Chapter 1

# COSMOLOGY WITH SUPERNOVAE

Bruno Leibundgut[1]

[1] *European Southern Observatory*
*Karl-Schwarzschild-Strasse 2, D-85748 Garching*
*Germany*
bleibundgut@eso.org

**Abstract** Modern cosmology is using many different methods to determine the structure of the universe. Supernovae are among the most important ones due to their extreme luminosity, the time-variability that allows to separate the different supernova explosions and relative ease with which they can be observed.

Since the recognition of supernovae as a separate class of astrophysical objects they have been proposed and used to measure the distance scale and the geometry of the universe.

There are several independent applications with supernovae to measure the current expansion rate, Hubble's constant, and the expansion history of the universe. The latter has led to the surprising discovery that the expansion is actually accelerating and a new component for the universe is needed. Supernovae are also poised to be a major player in the characterisation of the nature of the dark energy.

**Keywords:** Cosmology - supernovae - distance scale

## 1. Introduction

Cosmology with supernovae has developed over the second half of the last century. Their extreme luminosities always made them attractive candidates to measure large distances. Various methods were devised to use supernovae to measure cosmological parameters ranging from simple standard candle paradigms to physical explanations of the supernova explosions and subsequent derivation of distances. Essentially, supernovae have been used to determine luminosity distances, i.e. the comparison of the observed flux to the total emitted radiation. The trick is to find a reliable way to measure the absolute luminosity of the objects.

There are two major cosmological parameters that can be determined through supernova observations. They are the classical parameters, which govern the expansion of the universe in Friedmann-Robertson-Walker models: the Hubble constant, $H_0$, and the deceleration parameter, $q_0$. The former sets the scale of the universe and the magnitude of the current expansion of space and the latter describes the change of the expansion with time (e.g. [53, 54, 63, 41, 40]). There is a rich literature on the Hubble constant and Type Ia supernovae (SNe Ia) (see [4, 5, 31] for reviews). The deceleration parameter has been replaced by more modern formulations specifically including the cosmological constant or some variants thereof [7].

## 2. The Hubble constant

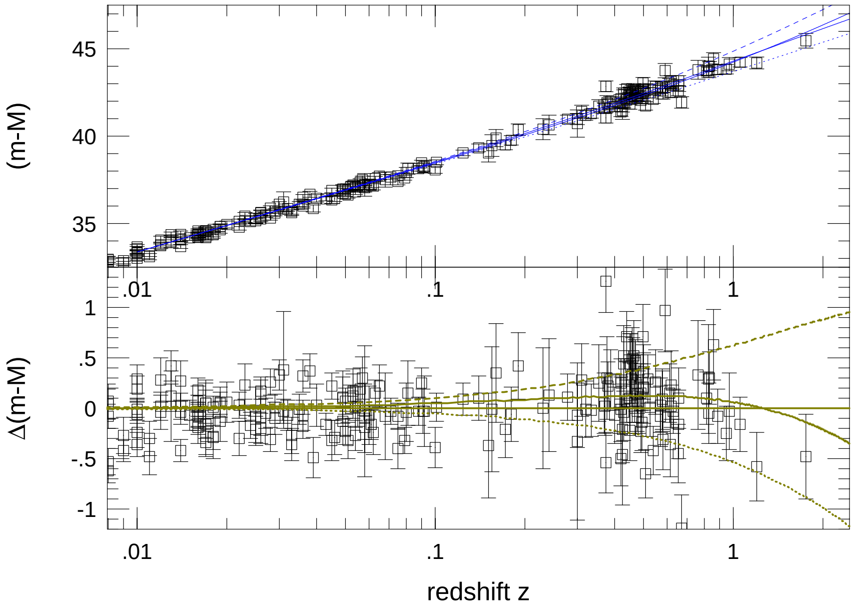
### Type Ia supernovae

The best way to show that objects provide good luminosity distances is to plot them in a Hubble diagram. Originally, this diagram was using recession velocity *vs.* apparent magnitude [24, 53]. The underlying assumptions are that the Hubble law holds and that the objects are all of the same luminosity, i.e. standard candles, so that the apparent brightness directly reflects distance.

