Investigating the Effect of Cosmic Opacity on Standard Candles

J. Hu\(^1\), H. Yu\(^1\), and F. Y. Wang\(^{1,2}\)

\(^1\) School of Astronomy and Space Science, Nanjing University, Nanjing 210093, China
\(^2\) Key Laboratory of Modern Astronomy and Astrophysics (Nanjing University), Ministry of Education, Nanjing 210093, China; fayinwang@nju.edu.cn

Received 2016 June 20; revised 2017 January 20; accepted 2017 January 20; published 2017 February 13

Abstract

Standard candles can probe the evolution of dark energy over a large redshift range. But the cosmic opacity can degrade the quality of standard candles. In this paper, we use the latest observations, including Type Ia supernovae (SNe Ia) from the “joint light-curve analysis” sample and Hubble parameters, to probe the opacity of the universe. A joint fitting of the SNe Ia light-curve parameters, cosmological parameters, and opacity is used in order to avoid the cosmological dependence of SNe Ia luminosity distances. The latest gamma-ray bursts are used in order to explore the cosmic opacity at high redshifts. The cosmic reionization process is considered at high redshifts. We find that the sample supports an almost transparent universe for flat \(\Lambda\)CDM and XCDM models. Meanwhile, free electrons deplete photons from standard candles through (inverse) Compton scattering, which is known as an important component of opacity. This Compton dimming may play an important role in future supernova surveys. From analysis, we find that about a few per cent of the cosmic opacity is caused by Compton dimming in the two models, which can be corrected.

Key words: cosmology; theory – distance scale

1. Introduction

In 1998, the accelerating expansion of the universe was discovered by measuring the relation between redshift and distance of Type Ia supernovae (SNe Ia) (Riess et al. 1998; Perlmutter et al. 1999). The physical origin of the acceleration is still debated. The term “dark energy” has been put forward to explain the accelerating universe. Meanwhile, a modification of the equations governing gravity can also explain the acceleration of the universe (i.e., Capozziello 2002). Besides SNe Ia, other observations, such as the cosmic microwave background (CMB; e.g., Spergel et al. 2003), baryonic acoustic oscillations (BAO; e.g., Eisenstein et al. 2005), Hubble parameters (e.g., Jimenez et al. 2003), and gamma-ray bursts (GRBs; e.g., Wang et al. 2015), can probe the nature of the accelerating expansion. SNe Ia are ideal standard candles to probe dark energy. But several effects can degrade their quality, such as dust in the light path (Avgoustidis et al. 2009), the possible intrinsic evolution in SN luminosity, magnification by gravitational lensing (Holz 1998), peculiar velocity (Hui & Greene 2006), and so on. These processes will degrade the usefulness of SNe Ia as standard candles. Besides the above effects, Compton dimming due to free electrons depleting photons from standard candles via (inverse) Compton scattering can cause a systematic error for cosmological studies (Zhang 2008). These effects can degrade the evidence for accelerating expansion, or even mimic the behavior of dark energy. So a comprehensive study of the cosmic opacity is needed. This is especially so for the era of the Wide Field Infrared Survey Telescope (WFIRST), which can detect more than 2000 SNe Ia (Green et al. 2012). If the cosmic opacity is not corrected, it will not increase statistical errors, but it may systematically bias the cosmological parameters.

Over the past several years, the cosmic distance duality (CDD) relation has been widely used to test the systematic errors and opacity in observations of SNe Ia. The CDD relation reads (Etherington 1933; Ellis 2007)

\[
\frac{D_L}{D_A}(1+z)^2 = 1, \tag{1}
\]

