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Can Λ be determined from nearby Type Ia Supernovae?

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Abstract. Type Ia Supernovae (SNe Ia) are the best standard candles known today. At high redshift ($z \sim 1$) SNe Ia are used to determine the Cosmological Constant Λ with great success. However the most serious concern is raised by the possible luminosity evolution of the SNe Ia explosion itself, i.e., that their intrinsic luminosity might vary with the look-back time. It is unknown to which extent high-redshift SNe Ia can directly be compared to near SNe Ia in order to determine Λ. A possibility to circumvent this problem is to restrict the analysis to nearby SNe Ia situated preferably in E/S0 galaxies. Since the signal will be much smaller, we have to consider an substantial sample. As there are not enough data yet available, we conducted our analysis based on 200 synthetic SNe Ia with a luminosity scatter $\sigma_{\rm m} = 0.^{\rm m}12$ (derived from observations) assuming a homogeneous space distribution and a limiting distance of $z \leq 0.16$. We show that this kind of data, which we expect from future observations, will allow us to distinguish between a matter dominated or Λ-dominated ($\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$) universe with a significance of up to 2-3 σ.

Key words. Supernovae: general – Cosmology: cosmological parameters

1. Introduction

The original hope of using HST to determine the Cosmological Constant Λ and the matter density parameter $\Omega_{\rm M}$ from high-redshift standard candles, as exemplified by SNe Ia (Tammann 1979), was substantiated by two brilliant experiments of independent groups using SNe Ia with redshifts of up to $z \sim 0.8$ (Riess et al. 1998; Perlmutter et al. 1999). The significant conclusion from these was that Λ is positive for any value of $\Omega_{\rm M}$. Various effects have been discussed which could alter this result, e.g., ad hoc postulated gray absorption or strong and weak gravitational (anti-) lensing (Valageas 2000). Yet the most severe question is raised by the possibility of luminosity evolution of SNe Ia, i.e., that their intrinsic luminosity at maximum vary with the look-back time.

The determination of Λ from nearby SNe Ia (see also Germany et al. 2004), say at $z \leq 0.16$, is therefore an intriguing possibility. In the Hubble diagram the $\Omega_{\rm M} = 1$ model is separated from an $\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$ model by $0.^{\rm m}53$ at $z = 0.8$, but only by $0.^{\rm m}15$ at $z = 0.16$. In the latter case the advantage is that the look-back time is reduced by roughly a factor of 3 to 2.3 Gyr. The decisive question for the present experiment is therefore whether luminosity evolution can be excluded or at least be controlled over such relatively short look-back times?

2. SNe Ia Model Considerations

Delayed detonation models (Höflich et al. 2000) predict that m evolution may arise from (1) lower metallicities Z, (2) higher main-sequence masses $\mathfrak{M}_{\rm MS}$, and from (3) different accretion rates at high redshifts.

(1) The dominant effect of decreasing the metallicity Z is a decrease of the C/O ratio in an exploding WD with roughly solar abundance (cf. Domínguez et al. 2002). A reduction of the C/O ratio reduces the energetics of the explosion. For models with similar Ni production, this leaves $M_{\rm V_{max}}$ virtually unchanged, but increases the rise and decline times. Every 1-day increase of the time scales causes an off-set in Δm_{15}[1] of about $-0.^{\rm m}1$. Therefore, if all apparent magnitudes of the SNe Ia are reduced to a common value of Δm_{15}, a SNe Ia with low C/O ratio will incorrectly be made fainter (see Reindl et al. 2005, eq. 23; the Z-dependent Δm_{15} corrections is only indicated if the explosion kinematics remain unchanged), but at the same time its line blanketing will make it bluer, causing an overestimate of the absorption, and hence it will be made brighter. Thus the two effects cancel in first approximation.

This conclusion is empirically confirmed by Ivanov et al. (2000) who showed for 56 nearby SNe Ia that their luminosities corrected for $\Delta \rm m_{15}$ and absorption do not significantly correlate with the distance from the center of their host galaxies, whereby this distance is a good metallicity indicator. A de-

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[1] The decline rate Δm_{15} is the change in magnitude during the first 15 days after B maximum.

crease of the metallicity decreases also the U and UV flux by $0.^{m}2$ up to $0.^{m}5$ (Höflich et al. 2003).

