Cosmological Parameters as measured by Type Ia Supernovae

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Abstract. Supernovae are among the most important cosmological distance indicators. Through the application of distance independent correction methods to the peak luminosity, it has become possible to determine very accurate luminosity distances. Type Ia supernovae have been used extensively to measure the current Hubble constant, H_0. More recently, they have been employed to determine the deceleration of the universe. From a first sample of distant supernovae strong indications of a non-vanishing cosmological constant Λ emerge. A careful analysis of the systematic effects does not change this result. The distant supernovae also indicate a dynamic age which is consistent with age determinations of the oldest stellar components of the Galaxy.

1 Introduction

The ability of Type Ia supernovae (SNe Ia) to measure cosmological distances is largely based on empirical evidence. Samples of nearby SNe Ia display a very narrow scatter around the expected linear expansion of the local universe (Kowal 1968, Tammann & Leibundgut 1990) and can be further improved by application of distance independent corrections like for light curve shape (Hamuy et al. 1996a, Riess et al. 1996). The dispersion of the nearby sample decreases to around 0.15 magnitude after an additional correction for absorption. Attempts to explain the empirical correlation between the peak luminosity and the decline rate of SNe Ia after maximum are, however, still controversial (Höflich et al. 1996, Eastman 1997).

With such a modified standard candle it is possible to derive accurate values of the few parameters which govern the expansion in a homogeneous, isotropic universe (e.g. Leibundgut & Pinto 1992, Goobar & Perlmutter 1995). Samples of SNe Ia out to redshifts of $z = 0.1$ combined with a measurement of the absolute

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luminosity yield values for the Hubble constant (Hamuy et al. 1996a, Riess et al. 1996, Reiss et al. 1998).

With a sample of distant supernovae ($z > 0.3$) we can measure the curvature of the universe and any possible contributions of a cosmological constant. This is a geometric measure of the universe. The deceleration can be determined by comparing the distant supernovae with the local sample (Goobar & Perlmutter 1995, Leibundgut 1998). Two experiments are trying to make use of SNe Ia to achieve a determination of the deceleration (Perlmutter et al. 1995, 1997, 1998; Leibundgut et al. 1996, Garnavich et al. 1998, Schmidt et al. 1998, Riess et al. 1998). The current status of the two searches is summarized in section 3.

Yet supernovae are not true standard candles. The light curves and spectral evolution show distinct variations among individual events (Phillips et al. 1987, 1992, Filippenko et al. 1992a, 1992b, Leibundgut et al. 1993). In particular the near-infrared light curves show a second maximum for many, but not all, SNe Ia (Elias et al. 1985, Frogel et al. 1987, Suntzeff 1996). The strength of the second maximum changes considerably and is also distinguishable in bolometric light curves (Vacca & Leibundgut 1996, Contardo et al. 1998).

2 Brief overview over SNe Ia

A generally accepted theory of SN Ia explosions has not yet emerged. For more than a decade explosion models with a subsonic burning front have been favored (Nomoto et al. 1984, Woosley & Weaver 1986), but the physics which sustains such a burning front without turning into a detonation is not understood. New models which explode a white dwarf through He detonation at the surface (Arnett & Livne 1994, Woosley & Weaver 1994), rather than the direct explosive carbon burning inside, cannot be distinguished by the current observations (Branch et al. 1995). The exact trigger of the explosion and the reaction of the white dwarf is not constrained and many models have been proposed (e.g. Höflich & Khokhlov 1996). The radiation transport is largely unsolved. The supernova radiation is not thermalized in the ejecta and the observed pseudo-continuum is dominated by line radiation. A simple way to see this is the fact that the occurrence of maximum in the observed filter light curves does not indicate a cooling shell, but rather a very complex redistribution of the emission (Contardo et al. 1998). The bolometric light curves display the characteristic shoulder of the near-infrared light curves and the total energy changes from event to event.

With this theoretical background it is difficult to support the standard candle picture. The observations have shown a significant variety of appearance. Nonetheless, most variations appear to correlate strongly so that the light curve decline (Hamuy et al. 1996a, Riess et al. 1996), the strength of the Ca II and Si II lines (Nugent et al. 1995), as well as the colors near maximum (Riess et al. 1998, Phillips et al. 1998) provide distance independent indicators of the intrinsic luminosity of SNe Ia. In this sense, SNe Ia appear to be an ordered set and can empirically be used as modified standard candles.

