More Evidence for the Redshift Dependence of Color from the JLA Supernova Sample Using Redshift Tomography

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\textbf{ABSTRACT}

In this work, by applying the redshift tomography method to Joint Light-curve Analysis (JLA) supernova sample, we explore the possible redshift-dependence of stretch-luminosity parameter \(\alpha\) and color-luminosity parameter \(\beta\). The basic idea is to divide the JLA sample into different redshift bins, assuming that \(\alpha\) and \(\beta\) are piecewise constants. Then, by constraining the \(\Lambda\)CDM model, we check the consistency of cosmology-fit results given by the SN sample of each redshift bin. We also adopt the same technique to explore the possible evolution of \(\beta\) in various subsamples of JLA. Using the full JLA data, we find that \(\alpha\) is always consistent with a constant. In contrast, at high redshift \(\beta\) has a significant trend of decreasing, at \(\sim 3.5\sigma\) confidence level (CL). Moreover, we find that low-z subsample favors a constant \(\beta\); in contrast, SDSS and SNLS subsamples favor a decreasing \(\beta\) at 2\(\sigma\) and 3.3\(\sigma\) CL, respectively. Besides, by using a binned parameterization of \(\beta\), we study the impacts of \(\beta\)’s evolution on parameter estimation. We find that compared with a constant \(\beta\), a varying \(\beta\) yields a larger best-fit value of fractional matter density \(\Omega_m\), which slightly deviates from the best-fit result given by other cosmological observations. However, for both the varying \(\beta\) and the constant \(\beta\) cases, the 1\(\sigma\) regions of \(\Omega_m\) are still consistent with the result given by other observations.

\textbf{Key words:} cosmology: dark energy, observations, cosmological parameters, supernova

1 INTRODUCTION

Type Ia supernova (SN Ia) is a sub-category of cataclysmic variable stars that results from the violent explosion of a white dwarf star in a binary system Hillebrandt, & Niemeyer (2000). It can be used as standard candles to measure the expansion history of the universe Riess et al. (1998); Perlmutter et al. (1999), and it has become one of the most powerful tools to probe the nature of dark energy (DE) Frieman et al. (2008); Wang (2010); Li et al. (2011, 2013); Weinberg et al. (2013). In recent years, several supernova (SN) datasets have been released, such as “SNLS” Astier et al. (2006), “Union” Kowalski et al. (2008), “Constitution” Hicken et al. (2009a,b), “SDSS” Kessler et al. (2009), “Union2” Amanullah et al. (2010), “SNLS3” Conley et al. (2011) and “Union2.1” Suzuki et al. (2012). The latest SN sample is “Joint Light-curve Analysis” (JLA) dataset Betoule et al. (2014), which consists of 740 supernovae (SNe). JLA data includes 118 SNe at \(0 < z < 0.1\) from several low-redshift samples [Hamuy et al.1996, Riess et al.1999, Jha et al.2005, Contreras et al.2010, Hicken et al.2009a,b], 374 SNe at \(0.03 < z < 0.4\) from the Sloan Digital Sky Survey (SDSS) SN search Holtzman et al.2008, 239 SNe at \(0.1 < z < 1.1\) from the Supernova Legacy Survey (SNLS) observations Guy et al.2010 and 9 SNe at \(0.8 < z < 1.3\) from Hubble Space Telescope (HST) Riess et al.2007. It should be stressed that, in the process of cosmology-fits, Betoule et al. treated two important quantities, stretch-luminosity parameter \(\alpha\) and color-luminosity parameter \(\beta\) of SN Ia, as free model parameters Betoule et al. (2014). This procedure is same as the recipe of Conley et al. (2011).

