Dust versus Supernova Cosmology

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Abstract. Here we present some critical discussions about the systematic uncertainty by dust extinction in the recent cosmological results of high-redshift Type Ia supernovae. First we argue that the currently available data do not robustly exclude the cosmologically significant extinction either by the reddening check or the dispersion argument because of the observational uncertainties, even in the case of ordinary dust that reddens. Then we discuss two theoretical possibilities that high-$z$ supernovae have larger extinction and hence they are fainter than local supernovae: the intergalactic dust and host galaxy evolution. Optical and near-infrared observations for a large number of supernovae with improved photometric accuracy are required to reject these possibilities and derive a compelling cosmological result.

1 Introduction

Type Ia supernovae (SNe Ia) have been known as a representative standard candle in the universe, and used in measurements of cosmological parameters such as the Hubble constant ($H_0$), density parameter ($\Omega_M$), and the cosmological constant ($\Omega_\Lambda$). Recently two independent groups have obtained the same result that a $\Lambda$-dominated flat universe is strongly favored, by using a few tens of supernovae at redshift $z \sim 0.5$ (Riess et al. 1998 [R98]; Perlmutter et al. 1999 [P99]). Several possible sources of the systematic error in these measurements have been discussed, including the Malmquist bias, $K$-correction, supernova evolution, gravitational lensing, and so on. The most serious among these is probably the effect of dust extinction. Considering the very strong impact of the conclusion that our universe is accelerating by vacuum energy density or dark energy, it is important to critically discuss how compelling these experimental results are, and discuss less exotic possibilities to explain the dimming of high-$z$ supernovae from various points of view.

Here we discuss the two points concerning the problem of dust extinction in supernova cosmology: (1) Do the current supernova data really exclude the extinction, either by ordinary dust or by speculative grey dust, affecting the cosmological result? (2) Are there theoretical expectations that the extinction of high-$z$ supernovae is more significant than that for local supernovae? As an answer to the question (1), we show that neither the color excess measurements nor the dispersion argument robustly exclude the extinction that is comparable with the difference between an open and $\Lambda$-dominated universes, even in the case of ordinary dust that reddens. Then we discuss two theoretical possibilities.
concerning the question (2), i.e., dust in intergalactic field and evolution of dust extinction by host galaxy evolution.

2 Observational checks against the extinction effect: are they compelling?

2.1 Reddening Check

Both the two groups have made a considerable effort to assess the systematic uncertainty due to extinction. For ordinary dust that reddens, this effect can be checked by measuring the difference of supernova colors at high-$z$ and local, provided that the photometric measurement is sufficiently accurate. Both groups reported that there is no significant color difference between the high-$z$ and local samples. However, it should be noted that there is considerable uncertainty in the color measurements of high-$z$ as well as local supernovae, and an important question is whether this uncertainty is sufficiently small compared with the color difference induced by extinction that may affect the cosmological results. The difference of an open universe and $\Lambda$-dominated universe in the Hubble diagram is about 0.2 mag, and extinction at the $B$ band with $A_B \sim 0.2$ mag would induce a color excess of $\Delta E(B-V) \sim 0.05$ mag in $B-V$ color with the standard extinction curve. Therefore supernova colors must be measured with an accuracy much better than $\sim 0.05$, for a compelling extinction check.

The mean $B-V$ colors of the high-$z$ R98 sample is $-0.13 \pm 0.05$ or $-0.07 \pm 0.05$ depending on two analysis methods, while expectation of unreddened color is $-0.10$ to $-0.05$. Hence there is uncertainty of $\sim 0.05$ mag in the color measurements and this is significant for a cosmological test, as shown above. In the sample of P99, error-weighted average reddening $\langle E(B-V) \rangle$ is $0.033 \pm 0.014$ mag for the local sample and $0.035 \pm 0.022$ for the high-$z$ sample (P99). This leads to the statistical uncertainty of at least $\sim 0.026$ in the difference of extinction $\Delta E(B-V)$ between the high-$z$ and local sample. Therefore this test cannot exclude the cosmologically significant extinction with confidence better than $2\sigma$. In addition to this, there should be systematic uncertainty in $\Delta E(B-V)$; for example, P99 quote an overall systematic uncertainty of 0.02 mag for the $K$-correction that may affect the color measurements. The extinction observed in gravitational lens galaxies also suggests that there may be systematic error in the extinction estimate (see the last paragraph of this section). Furthermore, it should be noted that this uncertainty is reduced by statistics of a few tens of supernovae, and typical error in the color measured for one supernova is typically $\sim 0.4$ mag in FWHM, that is much larger than the cosmologically important color difference of 0.05 (see Fig. 6 of P99). If the probability distribution of observational error is exactly the same for all supernovae, the error in the estimate of mean color can be reduced by statistics, but it is uncertain whether this condition is satisfied in the supernova observations.