(2) An increase of the main-sequence mass $\mathfrak{M}_{MS}$ will have the same effect on the O/C ratio as a decrease of Z, but at the same time it will cause lower expansion velocities, as can be measured, for instance, in the Si lines. A decrease of the expansion velocity by 2000 km s^{-1} will decrease the maximum luminosity by $\sim 0.^{m}1$, while the tail luminosity remains unchanged (Domínguez et al. 2001; Höflich et al. 2003). The distribution of $\mathfrak{M}_{MS}$ may vary even in nearby galaxies depending on the epoch of star formation. This effect, however, can be minimized by using only SNe Ia in E/S0 galaxies (see below), whose main star formation lies generally in the distant past.

(3) As a separate effect, the typical accretion rate may change with the epoch and, consequently, the central density at the time of explosion. The final kinetic energy of the envelope will change because the potential energy of the WD is increasing with the central density. $M_{V_{max}}$ will remain unchanged for the same amount of ^{56}Ni produced, but the light curve steepens during the rise and decline phase similar as under (1) with the corresponding effect on Δm_{15}.

Some SNe Ia may be the product of merges, and their contribution may change with redshift. However, this does not pose a problem because spectroscopic peculiarities are expected in this case (Höflich & Khokhlov 1996). Also unusual SNe Ia like 1986 G, 1991 T, 1991 gb, and 1999 aa can be easily weeded out by their (near-maximum) spectra.

Recent comparisons of the spectra of nearby SNe Ia and those with redshifts of up to $z = 0.8$ do not show systematic differences (Matheson et al. 2005; Hook et al. 2005), but it is uncertain whether the expected differences would show up in these first-level comparisons. Changes of the initial metallicity lead also to different yields of some trace elements. For instance ^{54}Fe is depressed by $\sim 10\%$ in case of low-metallicity progenitors (Höflich et al. 1998; Höflich et al. 2000). Bongard et al. (2005) have recently defined intensity ratios of certain spectral features which correlate directly with the (relative) luminosity of a SN Ia. Si-related features seem particularly successful giving a scatter of only $\sim 0.^{m}07$.

As stated above, the decisive point for the proposed experiment is that the mean luminosity of SNe Ia does not change systematically between $z = 0$ and $z = 0.16$. The above discussion of the known reasons, which may cause a luminosity variation, has shown that they cause simultaneously variations of the light curve parameters and spectra of SNe Ia. If the SNe Ia used for the experiment, or a statistically significant subset, show no such z-dependent variation of their light curve parameters and spectra it may safely be assumed that also their mean luminosity is constant over the z-interval considered, or at least that any luminosity variation is small in comparison to the signal of $0.^{m}15$ which we are seeking.

3. The Experiment

The possibility to detect a signal of Λ from nearby ($z \leq 0.16$) SNe Ia is investigated. The available high-quality SNe Ia with $z \leq 0.12$ are used as a Training Set in Sect. 3.1. Then, on the assumption that an equivalent sample of 200 SNe Ia with $z \leq 0.16$ will become available, the resulting confidence range of Λ is predicted in Sect. 3.2; an optimization is discussed in Sect. 3.3. The feasibility of the experiment is discussed in Sect. 4. The conclusions are given in Sect. 5.

3.1. The Training Set

A complete sample of 35 blue SNe Ia with $1200 \leq z \leq 30\,000$ km s^{-1} and $(B - V) < 0.20$ (after correction for galactic absorption) has been compiled by Parodi et al. (2000). Two SNe Ia with non-normal spectra and seven SNe Ia which appeared in the inner parts of their spiral parent galaxies and which show signs of internal absorption are omitted here. If, in addition, the nine SNe Ia are excluded which have large galactic absorption corrections ($A_V < 0.20$) according to Schlegel et al. (1998) the remaining 26 SNe Ia define, on the assumption of $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, a Hubble diagram with a scatter of only $\sigma_m = 0.^{m}12$ in B,V and I after they are homogenized as to decline rate Δm_{15} and intrinsic color (Parodi et al. 2000).

