K CORRECTIONS FOR TYPE IA SUPERNOVAE AND A TEST FOR SPATIAL VARIATION OF THE HUBBLE CONSTANT

The Supernova Cosmology Project: II

A. KIM[1], S. DEUSTUA, S. GABI, G. GOLDHABER, D. GROOM,
I. HOOK, M. KIM, J. LEE, R. PAIN[2], C. PENNYPACKER, S. PERLMUTTER AND
I. SMALL
E. O. Lawrence Berkeley National Laboratory & Center for Particle Astrophysics, University of California, Berkeley

A. GOOBAR
University of Stockholm

R. ELLIS, K. GLAZEBROOK[3] AND R. MCMAHON
Institute of Astronomy, Cambridge University

B. BOYLE, P. BUNCLARK, D. CARTER AND M. IRWIN
Royal Greenwich Observatory

H. NEWBERG
Fermi National Accelerator Laboratory

A. V. FILIPPENKO AND T. MATHESON
University of California, Berkeley

M. DOPITA AND J. MOULD
MSSSO, Australian National University

AND

W. COUCH
University of New South Wales

Abstract.

Cross-filter K corrections for a sample of "normal" Type Ia supernovae (SNe) have been calculated for a range of epochs. With appropriate filter choices, the combined statistical and systematic K correction dispersion of the full sample lies within 0.05 mag for redshifts $z < 0.7$. This narrow dispersion of the calculated K correction allows the Type Ia to be used as a cosmological probe. We use the K corrections with observations of seven

[1]Presented by A. Kim, e-mail address:*agkim@LBL.gov*
[2]Current address: CNRS-IN2P3, Paris
[3]Current address: Anglo-Australian Observatory

SNe at redshifts $0.3 < z < 0.5$ to bound the possible difference between the locally measured Hubble constant (H_L) and the true cosmological Hubble constant (H_0).

1. Introduction

The homogeneity and brightness of Type Ia SN peak magnitudes have long made it a popular standard candle (Branch and Tammann 1992). Recent observations, as discussed in this meeting, now indicate that Type Ia's appear to form a family, rather than a set of identical objects. However, magnitude corrections based on independent observables can make the Type Ia a calibrated candle. Correlations between peak magnitude and light curve shape (Hamuy et al. 1995; Riess, Press, & Kirshner 1995) or spectral features (Nugent et al. 1995), have made it possible to use the Type Ia as a calibrated candle with B magnitude dispersions of ~ 0.2 mag. Alternatively, the use of Type Ia sub-samples can provide an improved standard candle. Supernovae with high quality data that pass certain color cuts show a low dispersion in B magnitudes of < 0.28 mag (Vaughan et al. 1995).

In order to use SNe as a tool for cosmology, we use K corrections (Oke & Sandage 1968) to account for the redshifting of spectra and its effect on nearby and distant flux measurements in different passbands. The sparseness of spectroscopic observations of any individual high-redshift SN requires us to use a statistical approach to K corrections. K corrections must therefore show a small magnitude dispersion to maintain the usefulness of the SN as a standard or calibrated candle.

As of June 1995, the Supernova Cosmology Project had discovered seven SNe lying in the range $0.3 < z < 0.5$ (Perlmutter et al. 1995; Perlmutter et al. 1996) . In a standard Friedmann cosmology, their apparent magnitudes depend on Ω and Λ through the luminosity distance. Perturbations on a homogeneous and isotropic universe can cause the locally measured Hubble constant (H_L) to differ from the global Hubble constant (H_0), as demonstrated by Turner, Cen, and Ostriker (1992). In this case if the SN calibrators lie within the local peculiar flow, then the high-z SN apparent magnitudes will additionally depend on H_L/H_0. A scenario in which $H_L/H_0 > 1$ has been suggested by Bartlett et al. (1994) and others to reconcile theoretical arguments for a low Hubble constant with the recent observational evidence for a large Hubble constant. We use our seven supernovae, with K corrections, to place bounds on H_L/H_0.