P99 estimated the systematic uncertainty of extinction to be less than 0.025 mag ($1\sigma$) in $A_B$, based on an analysis after removing nine reddest supernovae.
Aguirre (1999b) argued that this limit does not apply if the dispersion in brightness and/or colors of high-z supernovae is dominated by factors other than extinction. As mentioned above, the typical observational uncertainty in $E(B-V)$ for one supernova is much larger than the effect of cosmologically significant extinction. Therefore, it is doubtful that P99 analysis successfully removed high-z supernovae reddened by the systematic effect of extinction. Rather, the supernovae removed by P99 might be reddened by intrinsic dispersion of supernovae, or simply by observational errors.

In the analysis of R98, the reddening correction is systematically included in the process of light-curve-shape fitting. However, as noted above, the reddening induced by the cosmologically significant extinction is comparable with or less than the observational error of color measurement for one supernova. In principle, it is difficult to correct the extinction effect when the reddening is as small as the observational error in colors, because the extinction correction is performed based on the observed colors. The reddening correction by R98 will be effective for supernovae strongly reddened beyond the color uncertainty, but it is not clear to us whether this correction has successfully corrected the systematic reddening that may affect the cosmological result.

Extinction observed in high-z gravitational lens galaxies provides us useful information about dust in host galaxies of supernovae. Falco et al. (1999) compared their estimates of extinction in lens galaxies in $0 < z \lesssim 1$ with those estimated for the supernovae in the R98 sample. In spite of comparable redshifts and impact parameters, they found the supernova sample to show markedly less extinction than the lens sample. They suggested four possible interpretations of this inconsistency. One of them is that the Type Ia fitting methods are underestimating errors in extinction by a factor of 1.5–1.7. Another is that an estimate of zero extinction in the supernova sample may not really be zero. The Type Ia extinction estimates are actually differential measurements relative to supernovae in nearby elliptical galaxies that are defined to have zero extinction. However, lens galaxies, that are dominated by massive elliptical galaxies, do have some extinction. These results raise some doubts in the extinction estimates of supernovae, and make the reddening check by the two groups somewhat questionable.

Recently Riess et al. (2000) performed a near-infrared observation and argued that this observation provides further evidence against significant extinction in supernova cosmology. We will discuss this point in §4.

2.2 Dispersion Test

The two groups (R98, P99) argued that the observed dispersion of apparent magnitudes showing no significant evolution to high redshifts gives further support that their results are not affected by extinction. Their argument on the dispersion test is valid if the observed dispersion is dominated by the dispersion of extinction. R98 quoted a value of dispersion $\sigma_{Ab} = 0.4$ mag when the mean extinction is $\langle A_B \rangle = 0.25$ mag, based on a theoretical model of spatial dust distribution by Hatano et al. (1998). If it is correct, such a large dispersion is already in contradiction to what observed.
However, there is large uncertainty in dust distribution models. The detailed procedure of deriving $\sigma_{AB} = 0.4$ mag is not clear in R98, but generally the dispersion estimate is highly dependent on the theoretical modeling as well as the selection effect. In fact, if the dispersion $\sigma_{AB} = 0.4$ is true, we should have already observed a significant dispersion also in the local supernovae, because various observations suggest that mean extinction in local galaxies is typically about $\langle A_B \rangle \sim 0.1$–0.2 mag (see §4.2). Since such a large dispersion is not observed in the local supernova sample, it is suggested that the estimate of $\sigma_{AB} = 0.4$ might be wrong.