3 The Hubble constant as derived from SNe Ia

The derivation of the Hubble constant from standard candles is in principle very simple. With knowledge of the absolute magnitude the linear relation of redshift and apparent magnitude provides the Hubble constant (Tammann & Leibundgut 1990, Leibundgut & Pinto 1992). The recent programs to determine distances to nearby galaxies which contained SNe Ia (Saha et al. 1997) provide a fairly accurate determination of the luminosity of SNe Ia. Differences arise in the treatment of the relative absorption of the Cepheid sample and the supernova, and corrections to the supernova light curves themselves. The small scatter of the measured peak luminosity of a sample of 7 nearby SNe Ia (Saha et al. 1997) is further indication of the standard behavior of these objects.

The distribution of SNe Ia in the Hubble diagram then yields a value of the Hubble constant. The controversy of the previous decades is finally subsiding and values of $55 < H_0 < 70$ km s^{-1} Mpc^{-1} are generally found (Hamuy et al. 1996a, Riess et al. 1996, Saha et al. 1997). This provides a measurement of H_0 to 15%. The differences are mainly in the treatment of the supernova light curves. It has to be noted that the light curve correction in general changes the value of H_0 by about 10% simply because the nearby SN sample with Cepheid distances and the set of SNe Ia in the Hubble flow have a zero-point difference of this order (Hamuy et al. 1996a, Leibundgut 1998). Other points of discussion are the exact selection of the nearby sample which, although distance limited, suffers from partially inadequate historical records of supernova photometry. These two effects combine to the differences in the reported values. With more Cepheid distances towards supernovae and better observed light curves the discrepancy will disappear.

4 Distant supernovae: Ω_M and Ω_Λ

The determination of the cosmological energy density rests on the measurement of objects distant enough so that the curvature of the universe becomes significant. SNe Ia discovered at redshifts larger than about 0.3 are very well suited for such an investigation. Two groups aggressively pursue this experiment (Perlmutter et al. 1995, 1997, 1998, Leibundgut et al. 1996, Garnavich et al. 1998, Schmidt et al. 1998, Riess et al. 1998). The cosmological frame work has been layed out by Carroll et al. (1992) and Goobar & Perlmutter (1995).

Supernovae are now regularly found at large redshifts. So far, there is no indication that their light curves and spectra differ from nearby objects. Many SNe Ia have been classified and the light curves are being analyzed. The results very strongly favor a positive value for Ω_Λ (Riess et al. 1998).

Of fundamental importance are systematic effects which can alter the result. Several technical steps lead to the luminosity distances. Accurate photometry of faint sources on a spatially variable background, phase-dependent K-corrections, and light curve determinations have to be applied. All of these corrections have been tested thoroughly and independently in several applications (Schmidt et al. 1998, Riess et al. 1998).

Other uncertainties are introduced by the light curve shape correction, extinction, possible evolution between the distant and the nearby supernovae, sample selection, and (de-)magnification due to gravitational lensing. A careful analysis can test for all effects with the exception of gravitational lensing which is achromatic and static. The systematic influence of weak lensing, however, is expected to be very small (Wambsganss et al. 1997). Should the supernovae be lensed significantly the scatter in the Hubble diagram would be increased, which is not observed (Riess et al. 1998).