where \(D_L\) is the luminosity distance and \(D_A\) is the angular diameter distance. We must note that the cosmic opacity has no effect on \(D_A\) (Weinberg 2008). It is valid for all cosmological models based on Riemannian geometry. The bases of this relation are that the number of photons is conserved and the photons travel along null geodesics in a Riemannian spacetime (Ellis 2007). But the conservation of photons may be violated in a wide range of well-motivated models. The CDD relation plays a significant role in modern astronomy, and many works have been performed in order to test it. For example, Bassett & Kunz (2004) found a 2\(\sigma\) violation of the CDD relation using \(D_L\) from SNe Ia and \(D_A\) from FRIIb radio galaxies. The angular diameter from X-ray observations of galaxy clusters also has been used to probe the CDD relation (Holanda et al. 2011). Similar work has also been done by other authors (Gonçalves et al. 2012; Meng et al. 2012). Räsänen et al. (2016) used CMB anisotropies to test the CDD relation. This relation is also applied extensively. Wang et al. (2012) and Cao et al. (2016) used the CDD relation to test the gas mass density profile of galaxy clusters. Evslin (2016) calibrated the distances of SNe Ia using the CDD relation.

A powerful method to study the opacity of the universe is to use the standard candles to detect possible CDD deviations, such as SNe Ia and GRBs. For example, Avgoustidis et al. (2010) adopted a modified CDD relation

\[
D_L = D_A(1+z)^{2+\varepsilon} \tag{2}
\]

to constrain the cosmic opacity by combining SNe Ia data (Kowalski et al. 2008) with measurements of the Hubble expansion over the redshift range \(0 < z < 2\) (Stern et al. 2007).
In the flat $\Lambda$CDM model, they found $\varepsilon = -0.04^{+0.08}_{-0.07}$ (2$\sigma$). Avgoustidis et al. (2009) marginalized over the parameter $H_0$ and used SNe Ia alone to constrain the parameters $\Omega_m$ and $\varepsilon$. Li et al. (2013) presented some tests for the cosmic opacity with observational data including the Union 2.1 SNe Ia sample and galaxy cluster samples compiled by Filippis et al. (2005) and Bonamente et al. (2006). They found that an almost transparent universe is favored by the sample (Li et al. 2013). Based on the validity of the Amati relation, Holanda & Busti (2014) determined the cosmic opacity at high redshifts using GRBs, and found that a transparent universe is favored. Systems with strong gravitational lensing are also used to probe the CDD relation (Liao et al. 2015; Holanda & Busti 2016).

Our paper makes three advancements in this field over previous papers. First, it must be noted that previous studies directly used the luminosity distances of SNe Ia, which are derived in the concordance cosmology (i.e., Avgoustidis et al. 2010; Li et al. 2013). The luminosity distances depend on the light-curve fitting parameters and cosmological models (Kowalski et al. 2008; Betoule et al. 2014). So the derived results are biased by the assumed cosmological model. Here, in order to avoid this problem, we perform a global fitting for the SNe Ia light-curve parameters, cosmological parameters, and cosmic opacity. Second, we also investigate the cosmic opacity at high redshifts, where the fraction of electrons is evolving with redshift. The reionization process is considered. The cross section of Compton scattering for high-energy photons is also a function of redshift. Third, the contribution from the Compton scattering effect to the cosmic opacity is constrained for the first time. In this paper, we investigate the cosmic opacity with SNe Ia, long GRBs, and Hubble parameter data. We pay special attention to the Compton scattering effect. This paper is organized as follows. In next section, we describe the cosmic opacity and Compton scattering extinction. The observational data used in the statistical analysis are presented in Section 3. The corresponding constraints on the cosmic opacity are given in Section 4. The paper finishes with a summary of the main results in the conclusion section.

2. Cosmic Opacity and Compton Scattering

Since photons can be scattered by free electrons and the interstellar medium when travel from the source to the observer, the number of photons received will be reduced. The distance modulus derived from standard candles will increase the systematic error. Any process reducing the photon number would increase the luminosity distance of the source. Then, the received factor $\mu(z) = 1 - \alpha(z)$, where $\alpha(z)$ is the opacity from the $z = 0$ to the source redshift due to extinction. The statistical errors for 100, 1000, 2700, and 10000 SNe are shown by the dashed lines. We adopt an intrinsic dispersion $\sigma_\mu = 0.1$ mag for SNe Ia.

