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DIMMING OF SUPERNOVAE AND GAMMA-RAY BUSTS BY COMPTON SCATTERING AND ITS COSMOLOGICAL IMPLICATIONS

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ABSTRACT

Free electrons deplete photons from Type Ia supernovae through the (inverse) Compton scattering. This Compton dimming increases with redshift and reaches 0.004 mag at $z = 1$ and 0.01 mag at $z = 2$. Although far from sufficient to invalidate the existence of dark energy, it can bias constraints on dark energy at a level nonnegligible for future supernova surveys. This effect is correctable and should be incorporated in supernova analysis. The Compton dimming has similar impact on cosmology based on gamma-ray bursts as standard candles.

Subject headings: cosmology: theory — distance scale

1. COMPTON DIMMING OF TYPE Ia SUPERNOVAE

Type Ia supernovae (SNe Ia) are standardizable as cosmological standard candles to measure cosmological distance and thus infer the expansion history of the universe. Current observations on SNe Ia have enabled the discovery of the late-time acceleration of the universe (Riess et al. 1998; Perlmutter et al. 1999). This discovery has had profound impact on fundamental physics, leading to either a dominant dark energy component with equation of state $w \equiv P/\rho < -1/3$, or significant deviations from general relativity at around the Hubble scale. Ongoing and planned supernova surveys have the power to significantly improve these cosmological constraints and hopefully clarify the role of the cosmological constant in our universe (Albrecht et al. 2006).

Various astrophysical processes, besides the possible intrinsic evolution in SN luminosity, can degrade the standard candle usefulness of SNe Ia by altering the supernova flux. An incomplete list includes gravitational lensing magnification (Holz 1998), peculiar velocity (Hui & Greene 2006), dust extinction, and incomplete K-correction. If not handled correctly, these can not only increase statistical errors, but may also systematically bias the cosmological constraints. In this paper, we point out a new source of systematic error, relevant for precision cosmology.

The universe is (almost) completely ionized after $z = 6$. Free electrons in the universe treat all low-energy photons ($h\nu \ll m_e c^2$) equally, and Compton scatter[1] off them with equal probability $\exp(-\tau)$, where τ is the Thomson optical depth,

$$\tau(z) = \int_0^z \sigma_{\rm T} n_e^{\rm free}(z) \frac{ac\,dz}{H(z)} = \int_0^z \sigma_{\rm T} n_e(0) X_e(z) \frac{(1+z)^2}{H(z)}\,dz. \quad (1)$$

Here $\sigma_{\rm T}$ is the Thomson cross section, $n_e^{\rm free}(z)$ is the number density of free electrons, $X_e(z)$ is the ionization fraction [$X_e(z) \simeq 1$ at $z < 6$], $H(z)$ is the Hubble constant, and $a = 1/(1+z)$ is the scale factor. There are two competing effects on the flux of a given celestial object. (1) For photons originally emitted toward us, on the average $1 - \exp(-\tau) \simeq \tau$ of them are Compton scattered away and escape of observation. (2) Photons that otherwise cannot reach us may be scattered toward us. If the celestial object is nonevolving and the universe is static, these two effects cancel each other exactly and the flux is unchanged.[2] This can be proved straightforwardly by the aid of photon number conservation. However, none of these conditions is realistic. First of all, our universe is expanding. Scattered photons take a longer time to reach us and thus suffer more energy loss. More importantly, SNe Ia only last for months, much shorter than the time it takes for photons to reach us. Scattered photons travel an extra distance and take extra time to reach us. As a consequence, only those photons originally emitted within a solid angle $\Omega_{\rm scatter} \sim ct/D$ toward us can be scattered and reach us during the event period. Here, t and D are the lifetime and the distance of the SN Ia, respectively. For SNe Ia, $\Omega_{\rm scatter}/4\pi \sim 10^{-11} \ll 1$. Thus, it is virtually certain that no scattered photons can reach us. Since effect (2) above vanishes, for SNe Ia, Compton scattering alters the flux F to $F\exp(-\tau)$. We call this the Compton dimming. Its amplitude is

$$\frac{\delta F}{F} = -2\frac{\delta D_L}{D_L} = \exp(-\tau) - 1 \simeq -\tau, \quad (2)$$

where D_L is the luminosity distance. This results in a systematic shift in the distance modulus μ,