A luminosity shift between SNe Ia in early and late type galaxies has been observed (Hamuy et al. 1996b). This has been attributed to the different ages, masses, or metalicities of the progenitor population. The light curve corrections can successfully neutralize the offset and the luminosity difference between samples in elliptical and spiral galaxies can be reduced to 0.05 magnitudes (Schmidt et al. 1998). This is an indication of what has to be expected for a comparison between the nearby and the distant sample. A critical parameter appears to be the C/O composition of the progenitor white dwarf (Höflich et al. 1998). Extinction can be detected through the color of the supernovae. Very few distant objects appear reddened (Garnavich et al. 1998, Riess et al. 1998). There is a bias which favors discovery of unabsorbed objects due to the luminosity and also the selection of objects well separated from the host galaxy. The latter is not a true selection by the search, but rather is applied when decisions on the follow up observations are taken. Thus, the absorption in the distant sample is likely to be less on average than in the nearby sample. Another important issue is the concordance of the nearby and the distant sample. Any systematic shift between the two would result in a distortion of the derived cosmological parameters. An obvious systematic effect would be different average luminosities of the two samples. This can be tested by comparing the light curve shapes of the two samples. For our sample of 10 distant and 27 nearby supernovae the average Δ of the MLCS method (Riess et al. 1996) is -0.126 and -0.147 for the nearby and the distant sample, respectively. The systematic offset is thus 0.02 magnitudes, which is negligible. The same investigation for the analysis with Δm_{15} yields values which are slightly different. The mean Δm_{15} for the local sample is 1.223, while the distant sample has 1.173 on average. This difference translates into a zero-point offset of 0.04 (0.03) magnitudes for B (V) using the second order treatment proposed by Phillips et al. (1998). The weighted mean value becomes somewhat larger: 0.09 (0.08) magnitudes for B (V). The local sample is on average less luminous than the distant one. This is also exemplified by Fig. 10 in Riess et al. (1998). Figure 1 displays the magnitude difference of the observed supernovae from an Einstein-de Sitter Universe ($\Omega_M = 1, \Omega_\Lambda = 0$). Most objects clearly lie above the line for an empty universe (0,0) and thus indicate a contribution of the vacuum energy to the energy density of the universe.

The comparison of 14 distant z>0.16 supernovae has shown that they appear to be too dim for an empty universe. No solution for a positive matter density ($\Omega_M > 0$) is found if $\Lambda = 0$ at a $> 2.5\sigma$ significance (Riess et al. 1998). Due to the rather limited range of redshifts an exact value for Ω_M and Ω_Λ cannot

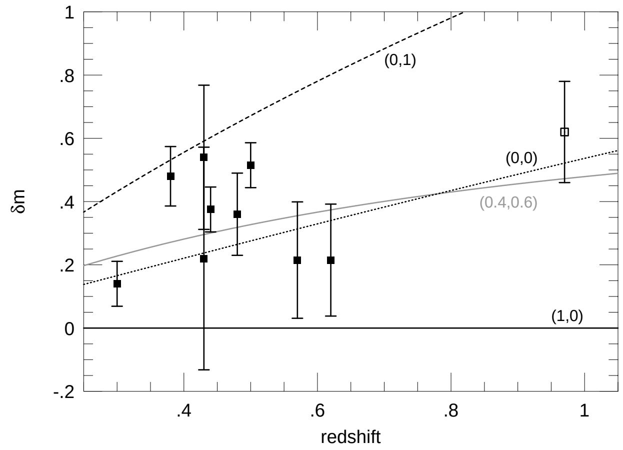

Fig. 1. Magnitude difference from an Einstein-de Sitter Universe ($\Omega_M = 1, \Omega_\Lambda = 0$). The empty case ($\Omega_M = 0, \Omega_\Lambda = 0$) and a mixed model with ($\Omega_M = 0.4, \Omega_\Lambda = 0.6$) are also indicated. The observed δm for the supernovae are based on B and V light curves. SN 1997ck is shown as an open symbol as no color information nor a spectrum for this supernova are available.

be derived yet without further constraints. This confirms the preliminary result presented by Garnavich et al. (1998) and is also in accordance with the one reported by Perlmutter et al. (1998).

5 Conclusions

The analysis of our distant set with two slightly different analysis methods resulted in a clear signature of a positive cosmological constant. A universe with negligible Λ is excluded at the 2.5 σ level, as no solution with a positive matter density is found. The effect is so strong that the value of the deceleration parameter q_0 is negative which indicates an accelerated expansion over the time span sampled by our observations (5 Gyr; Riess et al. 1998).

The dynamic age shows a dependency very similar to the uncertainty regions determined by the supernovae. It is thus possible to restrict the dynamic age of the universe quite accurately. Riess et al. (1998) find values in the range of 13 to 15 Gyr which is consistent with most age determination of the oldest stellar components.

