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Testing cosmic transparency with the latest baryon acoustic oscillations and type Ia supernovae data *

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Abstract Observations show that Type Ia supernovae (SNe Ia) are dimmer than expected from a matter dominated Universe. It has been suggested that this observed phenomenon can also be explained using light absorption instead of dark energy. However, there is a serious degeneracy between the cosmic absorption parameter and the present matter density parameter Ω_m when one tries to place constraints on the cosmic opacity using SNe Ia data. We combine the latest baryon acoustic oscillation (BAO) and Union2 SNe Ia data in order to break this degeneracy. Assuming a flat ΛCDM model, we find that, although an opaque Universe is favored by SNe Ia+BAO since the best fit value of the cosmic absorption parameter is larger than zero, $\Omega_m = 1$ is ruled out at the 99.7% confidence level. Thus, cosmic opacity is not sufficient to account for the present observations and dark energy or modified gravity is still required.

Key words: cosmology: dark energy — cosmology: distance scale

1 INTRODUCTION

By introducing the concept of an optical metric, Gordon (1923) proved that there is a map between solutions of Maxwell's equations in curved spacetime containing a fluid with a refraction index $n(x)$ and the vacuum solutions of the modified Maxwell's equations in related optical spacetime. Thus, the variation in speed of propagation for electromagnetic waves arising from the refraction is equivalent to motion in the modified geometry of the optical spacetime with $n = 1$. Later, Ehlers (1967) extended Gordon's work in an elegant paper. Chen & Kantowski (2008) first applied the optical metric theory to cosmology and found that the Type Ia supernovae (SNe Ia) Hubble diagram can be explained by photon refraction. They (Chen & Kantowski 2009a,b) also generalized, by

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taking a complex form of Gordon's metric, Gordon's theory to include light absorption in addition to refraction, and showed that both photon absorption and the combination of absorption and refraction can be used to account for the SNe Ia dimming. In this case, the luminosity distance D_{L} should be modified by multiplying a factor obtained from the cosmic opacity, which can be expressed as

$$D_{\mathrm{L}}(z) = \mathrm{e}^{\tau/2} D_{\mathrm{L}}^{\mathrm{S}}(z) = \frac{\mathrm{e}^{\tau/2}(1+z)}{H_0} \int_0^z \frac{dz'}{E(z')} , \tag{1}$$

where z is the redshift, the superscript S denotes the standard luminosity distance for which the Universe is assumed to be transparent, and $E(z) = H(z)/H_0$ with H_0 being the present value of the Hubble parameter. For a flat ΛCDM model

$$E(z) = \sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda} \tag{2}$$

with $\Omega_\Lambda = 1 - \Omega_m$. Here, Ω_m and Ω_Λ are the present dimensionless density parameter of matter and vacuum energy, respectively. Considering a spatially homogeneous and nondispersive (grey) absorptive Universe, Chen & Kantowski (2009a) showed that the quantity τ has the form

$$\tau(z) = \int_0^z \frac{\alpha_* dz'}{(1+z')E(z')} , \tag{3}$$

where α_* is the dimensionless cosmic absorption parameter, and we ignore light refraction and assume the Universe to be flat. Usually, two models, $\alpha_* =$ constant (Chen & Kantowski 2009a) and $\alpha_* = \alpha_0 E(z)$ (Avgoustidis et al. 2009; Lima et al. 2011), are discussed. Apparently, the photon absorption inevitably leads to a violation of the distance duality (DD) relation, also called the Etherington relation (Etherington 1933), $D_{\mathrm{L}} = (1+z)^2 D_{\mathrm{A}}$, since it is built on two assumptions: conservation of photon number and Lorentz invariance. Here D_{A} is the angular diameter distance.