$$E(z) = H(z)/H_0 = \sqrt{\Omega_m(1 + z)^3 + (1 - \Omega_m)(1 + z)^{3 + 3w}}.$$  

Combining Equations (2) and (3) we obtain the exact form of the cosmic opacity,

$$\tau = 2\varepsilon \ln(1 + z).$$  

2.1. The Optical Depth of Compton Scattering

Compton scattering is the inelastic scattering of a photon by a charged free electron. The optical depth for Compton
scattering is
\[
\tau_c(z) = \int \sigma_T n_e(z) dl
\]
\[= -(1 + y) \sigma_T c \int_0^z n_H(z) Q_{H_0}(z) \frac{dt}{dz} dz, \tag{8}\]
where \(\sigma_T\) is the Thomson cross section, \(n_e\) is the free electron density, \(c\) is the light speed, and \(z\) is the redshift. In the above equation, \(n_H(z) = 1.905 \times 10^{-3}(1 + z)^3\) cm\(^{-3}\) is the hydrogen number density at redshift \(z\), and \(y\) is a factor that is introduced by including the ionization of helium, because the reionization epoch contains both hydrogen and helium. The mass fractions of hydrogen and helium are \(X = 0.24668\) (Planck Collaboration et al. 2016), respectively. We assume that the helium was only ionized once. So we derive \(Q_{H_0}(z) = \frac{\dot{n}_\gamma(z)}{(1 + y) n_H(z) c} - \sigma_T c (1 + y) n_H(z) Q_{H_0}\). \tag{9}\]

\[Q_{H_0} = \frac{\dot{n}_\gamma(z)}{(1 + y) n_H(z) c} - \sigma_T c (1 + y) n_H(z) Q_{H_0}. \tag{9}\]

The Astrophysical Journal, 836:107 (9pp), 2017 February 10
Hu, Yu, & Wang

Figure 3. Systematic shift in distance moduli \(\Delta m\) for GRBs. We consider the ionization fraction as a function of redshift. The Compton scattering cross section is energy-dependent, because the photons of GRBs are energetic. The statistical errors for 100 and 1000 GRBs are shown by the dashed lines. We adopt an intrinsic dispersion \(\sigma_\Delta = 0.4\) mag for GRBs. The black dots are \(\Delta m\) of observed GRBs caused by Compton dimming.

Figure 4. 2D regions and 1D marginalized distributions in the \(\Lambda\)CDM model with 1\(\sigma\) and 2\(\sigma\) contours for the parameters \(M_B, \alpha, \beta, \Delta M, H_0, \Omega_m, \) and \(\varepsilon\) using SNe Ia + \(H(z)\).
In this equation, \( \alpha_B = 2.6 \times 10^{-13} \, \text{cm}^{-3} \, \text{s}^{-1} \) is the recombination coefficient for electrons with a temperature of about \( 10^4 \) K. \( \dot{n}_e (z) \) is the rate of ionizing photons escaping from the stars into the intergalactic medium, which can be derived from

\[
\dot{n}_e (z) = (1 + z)^3 \frac{\dot{\rho}_{\text{esc}}(z)}{m_B} N_e f_{\text{esc}},
\]

where \((1 + z)^3\) is used for converting the comoving density into the proper density, \( \dot{\rho}_{\text{esc}}(z) \) is the star formation rate (SFR), \( m_B \) is the baryon mass, \( N_e \) are the number of ionizing UV photons released per baryon, and \( f_{\text{esc}} \) is the escape fraction of these photons from stars into the intergalactic medium. The escape fraction is not well constrained from observations. \( f_{\text{esc}} \approx 0.2 \) is the average value suggested by Mao et al. (2007) and Robertson et al. (2015). Other similar value are reported. For instance, Razoumov & Sommer-Larsen (2006) found that \( f_{\text{esc}} \) evolves from \( \sim 1\% – 2\% \) at \( z = 2.39 \) to \( \sim 6\% – 10\% \) at \( z = 3.6 \) from star-forming regions in young galaxies. Hayes et al. (2011) proposed a redshift evolution of \( f_{\text{esc}} \). In this work, we take the value of \( N_e \) as \( \sim 4000 \), and the escape fraction \( f_{\text{esc}} \approx 0.1 \). \( C \equiv \langle n_{\text{H}_2} \rangle / \langle n_{\text{H}_2} \rangle^2 \) is the clumping factor of the ionized gas. Its value decreases with increasing redshift according to some numerical simulations (Gnedin & Ostriker 1997; Shull et al. 2012) and semianalytical studies (Madau et al. 1999; Chiu & Ostriker 2000). Following Shull et al. (2012), we take

