COSMOLOGICAL MEASUREMENTS WITH DISTANT TYPE Ia SUPERNOVAE

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ABSTRACT.

The High-Z SN Search is an international collaboration to discover and follow SNe Ia at z > 0.2 with the aim of tracing out cosmic deceleration and global curvature. This project has discovered 72 supernovae (0.09 < z < 0.97) using the Blanco 4-meter telescope at CTIO and the CFHT over the past 2.5 years. We have obtained spectra and two color photometry for most of these supernovae and find that 35 of the objects are SNe Ia useful for measuring distances. Using the extensive nearby set of supernovae gathered by members of our group, we discuss methods to overcome problems associated with K-corrections, Malmquist bias, extinction, and evolution which could affect the distances derived from SNe Ia. In addition to the SNe Ia, the search has uncovered several normal Type II supernovae on which the Expanding Photosphere can be applied, several Kuiper Belt asteroids, and a few short duration events of unknown origin.

1. Introduction

Measuring the global curvature and cosmic deceleration (often parameterized as q_0) of the Universe has been a fundamental question in astronomy ever since Robertson(1936) and Walker(1936) first formulated the metric for a homogeneous and isotropic universe. Although many methods for measuring the global properties of space exist, none has yet delivered anything close to a definitive measurement. By tracing how a standard candle dims as a function of redshift, usually shown as a Hubble diagram, the effects of global curvature and deceleration can be seen and quantified. Attempts to constrain the Hubble diagram at large z with standard candles have been plagued by poor precision and by evolution in the distance indicators, and have not been adequate to detect the effects of cosmic deceleration and curvature.

Recent work by members of the High-Z Search team[1] has produced a breakthrough in the use of supernovae as distance indicators. Based on information contained in the shape of SN Ia light curves, we have shown how to cut the effective scatter in absolute magnitudes for SN Ia in half, from >0.3 mag to 0.15 mag, making SN Ia *four times* more effective in determining cosmological parameters.

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We are currently leading a coordinated ground-based effort to discover, spectroscopically classify, and obtain photometry in two colors for a distant set of SNe Ia. The ultimate goal of this ground-based project is to obtain a measurement of q_0 which is free of systematic defects. Our effort, while very promising at the present time, has been dramatically improved and expanded with the precision photometry, temporal coverage, and wavelength accessibility which the Hubble Space Telescope affords. The HST light curves, in combination with ground-based spectroscopy and imaging, will enable us to measure q_0 to better than 0.1, and will have the precision to disentangle the geometrical effects of curvature and the kinematic effects of deceleration in our Hubble diagram. In this way, we will measure the mean equation of state of cosmic matter (including the influence of any dynamically significant forms of exotic matter, such as Einstein's cosmological constant), and will be able to discern whether we live in an open or closed universe, or one which is close to zero global curvature.

2. Expansion, Deceleration, and Curvature

The precise isotropy of the microwave background establishes beyond a reasonable doubt that the universe is described on large scales by the maximally symmetric, Friedmann-Robertson-Walker (FRW) metric. The global geometry has the character of a hypersphere specified by the curvature parameter, κ, where the radius of curvature is $\kappa^{-1/2}(c/H_0)$. The system expands as described by a scale factor $a(t)$ whose functional form is determined (from the Friedmann equation) by both the curvature and the contents of the universe. In general $a(t)$ can be either accelerating or decelerating, depending on the constituents of the universe. Up to now, both κ and $a(t)$ are essentially unconstrained— even the sign of the deceleration and curvature are unknown, although they have been observational targets for six decades.

Both the deceleration and the curvature affect the form of the relation between luminosity and redshift. By observing a standard candle of known luminosity, one measures the luminosity distance D_L (Weinberg, 1972), defined from the ratio of the intrinsic luminosity, $\mathcal{L}$, to the observed flux, $\mathcal{F}$,

$$D_L = \left(\frac{\mathcal{L}}{4\pi\mathcal{F}}\right)^{\frac{1}{2}}.$$

The luminosity distance is given directly by integrating the FRW metric:

$$D_L H_0 = (1+z)\kappa^{-1/2} S\{\kappa^{1/2}\int_0^z dz'[\kappa(1+z')^2 + \Sigma_i\Omega_i(1+z')^{3+3\alpha_i}]^{-1/2}\},$$