2. The K Correction

The generalization of the K correction of Oke & Sandage relating y band observations of redshifted objects with x band observations taken in the supernova rest frame is given by

$$\begin{aligned} K_{xy} &= -2.5\log\left(\frac{\int \mathcal{Z}(\lambda)S_x(\lambda)d\lambda}{\int \mathcal{Z}(\lambda)S_y(\lambda)d\lambda}\right) + 2.5\log(1+z) \\ &\quad + 2.5\log\left(\frac{\int F(\lambda)S_x(\lambda)d\lambda}{\int F(\lambda/(1+z))S_y(\lambda))d\lambda}\right) \\ &= -2.5\log\left(\frac{\int \mathcal{Z}(\lambda)S_x(\lambda)d\lambda}{\int \mathcal{Z}(\lambda)S_y(\lambda)d\lambda}\right) \\ &\quad + 2.5\log\left(\frac{\int F(\lambda)S_x(\lambda)d\lambda}{\int F(\lambda')S_y(\lambda'(1+z))d\lambda'}\right) \end{aligned} \tag{1}$$

where $F(\lambda)$ is the spectral energy distribution at the supernova, $S_x(\lambda)$ is the x'th filter transmission, and $\mathcal{Z}(\lambda)$ is an idealized stellar spectral energy distribution at $z = 0$ for which $U = B = V = R = I = 0$ in the photometric system being used. K_{xy} is thus defined so that $m_y = M_x + \mu + K_{xy}$. If $S_x = S_y$, the first term drops out and this reduces to the K correction of Oke & Sandage. If $S_x(\lambda)$ is proportional to $S_y(\lambda(1 + z))$, then statistical and systematic errors from the SN spectra, through the second term, are reduced.

We calculate generalized K corrections using Equation 1 with Bessell's (1990) color zeropoints and realizations of the Johnson-Cousins UBVRI filter system. (Note that Hamuy et al. (1995) had previously calculated single-filter standard K corrections.) We use a sample of SN data that includes 29 spectra from epochs $-14 \leq t^B_{max} \leq 76$ days (in the supernova rest frame) after blue maximum for SN 1981B, SN 1990N, and SN 1992A. The SN 1981B data are from Branch et al. (1983), SN 1990N data are described in Leibundgut et al. (1991), and SN 1992A data are described in Suntzeff et al. (1995) and Kirshner et al. (1993).

Figures 1 and 2 plot K_{BR} and K_{VR} for $z = 0.5$ as a function of SN rest frame epoch. The scatter in the data points reflects both statistical errors in the spectra, as well as SN to SN differences in K corrections. They also demonstrate the reduction of errors when filter pairs are chosen to match at the appropriate redshift, i.e. $S_x(\lambda)$ proportional to $S_y(\lambda(1 + z))$. Based on analysis of different filter combinations at a range of redshifts, we find that with proper filter choice, these errors can be constrained within < 0.05 mag for redshifts $0 < z < 0.7$ and to within even smaller errors at epochs prior to 20 days after maximum light.

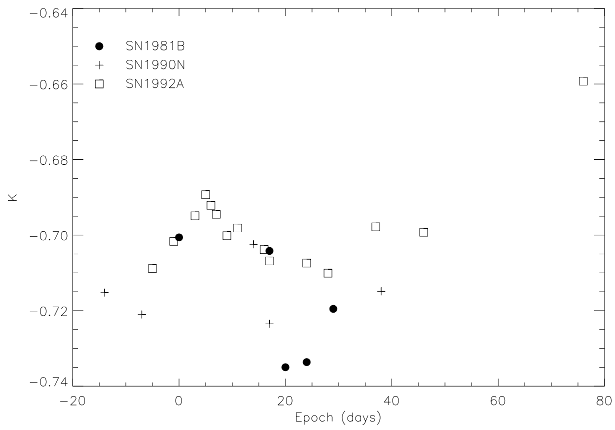

Figure 1. $K_{BR}(z = 0.5)$ as a function of epoch for SN 1981B, SN 1990N, and SN 1992A.

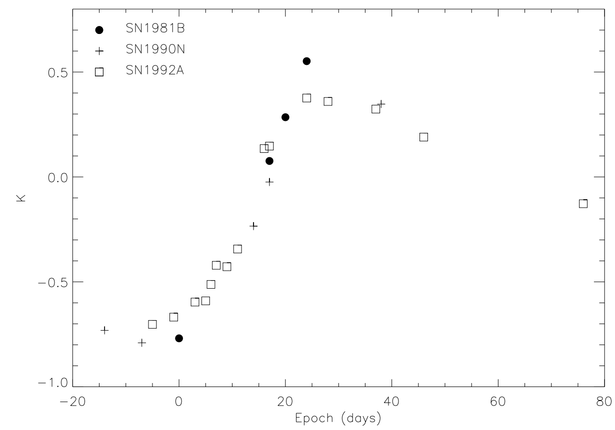

Figure 2. $K_{VR}(z = 0.5)$ as a function of epoch for SN 1981B, SN 1990N, and SN 1992A.