Since no astronomical standard candle is known – all proposed objects have been shown to be essentially non-uniform in one way or another – we nowadays have to calculate and plot the distance modulus for the objects. The scatter around the linear expansion line is less than 0.2 magnitudes or 20% [61]. Independent of our ignorance of the exact explosion mechanism or the radiation transport in the explosions this proves that SNe Ia can reliably be used as a distance indicator in the local universe. This situation is very much comparable to the Cepheid stars, where the period-luminosity relation is based on empirical data of objects in the Magellanic Clouds.

The simplest method is to assume that all supernovae are identical. This is, of course, not true (see previous paper) but it turns out that the subclass of the Type Ia supernovae is indeed rather homogeneous. The first to plot a Hubble diagram of Type Ia Supernovae was Kowal [26]. There are essentially three quantities that can be derived from such a Hubble diagram in the nearby universe: the slope of the expansion line, the scatter around the expansion line and the value of the local Hubble constant from the intercept at zero redshift (e.g. [60, 33]). The slope gives an indication of the local expansion and for a linear expansion in an

*Figure 1.1.* Hubble diagram of nearby Type Ia supernovae. The distances are derived from light curve shape corrected luminosities (data from [61]). The solid line is for an empty universe ($\Omega_\Lambda = \Omega_M = 0$), the dotted line for an Einstein-de Sitter model ($\Omega_\Lambda = 0, \Omega_M = 1$) and the dashed line for a model with no matter and all cosmological constant ($\Omega_\Lambda = 1, \Omega_M = 0$). The concordance model ($\Omega_\Lambda = 0.7, \Omega_M = 0.3$) is shown as the line fitting the data best. The bottom panel shows all distances relative to the empty universe model.




isotropic universe it has a fixed value. The scatter around the expansion line provides a measure of the accuracy of the standard candle and the measurement errors. The intercept of the line, finally, together with an estimate of the absolute luminosity gives the Hubble constant. It has become clear that SNe Ia in the optical are not standard candles and have their luminosity normalised to be used as distance indicators [45, 22, 48, 49, 43, 46, 17]. A systematic comparison of these different methods has been done [12, 30] and it has been shown that they are not internally consistent. The reason for this technical problem is still not clear and needs to be investigated. More accurate light curve data are becoming available (e.g. [27, 37, 38, 28, 6, 3]) and it should be possible to further investigate the correlations between light curve shape, colour and luminosity of SNe Ia. For these reasons modern Hubble diagrams show the distance modulus ($m$-$M$) rather than the directly observed apparent magnitude $m$. The latest version with over 200 SNe Ia has been assembled by Tonry ([61] see also [2, 51]) and is shown in Figure 1.1. It should be noted that SNe Ia may be standard candles in the nearinfrared [29]. The first significant IR sample shows very small scatter without prior correction for light curves shape. For the derivation of the Hubble constant the (normalised) luminosity of the SNe Ia has to be known. The most direct way to achieve this is through the distance ladder and in particular the calibration of nearby SNe Ia by Cepheids (for the most recent results see [52, 16]). The main discrepancy for the published values of the Hubble constant from SNe Ia is coming from the different interpretations of the Cepheids and application of the light curve shape correction.

### Core-collapse supernovae

The brilliance of core-collapse supernovae has enticed people to investigate their capabilities as distance indicators as well. Following early work by Baade [1], originally done for Cepheid stars, the expanding photosphere method (EPM, [13]) has been applied to several supernovae. The most comprehensive data sample has been assembled by Hamuy [18]. A critical test has become the distance to SN 1999em, which was determined through EPM [35, 20, 14] and which also has a Cepheid distance available [36]. The discrepancy is most likely attributable to the fact that the correction factor for the dilution of the black body flux in EPM are strongly model dependent and need to be calculated for each supernova individually.

