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FEASIBILITY OF MEASURING THE COSMOLOGICAL CONSTANT Λ AND MASS DENSITY Ω USING TYPE Ia SUPERNOVAE

ARIEL GOOBAR[1] AND SAUL PERLMUTTER[2]
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ABSTRACT

We explore the feasibility of resurrecting the apparent magnitude–redshift relation for a "standard candle" to measure the cosmological constant and mass density. We show that Type Ia supernovae, if measured with 0.15 mag uncertainty out to a redshift of $z = 1$, may provide a good standard candle or calibrated candle for this purpose. The recent discovery of probable Type Ia supernovae in the redshift range $z = 0.3$–0.5 (Perlmutter et al. 1994, 1995) indicates that the flux of optical photons from these events can be measured this accurately. The seven distant supernovae discovered to date do not by themselves distinguish among different cosmological models; however, the further discovery of about 50 Type Ia supernovae at redshifts in the range $0.5 \leq z \leq 1.0$ could strongly constrain the allowed range of these parameters. We estimate that the follow-up photometry necessary for this measurement would be on the order of 20–70 hr of time on a 10 m class telescope at a site with good seeing.

Subject headings: cosmology: observations — distance scale — supernovae: general

1. INTRODUCTION

Recent attention to the problem of measuring or bounding the cosmological constant Λ has yielded inconclusive results. The review article of Carroll, Press, & Turner (1992) surveyed the observational status of the cosmological constant based on (1) the existence of high-redshift objects, (2) the ages of globular clusters and cosmic nuclear chronometry, (3) galaxy counts as a function of redshift or apparent magnitude, (4) dynamical tests (clustering and structure formation), (5) quasar absorption-line statistics, (6) gravitational lensing counts and statistics, and (7) the astrophysics of distant objects. The conclusion of this exhaustive survey was that the current best "observationally secure" bounds on the cosmological constant are $-7 < \Lambda/(3H_0^2) < 2$, leaving a wide range of possible cosmological models from which to choose. In fact, we still do not know if we live in an infinite universe that will expand infinitely or in a finite universe that at some point will halt its expansion and recollapse. In this paper we explore the feasibility of resurrecting the apparent magnitude–redshift relation for a "standard candle" as an eighth method to add to this arsenal of measurement techniques.

The early work on the implications of cosmological models on the apparent magnitude–redshift (*m*-*z*) relation of a standard candle, the first-ranked cluster galaxies, did consider the possibility of a nonzero cosmological constant (e.g., Solheim 1966; Stabell & Refsdal 1966). As the difficulties of studying evolutionary effects for these galaxies became clear, the range of cosmological models considered narrowed to just those with a vanishing cosmological constant (e.g., Peach 1970). The equations of galaxy evolution and the deceleration parameter q_0 (or, equivalently, the mass density of the universe Ω_M) were considered complications enough in these *m*-*z* studies. The most recent work has generally been considered to be more a study of evolution than a measurement of q_0 or Ω_M (for a review, see Sandage 1988). In the past few years new evidence has been put forward suggesting that a group of Type Ia supernovae (SN Ia's) can be identified that are excellent standard candles or calibrated candles. There is reason to believe that evolution effects should be much less significant for SN Ia's than for first-ranked cluster galaxies, and even if such effects are present, they may be distinguishable on an event- by-event basis. The past few years have also seen the start of searches for distant supernovae, resulting in the discovery and study of seven SN Ia's at redshifts in the range $z = 0.3$–0.5 (Nørgaard-Nielsen et al. 1989; Perlmutter et al. 1994, 1995). This is clearly an opportune time to reconsider the use of standard candles to measure Λ.