\[
C(z) = \begin{cases} 
2.9 & \text{if } z < 5, \\
2.9 \left( \frac{1 + z}{6} \right)^{-1.1} & \text{if } z \geq 5.
\end{cases}
\]

(11)

\( \dot{\rho}_{\text{H}_2}(z) \) is the SFR. The SFR derived by Wang (2013) is used. Then we can solve the differential Equation (9) to obtain \( \Omega_{\text{H}_2} \). The result is shown in Figure 1.

2.2. The Compton Scattering Optical Depth for SNe Ia

Following Hu (1995) and Barkana & Loeb (2001), Equation (8) with a constant ionization fraction can be
expressed as
\[
\tau_c(z) = 0.0461(1 + y) Q_{HII}(1 - Y_p) \frac{\Omega_b h}{\Omega_m} \\
\times \{[1 - \Omega_m + \Omega_m(1 + z)^3]^{2/3} - 1\}
\]  
(12)
in the flat $\Lambda$CDM model by neglecting the radiation term. In the redshift range $0 < z < 3$, a constant ionization fraction $X_i(z) = 1$ is adopted, which is reasonable for SNe Ia. The optical depth can increase the distance modulus via the relation $\Delta \mu = 1.086 \sigma_t$ from Equation (4). Figure 2 shows the effect of Compton scattering on the distance modulus. From this figure, we can see that the value of $\Delta \mu$ is increasing with redshift, and the Compton scattering dims the supernova flux by 0.003 mag at $z = 1$ and 0.01 mag at $z = 2.35$. This dimming is too faint to rule out the existence of dark energy. However, its effect cannot be negligible for future planned SNe Ia surveys such as WFIRST, which will measure $\sim 2700$ SNe Ia to $z \sim 1.7$. For future surveys, the major statistical uncertainty is the SN intrinsic fluctuations. With the SNe Ia number $N$, the intrinsic fluctuations are reduced to a level of $\sigma_i/\sqrt{N}$ mag, where $\sigma_i$ is the intrinsic dispersion in SN luminosity. This means that the Compton dimming effect must be corrected. Otherwise the induced systematic errors would be comparable to the statistical errors. From the above analysis, we conclude that the Compton scattering can be corrected, as discussed by Zhang (2008).

2.3. The Compton Scattering Dimming for GRBs

The photons emitted by GRBs are different from those from SNe Ia. First, the GRB photons are much more energetic. At high energies, the cross section of Compton scattering is suppressed. So more photons can avoid scattering and reach the observer. Second, GRBs can be observed at high redshifts. High-energy photons have a much greater probability of interacting with free electrons. The optical depth of Compton scattering for high-energy photons can be written as
\[
\tau_c(z) = - (1 + y) c \int_0^z \sigma(x) n_H(z) Q_{HII}(z) \frac{dt}{dz},
\]  
(13)
where $\sigma(x) = \sigma(E_0(1 + z)/m_e c^2)$ is given by the Klein–Nishina formula (Rybicki & Lightman 1979)
\[
\sigma(x) = \frac{3}{4} \sigma_T \left[ \frac{2x(1 + x)}{(1 + 2x)} - \frac{1 + 3x}{2x} \ln \left( \frac{1 + 2x}{2x} \right) \right].
\]  
(14)
Here, $E_0$ is the observed energy of gamma-ray photons. The future SVOM (Space-based multiband astronomical Variable Objects Monitor) mission will detect some GRBs at $z > 10$ (Wei et al. 2016). At these high redshifts, hydrogen is not completely ionized. The parameter $Q_{HII}$ is a constant in Equation (13), and the reionization process must be considered.
We use the reionization process described in Section 2.1 to calculate the optical depth. The systematic shift in distance modulus $\Delta m_D$ due to Compton scattering is shown in Figure 3. It is obvious that the effect of Compton scattering for low-energy photons is significant, because the cross section is suppressed for high-energy photons. The evolution of $\Delta m_D$ becomes flat at high redshifts, because there are few free electrons from reionization. The $m_D$ caused by Compton dimming increases with redshift. Its value can reach 0.01–0.04 mag, which is smaller than the intrinsic error in the GRB distance (Wang et al. 2016). So we can ignore it if the number of GRBs is less than 100 and their redshift is not very high. However, if more than 100 high-redshift long GRBs are used to study cosmology, then Compton dimming is no longer negligible.

