Cosmic Deceleration measured with Type Ia Supernovae[a,b]

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With the observations of distant type Ia supernovae cosmological parameters can be measured with an unprecedented accuracy. It is found that the distant supernovae appear dimmer than expected in an empty universe indicating contributions by the vacuum energy density. Systematic errors are the largest uncertainties at the moment. Evolution, extinction, weak lensing, and sample discrepancies are the most important ones. All these systematics can in principle be tested observationally. The current data sample also indicates an age of the universe which is consistent with the oldest stellar components of the Galaxy.

1 Introduction

Type Ia Supernovae (SNe Ia) have proven to be excellent distance indicators when treated suitably[1,2]. They have several virtues that come with standard candles, even though they are not pure standard candles themselves. Combined with the high luminosity of the objects, which makes them detectable out to redshifts near 1, they can be used to measure cosmological distances and provide a determination of the deceleration of the universe[3,4]. The light curve shape corrections, however, are purely empirical and have changed considerably since their first application. Attempts to explain the empirical correlation between the peak luminosity and the decline rate of SNe Ia after maximum are still controversial.

With samples of nearby ($z < 0.1$) and distant ($z > 0.3$) supernovae we can measure the curvature of the universe and any possible contributions of a vacuum energy density based on luminosity distances. The deceleration can be determined by comparing the distant supernovae

[a] We report results by the High-z Supernovae Search Team. Members of the team are P. Challis, A. Clocchiatti, A. Diercks, A. Filippenko, P. Garnavich, R. Gilliland, C. Hogan, S. Jha, R. Kirshner, M. Phillips, D. Reiss, A. Riess, B. Schmidt, R. Schommer, C. Smith, C. Stubbs, N. Suntzeff, J. Tonry, and P. Woudt.

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with the local sample[4,5]. Two experiments are trying to make use of SNe Ia to achieve a determination of the deceleration[6,7,8,9,10,11]. We report here the recent results obtained by the High-z SN Search Team.

2 Type Ia supernovae as distance indicators

The light curves and spectral evolution show distinct variations among individual events. In particular the near-infrared light curves show a second maximum for many, but not all, SNe Ia[12]. The strength of the second maximum changes considerably and is also distinguishable in bolometric light curves[13].

A generally accepted theory of SN Ia explosions has not emerged yet. For more than a decade explosion models with a subsonic burning front have been favored[14,15], but the physics which sustains such a burning front without turning it into a detonation is not understood. New models which explode a white dwarf through He detonation at the surface[16,17], rather than the direct explosive carbon burning inside, cannot be distinguished by the current observations[18]. The exact trigger of the explosion and the reaction of the white dwarf is not constrained by observations and many models have been proposed. 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 provided by 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[13]. The bolometric light curves display the characteristic shoulder of the near-infrared light curves and the total energy changes from event to event.

Despite the lack of understanding of the explosion physics, observational trends have been found to account for the light curve and luminosity variations. The correlation between luminosity and light curve decline is well established[1,2]. The rest-frame colors are good indicators of reddening towards a supernova and extinction corrections can be applied. In this sense, SNe Ia appear to be an ordered set and can empirically be used as distance indicators.

3 Ω_M and Ω_Λ from SNe Ia

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 0.3 are very well suited for such an investigation.

Garnavich et al.[9] and Riess et al.[11] report the results from samples which include about 30 SNe Ia in the local sample and 10 objects at redshifts $z \geq 0.3$. With the exception of the most distant object, SN 1997ck at $z = 0.97$, all objects have been classified by a spectrum and detailed light curves in at least two filters are available, which allows us to apply the light curve corrections, either template fitting and the Δm_{15} analysis[1,19] or MLCS[2]. The color information is essential to obtain an estimate of the extinction towards the supernova. The local sample is used to determine the correlations between light curve shape and luminosity which are then applied to the distant supernovae.

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 independently in several applications[10,11].

Other uncertainties are introduced by the light curve shape correction, extinction, 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[20].