In this paper we first review the current understanding of the usefulness of a subgroup of SN Ia's as standard candles and the possibility of further "calibrating" these candles using light-curve decay time or shape. We then discuss the use of standard candles to measure the cosmological constant and mass density. Some of the earliest papers that treated the $\Lambda \neq 0$ case pointed out that the apparent magnitude–redshift measurement was insensitive to q_0 at certain redshifts while still sensitive to Ω_M (e.g., Refsdal, Stabell, & de Lange 1967). We propose to take advantage of this redshift dependence to measure Ω_M and Λ simultaneously. The special case of a "flat" universe, as implied by the inflationary theories of the universe, is discussed separately. We then draw conclusions about the observational requirements and hence the feasibility of a new measurement of Λ and Ω_M using SN Ia's.

2. TYPE Ia SUPERNOVAE

There is much evidence indicating that a distinguishable majority of Type Ia supernovae are likely to be good standard candles. The problem of estimating the intrinsic dispersion of SN Ia's, however, has been clouded by the inclusion of supernovae with peculiar spectra or light curves, supernovae that showed clear evidence of host galaxy extinction, and supernovae that had very large uncertainties on their photometry measurements. For a subsample of well-measured "local" SN Ia's that do not have peculiar spectra or light curves and do not show clear evidence of extinction, the *observed* dispersion is

[1] Physics Department, Stockholm University, Box 6730, S-113 85 Stockholm, Sweden; ariel@physto.se.
[2] Center for Particle Astrophysics, University of California, Berkeley, and Lawrence Berkeley Laboratory, 50-232, Berkeley, CA 94720; saul@lbl.gov.

$\sigma_V = \sigma_B = 0.3$ mag in both the V and B bands (Vaughan et al. 1995a). This dispersion of these "normal" SN Ia's is completely accounted for by measurement errors (most of this scatter is probably due to the relative distance measurement error), and thus the value of the *intrinsic* dispersion is likely to be smaller than the value of this observed dispersion. Sandage & Tammann (1993) use Monte Carlo modeling of Malmquist bias to argue that the largest intrinsic dispersion for SN Ia's which is compatible with the observed selection effects for nearby supernovae is $\sigma_{M_V}^{\text{intrinsic}} \approx 0.2$ mag.

Vaughan et al. (1995a) proposed that their criteria for "normal" SN Ia's be tested on an independent set of supernovae to confirm the small observed dispersions σ_V and σ_B. Hamuy et al. (1994) presented such an independent, new set of SN Ia's, including both "normals" and "peculiars," with smaller measurement errors. In particular, the relative distance measurement error was smaller because this set of supernovae was discovered at redshifts $z \approx 0.01$–0.1, where the peculiar velocities are negligible with respect to the Hubble flow. Selecting just the "normal" SN Ia's from this set, using the criteria of Vaughan et al. (1995a), results in an even narrower observed dispersion of $\sigma_V = 0.18$ mag in the V band and $\sigma_B = 0.20$ mag in the B band (Vaughan, Branch, & Perlmutter 1995b).

Hamuy et al. (1994) and Riess, Press, & Kirshner (1995) also reported a correlation of light-curve decay time or light-curve shape with peak absolute magnitude for this set of SN Ia's. (Note that this correlation would not be easily found in the earlier set of SN Ia's with larger measurement errors, although Phillips 1993 did report such a relation for a small sample of well-measured peculiar and normal SN Ia's.) Using this correlation to provide a "calibration" of the SN Ia standard candle may make it possible to include peculiar SN Ia's in distance measurements. The correlation also appears to hold within the "normal" SN Ia subset, allowing even this subset's already narrow dispersion to be further reduced after calibration, yielding σ_V as low as 0.12 (Hamuy et al. 1994) or 0.21 (Riess et al. 1995). Although this calibrated σ_V would imply a still smaller intrinsic dispersion, for this paper we will take the intrinsic dispersion to be the "uncalibrated" value, which is bounded by the observed dispersions to be $\sigma^{\text{intrinsic}} < 0.25$ in the V or the B band. This is a conservative value, given that the *observed* dispersions quoted in Vaughan et al. (1995b) are less than or equal to this.