Essential issues remain the systematic uncertainties of the experiment. Evolution, extinction and sample selection are the most important contributors. The only checks for evolution are extensive observations of distant objects to detect any differences with nearby supernovae. A spectroscopic sequence with good signal would allow us to investigate small differences in the ejecta. There are clear signatures in the R and I light curves of SNe Ia which can be observed for objects with $z < 0.4$.

References

Arnett, W. D., & Livne, E. 1994, ApJ, 427, 315

Branch, D., Livio, M., Yungelson, L. R., Boffi, F. R., & Baron, E. 1995, PASP, 107, 1019

Carroll, S. M., Press, W. H., & Turner, E. L. 1992, ARA&A, 30, 499

Contardo, G., Leibundgut, B., & Vacca, W. D. 1998, in preparation

Eastman, R. G. 1997, Thermonuclear Supernovae, eds. P. Ruiz-Lapuente, R. Canal, & J. Isern, Dordrecht: Kluwer, 571

Elias, J. H., Matthews, K., Neugebauer, G., & Persson, S. E. 1985, ApJ, 196, 379

Filippenko, A. V., et al. 1992a, ApJ, 384, L15

Filippenko, A. V., et al. 1992b, AJ, 104, 1534

Frogel, J. A., et al. 1987, ApJ, 315, L129

Garnavich, P., et al. 1998, ApJ, 493, L53

Goobar, A., & Perlmutter, S. 1995, ApJ, 450, 14

Höflich, P., & Khokhlov, A., 1996, ApJ, 457, 500

Höflich, P., Khokhlov, A., Wheeler, J. C., Phillips, M. M., Suntzeff, N. B., & Hamuy, M. 1996, ApJ, 472, L81

Höflich, P., Wheeler, J. C., & Thielemann, F.-K. 1998, ApJ, 495, 617

Hamuy, M., et al. 1996a, AJ, 112, 2398

Hamuy, M., et al. 1996b, AJ, 112, 2391

Kowal, C. T. 1968, AJ, 73, 1021

Leibundgut, B. 1998, Supernovae and Cosmology, eds. L. Labhardt, B. Binggeli, & R. Buser, Basel: University of Basel, in press (astro-ph/980169)

Leibundgut, B., & Pinto, P. A. 1992, ApJ, 401, 49

Leibundgut, B., et al. 1993, AJ, 105, 301

Leibundgut, B., et al. 1996, ApJ, 466, L21

Nomoto, K., Thielemann, F.-L., & Yokoi, K. 1984, ApJ, 286, 644

Nugent, P., Phillips, M. M., Baron, E., Branch, D., & Hauschildt, P. 1995, ApJ, 455, L147

Perlmutter, S., et al. 1995, ApJ, 440, L41

Perlmutter, S., et al. 1997, ApJ, 483, 565

Perlmutter, S., et al. 1998, Nature, 391, 51

Phillips, M. M., et al. 1987, PASP. 99, 592

Phillips, M. M., Wells, L. A., Suntzeff, N. B., Hamuy, M., Leibundgut, B., Kirshner, R. P., & Foltz, C. B. 1992, AJ, 103, 1632

Phillips, M. M., et al. 1998, in preparation

Reiss, D. J., Germany, L. M., Schmidt, B. P., & Stubbs, C. W. 1998, AJ, 115, 26

Riess, A. G., Press, W. M., & Kirshner, R. P. 1996, 473, 88

Riess, A. G., et al. 1998, AJ, submitted

Saha, A., Sandage, A., Labhardt, L., Tammann, G. A., Macchetto, F. D., & Panagia, N. 1997, ApJ, 486, 1

Schmidt, B. P., et al. 1998, ApJ, in press

Suntzeff, N. B. 1996, IAU Colloquium 145: Supernovae and Supernova Remnants, ed. R. McCray, (Cambridge: Cambridge University Press), 41

Tammann, G. A., & Leibundgut, B. 1990, A&A, 236, 9

Vacca, W. D., & Leibundgut, B., 1996, ApJ, 471, L37

Wambsganss, J., Cen, R., Xu, G., & Ostriker, J. P. 1997, ApJ, 475, L81

Woosley, S. E., & Weaver, T. A. 1986, ARA&A, 24, 205

Woosley, S. E., & Weaver, T. A. 1994, ApJ, 423, 371