so, several supernova data sets with hundreds of well-measured SNe Ia were released, such as “ESSENCE” [20], “Constitution” [21], “SDSS-II” [22], and “Union2.1” [23]. Since the SNe Ia has been proposed as a distance indicator, various empirical approaches (known as light-curve fitters) to distance estimation, using light-curve shape parameters ($\Delta m_{15}$ or a stretch factor) [24–26] or color information [27, 28], or both [29–33], have been advanced. Currently, the distance of the SNe Ia is usually estimated by expressing it as an empirical function of the observable quantities because of the variability of the large spectra features. Taking the SALT2 light-curve fitter [32] as an example, the distance estimator (distance modulus: $\mu = 5 \log \left[ \frac{d_L}{M_{\text{pc}}} \right] + 25$) of the SNe Ia is given by a linear combination of $m^*_B$, $x_1$, and $c$: 

$$
\mu_B(\alpha, \beta; M) = m^*_B - M + \alpha \cdot x_1 - \beta \cdot c
$$

where $x_1$ is the stretch (a measurement of the shape of the SNe light curve) and $c$ is
the color measurement for the SNe. $m_B^*$ is the rest-frame peak magnitude of an SNe.

$\alpha$ and $\beta$ are nuisance parameters which characterize the stretch-luminosity and color-luminosity relationships, reflecting the well-known broader-brighter and bluer-brighter relationships, respectively. The value of $M$ is another nuisance parameter representing the absolute magnitude of a fiducial SNe. In general, in SALT2 (similar for SiFTO [33], or SALT2/SiFTO combined [5]), $\alpha$ and $\beta$ are left as free parameters (on the same weight as cosmological parameters) that are determined in the global fit to the Hubble diagram. This treatment results in the dependence of distance estimation on cosmological model. Thus, cosmological implications derived from the distance estimation of the SNe Ia with the light-curve fitting parameters determined in the global fit to the Hubble diagram are somewhat cosmological-model-dependent.

On the other hand, besides the luminosity distance, $d_L$, measurement for the standard candle such as SNe Ia, distance estimation for objects with known size (that is, standard ruler) named as angular diameter distance (ADD), $d_A$, is also often employed in astronomy. Recently, an ADD sample of 25 galaxy clusters (0.023 ≤ $z$ ≤ 0.784) has been obtained by combining the X-ray brightness and Sunyaev-Zel’dovich temperature decrements (SZ effect [34]) observations [35]. In addition, the three-dimensional structure of galaxy cluster was also minutely studied in this work and it was found that the spherical hypothesis for geometry of cluster is generally rejected. The luminosity distance, $d_L$, and ADD, $d_A$, may be measured independently by different astronomical observations from different celestial objects, but they relate to each other by means of the Etherington’s reciprocity relation [36–38]:

$$\frac{d_L}{d_A}(1+z)^{-2} = 1.$$  \(2\)

This relation, sometimes referred as the distance-duality (DD) relation, is completely general and valid for all cosmological models based on the Riemannian geometry. That is, the validity is dependent neither on the Einstein field equation for gravity nor on the nature of the matter-energy content of the universe. It only requires that the source and observer be connected by null geodesic in a Riemannian spacetime and that the number of photons be conserved. The fundamental DD relation has played an essential role in modern observational cosmology, for instance, gravitational-lensing studies [39], the
plethora of cosmic consequences from primary and secondary temperature anisotropies of the CMBR observations [40] and analysis from galaxy cluster observations [41, 42].

Thus, the DD relation, the validity of which is a seemingly reasonable assumption without new physics, along with the ADD data of galaxy clusters, provides us a natural possibility to calibrate the light-curve fitting parameters, α and β, for distance estimation in the SNe Ia observation in a cosmological-model-independent manner before being used to estimate the distances of the SNe Ia for cosmological analysis. In the following, we will demonstrate that if we use α and β corrected this way to re-estimate the luminosity distances of the SNe Ia and explore cosmological implications in the framework of the spatially flat ΛCDM cosmology, we can obtain a higher value of matter density parameter, \( \Omega_m = 0.301^{+0.033}_{-0.031} \) (the original SNLS3 gives \( \Omega_m = 0.225^{+0.040}_{-0.037} \)), which is in good agreement with that obtained from the Planck observations. Thus, tension regarding \( \Omega_m \) can be alleviated without invoking new physics or resorting to extensions of the standard cosmological model. Furthermore, a low value of Hubble constant, \( H_0 = 66.0^{+0.3}_{-0.4} \) km s\(^{-1}\) Mpc\(^{-1}\), can also be obtained from SNLS3, which is consistent with Planck.