If SN Ia's are to be more useful as cosmological standard candles than the first-ranked cluster galaxies have been, either they must not evolve in absolute magnitude or this evolution must be easily detected and characterized. There are at least two reasons suggesting that SN Ia standard candles should not founder on the evolution problem:

1. Unlike first-ranked cluster galaxies, SN Ia's are dynamic events that display their internal composition and physical state through the many spectral lines that appear, shift in velocity, and disappear and also through the photometric light curves in various wavelength bands. It is possible to observe each individual SN Ia, match its spectra over time and its light curves against those of nearby SN Ia's, and check for subtle changes from the range of normal SN Ia's. These changes are very likely to be *more* sensitive to the details of the precursor star and environment than is the peak absolute magnitude and thus can provide "early warning" before there are differences large enough to affect the absolute magnitude significantly. For example, the light-curve decay time or shape and the spectral absorption-line velocities both appear to be sensitive indicators of explosion strength.

2. SN Ia's have been discovered in a wide range of nearby galaxy types. This variation in host galaxy environment can be used as a surrogate for the variation that would be expected because of evolution. This technique has been used, for example, by Branch & van den Bergh (1993), who suggest that Si II absorption-line velocity may be correlated with host galaxy type. Branch & van den Bergh did not see a correlation with absolute magnitude in this case, but such studies of nearby supernovae can in principle detect, and provide tests for, evolution of absolute magnitudes. Ideally, these tests would make it possible to distinguish degrees of evolution on a supernova-by-supernova basis.

Even if the SN Ia's themselves do not evolve, it is possible that the host galaxy dust may evolve, thus changing the apparent magnitude with redshift. Although very careful color photometry should provide checks for this effect, it is probably easier to compare SN Ia's in different galaxy types (both nearby and distant), once again using these types as surrogates, this time for evolution of host galaxy dust. So far, there does not appear to be such an effect for a range of nearby galaxy types.

These evolution tests will provide the underlying proof of SN Ia's as standard candles or calibrated candles and could of course someday find some SN Ia's exhibiting evolution effects that cannot be easily corrected. It is important to reemphasize, however, that SN Ia's are unusual standard candles in having such tests available on an individual basis: each SN Ia can be accepted or rejected by itself.

3. CONSTRAINING THE PARAMETERS BY STANDARD CANDLE LUMINOSITY DISTANCE

For an object of known absolute magnitude M, a measurement of apparent magnitude m at a given redshift is sensitive to the universal parameters Ω_M and $\Omega_\Lambda \equiv \Lambda/(3H_0^2)$ through the luminosity distance D_L:

$$m = M + 5 \log [D_L(z; \Omega_M, \Omega_\Lambda)] + K + 25 , \qquad (1)$$

where the K-correction in the equation appears because the emitted and detected photons from the receding object have different wavelengths. The dependence of D_L on Ω_M is different from the dependence on Ω_Λ, entering with different powers of z:

$$D_L(z; \Omega_M, \Omega_\Lambda) = \frac{(1+z)}{H_0\sqrt{|\kappa|}} \mathscr{S}\left\{\sqrt{|\kappa|} \int_0^z [(1+z')^2(1+\Omega_M z') - z'(2+z')\Omega_\Lambda]^{-1/2} dz'\right\} , \qquad (2)$$

where, for $\Omega_M + \Omega_\Lambda < 1$, $\mathscr{S}(x)$ is defined as $\sin(x)$ and $\kappa = 1 - \Omega_M - \Omega_\Lambda$; for $\Omega_M + \Omega_\Lambda > 1$, $\mathscr{S}(x) = \sinh(x)$ and κ as above; and for $\Omega_M + \Omega_\Lambda = 1$, $\mathscr{S}(x) = x$ and $\kappa = 1$.