Recently, Mario Hamuy has realised that the expansion velocity and the luminosity during the plateau phase correlate and that Type II SNe may be quite good distance indicators [21]. The distance accuracy achieved this way can be better than 20%. These determinations are based on the physical understanding of the plateau phase of SNe II and are linked to physics of the supernova atmosphere. This means that they are independent of the *distance ladder*, which is needed, e.g., for the SNe Ia. Typical values for the Hubble constant from SNe II are in the range of 65 to 75 km $s^{-1}$ $Mpc^{-1}$ [19].

## 3. The expansion history of the universe

The recent paradigm changes in the cosmological model are based on several new insights. The flatness of space-time as measured by the cosmic microwave background (CMB) fluctuations and the recognition, that the global matter density is near 30% of the critical density, require an additional component in the energy content of the universe. At the same time the observation that the luminosity distances derived from Type Ia supernovae are larger than the expectation in any non-accelerated universe model have conspired to change our view of the history of the cosmic expansion. The three measurements are complementary to each other and the combination of any two of them provides independent evidence for an additional component in the Friedman equation. However, only the supernova measurement gives a direct indication that we need a repulsive component in the universe. It will also be the supernovae that will provide a first indication to the nature of the dark energy.

There are several fundamental tests that will need to be performed until we can be sure that the current paradigm will persist. It is very appealing to think we know all constituents of the universe by now, but further surprises may still be in store for us. The testing has to concentrate on the reliability of the individual measurements. The Type Ia supernovae have been criticised for the fact that they are based on a rather simple assumption, namely that the distances derived from them are accurate. Many publications oversimplify this picture by calling Type Ia supernovae standard candles. This is not only incorrect, also it is misleading and belittles the result. The tests done on supernovae are solid and the theoretical work is progressing steadily.

Since SNe Ia are not standard candles, it is not admissible to simply assume a constant luminosity. Instead, one has to adopt that the luminosity normalisation of the distant objects follows what has been found in the nearby sample. Although the High-z Supernova Search Team (HZT; [55, 49, 61, 2]) and the Supernova Cosmology Project (SCP; [44, 25]) make this assumption in different forms, it is essentially identical. The SCP derives the corrections from all supernovae in their sample, i.e. nearby and distant ones, while the HZT derives the correlations from the (large) nearby sample and applies it to the distant objects (cf. [32]). It is also interesting to note that the SCP claims that both light curve shape correction and correction for host galaxy reddening affect their result rather little [44, 25]. On the other hand, the normalisation and absorption correction done by the HZT (in three different implementations) are important for the cosmological result. This discrepancy between the two teams will need to be resolved at some point.

## 4. Universal acceleration according to Type Ia supernovae

We will describe here the current status of the supernova research and outline ongoing projects to distinguish between a cosmological constant or a vacuum density contribution to the energy-momentum tensor in the Einstein equation.

Type Ia supernovae measure luminosity distances to objects out to about a redshift of 1. These distances are the most accurate currently available to astronomers for cosmological purposes, i.e. beyond the Coma cluster distance. Since the luminosity distances depend on the evolution of the Hubble parameter and this in turn depends on the energy content of the universe through the Einstein equation (e.g. [7]) one can derive the energy sources dominating over the lookback time covered by the observations (see [47, 31, 42] for a detailed review). Once the luminosity distances are derived from the supernova data a likelihood calculation provides the most statistically suitable values for the complete supernova data under certain assumptions, like the neglect of dust and evolution. It is pointless to divide the supernova data into subsamples that do not cover the complete redshift range as the effect is not detectable on smaller scales. Figure 1.1 shows that the current data by far do not warrant such a treatment (as proposed by [39, 8, 62]).