$$\Delta\mu = 5\log(1 + \delta D_L/D_L) \simeq 1.086\tau, \quad (3)$$

where τ increases quickly with redshift, scaling as $(1+z)^3 - 1$ at low redshift, and $(1+z)^{3/2}$ at high redshift, until the epoch of reionization. We adopt the *WMAP* cosmology with $\Omega_m = 0.26$, $\Omega_\Lambda = 1 - \Omega_m$, and $\Omega_b h = 0.032$ (Spergel et al. 2007) for the numerical evaluation. Compton scattering dims the supernova flux by 0.004 mag at $z = 1$ and 0.01 mag at $z = 2$ (Fig. 1). This dimming is far from sufficient to challenge the existence of dark energy. Nonetheless, its impact is nonnegligible for precision cosmology based on supernovae. Future SN surveys such as the Joint Dark Energy Mission (JDEM) will measure ~1000 SNe Ia at $z > 1$. For these surveys, the major statistical uncertainty is the SN intrinsic

[1] Free electrons have thermal and kinetic motions. Thus, what happens is actually inverse Compton scattering, which results in a photon energy change at a level of 10^{-3} ($k_{\rm B}T_e/m_e c^2$, $v/c \sim 10^{-3}$). For CMB photons, this process results in the well-known Sunyaev-Zel'dovich effect. However, this photon energy change is irrelevant for this paper, since none of scattered supernova photons reach us in time.

[2] Tiny energy changes in scattered photons are neglected in this statement.

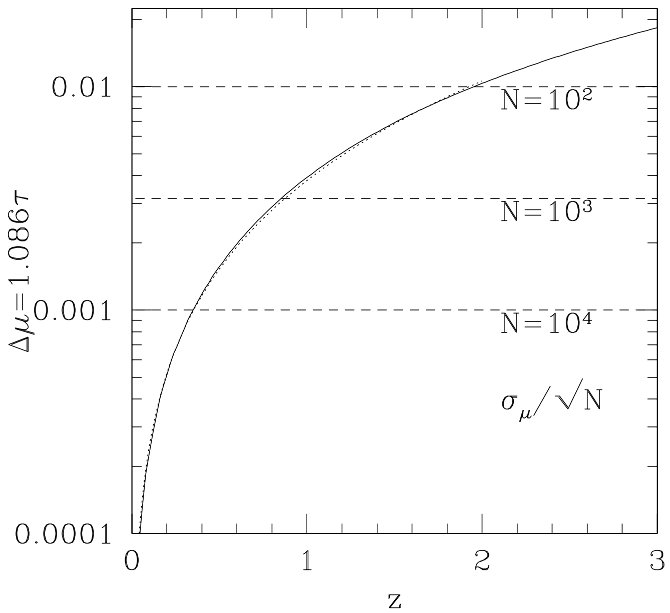

FIG. 1.—Systematic shift in the distance modulus μ caused by Compton scattering (*solid line*). Although the dimming is only 0.4% in flux at $z = 1$ and 1% at $z = 2$, the systematic errors induced are comparable to statistical errors induced by intrinsic dispersion in SN fluxes for future SN surveys with $\sim$1000 SNe Ia at $z > 1$. Here an intrinsic dispersion of $\sigma_\mu = 0.1$ mag is adopted; the associated statistical errors are shown as dashed lines. The function $\mu^L z + \mu^Q z^2$ adopted to handle possible unknown systematic errors is an excellent parameterization for this type of $\Delta\mu$ at $z \leq 2$, which is shown as the dotted line, almost indistinguishable from the real $\Delta\mu$.

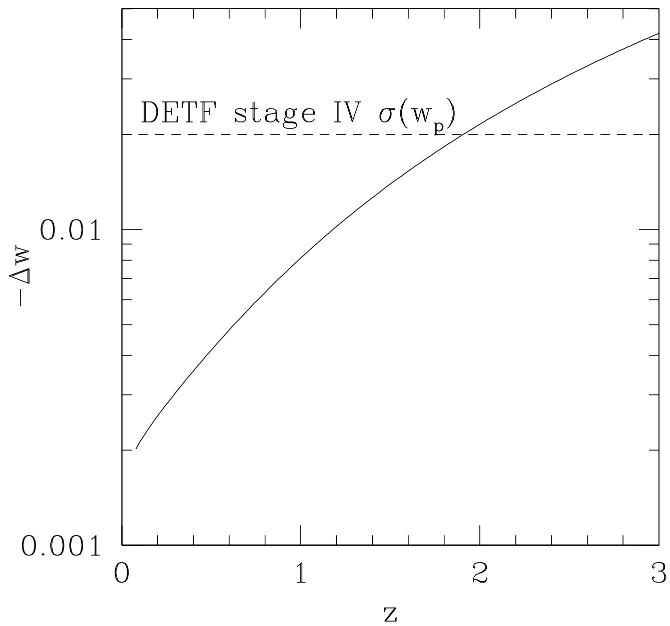

FIG. 2.—Bias in w induced by the Compton dimming (*solid line*). In this estimation, other cosmological parameters are fixed at their fiducial values in order to isolate the impact on w. Roughly, $\Delta w \sim -2\Delta\mu \simeq -2\tau$. The dashed line is the rms uncertainty in $w = w_p$ at the pivot $a = a_p$ for the stage IV supernova surveys (Albrecht et al. 2006).