Using equations (1) and (2) we can predict the apparent magnitude of a standard candle measured at a given redshift for any pair of values of Ω_M and Ω_Λ. Note that the value of the Hubble parameter drops out of the equations as it appears both in the expression for the luminosity distance and in the determination of the absolute magnitude of the standard candle based on nearby apparent magnitude–redshift measurements. Figure 1 shows the contours of constant apparent magnitude in the R band on the Ω_Λ-versus-Ω_M plane for the

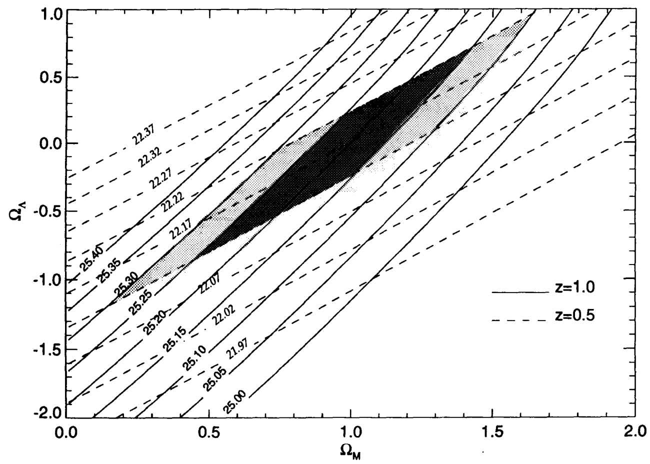

FIG. 1.—Contours of constant apparent magnitude (*R* band) predicted for a sample standard candle with absolute magnitude (*B* band) $M_B = -18.86 + 5 \log (H_0/75)$. The dashed lines show the predicted apparent magnitude, including *K*-corrections, for a standard candle at $z = 0.5$, and the solid lines are for $z = 1$. The dark-shaded region shows the "allowed" region of Ω_Λ-vs.-Ω_M parameter space if an apparent magnitude of $m_R = 22.17 \pm 0.05$ were measured at $z = 0.5$ and if $m_R = 25.20 \pm 0.05$ were measured at $z = 1$. Adding the faint-shaded region implies a 0.1 mag uncertainty for supernovae at $z = 1$.

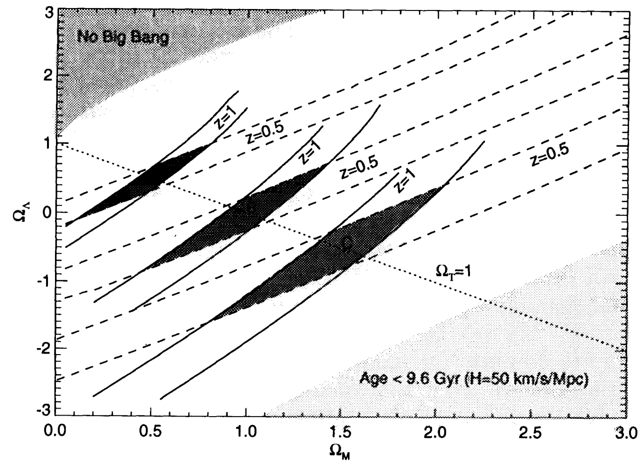

FIG. 2.—Map of parameter space for Ω_Λ and Ω_M. The top and bottom shaded areas are ruled out by observations (see text). The solid lines show the enclosed band that a 0.05 mag measurement of a standard candle at $z = 1$ would imply for three different universes. Similarly, the dashed lines correspond to the same standard candle at $z = 0.5$. The regions A, B, and C give the allowed parameter space for the cases in which the parameters are $\Omega_\Lambda = 0.5$ and $\Omega_M = 0.5$ for A, $\Omega_\Lambda = 0.0$ and $\Omega_M = 1.0$ for B, and $\Omega_\Lambda = -0.5$ and $\Omega_M = 1.5$ for C.

cases of $z = 0.5$ and $z = 1$, where we have taken the absolute luminosity of SN Ia's to be $M_B = -18.86 \pm 0.06 + 5 \log (H_0/75)$ (Branch & Miller 1993; Vaughan et al. 1995a).