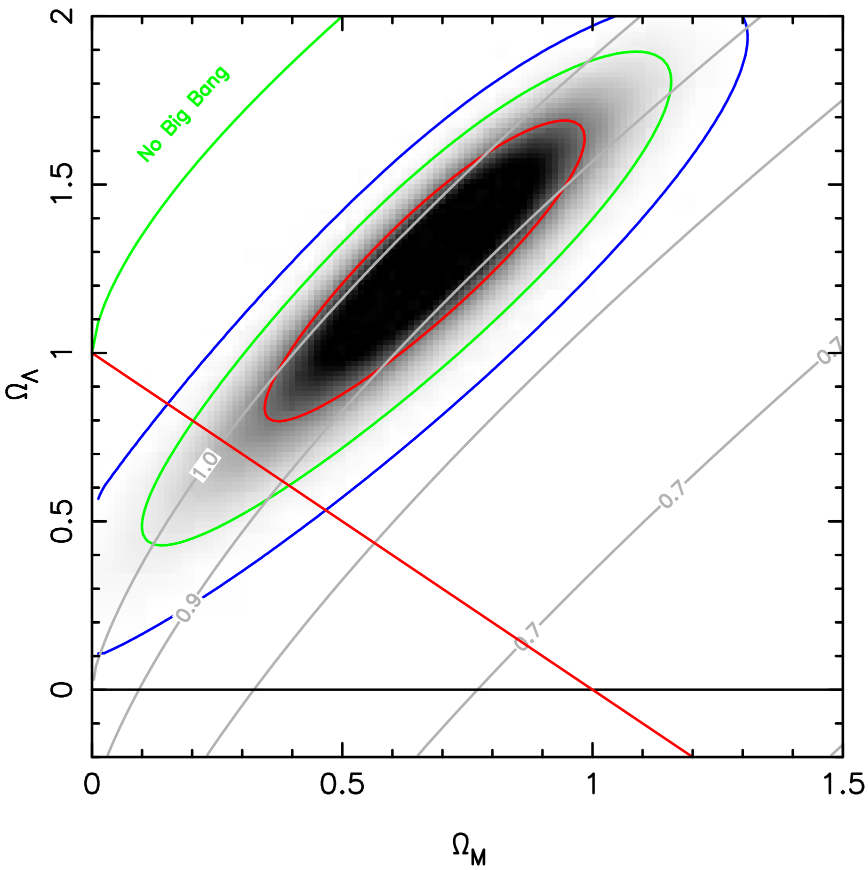
The largest available data set is provided by Barris et al. [2], which includes a significant set of supernovae at redshifts near 1. This data set confirms the earlier results of the HZT (cf. Fig. 1.2) and is consistent with the most recent result of the SCP [25]. All astrophysical effects, like dust or evolution of the supernovae, have been ignored in this derivation. The HZT applies a correction for dust in the Milky Way and the host galaxy of the supernova directly. Only if dust at high redshift is systematically different from the one in our galaxy, is this correction biased. Recent detection of $850\mu$m emission from host galaxies at $z \approx 0.5$ shows that dust is present in some of these galaxies [15], although the amount may be negligible for the supernova cosmology. These results are in contrast with the claim by Sullivan et al. [59] that the reddening of distant supernovae in spiral galaxies is very small, when these objects are compared to the SN data from dust-free elliptical galaxies. The reddening derived by Tonry et al. [61] for distant SNe Ia is typically smaller than the one found for nearby objects. This is not surprising considering that the distant searches are mostly flux limited and will not find many heavily extincted objects, while the nearby supernovae are drawn from a large heterogeneous sample, which in several cases includes highly reddened objects. There might be secondary selection effects at work as well, like the fact that the distant supernovae often have larger projected distances from their hosts than nearby ones. A last indication that dust is not a severe problem is the fact that among the first distant SNe Ia of the HZT were very blue [31] objects. In fact, six out of nine objects were bluer than their nearby counterparts. Although this has now been claimed to possibly be a selection effect [25], it is not clear whether this indeed is the case, as the effect should be redshift dependent, which it seems not to be, judging from the small sample in [31]. The recent publication by the SCP [25] does not find the same effect for the objects which have multi-wavelength light curves. Further analysis of the K-corrections and the dust properties is clearly required.