In addition, it has been found that photon absorption can be invoked to account for the dimming of SNe Ia (Riess et al. 1998; Perlmutter et al. 1999) without the need for dark energy or modified gravity (Aguirre 1999; Csáki et al. 2002). Based on a flat ΛCDM model, Lima et al. (2011) found that $\Omega_m = 1$ is allowed by the 506 supernovae data obtained from the Union2 sample at the 68.3% confidence level for the case of $\alpha_* =$ constant, and for the case of $\alpha_* = \alpha_0 E(z)$, it is allowed at the 95.4% confidence level. Thus, a decelerating Einstein-de Sitter Universe seems to be consistent with observations of SNe Ia when cosmic opacity is considered. However, there is a very serious degeneracy between Ω_m and the dimensionless cosmic absorption parameter when only the SNe Ia data are used (Lima et al. 2011).

In constraining cosmological models, baryon acoustic oscillation (BAO) data (Eisenstein et al. 2005) play an important role in breaking the degeneracy between model parameters. Recently, in addition to the BAO data measured at redshifts $z = 0.35$ and 0.20 (Percival et al. 2007) released from the Sloan Digital Sky Survey (SDSS) and the Two Degree Field Galaxy Redshift Survey (2dFGRS), respectively, the 6-degree Field Galaxy Survey (6dFGS) has reported a BAO detection in the low-redshift Universe at $z = 0.106$ (Beutler et al. 2011), and the WiggleZ Dark Energy Survey has released the baryon acoustic peak at redshifts $z = 0.44$, 0.6 and 0.73 (Blake et al. 2011). Combining the WiggleZ Dark Energy Survey with 6dFGS and SDSS, we now have six BAO data points. We list them in Table 1.

These data have been used to test some cosmological models (Gong et al. 2012) and a tight constraint on model parameters has been obtained by combining the BAO and SNe Ia data. Naturally, one may expect that adding the BAO data in Lima et al. (2011) could break the degeneracy between Ω_m and the dimensionless cosmic absorption parameter, and this is what we are going to explore in this paper. Furthermore, we also plan to research whether cosmic opacity can still explain the SNe Ia+BAO observations without the need of dark energy or modified gravity.

Table 1 Six BAO Data Points

Sample	z	$A\,(z)$
6dFGS	0.106	0.526 ± 0.028
SDSS	0.2	0.488 ± 0.016
SDSS	0.35	0.484 ± 0.016
WiggleZ	0.44	0.474 ± 0.034
WiggleZ	0.6	0.442 ± 0.020
WiggleZ	0.73	0.424 ± 0.021

2 COSMIC OPACITY OR ACCELERATED EXPANSION

From Equation (1), one can see that cosmic opacity leads to a correction to the luminosity distance, which means that the luminosity distance derived from SNe Ia is larger than the true one if the Universe is opaque. Thus, the dimming of SNe Ia may arise from the cosmic opacity rather than the accelerated expansion. Assuming a cosmological model and using Equation (2), one can obtain an analytic expression of the luminosity distance and the corresponding theoretical value of the distance modulus. Then, using the SNe Ia data, one can obtain constraints on the cosmic model parameters and the cosmic absorption parameter (α_* or α_0) by considering χ^2 statistics

$$\chi^2(\boldsymbol{p}) = \sum_i [\mu_{\rm obs}(z_i) - \mu_{\rm th}(z_i, \boldsymbol{p})]^2 / (\sigma^2_{{\rm obs},i} + \sigma^2_{{\rm sys},i})\,, \tag{4}$$

where

$$\boldsymbol{p} \equiv (\Omega_M, \alpha_*(\text{or } \alpha_0)), \qquad \mu_{\rm th}(z_i, \boldsymbol{p}) = 5 \log D_{\rm L}(z_i, \boldsymbol{p}) + \mu_0,$$

$\sigma_{\rm obs}$ is the uncertainty of SNe Ia data and $\sigma_{\rm sys}$ is the systematic error. μ_0 is a nuisance parameter which can be marginalized with an analytic method.