Strongly extincted supernovae may not be observed below the detection limits, or may not be included in the sample because they are clearly reddened. When such supernovae are removed in the estimate of dispersion [i.e., like an “extinction-limited subset” in Hatano et al. (1998)], the expected dispersion becomes considerably smaller. For example, consider the extinction distribution that is flat between a range $0 \leq A_B \leq 2\langle A_B \rangle$. The dispersion of such a reasonable distribution is $\sigma_{AB} = \langle A_B \rangle / \sqrt{2}$, that is significantly smaller than the estimate of R98. In this case, the dispersion becomes $\sigma_{AB} = 0.14(\langle A_B \rangle / 0.2 \text{mag})$ mag, that is comparable with the intrinsic dispersion observed in the peak supernova magnitudes after corrected by the light-curve-shape versus magnitude relation. Therefore, it is possible that extinction is not a single dominant origin in the observed dispersion and if it is the case the dispersion test does not give a robust test of extinction.

In conclusion, it seems difficult to clearly check from the current data a systematic change of average $B$-band extinction between the local and high-$z$ sample that may affect the cosmological result, either by the reddening check or the dispersion test. This conclusion applies to the ordinary dust that reddens with the standard Galactic extinction curve, and the check of possible greyer dust is, of course, even more difficult.

3 Theoretical Possibilities for Larger Extinction of High-$z$ Supernovae

Two theoretical possibilities have been proposed for the case that high-$z$ supernovae have larger extinction than local supernovae: the intergalactic dust (Aguirre 1999a, b) and host galaxy evolution (Totani & Kobayashi 1999).

Aguirre (1999a, b) considered the effect of intergalactic dust that may have been ejected from galaxies. It is known that a considerable fraction of metals in galaxies in rich clusters is in a form of metals in the intracluster medium. Renzini (1997) estimated that metal mass in cluster gas is larger than that in member galaxies by a factor of about 4. If the situation is the same for field galaxies, a significant part of metals in the universe may be in the intergalactic field. If the dust mass in the intergalactic field in units of the critical density is as large as $\Omega_{\text{dust}} \sim 5 \times 10^{-5}$, such intergalactic dust has an effect to change the cosmology from a $\Lambda$-dominated flat universe into an open universe. The total metal mass in the universe can be estimated by the cosmic star formation history, and it
is typically $\Omega_{\text{metal}} \sim 2 \times 10^{-4}$. Therefore, if 25% of metals in the universe is in the form of intergalactic dust, it could have a significant effect on supernova cosmology. Another important point of this idea is that such dust could have a significantly greyer extinction than the normal dust in galaxies. If it is the case, it makes the reddening check even less powerful. The dispersion argument discussed in the previous section does not apply to this possibility either, if the distribution of intergalactic dust is sufficiently homogeneous.

This scenario is an interesting possibility, but it may be rather speculative. It is highly uncertain whether the intrachuster medium is the same with the intergalactic field, and the mass fraction of dust in all metals ejected from galaxies is also uncertain. On the other hand, the other scenario of the host galaxy evolution is less exotic and an effect that is certainly existent. Even if supernovae themselves do not evolve to high redshifts, their host galaxies should undoubtedly evolve as shown by various observations of galaxies at high redshifts. Both the gas column density and gas metallicity, that are important physical quantities for dust opacity, change with time by various star formation histories depending on morphological types of galaxies. Therefore, average dust extinction in host galaxies must evolve systematically, and the question is whether this effect is small enough not to affect supernova cosmology. Unfortunately, it seems difficult to say the answer is yes, from a viewpoint of the standard picture of galaxy evolution.

In the next section we describe our recent work (Totani & Kobayashi 1999), making a quantitative estimate for this evolutionary effect by using a realistic model of photometric and chemical evolution of galaxies and supernova rate histories in various types of galaxies. We find that typical evolution in average $A_B$ is $\sim 0.1–0.2$ mag from $z = 0$ to $\sim 0.5$, that is significant for measurements of cosmological parameters and may have escaped from the reddening check. Therefore, this effect should not be ignored in measurements of cosmological parameters by high-$z$ supernovae.

4 Evolution of Average Extinction in Host Galaxies

Here we consider only the average extinction of a supernova in a host galaxy, and do not consider the variation within a galaxy depending on the supernova location in it. Although the variation within a host galaxy can be washed out by statistical averaging of many supernovae, evolution of galaxies will cause systematic evolution of average extinction which cannot be removed by statistical averaging. It is physically natural to assume that the dust-to-metal ratio is constant and hence the dust opacity is proportional to gas column density and gas metallicity of a host galaxy. In fact, it is well known that the extinction in our Galaxy is well correlated to the HI gas column density (e.g., Burstein & Heiles 1982; Pei 1992). It is also known that the dust opacity is correlated to the metallicity among the Galaxy and the Large and Small Magellanic Clouds, when gas column density is fixed (e.g., Pei 1992). Hence in the following we assume that
the dust opacity is proportional to gas column density and gas metallicity, which evolve according to the star formation history in a galaxy.