When an actual apparent magnitude measurement of a standard candle is made at, for example, $z = 0.5$, the ranges of possible values of Ω_M and Ω_Λ are narrowed to a single contour line on Figure 1 (dashed lines for $z = 0.5$). Since we are assuming some uncertainty in the apparent magnitude measurement, the allowed ranges of Ω_M and Ω_Λ are given by a strip between two contour lines. Two such measurements for standard candles at different redshifts (e.g., $z = 0.5$ and $z = 1$) can define two strips that cross in a more narrowly constrained "allowed" region, shown as a shaded rhombus in Figure 1. The darker shaded region in the plot corresponds to the result of measurements with 0.05 mag uncertainty in a flat universe with vanishing cosmological constant, while the fainter shaded region allows for a 0.10 mag uncertainty at $z = 1$. Note that the 1 σ error region is limited by an ellipse rather than by the rhombus shown in Figure 1. To simplify this figure and the following two figures, we have not drawn the 1 σ error ellipse.

For the case in which a standard candle is measured at $z = 0.5$ and $z = 1$, Figure 2 shows the allowed regions for Ω_Λ and Ω_M for a set of three sample universes *superposed* on the same graph (i.e., the actual measurements would result in only one of the shaded regions A, B, or C). Note that on this graph, very large positive values of Ω_Λ are ruled out because they would imply a "bouncing" (no big bang) universe, as discussed in Carroll et al. (1992). Also, extremely large values of Ω_M combined with negative Ω_Λ are ruled out because they would imply a universe younger than the oldest heavy elements, which have been dated to be 9.6 Gyr (Schramm 1990). The shaded regions correspond to hypothetical results in a universe with parameters $\Omega_\Lambda = 0.5$ and $\Omega_M = 0.5$ for A, $\Omega_\Lambda = 0.0$ and $\Omega_M = 1.0$ for B, and $\Omega_\Lambda = -0.5$ and $\Omega_M = 1.5$ for C. These examples all correspond to flat universes but with different contributions from matter and from cosmological constant. Similarly, Figure 3 shows how this method would distinguish case D ($\Omega_\Lambda = 0.0, \Omega_M = 0.2$) from case E ($\Omega_\Lambda = 0.8, \Omega_M = 0.2$).

In practice, more than two apparent magnitude measurements at two redshifts would be used for this measurement. A global fit of equations (1) and (2) to the measurements would then yield best-fit contours on the Ω_Λ-versus-Ω_M plane. Figures 1–3, however, give a direct understanding of how good the measurement errors need be to constrain Ω_Λ and Ω_M: the accuracy of the magnitude measurements translates into a region in the Ω_Λ-versus-Ω_M parameter space approximately as $(\Delta\Omega_\Lambda \times \Delta\Omega_M) \propto (\sigma_m^{z=0.5} \times \sigma_m^{z=1.0})$. Note that these magnitude errors are the combined error of the apparent magnitude measurement at redshift z, the absolute magnitude estimate for the standard candle used, and the intrinsic dispersion of SN Ia's. We see from the figures that a combined measurement error of $\sigma_m \leq 0.05$ mag significantly constrains Ω_Λ and Ω_M.

In this paper we assume that the photometric measurements will be sufficiently precise that the intrinsic dispersion of SN Ia's dominates, $\sigma^{\text{intrinsic}} < 0.25$ mag (in § 5 we discuss the