3. Data Set

In this section, we will show the data sets. These data sets will be used to constrain the cosmic opacity and cosmological parameters. Unlike previous works, we try to globally fit the SNe Ia light-curve parameters, cosmological parameters, and the cosmic opacity.

3.1. SNe Ia Sample

In this work, we use 740 SNe Ia from the “joint light-curve analysis” (JLA) sample compiled by Betoule et al. (2014). The redshift range is from 0.01 to 1.299. This sample includes SNe Ia from different surveys. In their work, they regard the possible extinction as a systematic uncertainty. In order to avoid any effect of the cosmological model, the parameters of the SNe Ia light curve, the cosmological parameters, and the cosmic opacity are fit simultaneously. Therefore, the only error that we need to consider in our work is the statistical error that arises from propagation of uncertainties in the light-curve fitting and the variation of magnitudes caused by the intrinsic variation in SN magnitude. The possible extinctions are all regarded as cosmic opacity. The distance modulus is written as

$$
\mu = m_B^* - (M_B - \alpha \times X_i + \beta \times C),
$$

where $m_B^*$ is the observed peak magnitude in the rest-frame $B$ band. $\alpha$ and $\beta$ are nuisance parameters that describe the stretch–luminosity and color–luminosity relations, reflecting the well-known broader–brighter and bluer–brighter relations, respectively. The nuisance parameter $M_B$ represents the absolute magnitude of a fiducial SNe Ia and is found to depend on the properties of host galaxies, e.g., the host stellar mass ($M_{\text{stellar}}$). Here, we follow the procedure in Conley et al. (2011) to approximately correct for this effect with a simple step function:

$$
M_B = \begin{cases} 
M_B^1 & \text{if } M_{\text{stellar}} < 10^{10} M_\odot, \\
M_B^1 + \Delta M & \text{otherwise.}
\end{cases}
$$

3.2. GRB Sample

For GRBs, we use the GRB data given in Wang et al. (2016). They use the $E_{\text{iso}}$–$E_{\nu}$ correlation (Amati et al. 2002) to build the Hubble diagram. Wang et al. (2016) combine their 42 GRBs.
with 109 GRBs from Amati et al. (2008, 2009). The $E_{iso} - E_p$ correlation can be written as
\[
\log \frac{E_{iso}}{\text{erg}} = c + d \log \frac{E_p}{\text{keV}},
\]
where $c$ and $d$ are free parameters, $E_{iso}$ is the isotropic equivalent energy, and $E_p$ is the peak energy of the $\nu F_\nu$ spectrum, which has been corrected into the cosmological rest frame. In their work, they calibrate 90 high-redshift GRBs in the redshift range from 1.44 to 8.1 with a fixed value of $H_0$. We constrain the cosmological parameters and the cosmic opacity using this subsample (Wang et al. 2016). In order to consider the effect of Compton dimming, we show the value of $m_D$ for this sample as dots in Figure 3, which is derived from Equations (4) and (13). The error bar is due to the uncertainty of the observational peak energy of GRBs. The value of $m_D$ caused by Compton dimming is far less than the top black dashed line. Therefore, we can ignore this effect in subsequent work.