where $S(x) \equiv \sin(x)$, x, or $\sinh(x)$ for closed, flat, and open models respectively. We have assumed matter is composed of a set of components each having a fraction Ω_i of the critical density, and having equations of state with $\rho_i \propto V^{-(1+\alpha_i)}$ (*e.g.* $\alpha = 0$ for normal matter, $\alpha = -1$ for a cosmological constant, $\alpha = +1/3$ for radiation). The curvature parameter, κ, is defined as $\kappa = 1 - \Sigma_i\Omega_i$. This equation can be expanded to give

$$D_L H_0 = z + z^2 \left(\frac{1-q_0}{2}\right) + z^3 \left(\frac{(1+q_0)^2}{2} - \frac{1+q_0}{2} + \frac{\kappa}{6}\right) + \mathcal{O}(z^4),$$

where the classical deceleration parameter is given by $q_0 = \Sigma\Omega_i(1+3\alpha_i)/2$; for example in a model with just matter and a cosmological constant, $q_0 = \Omega/2 - \Omega_\Lambda$. Although the redshift and distance measurements we propose are already beyond the range where this expansion is completely accurate, we use it below to show the sensitivity of the technique to deceleration and curvature. The linear term of the expansion— the Hubble law— has been studied for many years. Its linear form has been verified to high precision at low redshifts using SNe Ia and the same techniques we propose for this project (Hamuy et al. 1996b, Riess, Press, & Kirshner 1996). The current debate on its value centers on obtaining an absolute calibration for SNe Ia in nearby galaxies through accurate absolute distances. Fortunately, the measurements of curvature and deceleration only require a relative distance indicator, and are not affected by current uncertainties in H_0. With a distance modulus measured to precision Δm in an object at redshift z, the above expansion shows (using $\Delta m = 5\Delta\log_{10}[H_0 D_L]$) that we measure q_0 to a precision $\Delta q \approx 0.9\Delta m/z$; thus a single well observed SNe Ia ($\sigma \sim 0.14$ mags) at $z = 0.5$ yields a precision of about $\Delta q_0 = 0.25$ — or a 2-sigma discrimination between an empty and a flat universe. A similar result can be obtained with regard to κ: the difference in brightness between two models of the same q_0 is approximately $\Delta m = 0.36z^2\Delta\kappa$, indicating that the curvature can be extracted with reasonable efficiency for objects at $z > 0.6$.

3. Measuring distances to SNe Ia at low redshift

Type Ia supernovae have long been considered promising tools for measuring extragalactic distances, but only recent data sets and analytic work (Phillips 1993 [P93]; Hamuy et al. 1995 [H95]; Hamuy et al. 1996c; Riess, Press, and Kirshner 1995 [RPK95]; Riess, Press, and Kirshner 1996 [RPK96]) have truly shown the nature, power, and limitations of SNe Ia as distance indicators. H95 demonstrated that SNe Ia are not standard candles, but have an intrinsic scatter of approximately $\sigma(M_V) = 0.6$ mag. However, following the initial study by P93, our group has also demonstrated that the maximum luminosity of a SN Ia event is highly correlated with its decline rate from maximum light (H95, Hamuy et al. 1996a, RPK95) which can be used to significantly improve the accuracy of SNe Ia distances. Figure 1 shows a current calibration (Phillips et al. 1997) of SNe Ia absolute magnitudes as a function of the light curve shape (the $\Delta m_{15}B$ parameter of H95). We (Hamuy et al. 1996d, RPK96) have developed methods to fit the light curves of SNe Ia in many colors.

4. Searching for SNe from the ground

Although there is a long history of SNe searches (e.g., Zwicky 1968), many attempts over the past decades were not particularly productive. Many weeks of telescope time were used by Norgard-Nielsen et al. (1989), Couch et al. (1991), and Perlmutter et al. (1995a) to produce two SNe at $z = 0.31$ and $z = 0.46$. The advent of low-noise large-format CCDs