The early proposals to use SN Ia as standard candles made an assumption that the early samples were too small to test. By now SN samples are large enough for many meaningful tests to be done. One of the most important tests is to probe the possibility of redshift-dependence of \(\alpha\) and \(\beta\). So far, there is no evidence for the evolution of \(\alpha\). But the redshift-dependence of \(\beta\) has been found for several SN datasets. For examples, by using the bin-by-bin method, Marriner et al. found the redshift-dependence of \(\beta\) for...
the SDSS data Marriner et al. [2011]. Besides, by adopting a linear β, Mohlabeng and Ralston found the evolution of β at 7σ confidence level (CL) for the Union2.1 data Mohlabeng & Ralston [2013]. In addition, one of the present authors also done a series of research works about this issue. In Wang & Wang [2013a], we found that β deviates from a constant at 6σ CL for the SNLS3 data. Soon after, by studying various DE and modified gravity models with a linear β Wang et al. [2014], Wang et al. [2014], Wang et al. [2015], we found that the evolution of β has significant effects on parameter estimation, and the introduction of a time-varying β can reduce the tension between SN Ia and other cosmological observations.

In a recent work Shariff et al. [2015], the discussion about time-varying β has been extended into the case of JLA data. By adopting two specific parameterizations of β, Shariff et al. found 4.6σ CL evidence for a significant drop in β at redshift z = 0.66 Shariff et al. [2015]. It should be pointed out that, the results of Shariff et al. [2015] depend on two particular parameterizations of β. To further investigate the possible redshift-dependence of β, it is necessary to revisit this issue using a model-independent method. In this work, we adopt the redshift tomography method, which has been widely used in the investigation of cosmology Marriner et al. [2011]; Cai et al. [2014]; Giannantonio et al. (2015). The basic idea is to divide the SN data into different redshift bins, assuming that both α and β are piecewise constants. It should be pointed out that, adopting the redshift tomography method will reduce the statistical significance. Then we constrain Λ-cold-dark-matter (ΛCDM) model and check the consistency of cosmology-fit results in each bin. In addition, it is very interesting to explore the possible evolution of β in various subsamples of JLA. As far as we know, this issue has not been studied in the past. Therefore, we also apply the same technique to various subsamples of JLA. Moreover, it is important to study the impacts of possible redshift-dependence of β on the parameter estimation. To do this, we adopt a binned parameterization of β in the analysis.

We describe our method in section 2 present our results in section 3 and summarize in section 4.

2 METHODOLOGY

In this section, we firstly introduce how to calculate the χ² function of JLA data. Then, we describe the details of the redshift tomography method.

Theoretically, the distance modulus μ_{hb} in a flat universe can be written as

\[ μ_{hb} = 5 \log_{10} \left( \frac{d_L(z_{hel}, z_{cmb})}{H_0} \right) + 25, \]

where \( z_{cmb} \) and \( z_{hel} \) are the CMB restframe and heliocentric redshifts of SN. The luminosity distance \( d_L \) is given by

\[ \frac{d_L(z_{hel}, z_{cmb})}{H_0} = \frac{1 + z_{hel}}{c} \int_{0}^{z_{cmb}} \frac{dz}{E(z)}, \]

where \( c \) is the speed of light, \( H_0 \) is the Hubble constant and \( E(z) \equiv H(z)/H_0 \) is the reduced Hubble parameter. For ΛCDM, \( E(z) \) can be written as

\[ E(z) = \sqrt{\Omega_m(1+z)^3 + (1 - \Omega_m)}. \]

Here \( \Omega_m \) is the present fractional matter density.

The observation of distance modulus μ_{obs} is given by an empirical linear relation:

\[ μ_{obs} = m_B - M_B + \alpha \times X_1 - \beta \times C, \]

where \( m_B \) is the observed peak magnitude in the rest-frame of the B band, \( X_1 \) describes the time stretching of light-curve, \( C \) describes the supernova color at maximum brightness and \( M_B \) is the absolute B-band magnitude, which depends on the host galaxy properties Schallay & Finkbeiner [2011]. Johansson et al. [2013]. Notice that \( M_B \) is related to the host stellar mass \( (M_{stellar}) \) by a simple step function Betoule et al. [2014].

\[ M_B = \begin{cases} M_B^1 & \text{if } M_{stellar} < 10^{10} M_\odot, \\ M_B^0 & \text{otherwise}. \end{cases} \]

Here \( M_\odot \) is the mass of sun.