### 3.3. $H(z)$ Sample

The 19 Hubble parameter data given in Simon et al. (2005), Stern et al. (2010), and Moresco et al. (2012) are used in this work. The redshift range of these Hubble parameters is from 0.10 to 1.75. Because $H_0$ will affect the final results, we regard it as a free parameter.

### 4. Results

The maximum likelihood analysis is used to constrain the parameters. The $\chi^2$ fitting expression is
\[
\chi^2 = \sum_i \frac{\mu_{obs,i} - \mu_{th}(z_i) - 1.0866 \tau(z_i)}{\sigma_i^2} + \chi^2_{H(z)}
\]

In our analysis, we adopt the cosmic opacity from Equation (7). The parameter $\varepsilon$ is regarded as a constant. For data on SNe Ia and $H(z)$, $\mu_{obs}$ for SNe Ia is written as in Equation (15), $\sigma_i^2 = \sigma_{\mu,\text{stat}}^2 + \sigma_{\mu,\text{sys}}^2$ is the uncertainty in the distance modulus. $\sigma_{\mu,\text{stat}}^2$ is the propagated error from the covariance matrix of the light-curve fitting, and $\sigma_{\mu,\text{sys}}$ is the systematic error due to the intrinsic variation in magnitude of SNe Ia. The value $\sigma_{\mu,\text{sys}}$ is calculated in Betoule et al. (2014) and does not depend on a specific choice of cosmological model. $\mu_{th}$ is the theoretical distance modulus, which does depend on the cosmological model. $\chi^2_{H(z)}$ is the $\chi^2$ fitting of Hubble parameter data, and can
where $H_{\text{obs}}$ is the observational value, $H_{\text{th}}$ is the theoretical Hubble expansion rate related to the cosmological model, and $\sigma_{H_{\text{obs}}}$ is the error in $H_{\text{obs}}$. The value of $H_0$ is fixed when using the GRB data, because Wang et al. (2016) calibrated the distance moduli by fixing $H_0 = 67.8$ km s$^{-1}$ Mpc$^{-1}$. We use the Markov chain Monte Carlo (MCMC) method to fit the parameters of the SNe Ia light curve, cosmological parameters, and the cosmic opacity simultaneously. Our program is based on the public Python module emcee (Foreman-Mackey et al. 2013). The algorithm of emcee has several advantages over traditional MCMC methods and it has excellent performance as measured by the autocorrelation time.

### 4.1. Flat $\Lambda$CDM

In this model, the equation of state $w$ in Equation (6) has a fixed value of $w = -1$. When using the SNe Ia + $H(z)$ data, the free parameters are $M_B$, $\alpha$, $\beta$, $\Delta M$, $H_0$, $\Omega_m$, and $\varepsilon$. We use the Python module emcee to fit these parameters simultaneously. The fitting result is shown in Figure 4. The 2D regions and 1D marginalized distributions with $1\sigma$ and $2\sigma$ contours for the parameters $M_B$, $\alpha$, $\beta$, $\Delta M$, $H_0$, $\Omega_m$, and $\varepsilon$ are shown. The fitting results of the parameters are presented in Table 1. The value of $\varepsilon$ is $-0.0403$, which indicates an almost transparent universe. For GRB + $H(z)$ data, there are only two free parameters: $\Omega_m$ and $\varepsilon$. The fitting results are shown in Figure 5 and Table 1. The value $\varepsilon = 0.00718$ also supports a transparent universe.

### 4.2. Flat XCDM

In a flat XCDM cosmology, the parameter $w$ in Equation (6) is a free parameter. When using the SNe Ia + $H(z)$ data, the free parameters are $M_B$, $\alpha$, $\beta$, $\Delta M$, $H_0$, $\Omega_m$, $w$, and $\varepsilon$. Using the same method as above, we can fit these parameters simultaneously. The 2D regions and 1D marginalized distributions with $1\sigma$ and $2\sigma$ contours for the parameters $M_B$, $\alpha$, $\beta$, $\Delta M$, $H_0$, $\Omega_m$, $w$, and $\varepsilon$ are shown in Figure 6 and Table 1. They are shown in the fifth column of Table 1. The value $\varepsilon = 0.0517$ also supports a transparent universe.
$H(z)$ data, there are three parameters: $\Omega_m$, $w$, and $\varepsilon$. The fitting results are shown in Figure 7 and Table 1. The value $\varepsilon = 0.0718^{+0.0382}_{-0.0413}$ also indicates a transparent universe.