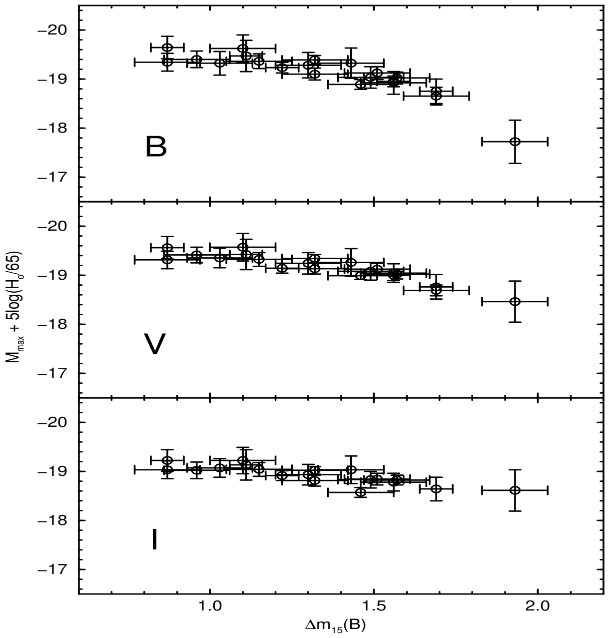
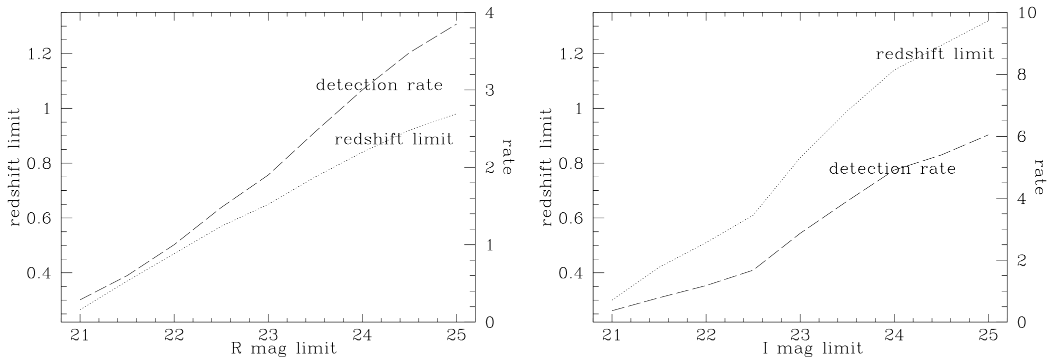


Fig. 1. The absolute B, V and I magnitudes of SNe Ia with low host galaxy reddening from a combined Calán/Tololo and CFA sample, plotted as a function of $\Delta m_{15}(B)$. These are SNe with z >0.01, and the magnitude scales have been set using the measured redshift and H_0=65 km/s/Mpc.

has revolutionized the ability to detect distant SNe as first demonstrated by Perlmutter et al. (1997). By observing fields at the end of a dark run, and then revisiting the fields 3 weeks later, young objects can be found by subtracting the first images from the second. Perlmutter et al. have used this technique to discover large numbers distant SNe since 1992, many of which have been spectroscopically confirmed (Perlmutter et al. 1992, 1994, 1995a, 1995b, 1997). For the past 30 months our consortium, The High-Z SN Search, has been searching for objects using the CTIO 4m Blanco Telescope. At present we have identified >70 SNe, >30 of which have been spectroscopically confirmed SNe Ia (Schmidt et al. 1995,1997; Kirshner 1995; Garnavich et al. 1996a, 1996b).

Thus it is clearly possible to find large numbers of SNe at interesting redshifts. With large mosaic cameras coming now on line, the future is even brighter. Figure 2 shows the detection rate and limiting redshift for objects as a function of limiting magnitude. With our present system of 5-minute integrations and a $29'$ field at the prime focus of the CTIO Blanco 4m, we reach a limit of $m_{\rm R} \sim 24$, depending on image quality, and survey approximately 6 square degrees per night. In collaboration with Luppino, Cowie, and Huang, we are used the University of Hawaii 8K CCD mosaic to survey 3-square degrees to $m_I = 25$ in April/May and Oct '97. This program has produced more than 10 SNe at high redshifts and yielded the most distant candidate in our sample ($z = 0.97$).



(a) (b)

Fig. 2. Redshift limits and detection rates over a 24 day baseline for SN searches using (a) R and(b) I band images, assuming $q_0 = 0$. The detection rates are given in units of SNe discovered per square degree.