Evolution is another potential effect, which could mimic a cosmological signal. This is much harder to control. For reasonable predictions of how progenitor metalicity or age could affect the brightness of SNe Ia one needs a detailed model of the explosion and the radiation escape from the explosion [23]. Both are unsolved problems. A detailed study of the properties of the SN host galaxies has not shown any correlation with supernovae distances or properties [64]. Progress can only be made through detailed observations of bright, nearby SNe Ia at all phases. Recent data sets are very encouraging [27, 28, 3] (for a review see [32]). In addition to the detailed spectral, light and colour curve data one can use bolometric light curves to derive the total emitted radiation from the explosion [10, 11]. The latter provides important information on the physical parameters that govern the explosion, like mass of synthesised nickel and the $\gamma-$ray escape fraction at late times.

With no clear indication of evolution, the simplest assumption is to disregard any evolutionary effects; a very dangerous approach, if it goes unchecked. This is the reason that the HZT has spectroscopically confirmed its distant SNe Ia. The spectra have been published together against the light curve data [49, 61, 2] and separately for a few objects [9, 34]. While the signal for some of the distant supernovae is not very good, and in a few early cases the SN classification may even be doubtful, there are no obvious strong deviations from the spectral appearance of the nearby supernovae. In some cases, the supernova spectra can be used to determine the phase of the distant SNe Ia and to check it with the light curves directly. This provides an independent consistency argument that the distant supernovae behave rather similar to their nearby counterparts. This means that the distant supernovae cannot be very different from the nearby ones. Yet, the colour of the distant objects appears to be systematically bluer. This could be the signature of evolution and will need to be worked out in more detail.

Luminosity distances over a limited redshift range result in degenerate likelihood distributions in the $\Omega_\Lambda vs.\Omega_M$ plane along a line corresponding roughly to $\Omega_\Lambda - 1.4\Omega_M = 0.35 \pm 0.14$ [44, 61] (cf. Fig. 1.2). These leads to an increased uncertainty along this direction. It should be noted that the most recent determinations of the cosmological parameters by the HZT favour values that are rather different from a flat universe solution [61, 2]. If the universe indeed has a flat geometry, as suggested by the CMB data (e.g. [57]) then this would be an indication of some unresolved systematic effect. The SCP has not observed a similar trend [25], but the

*Figure 1.2.* Likelihood distribution for $\Omega_\Lambda$ *vs.* $\Omega_M$. The input data are from [61]. This diagram should be compared to similar ones in [49, 44, 47, 31, 42, 2, 25]. The degeneracy along $0.8\Omega_\Lambda - 0.6\Omega_M$ is obvious. The overlap with the flat universe model is not within the 68% likelihood area here. The grey contour lines show the dynamical age of the universe $H_0 \cdot t_0$. Clearly the SN data favour an age near 1.




redshift range of their published data does not extend beyond $z \approx 0.8$ so far.

## 5. Characterising dark energy

It has been generally accepted that a large fraction of the energy content of the universe is in a form very similar to the vacuum energy or a cosmological constant. Competing theories have been developed to explain the low, but non-zero, value of this energy form. An often used description is the equation of state parameter ($w = \frac{p}{\rho c^2}$), which in the case of dark energy has to be negative, i.e. contain negative pressure $p$, as the energy density $\rho$ has to be positive ($c$ stands for the speed of light). With $w < -\frac{1}{3}$ the universe is actually accelerating. For field theories $w$ is most likely variable with time and different from the value for a cosmological constant ($w = -1$). The transition from a matter dominated universe ($\Omega_M > \Omega_\Lambda$) happened sometime during the second half the history of the universe, $0.4 < z < 0.8$. It should hence be possible to determine this transition and then map the change as a function of redshift in the interval $0.2 < z < 0.8$. With a well-calibrated and controlled data set of SNe Ia in this redshift interval it should be possible to accurately map the transition and determine the strength of the dark energy and the (integrated) value of $w$. Several projects have embarked on such a project. The HZT has started the ESSENCE project with the search and photometry carried out with the CTIO Blanco 4m-telescope with the supporting spectroscopy from VLT, Gemini, Keck, Magellan and MMT. The goal is to have 200 spectroscopically confirmed SNe Ia with densely sampled light curves in at least two filters evenly distributed in redshift with $z < 0.8$ [56]. The CFHT Legacy Survey is aiming for about 900 SNe Ia out to a slightly larger redshift with spectroscopy from VLT, Keck, Gemini and Magellan. In the future the SNAP satellite, in the meantime renamed to Joint Dark Energy Mission (JDEM), should observe about 2000 SNe Ia out to $z < 1.7$.