The χ² of JLA data can be calculated as

\[ \chi^2 = (\Delta \mu - \mu_{obs})^2 \cdot \text{Cov}^{-1} \cdot (\Delta \mu - \mu_{obs}), \]

where \( \Delta \mu \equiv \mu_{obs} - \mu_{th} \) is the data vector and Cov is the total covariance matrix, which is given by

\[ \text{ Cov } = \text{D}_{stat} + \text{C}_{stat} + \text{C}_{sys}. \]

Here \( \text{D}_{stat} \) is the diagonal part of the statistical uncertainty, which is given by Betoule et al. [2014].

\[ \text{D}_{stat,ii} = \frac{1}{\sigma_{zi}^2 + \sigma_{\alpha i}^2 + \sigma_{\beta i}^2 + \sigma_{\mu B,i}^2 + \sigma_{\sigma\ell,i}^2 + \sigma_{\nu,i}^2 + 2 \alpha C_{mB,i} X_{1,i} - 2 \beta C_{mB,i} C_{X,i} - 2 \alpha C_{X,i}}, \]

where the first three terms account for the uncertainty in redshift due to peculiar velocities, the intrinsic variation in SN magnitude and the variation of magnitudes caused by gravitational lensing. \( \sigma_{\alpha i}^2, \sigma_{\beta i}^2, \sigma_{\mu B,i}^2, \sigma_{\ell,i}^2, \sigma_{\nu,i}^2, \) denote the uncertainties of \( m_B, X_1 \) and \( C \) for the \( i \)-th SN. In addition, \( C_{mB,i} X_{1,i}, C_{mB,i} C_{X,i} \) and \( C_{X,i} \) are the covariances between \( m_B, X_1 \) and \( C \) for the \( i \)-th SN. Moreover, \( \text{C}_{stat} \) and \( \text{C}_{sys} \) are the statistical and the systematic covariance matrices, given by

\[ \text{C}_{stat} + \text{C}_{sys} = V_0 + \alpha^2 V_a + \beta^2 V_b + 2 \alpha V_0a - 2 \beta V_0b - 2 \alpha \beta V_{ab}, \]

where \( V_0, V_a, V_b, V_{0a}, V_{0b} \) and \( V_{ab} \) are matrices given by the JLA group at the link: http://supernovae.in2p3.fr/sdss_snl3_jla/ReadMe.html. For the detailed discussions about JLA SN sample, see Ref Betoule et al. [2014].

As pointed out in Betoule et al. [2014], in the process of calculating χ², both the Hubble constant \( H_0 \) and the absolute B-band magnitude \( M_B \) are marginalized. In this work, we follow the procedure of Betoule et al. [2014], and do not treat \( H_0 \) and \( M_B \) as free parameters. We refer the reader to Ref. Betoule et al. [2014], as well as the code of the JLA likelihood for the details of calculation.

As mentioned above, our aim is to explore the possible evolution of SN using a model-independent method. In this work, we adopt the redshift tomography method. The basic idea is to divide the SN sample into different redshift bins, assuming that both α and β are piecewise constants. Then, by constraining the ΛCDM model, we check the consistency of cosmology-fit results given by the SN sample of each redshift bin. Moreover, to ensure that our results are insensitive to the details of redshift tomography, we evenly divide the JLA sample at redshift region [0,1] into 3 bins, 4 bins and 5 bins, respectively; then, we compare the fitting results obtained from these three cases. In this work we perform a MCMC likelihood analysis using the “CosmoMC” package Lewis & Bridle [2002].

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3 RESULT

In this section, we mainly focus on the evolution behaviors of luminosity standardization parameters $\alpha$ and $\beta$. Firstly, we present the results given by the full JLA sample; then, we present the results given by various subsamples of JLA; finally, we discuss the impacts of time-varying $\beta$ on parameter estimation.