II. CONSTRAINTS ON LIGHT-CURVE FITTING PARAMETERS AND COSMOLOGICAL IMPLICATIONS

In order to place cosmological-model-independent constraints on α and β with the aid of the reciprocity relation in Eq. (2), the data pairs of observed \( d_L \) and \( d_A \) almost at the same redshift should be provided. For the observed \( d_L \), the SNLS3 SN Ia sample compiled with SALT2/SiFTO combined fitter [5] is considered. Galaxy clusters sample, where an elliptical geometry is supposed for the morphology of clusters and the ADDs are obtained by combining the SZE+X-ray brightness measurements [35], is responsible for providing the observed \( d_A \). Since the sample size of the SN Ia is much larger than that of the galaxy clusters, we bin the observed \( d_L \) from the data points of the SNLS3, with the corresponding redshifts satisfying the selecting criteria, \( \Delta z_{\text{max}} = |z_{\text{cluster}} - z_{\text{SNe Ia}}|_{\text{max}} \leq 0.005 \)\(^1\), to match

\(^1\) For the galaxy cluster MS 1137.5+6625 with redshift \( z = 0.784 \), only two SNe Ia, 04D1jd (\( z = 0.778 \)) and 05D4cs (\( z = 0.79 \)), satisfy \( \Delta z_{\text{max}} = 0.006 \). For the sake of completeness of the galaxy clusters
the observational data of the ADD sample,

\[ \mu_{\text{SN}}^\text{bin} = \frac{\sum (\mu_{\text{SN}}^i / \sigma_{\text{SN}}^2)}{\sum (1/\sigma_{\text{SN}}^2)}, \quad \sigma_{\mu,\text{bin}}^\text{SN} = \left( \frac{1}{\sum (1/\sigma_{\text{SN}}^2)} \right)^{1/2}. \]  

(3)

It should be noted that both binned distance modulus \( \mu_{\text{SN}}^\text{bin} \), and corresponding uncertainties \( \sigma_{\mu,\text{bin}}^\text{SN} \) are functions of \( \alpha \) and \( \beta \). In addition, we have to express the observed distances in terms of the distance modulus, that is, \( \mu_{\text{SN}}^\text{B}(\alpha, \beta; M) \) for the SNe Ia observations and \( \mu_{\text{cluster}} = 5 \log \left( \frac{(1+z)^2 d_{\text{cluster}}}{\text{Mpc}} \right) + 25 \) for the galaxy clusters sample, to marginalize the absolute magnitude of a fiducial SNe Ia, \( M \), when \( \alpha \) and \( \beta \) are fitted using the standard minimum-\( \chi^2 \) route,

\[ \chi^2(\alpha, \beta, M) = A - 2 * M * B + M^2 * C, \]  

(4)

where

\[ A(\alpha, \beta) = \sum_{i=1}^{25} \left[ \frac{\mu_{\text{SN}}^i(z_i; \alpha, \beta, M = 0) - \mu_{\text{cluster}}(z_i)}{\sigma_{\text{tot}}^2(\alpha, \beta)} \right]^2, \]  

(5)

\[ B(\alpha, \beta) = \sum_{i=1}^{25} \left[ \frac{\mu_{\text{SN}}^i(z_i; \alpha, \beta, M = 0) - \mu_{\text{cluster}}(z_i)}{\sigma_{\text{tot}}^2(\alpha, \beta)} \right], \]  

(6)

\[ C(\alpha, \beta) = \sum_{i=1}^{25} \frac{1}{\sigma_{\text{tot}}^2(\alpha, \beta)}. \]  

(7)

Here \( \sigma_{\text{tot}}^2 \) are propagated from both the statistical uncertainties in SNe Ia and that in galaxy clusters observations. Eq. (4) has a minimum at \( M = B/C \), and it is

\[ \tilde{\chi}^2(\alpha, \beta) = A(\alpha, \beta) - \frac{B^2(\alpha, \beta)}{C(\alpha, \beta)}. \]  

(8)

Different from the marginalization of a combination of the absolute magnitude of a fiducial SNe Ia and the Hubble constant in the global fit to the Hubble diagram, the analysis performed here can give an estimation for the absolute magnitude of a fiducial SNe Ia and thus break the degeneracy between them. Unfortunately, the systematic uncertainties of the SNe Ia (in terms of the covariance matrix) are difficult to be included when we bin the selected SNe Ia for the corresponding galaxy cluster to obtain our data pairs. However, the systematic errors are taken into consideration in our following cosmological sample, these two SNe Ia are binned for matching the very galaxy cluster.
implication analysis. The cosmological-model-independent constraint on $\alpha$ and $\beta$ is shown in Fig. 1. Compared to the light-curve fitting parameters determined from the global fit to the Hubble diagram in the framework of the constant $w$ dark energy model (marked as the red star), the result derived from our cosmological-model-independent analysis (indicated by the blue cross) favors a larger $\alpha$ and a smaller $\beta$. Along with these two light-curve fitting parameters, a model-independent estimation for the absolute magnitude of a fiducial SNe Ia $M = -19.30$ is also achieved, which is in good agreement with what obtained from photometric measurements (refer to review elsewhere). This may be seen as an indication of reliability of our proposal to calibrate the light-curve fitting parameters in the distance estimation for SNe Ia using the ADD data. It is worth noting that an estimation for $M$ can not be accomplished without any assumption prior for the Hubble constant in previous global fit procedure. With this estimation for the absolute magnitude of a fiducial SNe Ia, a constraint on Hubble constant from SNLS3 alone can be obtained in our following analysis for cosmological implications.