It is possible to explain the current supernova observations via a simple absorption model instead of requiring the existence of dark energy (Chen & Kantowski 2009a,b). Recently, based on the flat ΛCDM model, Lima et al. (2011) also found that the SNe Ia dimming can be explained in the framework of a pure cold dark matter model since $\Omega_m = 1$ is allowed by 506 SNe Ia data points at the 68.3% confidence level (α_* = constant) or the 95.4% confidence level ($\alpha_* = \alpha_0 E(z)$). Using the Union2 SNe Ia, the same result as Lima et al. (2011) is obtained, which is shown as the dashed lines in Figure 1 in this paper. Clearly, there is a very serious degeneracy between Ω_m and α_* (α_0). In order to break this degeneracy, besides the SNe Ia data, we add the latest BAO data to constrain Ω_m and α_* (α_0).

Since the BAO provides a standard ruler for the direct measurement of the cosmic expansion history, we can obtain the angular diameter distance from the BAO observation and this result is independent of photon attenuation. For the BAO data, the acoustic parameter $A(z)$ introduced by Eisenstein et al. (2005)

$$A(z) = \frac{100 D_V(z)\sqrt{\Omega_m h^2}}{cz}\,, \tag{5}$$

is usually used, where $h = H_0/100$, and the hybrid distance D_V is related to the angular diameter distance $D_{\rm A}$ through

$$D_V = \left(\frac{cz(1+z)^2 D_{\rm A}^2}{H(z)}\right)^{\frac{1}{3}}. \tag{6}$$

Here $H(z)$ is the Hubble expansion rate at redshift z. Using six BAO data points, which are listed in Table 1, we can obtain the constraints on Ω_m. Combining the BAO and SNe Ia gives a tight constraint on Ω_m and α_* (α_0).

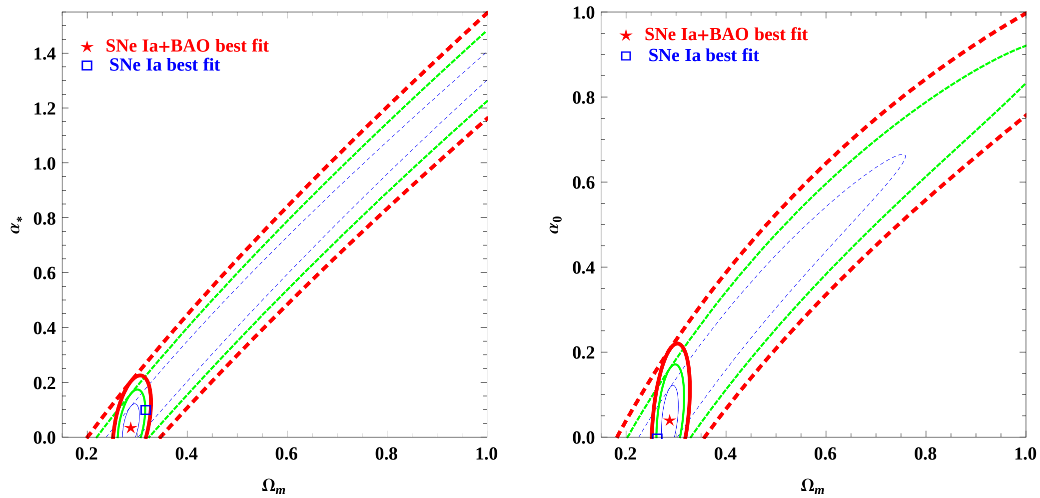

Fig. 1 The 68.3% (*blue*), 95.4% (*green*) and 99.7% (*red*) confidence regions. The dashed and solid lines are the results from SNe Ia and SNe Ia+BAO, respectively. *Left*: α_* is constant. *Right*: $\alpha_* = \alpha_0 E(z)$.