### 4.3. Considering the Effect of Compton Dimming

The effect of Compton dimming can be estimated, so the residual opacity can be derived. We try to eliminate the known opacity due to Compton scattering, and explore the contribution from the unknown part. In Equation (12), we obtain the optical depth of Compton scattering of SNe Ia. After subtracting the optical depth of Compton scattering from the total cosmic opacity, we repeat the above analysis to obtain the residual opacity $\tau_r$. The results from SNe Ia and $H(z)$ in the flat $\Lambda$CDM model are shown in Figure 8, which gives $\varepsilon = 0.0212^{+0.0382}_{-0.0413}$. Constraints on parameters are shown in the third column of Table 1. Similar results are also shown in Figure 9 and the sixth column of Table 1 for the XCDM model. Comparing the second and third columns in Table 1, it can be seen that the effect of Compton scattering can cause about 5% cosmic opacity in the $\Lambda$CDM model. A similar percentage is found for the XCDM model. So Compton scattering can contribute about a few per cent of cosmic opacity. It is obvious that the sample supports an almost transparent universe for both cosmological models.

### 5. Conclusions and Discussion

In this paper, we use the latest observations, including SNe Ia from the JLA sample and Hubble parameters, to study cosmic opacity. The effect of Compton scattering on standard candles is also considered. The extinction due to Compton scattering can be corrected in future SNe Ia surveys. In order to avoid the cosmological dependence of the luminosity distances of SNe Ia, a joint fitting of the SNe Ia light-curve parameters, cosmological parameters, and opacity is used. The latest GRBs are used in order to explore the cosmic opacity at high redshifts. The reionization process must be considered for Compton scattering, because some instruments will detect high-redshift GRBs in the future. The result shows that the Compton dimming effect is less than the systematic error for GRBs at present. However, if more than 100 high-redshift long GRBs are observed and used to constrain cosmological parameters, then the Compton dimming is not negligible. The results support an almost transparent universe at $z < 1.5$ for JLA SNe Ia and $H(z)$ data. In the redshift range $1.5 < z < 8.1$, we study the cosmic opacity through luminosity distances of GRBs. The flat $\Lambda$CDM model and the flat XCDM model are considered. We find that the effect of Compton scattering can cause about 5% cosmic opacity in both models. The current observations support an almost transparent universe for both cosmological models over a large redshift range.

We thank the anonymous referee for useful comments. This work is supported by the National Basic Research Program of China (973 Program, grant No. 2014CB845800), the National Natural Science Foundation of China (grants 11422325 and 11373022), and the Excellent Youth Foundation of Jiangsu Province (BK20140016).

**References**

Amati, L., Frontera, F., & Guidorzi, C. 2009, A&A, 508, 173

Amati, L., Frontera, F., Tanović, M., et al. 2002, A&A, 390, 81

Amati, L., Guidorzi, C., Frontera, F., et al. 2008, MNRAS, 391, 577

Avogoustidis, A., Burrage, C., Redondo, J., Verde, L., & Jimenez, R. 2010, JCAP, 10, 024

