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Calibration of AGN Reverberation Distance Measurements

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Abstract

In Yoshii et al., we described a new method for measuring extragalactic distances based on dust reverberation in active galactic nuclei (AGNs), and we validated our new method with Cepheid variable stars. In this Letter, we validate our new method with Type Ia supernovae (SNe Ia) that occurred in two of the AGN host galaxies during our AGN monitoring program: SN 2004bd in NGC 3786 and SN 2008ec in NGC 7469. Their multicolor light curves were observed and analyzed using two widely accepted methods for measuring SN distances, and the distance moduli derived are $\mu = 33.47 \pm 0.15$ for SN 2004bd and 33.83 ± 0.07 for SN 2008ec. These results are used to obtain independently the distance measurement calibration factor, g. The g value obtained from the SN Ia discussed in this Letter is $g_{\rm SN} = 10.61 \pm 0.50$, which matches, within the range of 1σ uncertainty, $g_{\rm DUST} = 10.60$, previously calculated ab initio in Yoshii et al. Having validated our new method for measuring extragalactic distances, we use our new method to calibrate reverberation distances derived from variations of Hβ emission in the AGN broad-line region, extending the Hubble diagram to $z \approx 0.3$ where distinguishing between cosmologies is becoming possible.

Key words: cosmological parameters – galaxies: distances and redshifts – galaxies: individual (NGC 3786, NGC 7469) – supernovae: individual (SN 2004bd, SN 2008ec)

1. Introduction

An active galactic nucleus (AGN) consists of a hot central engine, thought to be an accretion disk around a black hole, a dust-free region of ionized gas surrounding the accretion disk where broad emission lines originate and a dust torus that lies beyond the broad-line region (BLR). In Yoshii et al. (2014), we used the spectral energy distribution of the central engine and the dust properties to calculate the light travel time from the central engine to the dust torus in terms of the absolute luminosity of the central engine. We measured the light travel times, Δt in days, for 17 AGNs, and derived luminosity distances, d, in Mpc, using

$$d = \Delta t \times 10^{0.2(m_V - A_V - k_V - 25 + g)}, \quad (1)$$

where m_V is the mean observed apparent magnitude of the AGN in the V band, A_V is the Galactic extinction in the V band, k_V is the K-correction for the V band, and $g = g_{\rm DUST} = 10.60$ is the calculated calibration factor that characterizes the dust sublimation by the radiation field of the central engine (for details, see Yoshii et al. 2014). We obtained $H_0 = 73 \pm 3$ km s^{-1} Mpc^{-1} in good agreement with $H_0 = 75 \pm 10$ km s^{-1} Mpc^{-1} obtained from empirically calibrated Cepheid variable stars (Freedman et al. 2001; Freedman & Madore 2010).

During our AGN monitoring program for the MAGNUM project (Yoshii 2002; Yoshii et al. 2003), SNe Ia occurred in two of the monitored AGN host galaxies, SN 2004bd in NGC 3786 and SN 2008ec in NGC 7469. In Section 2, we use our multicolor observations of the SNe Ia to derive a luminosity distance, $d_{\rm SN}$, for each SN Ia, which we use in Equation (1) to obtain $g_{\rm SN}$. In Section 3, we compare $g_{\rm SN}$ with $g_{\rm DUST}$ and also discuss the error budget for the calculation of $g_{\rm DUST}$.

Fourteen of the AGNs studied in Yoshii et al. (2014) are common in the study by Watson et al. (2011) to obtain distances from the delay between continuum flaring and an increase in the Hβ emission line flux. They calibrated their relative distances using the surface brightness fluctuation distance of the companion galaxy of NGC 3227, $\mu = 31.86 \pm 0.24$. In Section 4, we calibrate their Hβ delays using our distances in Yoshii et al. (2014) for the AGNs that we have in common, and we derive $g_{\rm H\beta}$. We present our conclusions in Section 5.