If instead the 26 SNe Ia are fitted to a Hubble line corresponding to $\Omega_M = 1$, $\Omega_\Lambda = 0$ the scatter increases marginally to $\sigma_m = 0.^{m}13$. This suggests that the SNe Ia contain at least some information favoring a positive value of Ω_Λ. A χ^2-test excludes the assumption that the $\Omega_M = 1$ universe is an equally good fit to the data as the $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ universe at the 57% level. The result is unsatisfactory, but implies that a lager sample of SNe Ia must give a better result. The proviso is of course that the luminosity dispersion of homogenized normal SNe Ia is purely statistical.

3.2. Monte Carlo Calculation

A random sample of 200 SNe Ia is created with constant density in redshift space adopting a universe with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ (Carroll et al. 1992). The upper limit of their redshifts is taken to be $z = 0.16$. Their individual redshifts are used to calculate their (relative) apparent magnitudes under the assumption of a constant absolute magnitude M_{max}[2]. The resulting values of m were then degraded by a random luminosity scatter of $\sigma_m = 0.^{m}12$ as observed by Parodi et al. (2000).

The generated values of $\log cz$ and $m^{B}_{max} \pm \sigma$ are plotted in a Hubble diagram (Fig. 1). We ask now how well the data from the "observed" 200 SNe Ia can distinguish between a flat matter-only universe and a $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ model. A χ^2-test shows that the latter is favored with a 89% probability.

A more general solution is obtained if the $1\sigma-$, $2\sigma-$ and $3\sigma-$confidence intervals, as defined by the 200 randomly generated SNe Ia, are plotted in an Ω_M versus Ω_Λ diagram (Fig. 2). It can be seen that the probability of Λ being positive is lager than 68% ($\approx 1\sigma$) for any value of Ω_M, i.e., independent of the assumption of flatness. If flatness is assumed the significance is increased to 89%.

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[2] In the present case $M^{B}_{max} = -19.5$ and $H_0 = 60$ km s^{-1} Mpc^{-1} was assumed only for illustration; the choice is inconsequential for what follows.

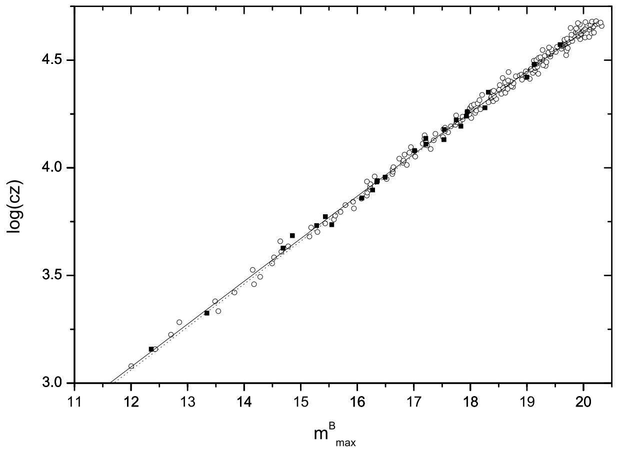

Fig. 1. The Hubble diagram of 200 randomly generated SNe Ia with $z \leq 0.16$ (circles) assuming a random luminosity scatter of $\sigma_{\rm m} = 0.^{\rm m}12$ (after correction for galactic absorption, decline rate, and intrinsic color). The dashed line is for $\Omega_{\rm M} = 1$, the full line for $\Omega_{\rm M} = 0.3$ and $\Omega_\Lambda = 0.7$. The sample of the 35 observed SNe Ia (Training Set) are represented by squares.