The supernovae cannot do this alone. They will require an accurate determination of the matter density $\Omega_M$ from a different source. The required accuracy of this parameter should be a few percent (cf. [61]).

In the meantime a survey for supernovae has been done within the GOODS collaboration. The goal was to find and follow supernovae at redshift larger than 1.2, which was achieved for about one third of the sample [50]. Spectroscopic confirmation of 18 supernovae (nine with $z > 1$) is available [58, 51]. Some of the distant objects could not be classified with a spectrum and rely on a spectroscopic redshift from the host galaxies only. These data constrain $\Omega_M$ more accurately than was possible so far, as the supernovae are in the deceleration portion of the Hubble diagram. They also show that evolutionary effects are not likely to explain the faintness of SNe Ia near z=0.5 and the change to more luminous objects at redshifts beyond z=1.

## 6. Conclusions

Supernovae at cosmological distances have provided some of the most accurate determinations of the Hubble constant. It is by now clear that the largest (systematic) uncertainties stem from the calibration of the local distance indicators, like the Cepheids. An intriguing result concerning the expansion history of the universe and its energy contents has emerged from the observations of very distant SNe Ia. The evidence for a cosmological constant or an energy field acting very similarly is strong and generally accepted. The future supernova observations have to concentrate on two aspects. One is to determine the (integrated) equation of state parameter for the dark energy to possibly distinguish between a pure cosmological constant and a scalar particle field. Secondly to control any evolution of the supernovae, which potentially could affect the cosmological result, it is mandatory to constrain the models with exquisite data from nearby supernovae. These projects are under way and we can expect to make significant progress in both directions very soon.

## References


[1] Baade, W. 1926, AN, 228, 359

[2] Barris, B., et al., 2004, ApJ, 602, 571

[3] Benetti, S., et al., 2004, MNRAS, 348, 261

[4] Branch, D., Tammann, G.A., 1992, ARA&A, 30, 359

[5] Branch, D., 1998, ARA&A, 36, 17

[6] Candia, P., et al. 2003, PASP, 115, 277

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

[8] Choudhury, T. R., Padmanabhan, T., 2004, MNRAS, in press (astro-ph/0311622)

[9] Coil, A.L., et al., 2000, ApJ, 544, L111

[10] Contardo, G., Leibundgut, B., Vacca, W. D., 2000, A&A, 359, 876

[11] Contardo, G., PhD Thesis, Technical University Munich

[12] Drell, P.S., Loredo, T.J., Wasserman, I., 2000, ApJ, 530, 593

[13] Eastman, R. G., Schmidt, B. P., Kirshner, R. P. 1996, ApJ. 466, 911

[14] Elmhamdi, A., et al. 2003, MNRAS, 338, 939

[15] Farrah, D, Meikle, W. P. S., Clemens, D., Rowan-Robinson, M., Mattila, S., 2002, MNRAS, 336, L17