2. Supernovae

2.1. Observations

Photometric data for SN 2004bd and SN 2008ec were obtained during the MAGNUM AGN monitoring program. The Multiwavelength Imaging Photometer (Kobayashi et al. 1998) on the MAGNUM telescope had a 90 arcsec field of view and obtained images including each host galaxy and its SN. Observations were made in four optical photometric bands U, B, V, and I, from MJD 53,097 to 53,208 for SN 2004bd and from MJD 54,661 to 54,761 for SN 2008ec. For each SN, the basic characteristics are listed in Table 1.

2.2. Data Reduction

Standard reduction procedures were applied to the images, such as bias subtraction and flat fielding, as in Koshida et al. (2014), Suganuma et al. (2006), and Minezaki et al. (2004).

[8] The principal investigator of the MAGNUM project.

Table 1
List of Target Supernovae

SN	Host	R.A.	Decl.	z[a]	d_{DUST}[b] (Mpc)	Reference
SN 2004bd	NGC 3786	11 39 42.2	+31 54 31.8	0.00893	74.3 ± 7.8	IAUC 8316, 8317
SN 2008ec	NGC 7469	23 03 16.6	+08 52 19.8	0.01632	47.7 ± 1.5	CBET 1437, 1438

Notes. Listed references are the first report of the SN detection.
[a] The heliocentric redshift from the NASA/IPAC Extragalactic Database (NED).
[b] The luminosity distance of host galaxy based on the dust reverberation of an AGN (Yoshii et al. 2014).

Before proceeding to the photometry, the host galaxy flux was subtracted from each image using template galaxy images made as follows. First, we selected the images observed on nights just before the occurrence of an SN, which had seeing of one arcsec or better. For SN 2004bd, images of NGC 3786 obtained at MJD 53046.4 were used for all bands. For SN 2008ec, the images obtained at MJD 54649.6, 54651.6, 54653.5, and 54651.6 were used for the U, B, V, and I bands, respectively. Second, we stacked all the images in a band, obtained on the night, in order to improve the signal-to-noise ratio of the template galaxy image. Any variable AGN components in the template image should not affect the SN photometry, unless the position of the AGN is inside the photometric aperture. However, SN 2004bd was only 5.3 arcsec from the nucleus, which would contaminate the photometry aperture and sky flux measurement area. To avoid AGN effects on the photometric results, we subtracted the AGN component from the template image using GALFIT (Peng et al. 2002), which models the surface brightness distribution of galaxies or point sources. The template image was subtracted from each observed image after adjusting the seeing size of the template image by Gaussian convolution using the IRAF task GAUSS. The varying AGN component in each observed image remained after the subtraction, so we subtracted it from each observed image using the GALFIT PSF model.

We performed aperture photometry with an 8.3 arcsec diameter aperture. Flux in the aperture was calibrated using standard stars listed in Landolt (1992) that were observed on the same night. The resultant light curves in the U, B, V, and I bands of SN 2004bd and SN 2008ec are plotted with filled circles in the upper and lower panels, respectively, in Figure 1. The photometry following the process above achieved a photometric error around 1% in flux.[9]

2.3. Light Curve Fitting

A variety of methods have been developed to correct the intrinsic dispersion of the peak brightness of SN Ia using light curve shapes (e.g., Riess et al. 1996; Perlmutter et al. 1999). We selected two methods: the Multicolor Light Curve Shape method (MLCS2k2; Jha et al. 2007) and the second version of the Spectral Adaptive Light curve Template method (SALT2; Guy et al. 2007, 2010) to measure the distances of the SNe Ia. These standard and sophisticated methods provide the template light or color index curves and the necessary basic parameters to model the multicolor light curves of any SN Ia and to measure its distance.