Now let us explore the cosmological implications of the corrected distance for the SNLS3 using the best fit values for the light-curve fitting parameters $\alpha$ and $\beta$ constrained from our model-independent analysis. Following the minimum-$\chi^2$ route presented in Appendix C of Ref. [5], we place constraints from the corrected SNLS3 SN Ia on the spatially flat $\Lambda$CDM cosmology. The results are shown in Fig. (2, 3). From Fig. 2, we find that, compared to the original SNLS3 SN Ia, the corrected one yields a higher value of the matter density parameter, $\Omega_m = 0.301^{+0.033}_{-0.031}$. This agrees with that obtained from Planck observations very well. Moreover, with the previously determined $M = -19.30$, we can also derive a constraint on the Hubble constant from the corrected SNLS3. As shown in Fig. 3, we obtain a low value of $H_0 (66.0^{+0.3}_{-0.4}$ km $\cdot$ s$^{-1}$ $\cdot$ Mpc$^{-1}$) which is also in agreement with that from Planck observations at 68.3% confidence.

III. CONCLUSION AND DISCUSSION

We have demonstrated that the tension between Planck measurements and the observed magnitude-redshift relation for the SNe Ia may be alleviated if we first calibrate,
FIG. 1: Cosmological-model-independent constraint on light-curve fitting parameters, $\alpha$ and $\beta$, from SNLS3 SN Ia analyzed with SALT2/SiFTO combined fitter and the galaxy clusters sample.

FIG. 2: Constraints on the matter density parameter, $\Omega_m$, in the context of spatially flat $\Lambda$CDM cosmology.

with help of the distance-duality relation, the light-curve fitting parameters $\alpha$ and $\beta$ in the distance estimation of the SNe Ia using the data on angular diameter distance of the galaxy clusters. This eliminates the cosmological model-dependence that exists in the
FIG. 3: Constraints on the Hubble constant, $H_0$, at 68.3% confidence, in the context of the spatially flat $\Lambda$CDM cosmology.

global fit to the Hubble diagram where the parameters are treated free on the same footing as cosmological parameters. We can use $\alpha$ and $\beta$ corrected in this manner to re-estimate the luminosity distances of the SNLS3 SNe Ia and explore their cosmological implications in the framework of the spatially flat $\Lambda$CDM cosmology, and so a higher value of the matter density parameter, $\Omega_m = 0.301^{+0.033}_{-0.031}$, can be obtained. This alleviates the tension between Planck and SNe Ia observations regarding $\Omega_m$ significantly (rendering them be consistent at 68.3% confidence).

Another unusual feature in our approach is that the estimation for the absolute magnitude of a fiducial SNe Ia, $M = -19.30$, can simultaneously be obtained from the standard minimum-$\chi^2$ fitting route for $\alpha$ and $\beta$ without any assumption for the Hubble constant prior. This makes constraining the Hubble constant with SNLS3 alone possible and a low value of $H_0$ ($66.0^{+0.3}_{-0.4}$ km $\cdot$ s$^{-1}$ $\cdot$ Mpc$^{-1}$) is obtained, which is also in good agreement with what obtained from Planck observations. However, the globally averaged Hubble constant we obtained here from SNLS3, although consistent with Planck, is in tension with the locally measured expansion rate of the universe. This might be a result of the cosmic variance, or even more speculatively, a dilute local environment.

Finally, we must note that although the method for determining the light-curve fitting
parameters proposed here can remove the cosmological model-dependence that is present in the global fit to the Hubble diagram, yielding a reasonable absolute magnitude of a fiducial SNe Ia, and thereby reducing the tensions between Planck measurements at high redshift and the observed magnitude-redshift relation for the SNe Ia at relatively low red-shifts, the presence of systematic uncertainties in measurements using SZE+X-ray surface brightness observations and the limited samples of the galaxy clusters may lead to biases of our result. Thus, ADD data of more samples of galaxy clusters with greater precision are needed to increase the statistical power of our result. This being considered, the analysis herein presented suggests a possibility to reconcile the Planck and SNe Ia observations without invoking new physics or resorting to extension of the standard cosmological model thus giving a direction for future observational endeavors.

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