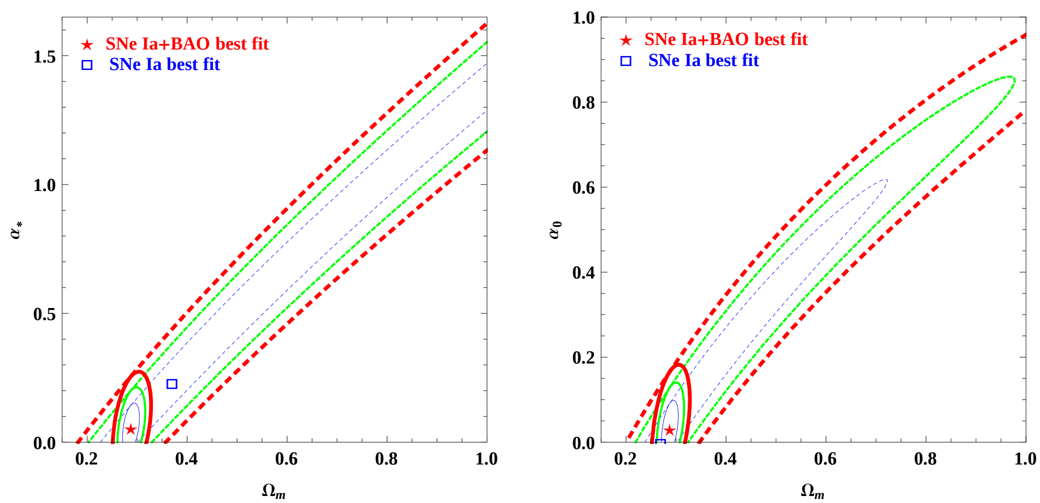

Fig. 2 The 68.3% (*blue*), 95.4% (*green*) and 99.7% (*red*) confidence regions. The dashed and solid lines are the results from SNe Ia and SNe Ia+BAO, respectively. In SNe Ia data, the systematic error is considered. *Left*: α_* is constant. *Right*: $\alpha_* = \alpha_0 E(z)$.

Figures 1 and 2 and Tables 2 and 3 show the results. In Figure 2 and Table 3, the systematic error of the SNe Ia data is considered. The solid lines in Figures 1 and 2 give the constraints from the BAO + SNe Ia data. Apparently, whether or not the systematic error is considered, the degeneracy between Ω_m and α_* (α_0) is broken as expected, and $\Omega_m = 1$ is ruled out at the 99.7% confidence

Table 2 The best values of Ω_m and α_* (α_0) from the SNe Ia and BAO data.

Observational data	α_*	Ω_m
SNe Ia	0.1055	0.3176
SNe Ia+BAO	0.0409	0.2874
Observational data	α_0	Ω_m
SNe Ia	0	0.2691
SNe Ia+BAO	0.0321	0.2872

Table 3 The best values of Ω_m and α_* (α_0) from the SNe Ia and BAO data. The systematic error is considered in SNe Ia.

Observational data	α_*	Ω_m
SNe Ia	0.2319	0.3698
SNe Ia+BAO	0.0570	0.2875
Observational data	α_0	Ω_m
SNe Ia	0	0.2627
SNe Ia+BAO	0.0442	0.2873

level. However, the best fit values show that $\alpha_* > 0$ and $\alpha_0 > 0$ are favored by SNe Ia+BAO and, when the systematic error is included, a more opaque Universe is preferred. Therefore, the cosmic opacity is not enough to explain the present observations, although an opaque Universe is preferred.

3 CONCLUSIONS

Recently, Lima et al. (2011) have found that cosmic opacity can explain the SNe Ia dimming without an accelerated cosmic expansion because $\Omega_m = 1$ is allowed by the SNe Ia data within the framework of the ΛCDM model. However, there is a serious degeneracy between Ω_m and the dimensionless cosmic absorption parameter α_* (or α_0) in their work. In this paper, by adding the latest BAO data, we find that this degeneracy is effectively broken as expected, and an opaque Universe is favored by BAO+SNe Ia since the best fit value of α_* (or α_0) is larger than zero. In addition, we find that, when the systematic error of SNe Ia is considered, a more opaque Universe is favored. However, $\Omega_m = 1$ is ruled out by SNe Ia+BAO at the 99.7% confidence level. Therefore, although the observations prefer an opaque Universe, the cosmic opacity is not enough to account for the present observations and dark energy or modified gravity is still required.

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