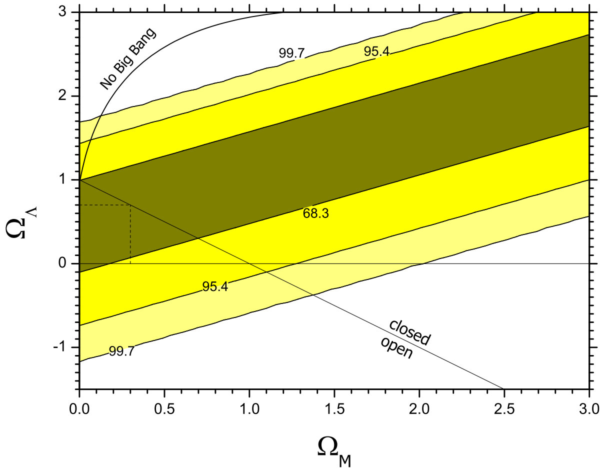

Fig. 2. Confidence contours in the $\Omega_{\rm M}$, Ω_Λ plane as defined by 200 randomly generated nearby SNe Ia ($z < 0.16$) with a luminosity scatter of $\sigma_{\rm M} = 0.^{\rm m}12$.

3.3. Improvement of the Experiment

The very uneven distribution of the SNe Ia along the Hubble line in Fig. 1 is highly unfavorable for the determination of the curvature of that line and hence of Λ. The less than optimal distribution of the SNe Ia is the result of the adopted constant space density. If it will be possible to obtain 50 SNe Ia with $4000 \lesssim v \lesssim 7000\,{\rm km\,s^{-1}}$ out of a total of 200 with $z \leq 0.16$ (with a luminosity scatter of $\sigma_{\rm M} = 0.^{\rm m}12$ as before), a distinction between a flat model with $\Lambda = 0$ and $\Lambda = 0.7$ can be achieved with a confidence of 95.4% (2σ), instead of 89% from a sample reflecting constant space density. Of course the discovery of these relatively nearby SNe Ia is time-consuming because of the lower surface density of the nearer parent galaxies. SNe Ia with $v \lesssim 3000\,{\rm km\,s^{-1}}$ are not useful for the experiment, because their expected peculiar motions of $\sim 300\,{\rm km\,s^{-1}}$ will substantially add to the statistical noise.

The experiment would be further improved if sufficient SNe Ia are available to restrict the analysis to events in E/S0 galaxies. Their in first approximation homologous average star formation, taking place predominantly at early epochs, will cause even less variations of the C/O ratios and metallicities of the SN Ia progenitors during the last 15% of the age of the universe. Moreover, a considerable part of the observed scatter of the Hubble diagram must be due to unaccounted dust in late-type host galaxies. In fact 20 SNe Ia in E/S0 galaxies with $5000 < v_{\rm CMB} < 20\,000\,{\rm km\,s^{-1}}$ exhibit a scatter of only $\sigma_{\rm m} = 0.^{\rm m}10$ in I (Reindl et al. 2005). This seemingly modest reduction of the scatter would considerably strengthen the detection of Λ.

4. Feasibility

4.1. Luminosity Dispersion of SNe Ia

The first question is whether the adopted luminosity dispersion of $0.^{\rm m}12$ is realistic, once the SNe Ia are reduced to a common decline rate and color. Parodi et al. (2000) have found $\sigma_{\rm B} = 0.^{\rm m}12$, but their sample is confined to blue objects. An unrestricted sample of 62 SNe Ia with $3000 \leq v_{\rm CMB} \leq 20\,000\,{\rm km\,s^{-1}}$ gives a somewhat larger scatter of $\sigma_{\rm B} = 0.^{\rm m}14$ or $0.^{\rm m}12$, much of which, however, must be due to the attempted corrections for internal absorption (Reindl et al. 2005; Wang et al. 2006). As mentioned before, a subset of 20 SNe Ia in E/S0 galaxies yields a scatter of only $\sigma_{\rm I} = 0.^{\rm m}10$ due to the generally small dust content of the parent galaxies. Even this small scatter is probably still inflated by observational magnitude errors. The dispersion of $0.^{\rm m}12$ adopted for the present experiment is therefore rather conservative.