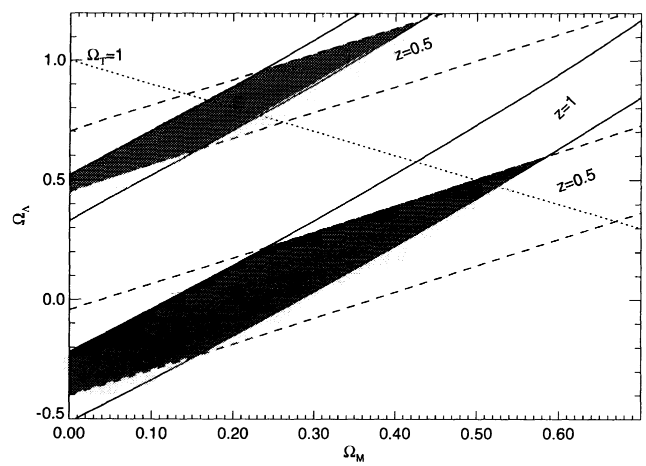

FIG. 3.—Map of allowed parameter space for Ω_Λ and Ω_M. Region D corresponds to $\Omega_\Lambda = 0$ and $\Omega_M = 0.2$, and region E corresponds to $\Omega_\Lambda = 0.8$ and $\Omega_M = 0.2$.

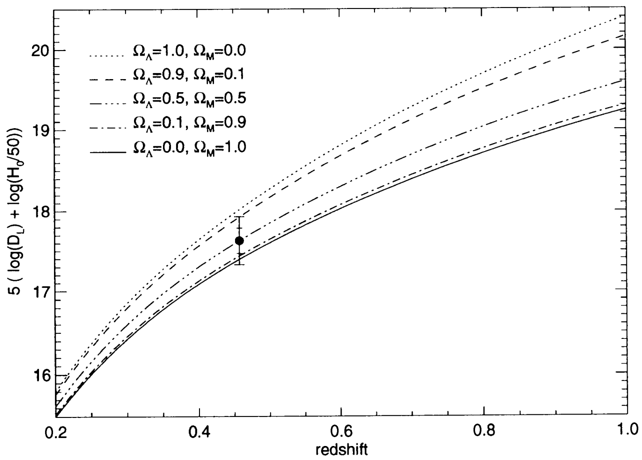

FIG. 4.—Luminosity distance as a function of redshift for various values of Ω_M and Ω_Λ in a flat universe ($\Omega_M + \Omega_\Lambda = 1$). The filled circle corresponds to $(m - M - K - 25)$ for SN 1992bi (Perlmutter et al. 1995), where the smaller error bar is due to the photometry measurement error, $\sigma^{\text{photometry}} \approx 0.15$, and the larger error bar includes a 0.25 mag intrinsic dispersion for SN Ia's.

observational requirements to achieve this photometric accuracy). In order to be able to make the ± 0.05 mag measurement at $z = 0.5$ and $z = 1$ shown in Figures 1–3, we thus must have a sample of at least 25 supernovae at each redshift.

4. Ω_Λ IN THE FLAT UNIVERSE CASE

An important special case to consider is the "flat" universe predicted by the inflationary theories, in which the total energy density of the universe $\Omega_T \equiv \Omega_\Lambda + \Omega_M = 1$. (The other special case in which $\Lambda = 0$ has been discussed in Perlmutter et al. 1995.) In a flat universe, the apparent magnitude of a standard candle as a function of redshift is extremely sensitive to Ω_Λ. Figure 4 shows the theoretical curves for the luminosity distance as a function of redshift for flat universes.

A measurement of the apparent magnitude of a standard candle at $z = 1$ would strongly constrain the cosmological constant and thus test inflationary models. As an example, for the case in which Ω_T is dominated by Ω_Λ, it could be measured with $\sim 10\%$ accuracy even with σ_m as large as 0.25 mag. The ratio of photon flux for the Ω_M-dominated versus the Ω_Λ-dominated case is about a factor of 3 for a standard candle at $z = 1$.

At redshift $z = 0.458$, where the most distant SN Ia was found, the total measurement error, $\sigma_m \approx 0.3$ mag (including the uncertainty in the photometry, $\sigma^{\text{photometry}} \approx 0.15$ mag, as well as the uncertainties in the K-correction and the intrinsic dispersion of Type Ia SN's), yielded a 1 σ allowed interval of $-0.2 < \Omega_\Lambda < 0.9$ for $\Omega_T = 1$. This allowed interval is shown by the data point and outer error bar in Figure 4. Note that this particular supernova did not have the color measurements that would make it possible to distinguish host galaxy extinction or a peculiar supernova, and therefore this provides only a demonstration data point.