fluctuations. With $N \sim 1000$ SNe, intrinsic fluctuations are reduced to a level of $\sigma_\mu/\sqrt{N} \simeq 0.003$ mag, where σ_μ is the intrinsic dispersion in SN luminosities. This means that the Compton dimming must be corrected; otherwise the induced systematic errors would be comparable to the statistical errors. The Large Synoptic Survey Telescope (LSST) will be able to measure $\sim 10^5$ SNe Ia to $z \sim 1$. For it, there are extra errors associated with photo-z uncertainties, whose dispersion is $\sim$0.01–0.1. Even so, for LSST, systematic error induced by Compton scattering likely overwhelms the statistical errors induced by intrinsic fluctuations and photo-z uncertainties.

Since the Compton dimming increases toward high redshift, it biases w toward more negative values at higher redshift (Fig. 2). We isolate the impact on w by fixing other cosmological parameters at their fiducial values, and show the result in Fig. 2. The systematic shift is $\Delta w \sim -2\tau$ (roughly 4 times the fractional error in the distance). It shifts w by -0.008 for SNe Ia at $z = 1$ and by -0.017 for SNe Ia at $z = 1.7$. This systematic bias is comparable to the rms uncertainty in the pivot w for stage IV SN surveys (Albrecht et al. 2006). Thus, it is of particular importance for the key dark energy task, to confirm or invalidate the existence of the cosmological constant.

Clearly, we must take this effect into account in the analysis of these future surveys in order not to bias the cosmological constraints. Observationally, this effect cannot be corrected, since it lacks observational consequences such as reddening that can be applied to separate it from other effects. Can commonly adopted parameterizations of systematic uncertainties, such as the intrinsic evolution, reasonably incorporate this effect? The answer is yes. It can be fitted with excellent accuracy by $\Delta\mu = \mu^L z + \mu^Q z^2$, where $\mu^L = 2.3 \times 10^{-3}$ and $\mu^Q = 1.5 \times 10^{-3}$ (Fig. 1). This means that the Compton dimming can be automatically corrected for through this kind of self-calibration. It also implies that without knowledge of the Compton dimming, it could be misinterpreted as an intrinsic evolution in supernova luminosity.

Fortunately, this effect is straightforward to take into account in theory. Besides the cosmological parameter Ω_m, the dark energy density $\Omega_{\rm DE}$ and equation of state w that supernova cosmology aims to constrain, only an extra input of $\Omega_b h$ ($\tau \propto \Omega_b h$) is required to predict τ. Furthermore, we do not need the exact value of $\Omega_b h$ to perform this correction. 10% accuracy in $\Omega_b h$ is sufficient to render this source of error negligible for any foreseeable surveys. Current constraints from the CMB already reach this accuracy. So, the Compton dimming is completely correctable.

So far, we have implicitly neglected fluctuations in τ along different lines of sight, so the τ calculated above is actually the ensemble average, $\langle\tau\rangle$. In reality, there are fluctuations in τ along different lines of sight. For SNe Ia, which are observed at $z \lesssim 2$, the ionization fraction $X_e(z) = 1$ is an excellent approximation. Fluctuations in τ are thus mainly caused by fluctuations in the electron number density. It is straightforward to show that $\sigma_\tau/\langle\tau\rangle \ll 1$, where σ_τ is the rms fluctuation in τ. Since the Compton dimming is already a small effect, tiny fluctuations above its mean do not cause any observable effect and can thus be safely neglected.

2. COMPTON DIMMING OF GAMMA-RAY BURSTS

Gamma ray bursts (GRB) are likely standardizable and can also serve as cosmological standard candles (Xu et al. 2005, and references therein). They have the merit of being sufficiently bright to be observed at redshift $z > 6$, and thus provide important cosmological constraints complementary to SNe Ia.