The star formation history can be inferred from the present-day properties of observed galaxies, by using the well-known technique of stellar population synthesis. We can estimate the time evolution of gas fraction and metallicity in a galaxy by using photometric and chemical evolution models for various galaxy types. Since the observed extinction of high-$z$ SNe Ia is an average over various types of galaxies, we also need the evolution of SN Ia rate in various galaxy types. In the next section, we describe the model of galaxy evolution and SN Ia rate evolution used in this paper, which is constructed to reproduce various properties of the present-day galaxies.

4.1 Evolution of galaxies and Type Ia supernova rate

We use photometric and chemical evolution models for five morphological types of E/S0, S0a-Sa, Sab-Sb, Sbc-Sc, and Scd-Sd. The basic framework of the model is the same as that of elliptical galaxies of Arimoto & Yoshii (1987) and that of spiral galaxies of Arimoto, Yoshii, & Takahara (1992), but model parameters are updated to match the latest observations (Kobayashi et al. 1999), by using an updated stellar population database of Kodama & Arimoto (1997) and nucleosynthesis yields of supernovae of Tsujimoto et al. (1995). The model parameters for spiral galaxies are determined to reproduce the present-day gas fractions and $B - V$ colors in various galaxy types at 15 Gyr after the formation. The model of elliptical galaxies is the so-called galactic wind model, in which star formation stops at about 1 Gyr after the formation by a supernova-driven galactic wind (Larson 1974; Arimoto & Yoshii 1987). We assume that gas fraction in a elliptical galaxy decreases exponentially after the galactic wind time ($\sim 1$ Gyr), with a time scale same as the galactic wind time. These models give the evolution of gas fraction and metallicity in each galaxy type depending on the star formation history.

SN Ia rate history in each type of galaxies is calculated with the metallicity-dependent SN Ia model introduced by Kobayashi et al. (1998). In their SN Ia progenitor model, an accreting white dwarf (WD) blows a strong wind to reach the Chandrasekhar mass limit. If the iron abundance of progenitors is as low as $[\text{Fe/H}] \lesssim -1$, the wind is too weak for SNe Ia to occur. Their SN Ia scenario has two progenitor systems: one is a red-giant (RG) companion with the initial mass of $M_{\text{RG},0} \sim 1M_\odot$ and an orbital period of tens to hundreds days (Hachisu, Kato, & Nomoto 1996, 1999a). The other is a near main-sequence (MS) companion with an initial mass of $M_{\text{MS},0} \sim 2-3M_\odot$ and a period of several tenths of a day to several days (Li & van den Heuvel 1997; Hachisu et al. 1999b). The occurrence of SNe Ia is determined from two factors: lifetime of companions (i.e., mass of companions) and iron abundance of progenitors. (See Kobayashi et al. 1998, 1999 for detail.) This model successfully reproduces the observed chemical evolution in the solar neighborhood such as the evolution of oxygen to iron ratio and the abundance distribution function of disk stars (Kobayashi et al. 1998), the present
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SN II and Ia rates in spirals and ellipticals, and cosmic SN Ia rate at $z \sim 0.5$ (Kobayashi et al. 1999).