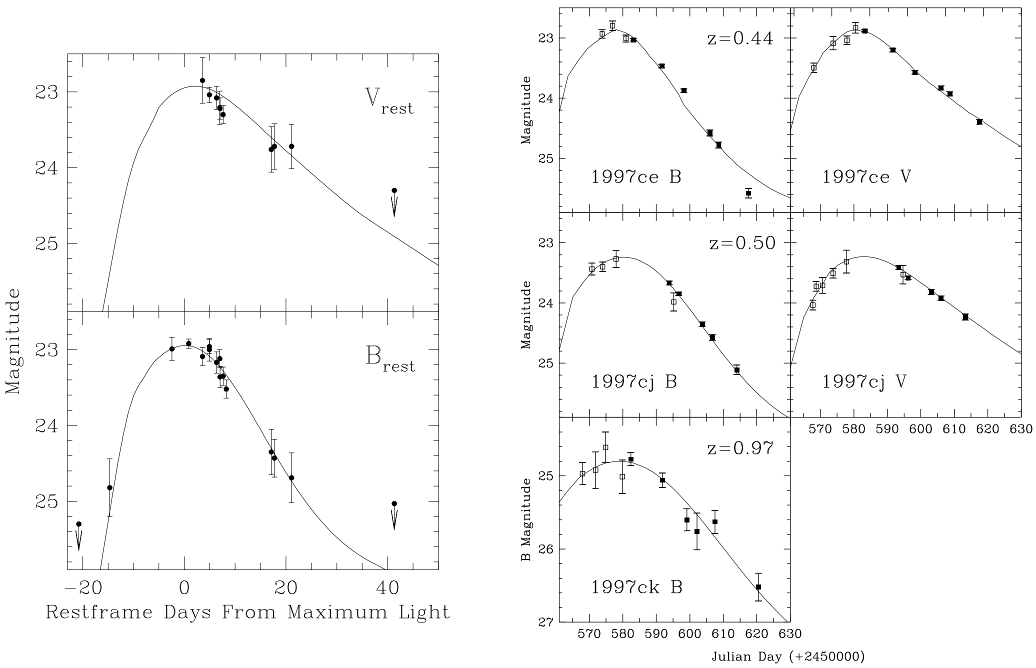
5. The Pitfalls of Measuring SNe distances at Large Redshifts

The path to using SNe Ia as accurate distance indicators at large redshifts has at least four pitfalls: transformation to a common photometric system, extinction, evolution, and Malmquist bias.

5.1. Transformation to a Common Photometric System

Since our nearby SNe Ia have been observed extensively in B and V, and their properties are well understood within these broad band filter systems, it makes sense to observe distant SNe Ia at wavelengths that can be easily transformed to rest frame B and V. It would be foolish for us to attempt to observe in other bands: for example, the ultraviolet behavior of SNe Ia has been documented in just a few cases, and for these objects, the systematic differences between different sets of ground-based photometry are unacceptably large for cosmological use.

We have determined the uncertainty (akin to a K-correction, see Kim et al. 1996) in transforming from HST broadband filters to rest frame B and V. Rather than constrain ourselves to existing broadband filter sets, we have defined a set of four redshifted filters– pairs of B and V filters redshifted to z= 0.35 and z=0.45. Although adopting this new photometric system adds the complication of defining standards for these filters, we believe the ability to translate SN Ia observed in the range $0.25 < z < 0.55$ to standard B and V filters with small systematic uncertainties is worthwhile (Schmidt et al. 1997). We have also used accurate spectrophotometry of nearby SNe Ia, obtained by members



(a) (b)

Fig. 3. a)The restframe B and V light curves of SN 1995K. The data are K-corrected and time dilated and RPK96 and H95 fits are superposed; b) Rest frame light curves for SNe 1997ce, 1997cj and 1997ck (B only). The filled points represent HST observations while the open points are from ground-based telescopes. The solid lines show the best fit light curve from the MLCS method.

of our team, to show that it is possible to translate to $B_{\rm rest}$ and $V_{\rm rest}$ accurately (scatter less than 0.035 mags in $(B-V)_{\rm rest}$) over a significant range of redshifts in two windows, $0.42 < z < 0.80$ and $0.92 < z < 1.24$ with HST WFPC2/Nicmos measurements. This uncertainty has a random component, which diminishes as we accrue observations and objects, and a systematic component for individual objects. If the bandpasses are poor matches to rest frame B and V, an overall systematic error can creep into the SN sample if the objects with spectrophotometry are not representative of the high-z objects. Sample light curves from ground based (Schmidt et al, 1997) and ground based + HST measures (Garnavich et al. 1997) are given in Figure 3. The HST photometry has several inherent advantages, if the systematic issues concerning the detectors can be accurately removed (which is *not* a trivial task).