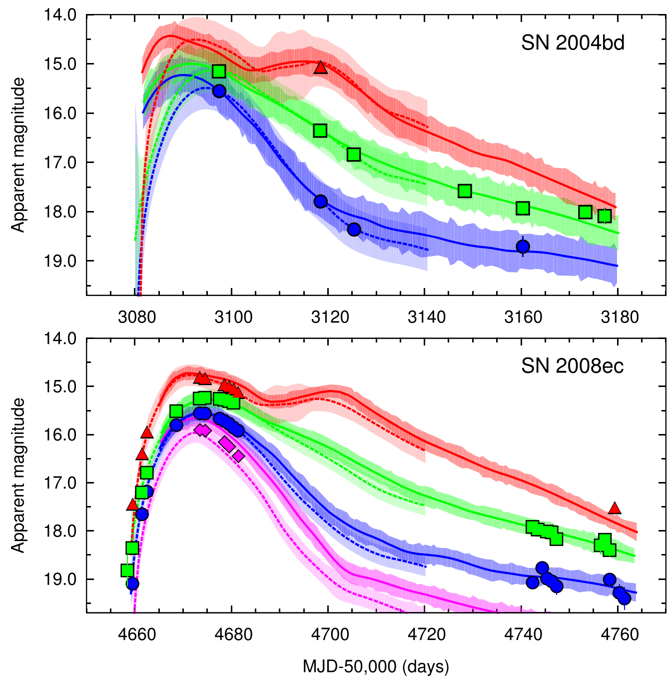

Figure 1. Light curves of SN 2004bd in the upper panel and those of SN 2008ec in the lower panel. The MAGNUM observations are plotted as filled diamonds, circles, squares, and triangles to represent $U + 0.4$, B, V, and $I - 0.4$ in apparent magnitude, respectively. The solid lines are the model light curves obtained using the MLCS2k2 method, while the dashed lines are the model light curves obtained with SALT2. Dark and light shadows along the curves indicate the error of the model light curves for MLCS2k2 and SALT2, respectively.

2.3.1. MLCS2k2

In the MLCS2k2 method, the observed light curve set of any SN Ia in U, B, V, R, and I is fit using the parameter Δ with the template set trained by a sample of nearby SNe Ia. The difference from the template curve at the peak magnitude in the V band is represented by Δ.

Using the color variation curve, the MLCS2k2 method can also estimate total extinction A_V along the light path to the SN in addition to the peak magnitude. The wavelength-independent distance modulus, μ, can be obtained as $\mu = \mu_\lambda - A_\lambda$. For instance, the model formula for the V band is given as

$$\mu = m_\lambda(t_0) - M_\lambda^{\mathrm{peak}} - \zeta_\lambda\left(\alpha_\lambda + \frac{\beta_\lambda}{R_V}\right)A_V - P_\lambda\Delta - Q_\lambda\Delta^2, \quad (2)$$

where A_V is total extinction in the V band, and Δ is differential magnitude from template light curve at the peak in V, which

[9] The Open Supernova Catalog project (https://sne.space/; Guillochon et al. 2017) accumulates the photometric data of SNe in literature, including SN 2004bd and SN 2008ec, and provides their multicolor light curves. However, we used only the data of our own in this Letter in order to avoid possible biases that may arise from using heterogeneous data sets obtained with different instruments, photometric methods, host galaxy flux estimation methods, etc.

Table 2
Results from Light Curve Modeling

	SN 2004bd		SN 2008ec	
	MLCS2k2	SALT2	MLCS2k2	SALT2
μ	33.53 ± 0.24	33.43 ± 0.19	33.88 ± 0.13	33.79 ± 0.08
$t_{\mathrm{peak},B}$ (MJD)	53090.31 ± 2.59	53095.20 ± 1.41	54674.00 ± 0.52	54674.46 ± 0.11
A_V (mag)	0.93 ± 0.29	0.82 ± 0.13[a]	1.03 ± 0.09	0.65 ± 0.07[a]
Width parameter[b]	0.07 ± 0.12	−0.15 ± 0.03	−0.19 ± 0.09	−0.07 ± 0.02
reduced χ^2	0.519004	0.072918	0.247278	0.773540

Notes.
[a] The extinction in the V band is estimated from the B band extinction, which SALT2 calculated, adopting $A_B/A_V = 1.34$ (Cardelli et al. 1989).
[b] Parameters for light curve width of SNe Ia, Δ in MLCS2k2 and x_1 in SALT2.

parameterizes the whole light curve model with the coefficients P_λ and Q_λ. Details of parameters ζ_λ, α_λ, and β_λ, concerning the extinction estimation, are discussed in Jha et al. (2007).