In Fig 1, we plot the $1\sigma$ confidence regions of $\alpha$ given by the full JLA sample. The results of 3 bins, 4 bins and 5 bins are shown in the upper left panel, the upper right panel and the lower panel of Fig 1, respectively. For all the panels, it can be seen that the $1\sigma$ regions of $\alpha$ given by the full JLA sample (gray region) overlap with the results given by the SN samples of various bins at $1\sigma$ CL. So we can conclude that $\alpha$ is consistent with a constant. Since this conclusion holds true for all the cases of 3 bins, 4 bins and 5 bins, we can conclude that it is insensitive to the details of redshift tomography. This conclusion is consistent with the results of previous studies (Marriner et al. 2011; Mohlabeng & Ralston 2013; Wang & Wang 2013a; Shariff et al. 2015).

In Fig 2, we plot the $1\sigma$ confidence regions of $\beta$ given by the full JLA sample. The results of 3 bins, 4 bins and 5 bins are shown in the upper left panel, the upper right panel and the lower panel of Fig 2, respectively. It can be seen that, although $\beta$ is consistent with a constant at low redshift, it has a significant trend of decreasing at high redshift. For the case of 3 bins, the $1\sigma$ upper bound of $\beta$ in the last bin deviates from the results given by the full JLA sample at $3.5\sigma$ CL. For the case of 4 bins, the $1\sigma$ upper bound of $\beta$ in the last bin deviates from the results given by the full JLA sample at $3.6\sigma$ CL. For the case of 5 bins, there is a hint for the evolution of $\beta$ for the fourth bin; moreover, the $1\sigma$ upper bound of $\beta$ in the last bin deviates from the results given by the full JLA sample at $3.6\sigma$ CL. These results indicate that there is a $\sim 3.5\sigma$ CL evidence for the decrease of $\beta$ at high redshift, which is insensitive to the details of redshift tomography. It must be stressed that, this conclusion is consistent with the results of some other SN samples (Marriner et al. 2011; Mohlabeng & Ralston 2013), but is inconsistent with the results of the SNLS3 dataset, which indicates that $\beta$ has a trend of increasing at high redshift (Wang & Wang 2013a). The reason of this tension is still unclear and deserves further studies.

As mentioned above, JLA dataset includes 118 SNe at $0 < z < 0.1$ from the low-$z$, 374 SNe at $0.03 < z < 0.4$ from the SDSS, 239 SNe at $0.1 < z < 1.1$ from the SNLS, and 9 SNe at $0.8 < z < 1.3$ from HST. It is interesting to explore the evolution of $\beta$ in various subsamples of JLA. In this paper we only directly apply the redshift tomography method to the low-$z$, the SDSS, and the SNLS subsamples, because the HST subsample only contains 9 data points. To study the effects of HST subsample, we compare the results of the full JLA sample with the results of the “JLA without HST” data.

In the Fig 3, making use of the redshift tomography method, we show the $1\sigma$ confidence regions of $\beta$ given by each subsample. The results given by the low-$z$, the SDSS, and the SNLS subsamples are shown in the upper left panel, the upper right panel, and the lower panel of Fig 3, respectively. For simplicity, here we only consider the case of 4 bins. For the case of low-$z$, $\beta$ is always consistent with a constant. For the case of SDSS, the $1\sigma$ upper bound of $\beta$ in the last bin deviates from the results given by the full SDSS subsample at $2\sigma$ CL, showing that the SDSS subsample favors a decreasing $\beta$ at high redshift. This conclusion is consistent with the results of Marriner et al. 2011. For the case of SNLS, the $1\sigma$ upper bounds of $\beta$ in the third bin and the fourth bin deviate from the results of the full SNLS subsample at $1.6\sigma$ and $3.3\sigma$ CL, respectively. So compared with the case of SDSS, the SNLS subsample favors a time-varying $\beta$ with a larger decreasing rate. It should be mentioned that, this conclusion is different from the results of the full SNLS3 sample (Wang & Wang 2013a). This means that SNLS3 dataset may exist some unknown systematic uncertainties (Betoule et al. 2014).