4.2 Average extinction evolution towards high redshifts

We have modeled the evolution of gas fraction ($f_g$), metallicity ($Z$), and SN Ia rate per unit baryon mass of a galaxy ($R_{\text{Ia}}$) in various types of galaxies, from which we calculate the evolution of average extinction in the universe. We assume that these quantities do not depend on the mass of galaxies. The basic assumption is that the dust opacity, and hence average $A_B$ in a galaxy is proportional to gas column density and gas metallicity. The average extinction at redshift $z$ in a $i$-th type galaxy with the present-day $B$ luminosity $L_B$ is given by $A_{B,i}(z, L_B) = \kappa f_{g,i}(t_z)Z_i(t_z)(r_{e,i}(L_B))^{-2}(M_b/L_B) L_B$, where $t_z$ is the time from formation of galaxies, $r_e$ the effective radius of galaxies, and $(M_b/L_B)$ is the baryon-mass to light ratio which is determined by the evolution model. We assume a single formation epoch $z_{F}$ for all galaxy types for simplicity. The proportional constant $\kappa$ will be determined later. We do not consider the size evolution of galaxies, and determine $r_e(L_B)$ from empirical relations observed in local galaxies (Bender et al. 1992 for ellipticals, and Mao & Mo 1998 for disk galaxies). It should be noted that the extinction depends on the absolute luminosity of galaxies. From the empirical $L_B$-$r_e$ relation, the surface brightness becomes brighter with increasing luminosity of disk galaxies, and hence the massive galaxies should be more dusty than smaller ones. This trend is consistent with observations (van den Bergh and Pierce 1990; Wang 1991). Then the average extinction of SNe Ia over all galaxy types at a given redshift is

$$\langle A_B(z) \rangle = \sum_i \int dL_B A_{B,i}(z, L_B) R_{\text{Ia},i}(t_z) (M_b/L_B) L_B \phi_i(L_B),$$

where $\phi_i$ is the type-dependent galaxy luminosity function at $z = 0$, for which we adopted the Schechter parameters derived by Efstathiou, Ellis, & Peterson (1988) using the catalog of the Center for Astrophysics (CfA) Redshift Survey (Huchra et al. 1983).

We have to determine the overall normalization of extinction, $\kappa$, for which we use the average $V$ extinction of the Milky Way (Sbc type, $L_B = 1.4 \times 10^{10} L_{B\odot}$) at $z = 0$: $\langle A_V \rangle_{\text{MW}}$. This is an average of extinction of SNe Ia occurring in our Galaxy seen by an extragalactic observer, and hence it is different, in a strict sense, from the average of the Galactic extinction which is extinction of extragalactic objects observed by us. However, if the location of the Sun is typical in the Milky Way, we may infer this quantity by the average of the Galactic extinction. The average Galactic extinction of the 42 SNe Ia observed by P99 is $\sim 0.1$ mag in $A_R$ or $A_I$ (see Table 1 of P99). This suggests $\langle A_V \rangle_{\text{MW}} \sim 0.1$–0.2 mag.

\footnote{In reality, there should be some dispersion in galaxy ages. However, the systematic evolution of dust extinction is owing to the fact that all galaxies should become younger on average towards high redshifts, and present-day age dispersion cannot remove this systematic effect.}
with the standard Galactic extinction law (e.g., Pei 1992). The average reddening of the Galaxy then becomes \( \langle E(B - V) \rangle_{\text{MW}} \sim 0.03-0.06 \) mag, which is a typical reddening at the Galactic latitude of \( \sim 40-50^\circ \) in the Galactic extinction map (Burstein & Heiles 1982; Schlegel, Finkbeiner, & Davis 1998). This estimate is consistent with a model of dust distribution in our Galaxy, which suggests that the average extinction of SNe Ia in the Galaxy seen by an extragalactic observer is typically \( \langle A_V \rangle_{\text{MW}} \sim 0.1-0.2 \) mag (Hatano, Branch, & Deaton 1998). Therefore we use \( \langle A_V \rangle_{\text{MW}} \sim 0.1-0.2 \) mag as a plausible range of the average extinction of our Galaxy.

Figure 1 shows the evolution of extinction for each galaxy type as well as the average over all galaxy types, normalized by \( \langle A_V \rangle_{\text{MW}}, \) i.e., \( \langle A_B(z) \rangle/\langle A_V \rangle_{\text{MW}}. \) Here we used a cosmological model with \( (h, \Omega_M, \Omega_\Lambda) = (0.5, 0.2, 0), \) and set \( z_F = 4.5 \) so that the age of galaxies is 15 Gyr which was assumed in the evolution model. The thick solid line is the average over all galaxy types, and the thin lines are for individual galaxy types as indicated. Since we have used a galactic wind model for elliptical galaxies, they do not have interstellar gas and hence there is no extinction in elliptical galaxies at \( z < 1. \) (However, this may not be true as suggested by observations of gravitational lens galaxies, see discussion in §2.1.) The evolution of extinction is caused by spiral galaxies, but the behavior of evolution is considerably dependent on galaxy types. Early-type spiral galaxies become more dusty towards \( z \sim 1, \) but an opposite trend is seen for late types. These behaviors can be understood as a competition of the two effects: gas fraction evolution and metallicity evolution. The gas fraction in early spiral galaxies is much smaller than late types at present, but rapidly increases towards high redshifts. This increase is responsible for increase of gas column density and hence the dust opacity. On the other hand, the gas fraction does not increase so much in late type galaxies, and decrease of metallicity towards high redshifts is responsible for the decrease of dust opacity. In redshifts more than 1, the extinction decreases towards higher redshifts in all spiral galaxies because the metallicity evolution becomes dominant.