The correction for the Galactic extinction $A_{V,\mathrm{MW}} = 0.079$ for SN 2004bd and $A_{V,\mathrm{MW}} = 0.228$ for SN 2008ec, according to Schlegel et al. (1998), was applied to the observed light curves prior to fitting. The fit converged with a slightly better chi-square value than without the correction. We fixed $R_V = 3.1$ following the discussion in Jha et al. (2007). Most R_V derived by MLCS2k2 are distributed the range 3.0 ± 0.1. Setting R_V as a free parameter made our fitting unstable.

The best-fit model curves for SN 2004bd are shown in the upper panel of Figure 1 as solid lines. The derived distance modulus is $\mu = 33.53 \pm 0.24$ with a total extinction of $A_V = 0.93 \pm 0.29$ mag in the V band. Similarly, the fitted model curves for the SN 2008ec observations are displayed in the lower panel of Figure 1. The derived distance modulus is $\mu = 33.88 \pm 0.13$ with a total extinction of $A_V = 1.03 \pm 0.09$ in the V band. The systematic errors in these distance moduli are ± 0.21 for SN 2004bd and ± 0.18 for SN 2008ec, originating from several error sources such as uncertainty of model parameters, intrinsic dispersion of SN Ia luminosity, and residuals of the training set light curves from the model curves. These results are listed in the Table 2.

2.3.2. SALT2

SALT2 is a set of template light curves of SN Ia based on a training set from the spectroscopic monitoring of SN Ia (Guy et al. 2007, 2010). They modeled the light curve set as

$$\mu = m_\lambda^* - M_\lambda + \alpha_x x_1 - \beta c, \quad (3)$$

where m_λ^* is a rest-frame magnitude at wavelength λ, α_x is the slope of light curve width to luminosity relationship that encodes time-variable color as a function of light curve shape, and β is the coefficient for constant dust extinction. The values of the parameters obtained from the training set are reported in Guy et al. (2010), and we adopt their results.

The SALT2 team provides their fitting code named SNFIT platformed on Python. We used their code, setting the range of wavelength and period to $2000\,\text{Å} < \lambda < 9200\,\text{Å}$ and $-20 < t < 50$ days, as similar as possible to the MLCS2k2 method. We again subtract the Galactic dust extinction from the light curves used for the fit, so the fitting model gives only the extinction in the SN host galaxy, as for MLCS2k2.

The best-fit model light curves for SN 2004bd and SN 2008ec from SALT2 are overdrawn with dashed lines in the upper and lower panels, respectively, in Figure 1. The distance moduli obtained from this method are, for SN 2004bd, $\mu = 33.43 \pm 0.19$ with $A_V = 0.82 \pm 0.13$ and, for SN 2008ec, $\mu = 33.79 \pm 0.08$ with $A_V = 0.65 \pm 0.07$. Systematic errors in these distance moduli are ± 0.17 for SN 2004bd and ± 0.16 for SN 2008ec, considering the same error sources as in MLCS2k2.

Our derived apparent magnitude at maximum luminosity in the B-band for SN 2008ec is $m_{B,\mathrm{max}} = 15.51 \pm 0.02$. This is consistent with 15.49 ± 0.03 in Ganeshalingam et al. (2010) and 15.51 ± 0.03 in Ganeshalingam et al. (2013). Our derived color parameter of 0.24 ± 0.03 is consistent with 0.21 ± 0.03 in Scalzo et al. (2014), but not with 0.09 ± 0.03 in Ganeshalingam et al. (2013). We could not find any comparable results for SN 2004bd in the literature.

2.4. SN Ia Distances

For each of the two SNe Ia, the distance moduli obtained from the different methods, MLCS2k2 and SALT2, are consistent. In order to insure that our relatively poor sampling of the SN 2004bd light curve has not affected the fitting results, we included the photometric data from Ganeshalingam et al. (2010) and obtained $\mu = 33.43 \pm 0.16$ using MLCS2k2 and $\mu = 33.37 \pm 0.14$ using SALT2, which are consistent with $\mu = 33.43 \pm 0.19$ with only our own data. The light curve width parameter and the extinction are also consistent within 1σ. Therefore, we adopt the results from our homogeneous data for further discussion.