[16] Freedman, W.L., et al., 2001, ApJ, 553, 47

[17] Goldhaber, G., et al., 2001, ApJ, 558, 359

[18] Hamuy, M. 2001, PhD Thesis, Tucson: University of Arizona

[19] Hamuy, M. 2003, ApJ, 582, 905

[20] Hamuy, M., et al. 2002, AJ, 124, 417

[21] Hamuy, M., Pinto, P. A. 2002, ApJ, 566, L63

[22] Hamuy, M., et al. 1996, AJ, 112, 2438

[23] Hillebrandt, W., Niemeyer, J. C., ARA&A, 38, 191

[24] Hubble, E., The Realm of the Nebulae, 1936, (New Haven: Yale University Press)

[25] Knop, R., et al., 2004, ApJ, 598, 102

[26] Kowal, C. T. 1968, AJ, 73, 1021

[27] Krisciunas, K., et al., 2001, AJ, 122, 1616

[28] Krisciunas, K., et al., 2003, AJ, 125, 166

[29] Krisciunas, K., Phillips, M.M., Suntzeff, N.B., 2004, ApJ, 602, L81

[30] Leibundgut, B., 2000, A&AR, 10, 179

[31] Leibundgut, B., 2001, ARA&A, 39, 67

[32] Leibundgut, B., Suntzeff, N. B., in *Supernovae and Gamma–Ray Bursts*, ed. K. Weiler, (Heidelberg: Springer), 77

[33] Leibundgut, B., Pinto, P.A., 1992, ApJ, 401, 49

[34] Leibundgut, B., Sollerman, J., 2001, Europhysics News, 32, 4

[35] Leonard, D. C., et al. 2001, PASP, 114, 35

[36] Leonard, D. C., et al. 2003, ApJ, 594, 247

[37] Li, W., et al., 2001, PASP, 113, 1178

[38] Li, W., et al., 2003, PASP, 115, 453

[39] Padmanabhan, T., Choudhury, T. R., 2003, MNRAS, 344, 823

[40] Peacock, J.A., 1999, *Cosmological Physics*, Cambridge: Cambridge University Press

[41] Peebles, P.J.E., 1993, *Principles of Physical Cosmology*, Princeton: Princeton University Press

[42] Perlmutter, S., Schmidt, B. P., in *Supernovae and Gamma-Ray Bursts*, ed. K. Weiler, (Heidelberg: Springer), 195

[43] Perlmutter, S., et al., 1997, ApJ, 483, 565

[44] Perlmutter, S., et al., 1999, ApJ, 517, 565

[45] Phillips, M. M., 1993, ApJ, 413, L105

[46] Phillips, M.M., Lira, P., Suntzeff, N.B., Schommer, R.A., Hamuy, M., Maza, J., 1999, AJ, 118, 1766

[47] Riess, A. G., 2000, PASP, 112, 1284

[48] Riess, A. G., Press, W. M., & Kirshner, R. P., 1996, ApJ, 473, 88

[49] Riess, A. G., et al., 1998, AJ, 116, 1009

[50] Riess, A. G., et al., 2004, ApJ, 600, L163

[51] Riess, A. G., et al., 2004, ApJ, in press (astro-ph/0402512)

[52] Saha, A, Sandage, A., Tammann, G.A., Labhardt, L., Macchetto, F.D., Panagia, N., 1999, ApJ, 522, 802

[53] Sandage, A., 1961, ApJ, 133, 355

[54] Sandage, A., 1988, ARA&A, 26, 561

[55] Schmidt, B.P., et al., 1998, ApJ, 507, 46

[56] Smith, R. C., et al. 2002, BAAS, 78.08

[57] Spergel, D. N., et al., 2003, ApJS, 148, 175

[58] Strolger, L., et al., AJ, submitted

[59] Sullivan, M., et al., 2003, MNRAS, 340, 1057

[60] Tammann, A.G, Leibundgut, B., 1990, A&A, 236, 9

[61] Tonry, J. L., et al., 2003, ApJ, 594, 1

[62] Wang, Y., Mukherjee, P., 2004, ApJ, submitted (astro-ph/0312192)

[63] Weinberg, S., 1972. *Gravitation and cosmology: principles and applications of the general theory of relativity*, New York: Wiley

[64] Williams, B. F., et al., 2003, AJ, 126, 2608