GRBs suffer similar Compton dimming. However, since the γ photon energy is comparable to the electron mass, the cross section of the Compton scattering is suppressed and becomes energy dependent. Thus, the $\sigma_{\rm T}$ in equation (1) should be replaced by

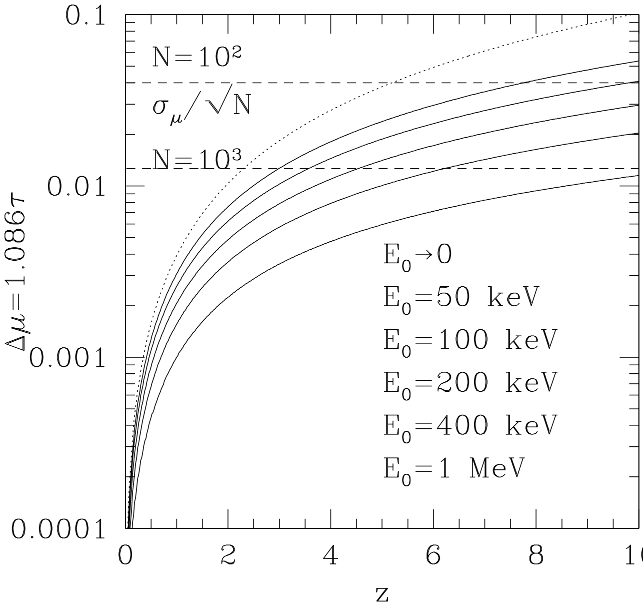

FIG. 3.—Systematic shift in the distance modulus $\Delta\mu$ for GRBs, assuming the universe is completely ionized at $z \leq 10$. Since γ-ray photons are energetic, the Compton scattering cross section is now energy dependent. This causes $\Delta\mu$ and τ to decrease with photon energy. Here, E_0 is the redshifted γ-ray photon energy. The dashed lines are the statistical errors for 100 and 1000 GRBs, respectively; $\sigma_\mu = 0.4$ mag is adopted for GRBs.

$\sigma(E_0(1+z)/m_e c^2)$, which is given by the Klein-Nishina formula (Rybicki & Lightman 1979)

$$\sigma(x) = \frac{3}{4}\sigma_{\rm T}\left\{(1+x)\frac{2x(1+x)/(1+2x) - \ln(1+2x)}{x^3} + \frac{\ln(1+2x)}{2x} - \frac{1+3x}{(1+2x)^2}\right\}.$$

Here E_0 is the observed redshifted energy of γ-ray photons, and τ and $\Delta\mu$ are now energy (frequency) dependent. The Compton dimming decreases with the photon energy (Fig. 3). Despite the suppression in cross section, the Compton dimming can still reach $\sim$0.01–0.05 mag, because GRBs often reside at high redshifts. GRBs have larger intrinsic fluctuations than SNe Ia. However, if more than 100 high-redshift GRBs are observed and applied to constrain cosmology, this Compton dimming may become nonnegligible.

Similar to the case of SNe Ia, it is straightforward to correct this Compton dimming effect for GRBs at $z < 6$. However, correcting it for GRBs at $z > 6$ is subtle. For example, patchy reionization can cause order of unity fluctuations in τ along different lines of sight, as suggested in radiative transfer simulations (Holder et al. 2007). This could prevent complete correction of Compton dimming, even if the average reionization fraction $X_e(z)$ at $z > 6$ is perfectly known. Since the reionization history is poorly understood, we are not able to estimate to what level the Compton dimming can be corrected for these high-redshift GRBs. One possibility is to rely on other surveys to measure τ along each line of sight and to correct for the Compton dimming. For example, future 21 cm surveys of the reionization epoch can be applied to reconstruct the optical depth along each line of sight, through tight correlation between the optical depth and the 21 cm brightness temperature (Holder et al. 2007).

3. SUMMARY

We point out that Compton scattering dims supernova flux at a level nonnegligible for future supernova cosmology, and must be taken into account in the analysis. It also has similar impact on cosmology based on GRBs.

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REFERENCES

Albrecht, A., et al. 2006, Report of the Dark Energy Task Force (Washington: NASA), astro-ph/0609591
Holder, G. P., Iliev, I. T., & Mellema, G. 2007, ApJ, 663, L1
Holz, D. E. 1998, ApJ, 506, L1
Hui, L., & Greene, P. B. 2006, Phys. Rev. D, 73, 123526
Perlmutter, S., et al. 1999, ApJ, 517, 565
Riess, A. G., et al. 1998, AJ, 116, 1009
Rybicki, G. B., & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York: John Wiley & Sons)
Spergel, D. N., et al. 2007, ApJS, 170, 377
Xu, D., Dai, Z. G., & Liang, E. W. 2005, ApJ, 633, 603