The average over all types is weighted by the SNe Ia rate in each type. Because the star formation rate increases more rapidly to high redshifts in early-type spiral galaxies than late types, the average extinction is more weighted to early types at higher redshifts. Hence \( \langle A_B \rangle/\langle A_V \rangle_{\text{MW}} \) increases to high redshifts by \( \sim 1 \) from \( z = 0 \) to 0.5. This result suggests that, with \( \langle A_V \rangle_{\text{MW}} \sim 0.1-0.2, \) the average extinction \( \langle A_B \rangle \) of SNe Ia at \( z \sim 0.5 \) is larger than the local sample by about 0.1–0.2 mag. This systematic evolution of average extinction is comparable with the difference between an open and a \( \Lambda \)-dominated universe in the Hubble diagram, and hence this effect significantly affects measurements of cosmological

Hatano et al. suggested that most supernovae are only mildly obscured but there is a long tail to stronger extinctions in the extinction distribution. In the actual observations, such a tail will be cut out due to a magnitude limit of a survey. Hence, we have used here the mean extinction of the “extinction-limited subset” in the Table 1 of Hatano et al., in which strongly obscured supernovae with \( A_B > 0.6 \) are removed.
Fig. 1. Average $B$-band extinction of type Ia supernovae as a function of redshift. Extinction $A_B$ is normalized by the average $V$ extinction of our present-day Galaxy, <A_V>_{MW} (see text). The thick solid line is the average over the five morphological types of galaxies, which is weighted by SN Ia rate in them. Five thin lines are extinction evolution in individual galaxy types, as indicated. An open universe with $(h, \Omega_M, \Omega_\Lambda) = (0.5, 0.2, 0.0)$ is assumed, and the formation epoch of galaxies is set to $z_F = 4.5$.

parameters. In the next section we apply the above model in the estimate of cosmological parameters by using the sample of P99.

4.3 Effect on the Cosmological Parameters

Figure 2 shows the Hubble diagram for SNe Ia of the primary fit C of P99, which plots restframe $B$ magnitude residuals from a $\Lambda$-dominated flat cosmology [(h, $\Omega_M$, $\Omega_\Lambda$) = (0.65, 0.2, 0.8)] without dust effect (thin solid line). Thin long- and short-dashed lines are the predictions of the dust-free case with an open universe (0.5, 0.2, 0.0) and the Einstein-de Sitter (EdS) universe (0.5, 1.0, 0.0), respectively. As reported by P99, the $\Lambda$-dominated flat universe gives the best-
fit to the data. Next, the thick lines show the predictions when the model of extinction evolution is taken into account, where the cosmological parameters are the same with the dust-free curves of the same line-markings. Here we adopt ⟨AV⟩MW = 0.2 mag. In the open and Λ-dominated models, the galaxy formation epoch is set to zF = 4.5 and 5.0 so that the age of galaxies becomes 15 Gyr. In the EdS model, the age of the universe is shorter than 15 Gyr, and hence we set zF = 5 which gives an age of galaxies as ∼ 12 Gyr. Although this age is a little shorter than that assumed in the evolution model, the evolutionary effect during 12–15 Gyr is small and hence this inconsistency is not serious. As expected, the model curves with the dust effect are typically 0.1–0.2 mag fainter than those without dust. As a result, the open universe becomes the most favored cosmology among the three when the extinction evolution is taken into account.

We avoid more detailed statistical analysis to derive any decisive conclusion about the cosmological parameters, because the result would be highly dependent on the extinction evolution model. However, the evolution model presented here is quite a natural and standard one without any exotic assumption. Hence, our conclusion is that the systematic evolution of average extinction in host galaxies should more carefully be taken into account when one uses SNe Ia to constrain the cosmological parameters.