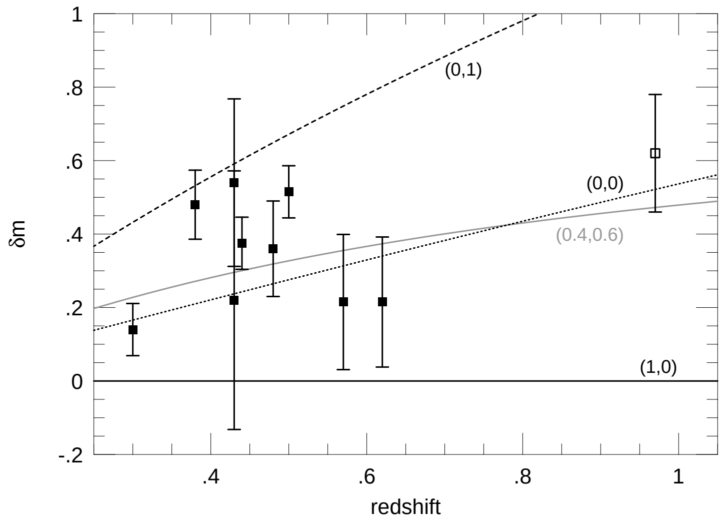

Figure 1: Magnitude difference from an Einstein-de Sitter Universe ($\Omega_M = 1, \Omega_\Lambda = 0$). The empty case ($\Omega_M = 0, \Omega_\Lambda = 0$) and a mixed model with ($\Omega_M = 0.4, \Omega_\Lambda = 0.6$) are also indicated. The observed δm for the supernovae are based on B and V light curves. SN 1997ck is shown as an open symbol.

A luminosity shift between SNe Ia in early and late type galaxies has been observed. 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[10]. 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[21]. Extinction can be detected through the color of the supernovae. Very few distant objects appear reddened[9,11]. 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.

Of paramount importance is the concordance of the nearby and the distant supernova sample. Any systematic shift between the two would result in a distortion of the derived cosmological parameters. Contamination by objects which are not SNe Ia has to be avoided. The spectroscopy and the light curves provide ample information to make such a distinction, but there is at least one case where a luminous SN Ic could not be excluded[11]. No classification of SN 1997ck, with no observed supernova spectrum and only one filter light curve, is available. The light curve is, however, consistent with a SN Ia at the observed galaxy redshift[9,5]. An obvious systematic effect would be different average luminosities of the two samples. To first order, this can be tested by comparing the light curve shapes. For our sample of 10 distant and 27 nearby supernovae the average Δ of the MLCS method 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 weighted mean Δm_{15} for the local sample is 1.296, while the distant sample has 1.184 on average. This difference translates into a zero-point offset of 0.09 magnitudes using the second order treatment proposed by Phillips et al.[19] The local sample is on average less luminous than the distant one.

Figure 1 displays the magnitude difference of the observed supernovae from an Einstein-de Sitter Universe ($\Omega_M = 1, \Omega_\Lambda = 0$). Many objects 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 10 distant supernovae appear to be too dim even for an empty universe. The magnitude offset is 0.11 ± 0.03 magnitudes. However, the RMS of the distribution is 0.19 magnitudes. Excluding SN 1997ck does not change the values.

An analysis based on probability density functions finds that no solution for a positive matter density ($\Omega_M > 0$) exists, if $\Lambda = 0$ at a $> 2.5\sigma$ significance from both methods[11]. This confirms the preliminary result presented by Garnavich et al.[9] and is also in accordance with the one reported by Perlmutter et al.[7] Due to the rather limited range of redshifts an exact value for Ω_M and Ω_Λ cannot be derived yet without further constraints.

4 Conclusions

The analysis of our distant set with two slightly different methods resulted in a signature of a positive cosmological constant barring undetected systematic errors. A universe with negligible Λ is (statistically) 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[11] which indicates an accelerated expansion over the time span sampled by our observations (5 Gyr).

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.[11] 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. The magnitude offset from an empty universe model is very small ($\sim$0.1 mag) and even small systematic effect are important. 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 $z < 0.4$.

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