With the standard dust extinction law, $R_V = 3.1$ and therefore $A_B/A_V = 1.34$ (Cardelli et al. 1989), the total extinction in the V band, A_V, estimated for SN 2004bd by the two methods is consistent within the large errors, while the two values of A_V estimated for SN 2008ec differ by 0.4 mag. This difference might come from including the U band in the color determination for SN 2008ec, because, in both methods, the U band training set uncertainties are large.

In order to avoid underestimating the errors, we adopt the simple mean for μ and its error instead of the weighted mean because the two methods are not independent. They use training sets with many data sets in common. For SN 2004bd, $\mu = 33.48 \pm 0.22$, which corresponds to a luminosity distance of $d_{\mathrm{SN}} = 49.68 \pm 4.92$ Mpc. The systematic errors are ± 0.19 in μ and ± 4.37 Mpc in d_{SN}. For SN 2008ec, $\mu = 33.84 \pm 0.10$, corresponding to $d_{\rm SN} = 58.48 \pm 2.80$ Mpc. The systematic errors are ±0.17 in μ and ±4.63 Mpc in $d_{\rm SN}$.

Our SN Ia derived distances are consistent with those in the literature for the parent galaxies derived by other methods, such as the Tully–Fisher relation (Schoniger & Sofue 1994; Theureau et al. 2007), AGN reverberation (Collier et al. 1999; Cackett et al. 2007; Wang et al. 2014), and galaxy ring structure diameter (Pedreros & Madore 1981). The mean and standard deviation of the results from these studies are $\mu = 33.32 \pm 0.15$ for NGC 3786 and $\mu = 34.02 \pm 0.56$ for NGC 7469.

3. Dust Properties of AGNs

Substituting $d_{\rm SN}$ into the LHS of Equation (1), we obtain the calibration factor of $g_{\rm SN} = 9.73 \pm 1.16$ for SN 2004bd and $g_{\rm SN} = 11.04 \pm 0.56$ for SN 2008ec. Taking both random errors and systematic errors into account, the weighted average for our two SNe Ia is $g_{\rm SN} = 10.61 \pm 0.50$, and the systematic error in $g_{\rm SN}$, from that in $d_{\rm SN}$, is ±0.69. The calculated calibration factor $g_{\rm DUST} = 10.60$ used in Yoshii et al. (2014) is within 1σ of $g_{\rm SN}$. This agreement provides an independent confirmation of the validity of our new method for measuring extragalactic distances described in Yoshii et al. (2014).

The standard deviation $\sigma_{g_{\rm SN}}$ for our two SNe Ia is 0.62, which, in principle, should be the combination of the random and systematic errors in $g_{\rm SN}$. The errors discussed above give the combined error of $\sqrt{0.50^2 + 0.69^2} = 0.85$, which is greater than $\sigma_{g_{\rm SN}}$ indicating that the individual random and systematic errors are overestimated by taking the simple mean of the MLCS2k2 and SALT2 methods. Using the weighted mean, and ignoring any covariance from using similar training sets, gives random and systematic errors of 0.34 and 0.49, respectively, and a combined error of 0.60, similar to $\sigma_{g_{\rm SN}}$.

An estimate of the cosmic variation in our dust-reverberation distances can be obtained by examining the differences between $d_{\rm DUST}$, as given by Equation (1) with $g_{\rm DUST} = 10.60$ and $d_H = v/H_0$ ($H_0 = 73 \pm 3\,{\rm km\,s^{-1}\,Mpc^{-1}}$) for the 17 AGNs studied in Yoshii et al. (2014). In practice, by substituting d_H into the LHS of Equation (1), we express the cosmic variation of the dust properties in terms of the distribution of $g_{\rm DUST}$, which reflects random errors as well as systematic errors, including possible object to object variations. Our dust-reverberation model has three parameters: (1) the dust sublimation temperature, $T_{\rm d} = 1700 \pm 50$ K, derived from the $H-K$, $J-K$, and $J-H$ color temperatures of the variable near-infrared component in our sample of Seyfert 1 galaxies (Tomita 2005; Tomita et al. 2006); (2) the power-law index, $\alpha_{\rm UV} = -0.5 \pm 0.2$, for the UV to optical continuum emission from the central engine that heats the dust, as found in the SDSS sample of QSOs (Vanden Berk et al. 2001; Davis et al. 2007); and (3) the grain size, a, represented by the distribution of $f(a) \propto a^{-2.75}$ ($0.005\,\mu{\rm m} \leqslant a \leqslant 0.20\,\mu{\rm m}$) that is intermediate between the two opposite extreme distributions of grain size in the literature (see Yoshii et al. 2014).