5.2. Extinction

Extinction is a particularly challenging problem. The selection effect against extinction for SNe Ia discovered in both the nearby and distant searches is a complicated function of redshift, instrument, and observing conditions. It is therefore likely that the average extinction will be different between the nearby and distant SN samples (and the difference could be of either sign), mimicking the deviations from linearity we are trying to measure in the Hubble diagram. B-band work is more vulnerable to these errors than V-band, and U-band is unthinkable without a powerful grasp on this problem based on low redshift objects. A recent study by Phillips et al. (1997) on the intrinsic color evolution of SN Ia has developed a consistent method to de-redden the type Ia light curves. Correcting for reddening is essential to remove any systematic biases that absorption might introduce, although with current samples it appears not to decrease the disperion of the distance indicator.

5.3. Evolution

Evolution has been the death of other methods used to trace luminosity distances with redshift. There are strong hints from the low-redshift samples (Hamuy et al 1996a) that the most luminous supernovae are found in later type galaxies. This suggests that the luminosity of the supernovae in a galaxy depends on the age of the stellar population (von Hippel, Bothun, & Schommer 1997). So we should expect, as a function of look-back time, a possible drift in the intrinsic luminosity of the supernovae. Left untreated, this evolution could be fatal to attempts to find cosmological parameters from supernovae. However, as long as the nearby samples include objects which are similar to the distant objects, we can immunize our procedure against this possible drift in luminosity with redshift, at least to first order. Corrected SN Ia luminosities in the nearby sample exhibit a bias with host galaxy type of less than $m - M = 0.06$ (Schmidt et al. 1997).

5.4. Malmquist Bias

Most SN discoveries in our magnitude-limited samples are inevitably found near the detection limit, and therefore Malmquist bias cannot be ignored. Malmquist bias corrections are difficult to make because the selection function for discovering SNe Ia is not well defined — it depends critically on the point spread function of both the prediscovery and discovery images, and ultimately rests on a human decision of whether an object is real (false detections are enormously costly and no object is followed up on unless it is an absolute certainty). The size (and therefore uncertainty) of Malmquist bias corrections is proportional to the dispersion of a distance indicator, squared. Since we only suffer the bias left over *after* the correction for light curve shape, and since the residual dispersion of the method is so small, it is possible to reduce the uncertainty in the Malmquist bias corrections to approximately ~ 0.02 mags (the corrections themselves are about 3 times this size) with a large sample of nearby and distant objects; with a less precise distance indicator, the uncertainty would be much larger. However, Malmquist bias corrections require that we have an accurate knowledge of the distribution of SN luminosities as a function of their light curve shape from the nearby sample.

6. Conclusions and Results

We show in Figure 4 our current best effort to measure cosmological parameters (Garnavich et al. 1997). With the constraint of a flat universe ($\Omega_M + \Omega_\Lambda = 1$), we find $\Omega_M = 0.4\pm0.3$ (using MLCS fitting). On the other hand, if we assume Ω_Λ=0, we find Ω_M =–0.1 ± 0.5, and that Ω_M <1 with 95% confidence. These results contrast with those of Perlmutter et al. (1997), which preferred a high matter density even in flat models. Both sets of results are preliminary, and more precise and detailed analysis of larger samples should be forthcoming in the next year.

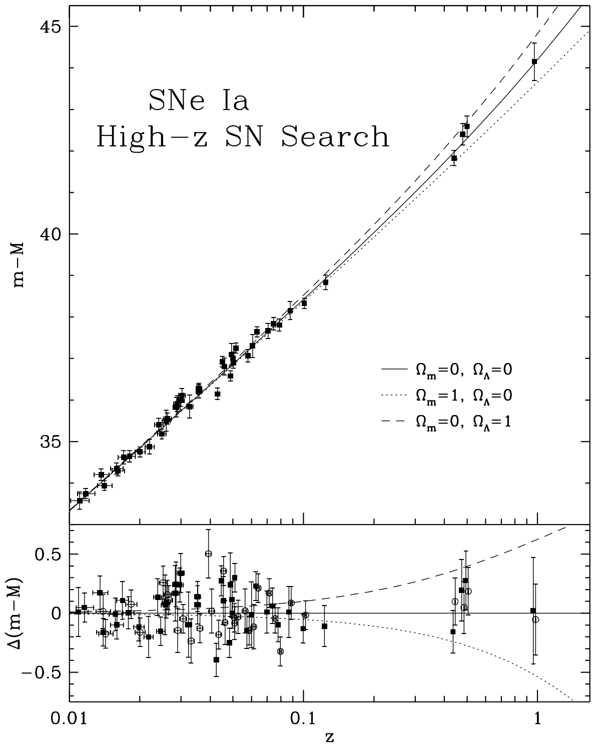


Fig. 4. A Hubble diagram for SNe Ia; the scatter is less than σ = 0.15 mag (7%) in the nearby sample; The top panel shows the MLCS distance modulus versus z for the nearby sample and four high-z SNe. The lower panel plots the magnitude difference between the observed SNe and the magnitude espected from a Universe with $\Omega_M = \Omega_\Lambda = 0$. The open circles show the estimates using the techniques and scale from H96 (the reshift has been slightly shifted for clarity where both techniques are applied).