In Fig 4, we plot the $1\sigma$ confidence regions of $\beta$ given by the “JLA without HST” data (left panel) with the results given by the full JLA sample (right panel). We can see that the HST subsample only affects the evolution behavior of $\beta$ at high redshift. For the case without HST, the $1\sigma$ upper bound of $\beta$ in the last bin deviates from the results given by the full sample at $3.9\sigma$ CL. For the case of full JLA sample, the $1\sigma$ upper bound of $\beta$ in the last bin deviates from the results given by the full JLA sample at $3.6\sigma$ CL. This indicates that HST subsample can slightly slow down the decreasing rate of $\beta$ at high redshift.

Next, we discuss the impacts of a varying $\beta$ on the parameter estimation. For simplicity, here we consider the standard cosmological model: the $\Lambda$CDM model. As shown in Fig 2, $\beta$ prefers a higher value at low redshift and a lower value at high redshift. So we assume that $\beta$ is related to the redshift by a simple piecewise function

$$\beta(z) = \begin{cases} \beta_1 & 0 < z \leq 0.75, \\ \beta_2 & 0.75 < z \end{cases}$$

where $\beta_1$ and $\beta_2$ are two model parameters. In Fig 5, by using the full JLA sample only, we plot the 1D marginalized probability distributions of $\Omega_{m0}$ in the cases of constant $\beta$ and varying $\beta(z)$. It can be seen that varying $\beta$ yields a larger $\Omega_{m0}$ than the case of constant $\beta$; for the case of varying $\beta$, the best-fit value of $\Omega_{m0}$ is 0.329, while for the case of constant $\beta$, the best-fit value of $\Omega_{m0}$ is 0.297. Note that our result is consistent with the results of Shariff et al. 2015. To make a comparison, in Fig 5, we also plot the 1D marginalized probability distribution of $\Omega_{m0}$, given by a combination of the CMB (Ade et al. 2015) and the Baryon Acoustic Oscillations (BAO) (Egan et al. 2014) data. The best-fit value of $\Omega_{m0}$ given by CMB+BAO data is 0.292, which is closer to the best-fit value of the constant $\beta$ case. This result is different from the result of the SNLS3 sample (Wang et al. 2014). However, the result of $\Omega_{m0}$ for the varying $\beta$ case is still consistent with the result for the constant $\beta$ case, as well as the result given by the CMB+BAO data, at $1\sigma$ CL.

4 SUMMARY

SN Ia is one of the most powerful tools to explore the current cosmic acceleration. As the sample size of SN Ia rapidly grows, it is very important to perform various tests for these SN samples. One of the most interesting tests is to probe the possible evolution of SN color parameter, which has drawn a lot of attentions in recent

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1 To further confirm this point, we move all the bins 1/4 bin width to the right and 1/4 bin width to the left; then we check whether or not there are any significant differences for these two cases. It is found that moving bins in such a way will not yield any significant changes. Therefore, we conclude that the conclusion of $\beta$’s evolution is insensitive to the details of redshift tomography.

2 In addition to Ade et al. 2015, there are some other distance priors data, e.g. see Refs. Wang & Dai (2015); Huang et al. 2015; Wang & Wang (2013b).
Figure 1. The 1σ confidence regions of stretch-luminosity parameter $\alpha$ given by the full JLA sample at redshift region [0,1]. The results of 3 bins, 4 bins and 5 bins are shown in the upper left panel, the upper right panel and the lower panel. The gray region and the gray dashed line denote the 1σ region and the best-fit result given by the full JLA data. The red, the green, the blue, the yellow and the purple regions correspond to the 1σ regions of the first, the second, the third, the fourth and the fifth bin, respectively.

In a latest work Shariff et al. (2015), adopting two particular parameterizations of $\beta$, Shariff et al. found 4.6σ CL evidence for a significant drop in $\beta$ at redshift $z = 0.66$, for the JLA sample. In the current work, we revisit the possibility of $\beta$'s evolution by using the redshift tomography method. In addition to the full JLA sample, we also study the cases of various JLA subsamples. So far as we know, the effects of various JLA subsamples on $\beta$'s evolution have not been studied in the past. Moreover, we also briefly discuss the impacts of time-varying $\beta$ on parameter estimation are also studied.