For more detailed discussion of the generalized K correction, see Kim, Goobar, & Perlmutter (1996).

3. Hubble Constant Constant?

We consider objects at a distance of $z > 0.3$ to be within the cosmological flow of standard Friedmann cosmology. Thus, the expected peak apparent magnitude of a Type Ia supernova beyond $z = 0.3$ can be calculated as a function of the mass density of the universe Ω_M ($\Lambda = 0$):

$$m_R = M_B + 5\log(3 \times 10^3 R_L(z; \Omega_M)) + K_{BR} + 25 - 5\log(h_0), \quad (2)$$

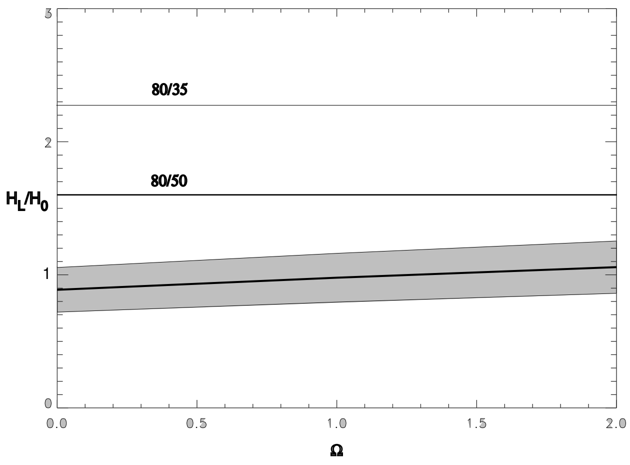

Figure 3. H_L/H_0 as determined from seven supernovae, as a function of Ω ($\Lambda = 0$).

where K_{BR} is the K correction and

$$R_L(z;\Omega_M) = \frac{4}{\Omega_M^2}\left[1 + \Omega_M(z-1)/2 + (\Omega_M/2 - 1)\sqrt{\Omega_M z + 1}\right] \qquad (3)$$

If we use $M_B = -18.52 + 5\log(h_L/0.85) \pm 0.06$ from Vaughan, Branch, & Perlmutter 1995, we find

$$5\log\left(\frac{H_L}{H_0}\right) = m_R - 5\log(R_L) - K_{BR} - 24.22 \pm 0.06. \qquad (4)$$

We have used preliminary analysis of seven high redshift supernovae (described by Perlmutter et al. in this volume), to calculate values for H_L/H_0 for a range of Ω_M, varying from 0 to 2 (see Figure 3). The shaded region represent a one sigma error bar on the value of H_L/H_0. A value of $H_L/H_0 = 80/35 = 2.29$ is strongly excluded, making peculiar velocities an unlikely cause for the disparity between Freedman et al.'s (1994) recent H_0 measurements for Virgo Cepheids and theoretical arguments (e.g. Bartlett et al.) for a low Hubble constant. We reach the same conclusion when using the magnitude corrections based on the width-brightness relation described in Perlmutter et al. 1996.

With the current data, it is impossible to simultaneously measure q_0 and H_L/H_0. In the future, with SNe well sampled in a broad range of redshifts, it should be possible to look for significant spatial (or temporal) deviations from the predicted Friedmann expansion.

4. Conclusions

We conclude that filter-matching K corrections give small enough errors to make SNe useful as cosmological probes. In the future, we will calculate K corrections using more SN spectra and we will search for a relation between light curve shapes and K corrections. Although we do not see such a correlation for the SNe that we have examined so far, which have only moderate departures from the Leibundgut template lightcurve, such a relation is likely to exist at some level since SN colors appear to be correlated with light curve shape, as discussed at this meeting by Riess et al.(1996) and Suntzeff et al.(1996).

We find that we can rule out significant spatial variation of the Hubble constant for $0 \leq \Omega_M \leq 2$. We plan to calculate H_L/H_0 for cosmologies with a cosmological constant, although positive values of Λ will only strengthen our limit.

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