Avogoustidis, A., Verde, L., & Jimenez, R. 2009, JCAP, 06, 012

Barkana, R., & Loeb, A. 2001, PhRv, 349, 125

Basett, B. A., & Kunz, M. 2004, PhRvD, 69, 101305

Betoule, M., Kessler, R., Guy, J., et al. 2014, A&A, 568, A22

Bonamente, M., Joy, M. K., LaRoque, S. J., et al. 2006, ApJ, 647, 25

Cao, S., Biesiada, M., Zheng, X., & Zhu, Z.-H. 2016, MNRAS, 457, 281

Capozziello, S. 2002, IJMPD, 11, 483

Chiu, W. A., & Ostriker, J. P. 2000, ApJ, 534, 507

Conley, A., Filippenko, A. V., Challis, P., et al. 2011, ApJS, 192, 1

Drell, P. S., Loredo, T. J., & Wasserman, I. 2000, ApJ, 530, 593

Eisenstein, D. J., Zehavi, I., Hogg, D. W., et al. 2005, ApJ, 633, 560

Ellis, G. F. R. 2007, GRRe, 39, 1047

Everingham, L. M. H. 1933, PMag, 15, 761

Esiwun, J. 2016, PDU, 3, 57

Filipps, E. D., Serno, M., Bautz, W., & Longo, G. 2005, ApJ, 625, 108

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306

Gnedin, N. Y., & Ostriker, J. P. 1997, ApJ, 486, 581

Gonçalves, R. S., Holanda, R. F. L., & Alcaniz, J. S. 2012, MNRAS, 420, L43

Green, J., Schechter, P., Balatay, C., et al. 2012, arXiv:1208.4012

Hayes, M., Schaefer, D., Östlin, G., et al. 2011, ApJ, 730, 8

Holanda, R. F. L., & Bautz, V. C. 2014, PhRvD, 89, 103517

Holanda, R. F. L., & Bautz, V. C. 2016, JCAP, 02, 054

Holz, D. E. 1998, ApJL, 506, L1

Hu, W. 1995, PhD thesis, astro-ph/9508126 UC Berkeley

Hui, L., & Greene, P. 2006, PhRvD, 73, 123526

Jimenez, R., Verde, L., Treu, T., & Stern, D. 2003, ApJ, 593, 622

Kowalski, M., Rubin, D., Aldering, G., et al. 2008, ApJ, 686, 749

Li, Z. X., Wu, P. X., Yu, H. W., & Zhu, Z. H. 2013, PhRvD, 87, 103013

Liao, K., Li, Z. X., Cao, S., et al. 2015, ApJL, 822, L2

Madau, P., Rall, R., Audunson, G., et al. 2001, ApJ, 486, 581

Mao, J., Lap, A., Granato, G. L., de Zotti, G., & Danese, L. 2007, ApJ, 667, 655

Meng, X. L., Zhang, T. J., Zhan, Hu., & Wang, X. 2012, ApJ, 745, 98

Moresco, M., Cimatti, A., Jimenez, R., et al. 2012, JCAP, 08, 006

Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565

Planck Collaboration, Ade, P. A. R., et al. 2016, ApJL, 802, L19

Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009

Robertson, B. E., Ellis, R. S., Furlanetto, S. R., & Dunlop, J. S. 2015, ApJL, 802, L19

Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: Wiley)

Shull, J. M., Harness, A., Trenti, M., & Smith, B. D. 2012, ApJ, 747, 100

Simion, J., Verde, L., & Jimenez, R. 2005, PhRvD, 71, 123001

Sterl, D. N., Verde, L., Peiris, H. V., et al. 2003, ApJS, 148, 175

Stern, D., Jimenez, R., Verde, L., Stanford, S. A., & Kamionkowski, M. 2010, ApJS, 188, 280

Tan, W. W., Wang, F. Y., & Cheng, K. S. 2016, ApJ, 829, 29

Wang, F. Y. 2013, A&A, 556, A90

Wang, F. Y., Dai, Z. G., & Liang, E. W. 2015, NewAR, 67, 1

Wang, J. S., Wang, F. Y., Cheng, K. S., & Dai, Z. G. 2016, A&A, 585, A68

Wang, X., Meng, X. L., Huang, Y. F., & Zhang, T. J. 2012, A&A, 585, A68

Wei, J., et al. 2016, SVOM: White Book, arXiv:1610.06892

Weinberg, S. 2008, Cosmology (Oxford: Oxford Univ. Press)

Zhang, P. J. 2008, ApJ, 682, 721