Figure 5 shows the 1σ joint confidence region for Ω_M and Ω_Λ that is obtainable with a sample of 30 SNe Ia observed at z=0.5, augmented with 10 SN Ia observed at z=1 with HST. Recently considerable effort has been devoted to studies of the power spectrum of fluctuations in the cosmic microwave background (CMB), in order to measure cosmological paramenters. Future satellite missions will measure temperature fluctuations across the sky, determining the power spectrum of fluctuations out to a multipole expansion of $l > 500$. Model fits to these observations promise to provide simultaneous measurement of ten cosmological parameters (Zaldarriaga, Spergel, & Seljak 1997). The error ellipse in the $\Omega_{\rm M}$– Ω_Λ plane of the Planck Surveyor measurements (the dottedd curves in Figure 5) are fortunately nearly perpendicular to the SNe determinations , and the combination should have great power to discrimate between various global parameters of our Universe.

The members of our group have led the way in developing new understanding of SNe Ia at $z < 0.1$, and understand the power and limitations of this distance indicator. Our large nearby sample of SNe Ia provides the essential information to correct for Malmquist bias and for the understanding and elimination of the other pitfalls described above. But, since our ability to measure q_0 ultimately rests on our understanding of SNe Ia as distance indicators, we continue to search and follow new SNe Ia at moderate redshifts ($z < 0.1$) to add to the 42+ objects our team has already measured. Specific searches include using the 1.2m "MACHO" telescope at Mount Stromlo, the Curtis Schmidt telescope at CTIO, a 0.8m robotic telescope at Lick Observatory, and a Schmidt plate search with the UKST at Siding Spring Observatory. The use of SNe as distance indicators to measure cosmological parameters requires a deep understanding of the low redshift supernovae, and a continuing effort to use that knowledge to avoid the pitfalls that can ensnare the unwary.

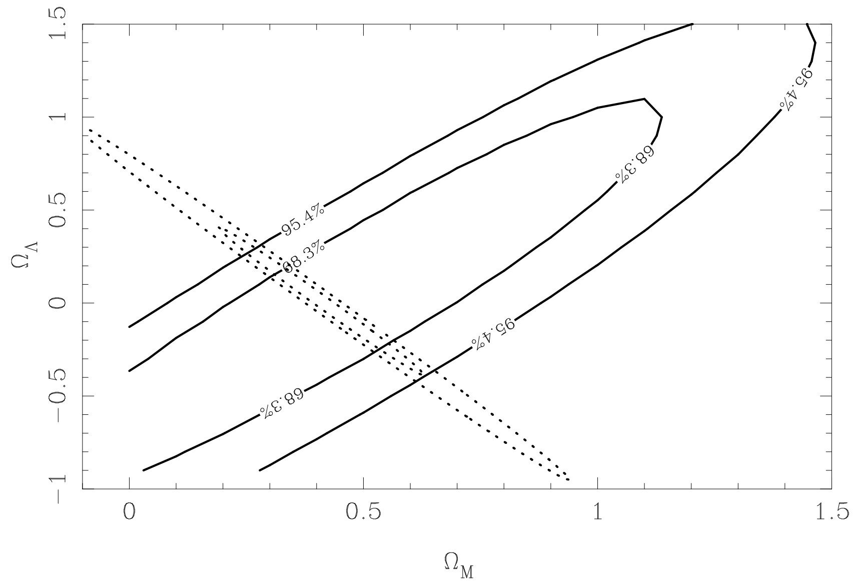


Fig. 5. Predicted error contours (68.3% and 95.4% joint confidence) in measuring $\Omega_{\rm M}$ and Ω_Λ simultaneously for a sample of 30 z=0.5 SN Ia augmented with 10 z=1 SN Ia observed with HST. Also shown as dotted lines, are the predicted uncertainty countours from future CMB anisotropy measurements to be made by the Planck Surveyor mission (see text).

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