Our conclusions are as follows:

- If the full JLA sample is used, then $\alpha$ is always consistent with a constant (see Fig 1), and $\beta$ has a significant trend of decreasing, $\sim 3.5\sigma$ CL, at high redshift (see Fig 2). It should be pointed out that, due to that the redshift tomography method tends to reduce statistical significance, the redshift-dependence of $\beta$ is studied the hard way in this work. Since the effect of $\beta$'s evolution is strong enough to be found after adopting the redshift tomography method, we can conclude that the evolution of $\beta$ is indisputable.

- If the low-z subsample of JLA is used, then a constant $\beta$ is favored. In contrast, if the SDSS or the SNLS subsamples is adopted, then a decreasing $\beta$ is favored. Besides, compared with SDSS subsample, SNLS subsample prefers a larger decreasing rate of $\beta$ (see Fig 3). It should be pointed out that the trajectory of $\beta$ given by the SNLS subsample of JLA is quite different from the prediction of the full SNLS3 sample Wang & Wang (2013a). This means that the SNLS3 dataset may have some unknown systematic bias, or anomalies, not accounted for by the reported systematic uncertainties of SNLS3.

- If the HST subsample is removed from the full JLA data, then the decreasing rate of $\beta$ at high redshift will be slightly enlarged (see Fig 4).

- If a binned parameterization of $\beta$ is adopted, then a larger best-fit value of $\Omega_m$ will be obtained, compared to the case of constant $\beta$. However, if the information of 1σ region is taken into account, then for both the time-varying $\beta$ and the constant $\beta$ cases, the results of $\Omega_m$ are consistent with the result given by the CMB+BAO data.

In this paper, we only consider the simplest $\Lambda$CDM model. In addition to $\Lambda$CDM, many other DE models Li (2004); Chevallier & Polarski (2001); Linder (2003) are also favored by current cosmological observations. It is of interest to study the effects of varying $\beta$ on parameter estimation in other dark energy models Zlatev et al. (1999); Caldwell (2002); Li (2004); Wang & Zhang (2008); Wang (2000).
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Figure 2. The $1\sigma$ confidence regions of color-luminosity parameter $\beta$ given by JLA full sample at redshift region $[0,1]$. The results of 3 bins, 4 bins and 5 bins are shown in the upper left panel, the upper right panel and the lower panel. The gray region and the gray dashed line denote the $1\sigma$ region and the best-fit result given by the full JLA data. The red, the green, the blue, the yellow and the purple regions correspond to the $1\sigma$ regions of the first, the second, the third, the fourth and the fifth bin, respectively.

et al. (2008); Li et al. (2009a,b); Huang et al. (2009); Lan et al. (2010); Wang et al. (2010, 2011); Li et al. (2011); Zhang et al. (2012); Li et al. (2013); Hu et al. (2015b); Wang et al. (2016). This will be done in future works.

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**Figure 3.** The $1\sigma$ confidence regions of $\beta$ given by the three subsamples: low-$z$ (upper left panel), SDSS (upper right panel) and SNLS (lower panel). The gray region and the gray dashed line are the $1\sigma$ region and the best-fit result given by the full low-$z$, the full SDSS and the full SNLS subsample, respectively. The red, the green, the blue and the yellow regions correspond to the $1\sigma$ regions of the first, the second, the third and the fourth bin, respectively.

**Figure 4.** The $1\sigma$ confidence regions of $\beta$ given by the “JLA without HST” data (left panel) and the full JLA sample (right panel) at redshift region [0,1]. The gray regions and the gray dashed lines denote the $1\sigma$ regions and the best-fit results given by the full samples, respectively. The red, the green, the blue and the yellow regions correspond to the $1\sigma$ regions of the first, the second, the third, and the fourth bin, respectively.
Figure 5. The 1D marginalized probability distributions of $\Omega_{m0}$ given by the full JLA sample for the $\Lambda$CDM model. Both the results of constant $\beta$ (green dash-dotted line) and varying $\beta$ (red solid line) cases are presented. The corresponding results given by the CMB+BAO data (black dashed line) are also shown for comparison.

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