5. OBSERVING REQUIREMENTS

The analysis of the photometry of SN 1992bi showed that one can measure the apparent R magnitude at peak of a supernova at $z = 0.458$ with a photometric uncertainty $\sigma^{\text{photometry}} \approx 0.15$ mag (Perlmutter et al. 1995). Using a 2.5 m telescope and a "thick" CCD (peak quantum efficiency $\sim 43\%$ at 650 nm), a total of 135 minutes of exposures were required, 90 minutes distributed over the 4 months near peak and a reference image of 45 minutes 1 yr after peak. The average seeing was approximately 1".5. For SN 1992bi, the uncertainty at peak relative to the reference image was only 0.06 mag, and the error on the reference image photometry of the host galaxy dominated. Clearly, the longest single exposure should be that of the reference image of the host galaxy after the supernova has faded. In order to take advantage of the further magnitude calibration from light-curve decay time or light-curve shape, this series of observations must begin before maximum light; the search technique of Perlmutter et al. (1994, 1995) makes this possible on a systematic basis.

Scaling to a 10 m class telescope, at a site such as Mauna Kea with 0".75 median seeing and with a thinned CCD, we estimate that the uncertainty in apparent magnitude of distant supernovae at $z = 0.5$ (~ 0.2 mag fainter) can be kept below $\sigma^{\text{photometry}} = 0.15$ mag with 1.5ϵ minutes of photometric measurements, where ϵ accounts for the scaling factors: $\epsilon = (\text{seeing}/0''.75)^2(10\text{ m/aperture})^2$. The photometric uncertainty is dominated by the sky background at these high redshifts, typically more than 4 mag brighter than the count rate from the supernova and the host galaxy. Mauna Kea and La Palma, where SN 1992bi was observed, have essentially the same sky brightness but at a different site exposure time would scale with the sky, too, as $10^{0.8(\text{sky}_1 - \text{sky}_2)}$.

Observing $N = 25$ supernovae at $z = 0.5$ would require less than 1ϵ hr of 10 m telescope photometry time. The overall measurement uncertainty would then be $\sigma_m = N^{-1/2}[(\sigma^{\text{intrinsic}})^2 + (\sigma^{\text{photometry}})^2]^{1/2} \leq 0.05$ mag for $\sigma^{\text{intrinsic}} < 0.25$ mag when one neglects the much smaller error in the mean SN Ia absolute magnitude. This is the value of σ_m discussed in § 3 and shown in the dark-shaded regions of Figures 1–3.

For a SN Ia at $z = 1$, 5 log D_L is about 2 mag fainter than for $z = 0.5$ (see Fig. 4 for the effect of different cosmologies on this distance modulus). Although the choice of the R filter is well suited for the $z = 0.5$ supernovae, the I filter is more appropriate for $z > 0.85$ supernovae because the rest-frame flux from SN Ia's falls rather steeply below ~ 300 nm. The sky is approximately 0.8 mag brighter in the I band, but the difference of zero points between the I and R bands is -0.8 mag, so there are roughly the same number of sky background *photons per second* in both R and I in spite of the difference in magnitudes (Massey et al. 1995). Taking into account a reduction of the quantum efficiency by a factor of ~ 2 above 800 nm, it would take $\sim 2\epsilon$ hr of observing time per supernova at $z = 1$ to obtain $\sigma^{\text{photometry}} \leq 0.15$ mag uncertainty in the apparent magnitude.

To achieve an overall measurement uncertainty of $\sigma_m \leq 0.05$ mag would then require 34 SN Ia's or $\sim 70\epsilon$ hr of 10 m photometry time. Alternatively, $\sigma_m \leq 0.1$ mag could be achieved with only nine SN Ia's observed at $z = 1$, requiring $\sim 18\epsilon$ observing hr. Note that a $\sigma_m = 0.1$ mag uncertainty at $z = 1$ still yields quite useful bounds on the Ω_M-versus-Ω_Λ plane as shown by the faint-shaded region of Figure 1.