4.2. The Frequency of SNe Ia

The annual frequency of detectable SNe Ia is approximated by

$$\log N = 2.44 + 0.6\,(m_{\rm limit} - 17.0) \tag{1}$$

(Høg et al. 1999), where $m_{\rm limit}$ is measured in B or V. The apparent maximum magnitude in B or V of a SN Ia at redshift z is given by

$$m_{\rm max} = 5 \log cz - 3.465 \tag{2}$$

(Reindl et al. 2005). Hence an unreddened SN Ia at redshift $z = 0.16$, i.e., the limit chosen here, will have $m_{\rm B} \approx m_{\rm V} = 20.^{\rm m}0$. Inserting this value into (1) will yield 17000 SNe Ia per year. The number is high enough to choose the most favorable objects in early-type galaxies (∼ 25%), at high galactic latitudes, and with the possibility to follow them up for at least 2-3 weeks post maximum.

Here is not the place to develop a detailed strategy for the discovery and follow-up of the SNe Ia. It is expected that the ”Nearby Supernova Factory” (Wood-Vasey et al. 2004) will contribute many useful SNe Ia with $0.03 < z < 0.08$. Also the GAIA satellite will efficiently find about half of all SNe Ia with $m_{\rm max} = 18.^{\rm m}0$ ($z \lesssim 0.07$), i.e., ~ 4500 SNe Ia during its projected four-year lifetime (Tammann & Reindl 2002). GAIA as well as Pan-STARRS (Kaiser & Pan-STARRS Project Team 2005) and Sky Mapper (Schmidt et al. 2005) will also be important for detecting the desirable, but rare SNe Ia with $0.01 < z \lesssim 0.02$ due to their full-sky coverage. The SNe Ia with $0.07 \lesssim z < 0.16$ have high surface densities and will be found by ongoing (e.g., ESSENCE, Miknaitis et al. (2004); SDSS, Frieman et al. (2004)) or future searches for intermediate- or high-z SNe Ia.

All SNe Ia require excellent photometric follow-up from the ground at least in B, V, and I. Spectroscopy is desirable for as many SNe Ia as possible. Only the spectroscopic subtypes like SN1991 T and SN1999 aa, which make up $\lesssim 15\%$ of all SNe Ia, compete with or exceed the high luminosity of normal SNe Ia (Reindl et al. 2005). They have all small decline rates of $\Delta m_{15} < 1.0$ and could be eliminated on this basis (this, however, would also eliminate about one third of all SNe Ia), or simply by 2σ-clipping. All SNe less luminous than normal SNe Ia are either much fainter or - in the case of SN1989 G - very red.

5. Conclusions

The main purpose of the proposed experiment is to reduce the possible effect of cosmic luminosity evolution of SNe Ia on the determination of Λ.

If Λ is determined from a comparison of local SNe Ia with those at $z \approx 0.8$ it is expected that the latter come on average from more massive and metal-poor progenitors. If the comparison is restricted to SNe Ia with $0 < z < 0.16$, as proposed here, it is possible to obtain their high-quality spectra and light curve parameters. If these turn out to be independent of distance, it is a strong argument that also their mean luminosities are (nearly) the same.

The main conclusion is that 200 local SNe Ia with $z \leq 0.16$ can decide about $\Lambda > 0$ for any value of $\Omega_{\rm M}$ with a significance of 68%, provided the luminosity distribution of normal SNe Ia is Gaussian. The significance is increased to 89% if a flat universe is assumed. The experiment can gain considerable significance if the adopted luminosity dispersion of $0.^{\rm m}12$ can be reduced by the restriction to SNe Ia in E/S0 galaxies with little internal absorption and/or by precision photometry; it will also be possible in the future to increase the sample size.

It is conceivable that local and not so local SNe Ia will eventually contribute to map the acceleration as a function of z and thus provide a clue to the true nature of the Dark Energy in the universe. If, however, it will be found that the light curve parameters and/or spectra change systematically even within $z < 0.16$, the role of SNe Ia as cosmological standard candles must be rediscussed.

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