Using d_H in the LHS of Equation (1), the standard deviation of $g_{\rm DUST}$ for the 17 AGNs studied in Yoshii et al. (2014) is derived as 0.44. This must include the well-estimated errors of ±0.24 from our $\Delta t_{\rm DUST}$ measurements, ±0.1 from intrinsic extinction (Cackett et al. 2007), ±0.18 from the possible range of $T_{\rm d}$, and ±0.32 from α. The remaining, necessary error is ±0.09 and is attributed to the systematic error from the grain size for $f(a)$, much less than the conceivable maximum error $\sim\pm0.5$ (Yoshii et al. 2014) from assuming the two opposite extreme distributions of a. Thus, the dust properties of all AGNs are not very different.

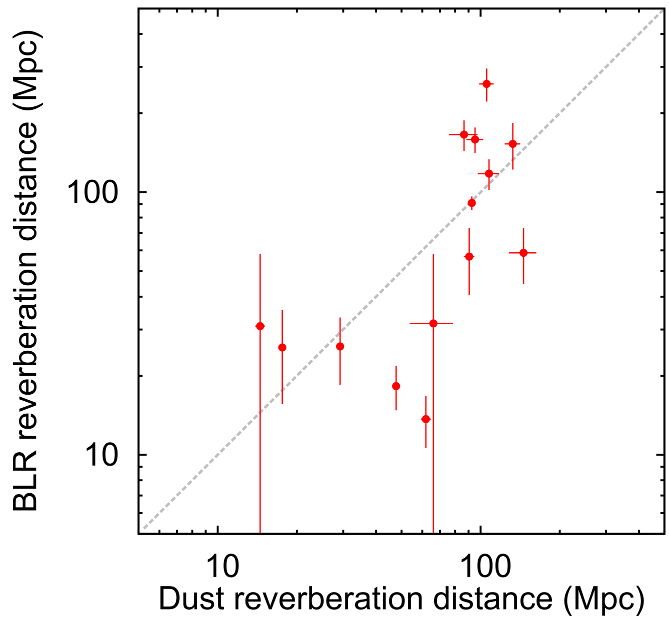

Figure 2. Distances calculated using $\Delta t_{\rm H\beta}$ and $g_{\rm H\beta} = 13.56$ are plotted against the distances using $\Delta t_{\rm DUST}$ and $g_{\rm DUST} = 10.60$ for the 14 Seyfert 1 galaxies in our AGN monitoring program in common with Watson et al. (2011).

Hönig et al. (2017) claimed that distances measured by Yoshii et al. (2014) suffered from the degeneracy between H_0 and dust emissivity because AGN luminosity was calculated by redshift-based distance. This claim is not correct because Yoshii et al. (2014) calculated the luminosity based on the physical model of radiative thermal equilibrium (e.g., Barvainis 1987), which is independent of H_0. The SN distances in this Letter confirm that the dust parameters used in Yoshii et al. (2014) are reasonable.

4. Hβ Distances of AGNs

Watson et al. (2011) reported a relation between the relative distances for AGN based on the correlation of the BLR size with absolute luminosity. For the 14 AGNs in Yoshii et al. (2014) that we have in common, substituting their dust-reverberation distances of $d_{\rm DUST}$ into the LHS of Equation (1), we use the time delay $\Delta t_{\rm H\beta}$ between a continuum flare and the increase in the flux in the Hβ emission line from Bentz et al. (2009) to obtain the distribution of $g_{\rm H\beta}$. The mean of $g_{\rm H\beta}$ is 13.56, and the deviation is as small as 0.08. Thus, we attribute most of the scatter to cosmic variation in the properties of the BLR. In Figure 2, we plot the reverberation distances obtained from Equation (1) using $\Delta t_{\rm H\beta}$ and $g_{\rm H\beta} = 13.56$ versus $\Delta t_{\rm DUST}$ and $g_{\rm DUST} = 10.60$.