The time needed in order to *find* tens of supernovae is significantly larger. For example, at a 10 m telescope about 15ϵ minutes would be needed to find a supernova at $z \approx 0.5$ using a wide-field camera such as the four-CCD mosaics currently being commissioned at several observatories. Using the 2.4 m *Hubble Space Telescope* to study high-redshift supernovae, as suggested by Colgate (1979), would not significantly diminish the length of exposures needed for supernovae at redshifts $z \lesssim 1$ (see Nelson, Mast, & Faber 1985 for Keck-*HST* comparisons).

Based on a 1 hr spectrum of a supernova at $z = 0.425$ observed at a 3.6 m telescope (Perlmutter et al. 1994), we estimate that 10 hr of 10 m telescope time are required to obtain a spectrum of a supernova at $z = 1$ and only 15 minutes for a supernova at $z = 0.5$. For the first set of high-redshift supernovae, these spectra would be necessary in addition to color photometry to check identification and evolution. If these spectra show no surprises, it may be possible to spot-check the subsequent supernova spectra and use multicolor light curves instead.

In this estimate of the observation time required, we have implicitly included the K-correction by moving to a longer wavelength band for the higher redshift measurements. An important calibration step in the actual experimental protocol for this measurement will be the careful determination of the K-correction for each supernova studied. Currently available spectra of nearby supernovae allow traditional K-correction estimates (e.g., corrections for light emitted in the B band at high redshifts to the light observed in the B band) to be made with reasonable accuracy (<0.05 mag) out to redshifts of order $z \approx 0.2$, within less than 20 days (supernova rest frame) of maximum light (Hamuy et al. 1993a). A generalization of the K-correction that corrects for light emitted in the B band, for example, at high redshifts, but observed in the R band can be calculated with this same accuracy for objects out to at least $z = 0.6$ (Kim, Goobar, & Perlmutter 1995). However, for the most accurate corrections, particularly at high redshifts, it will be important to make further well-calibrated observations of the spectra and light curves of a number of newly discovered nearby SN Ia's to ensure that any supernova-to-supernova differences are sampled. In particular, it may be useful to observe nearby SN Ia's with a range of filters specifically designed to match "blueshifted" I or R standard filters for a sample of redshifts (e.g., for $z = 0.3$, 0.4, 0.6, and 0.7; the current data in B and V may serve for "blueshifted" R at $z \approx 0.5$ and 0.2 or I at $z \approx 0.8$ and 0.5). This would allow an accurate K-correction interpolation table to be constructed. Note that this K-correction work requires a well-calibrated data set, since any wavelength-dependent error in the K-corrections could mimic redshift-dependent changes in magnitude and hence confound the measurements of Ω_M and Ω_Λ.

In practice, actual telescope observing time is, of course, always significantly longer than the theoretical predicted time. These time estimates are intended to convey the scale of this observing program; it is an ambitious but practicable program.

6. DISCUSSION

As with the other methods for determining the cosmological constant discussed in § 1, this approach depends on results from an entire research program. More nearby SN Ia's must be discovered and studied, as can be expected from a few projects (e.g., Hamuy et al. 1993b; Muller et al. 1992). This will make it possible to test and refine the criteria used to distinguish "normal" unextincted SN Ia's, to develop further light-curve decay time/shape calibration, and to determine the true intrinsic magnitude distribution. Distant SN Ia's must also be discovered before maximum light on a regular basis (e.g., Perlmutter et al. 1994, 1995), and the observational effort necessary to study them as outlined in this paper will not be trivial. Both the nearby and distant SN Ia's will contribute to the tests for evolution. Finally, careful photometric and spectral work will still be needed to ensure that the uncertainty in the K-corrections is negligible compared to the other sources of error. Given that research programs are already underway in all of these areas, this approach to the measurement of Λ and Ω_M may soon be feasible.

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