5 Discussion & Conclusions

Riess et al. (2000) reported near infrared observations of a supernova (SN1999Q) at z = 0.46. Such an observation is useful to check the extinction, because the reddening of (B − I) color is larger than (B − V) color for the same amount of dust and hence it is easier to detect. Riess et al. (2000) found the reddening of (B − I) color, i.e., E(B − I) = −0.09 ± 0.10 mag for this supernova. This is consistent with almost no extinction and inconsistent at the 3.4σ confidence level with the reddening in this color of E(B − I) ∼ 0.25 mag that is required to save an open universe. However, it seems an overestimate that the reddening of E(B − I) ∼ 0.25 mag is required to save an open universe. According to the Galactic extinction curve of Savage & Mathis (1979), it is found that A_B/E(B − I) = 1.58. Then the B extinction corresponding to E(B − I) = 0.25 becomes A_B = 0.39 mag. This A_B seems larger than the difference between an open and Λ-dominated flat universe in the Hubble diagram, Δm ∼ 0.25 mag at z ∼ 0.5 (see Fig. 4 of R98). If we take A_B = 0.25 as the extinction required to save an open universe, corresponding reddening becomes E(B − I) = 0.16 mag, and the confidence level of inconsistency is lowered to 2.5σ.

It still seems that there is 2.5 σ inconsistency between the observed infrared color and reddening to save an open universe, but it should be noted that any strong conclusion cannot be derived by only one supernova. This argument may apply with only one supernova to the intergalactic dust that is distributed homogeneously, but does not directly apply when there is scatter in extinction of each supernova, as is the case of host galaxy extinction. It is possible that SN1999Q had extinction that is smaller than a mean value, due to its location in
Fig. 2. The Hubble diagram of type Ia supernovae. The data are those used in the primary fit C of Perlmutter et al. (1999). Restframe $B$ Magnitude residuals are from a $\Lambda$-dominated universe with $(h, \Omega_M, \Omega_\Lambda) = (0.65, 0.2, 0.8)$ without dust effect (thin solid line). Thin long- and short-dashed lines are predictions of an open universe $(0.5, 0.2, 0.0)$ and Einstein-de Sitter universe $(0.5, 1.0, 0.0)$ without dust. The three thick lines are predictions for the case with dust evolution, where the cosmological parameters are the same with the dust-free curves of the same line-markings.

its host galaxy. We must await a statistically large number of supernovae whose colors are measured in infrared to conclude that the extinction effect is negligible. The danger of discussing with a small number of supernovae is obvious from the historical fact that the supernova cosmology project originally claimed that the $\Lambda$-dominated universe is disfavored with a smaller number of supernovae (Perlmutter et al. 1997).

A more reliable way to constrain the cosmological parameters by high-$z$ supernovae would be an analysis using only supernovae in elliptical galaxies, in which the dust evolution effect is expected to be much smaller than spiral galaxies at $z < 1$. (However, as discussed in §2.1, extinction observed in gravitational
lens galaxies suggests that even such an analysis may not be perfectly secure.) In fact, P99 tried to analyze their supernovae with known host-galaxy types, and found no significant change in the best-fit cosmology. However, the host-galaxy classification is only based on spectra of host galaxies without high-resolution images. The uncertainty of a fit with a specified host-galaxy type is still large due to the limited number of supernovae, and P99 concluded that this test will need to await the host-galaxy classification of the full set of high-\(z\) supernovae and a larger low-\(z\) supernova sample. It is expected from our calculation that the fitting result of such an analysis in the future will be dependent on host-galaxy types, giving important information for chemical evolution of galaxies. High-\(z\) supernovae beyond \(z \sim 1\) are also desirable to study galaxy evolution as well as cosmological parameters.

We have argued that the observational check of dust extinction effect on supernova cosmology, either by the reddening check or dispersion argument, is not sufficiently compelling because of the uncertainties in the photometric measurement of colors or large uncertainty of expected dispersions of extinction. Observations of gravitational lens galaxies suggest that there may be some systematic uncertainties that have not yet been identified in the extinction estimates of supernovae. On the other hand, it is theoretically not unreasonable that extinction of high-\(z\) supernovae is larger than that of local supernovae, by the intergalactic dust or host galaxy evolution. These points should be kept in mind when one interprets the cosmological results of high-\(z\) supernovae. Optical and near-infrared observations for a large number of supernova events with improved photometric accuracy are required to derive a compelling cosmological result.

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