Having determined the mean value of $g_{\rm H\beta} = 13.56$, we use Equation (1) to obtain the luminosity distances for all the AGNs with measured $\Delta t_{\rm H\beta}$ (Bentz et al. 2009). These are plotted against redshift as black squares in Figure 3 along with our AGNs from Yoshii et al. (2014; red circles) and the galaxies with Cepheid distances (Freedman et al. 2001; Freedman & Madore 2010; green filled circles).

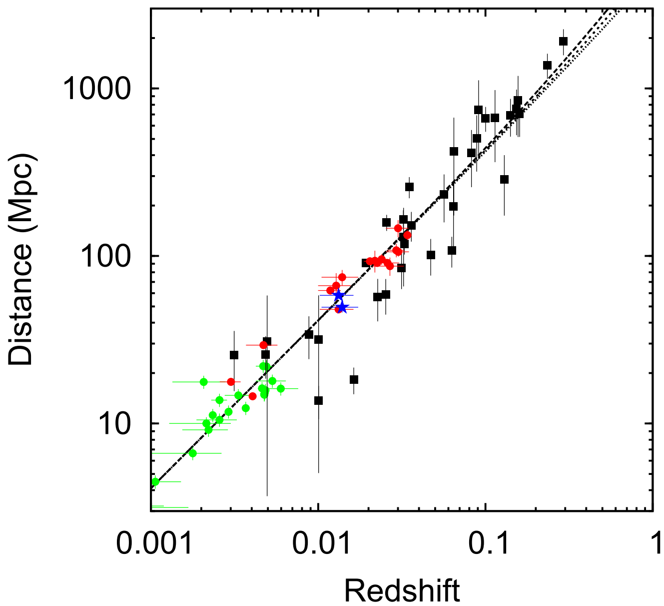

Figure 3. Hubble diagram where luminosity distances are plotted against redshift. Black filled squares represent all the AGNs with measured $\Delta t_{\mathrm{H}\beta}$ from Bentz et al. (2009), and their distances were calculated using Equation (1) with $g_{\mathrm{H}\beta} = 13.56$ (see Section 4). Red filled circles represent AGNs with measured Δt_{DUST}, and their distances were calculated using Equation (1) with $g_{\mathrm{DUST}} = 10.60$ (see Yoshii et al. 2014). Green filled circles represent the galaxies with Cepheid distances and illustrate the consistency of Cepheid and reverberation distances (see Freedman et al. 2001; Freedman & Madore 2010; Yoshii et al. 2014). Blue stellate symbols represent two SNe Ia with the distances measured in this Letter. From top to bottom, the dashed, the dotted–dashed, and the dotted lines represent the cosmological models with $(\Omega_m, \Omega_\Lambda) = (0.3, 0.7)$, (0.3, 0.0), and (1.0, 0.0), respectively, with $H_0 = 73$ km s^{-1} Mpc^{-1}. The redshift errors come from the range of model estimates of local velocity field correction.

5. Conclusion

The calculation in Yoshii et al. (2014) of the calibration factor, $g = 10.60$, in Equation (1) that characterizes the dust sublimation by the radiation field of the AGN central engine is independently supported by the distances of two SNe Ia that occurred in two different AGN host galaxies during our AGN monitoring program.

The agreement between g_{SN} and g_{DUST} as well as the small estimated scatter of g_{DUST}, after excluding measurement errors (Section 3), indicates that our characterization of the AGN dust is essentially correct and that the dust properties of all AGNs are very similar to our characterization.

We have used 14 of our AGNs to evaluate $g_{\mathrm{H}\beta}$, and we have used this calibration to produce a Hubble diagram reaching $z = 0.3$ that begins to distinguish between possible cosmologies (Section 4). With further ground-based Hβ observations, this could be extended to $z \approx 1$.

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