

SPECTROSCOPY OF HIGH-REDSHIFT TYPE Ia SUPERNOVAE – IMPACTS ON COSMOLOGY

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Abstract. The cosmological results derived from observations of Type Ia Supernovae (SNe Ia) – namely the present day acceleration of the universe’s expansion – rely on the assumption that the distant supernovae are indeed the same objects as the nearby ones i.e. that SNe Ia form a quasi-homogeneous class of objects at all ages, that can be normalized via their light curve shape. This we know to not be entirely true: significant departures from the above scheme have been observed in the local universe, some of which could indicate a possible evolution of SNe Ia as we move to higher redshifts. For instance, distant SNe Ia ($z \lesssim 0.5$) appear bluer on average than their local counterparts. Though we know that other effects could induce systematic errors in the measurement of the luminosity distance to the various SNe Ia, only through a systematic comparison of high-redshift and local SNe Ia *spectra* will one be able to judge the extent to which evolution of these objects should be of a concern when using them as cosmological probes.

1 Introduction

The claim made by two independent teams – the High-Z Supernova Search Team (Schmidt et al.) and the Supernova Cosmology Project (Perlmutter et al.) – that the Type Ia Supernova data was best fit by a set of cosmological parameters describing a Λ -dominated universe, is of such importance that further efforts must be made to test these claims against potential systematic uncertainties.

Type Ia Supernovae are exquisite distance indicators, due to the fact that their peak luminosity can be normalized by an empirically determined relation between the luminosity at maximum and the subsequent decline rate. In applying this normalisation method to the high- z sample of SNe Ia one must be certain that the high- z objects are indeed identical to their local counterparts. The issue of evolution is thus of central importance and has not yet been convincingly addressed via SN Ia spectroscopy, which remains the only feasible method in detecting such effects – usually associated with the progenitor’s initial composition and environment.

In this paper I will review the status of SNe Ia as distance indicators and discuss the impacts of simple evolutionary models on the determination of cosmological parameters.

2 SNe Ia as Distance Indicators

Type Ia Supernovae are often referred to as “standard candles”. Despite being the best distance indicators beyond the Virgo cluster, SNe Ia are most certainly *not* standard. What one then means by such a statement is that the scatter in peak luminosity of SNe Ia is very small: the intrinsic dispersion in both B and V maximum is $< 0.25^m$ [1]. However some SNe Ia have been observed that are over- or sub-luminous by several magnitudes with respect to the canonical value for their peak luminosity of $M_B = -19.5$. Such events are referred to as “peculiar” as opposed to the so-called “Branch normal” SNe Ia, which make up the majority of the sample and indeed show a $< 0.25^m$ scatter in peak luminosity. How “standard” can a candle be which has a subclass of “peculiar” events?

However a closer look at SNe Ia light curves reveals a tight empirical correlation between the peak luminosity and its subsequent decline rate: brighter SNe Ia happen to decline more slowly, and vice-versa [2]. This is also true of the peculiar events, and thus provides the motivation for describing type Ia events with a single parameter, namely the difference in luminosity between maximum and 15 days later in the B band – referred to as $\Delta m_{15}(B)$ in the literature. This enables an accurate normalisation of these objects and in turn to efficiently use them as distance indicators. In fact, the statistical error in peak luminosity once the normalisation is applied is reduced to $\sigma \sim 0.12^m$ - 0.18^m ,

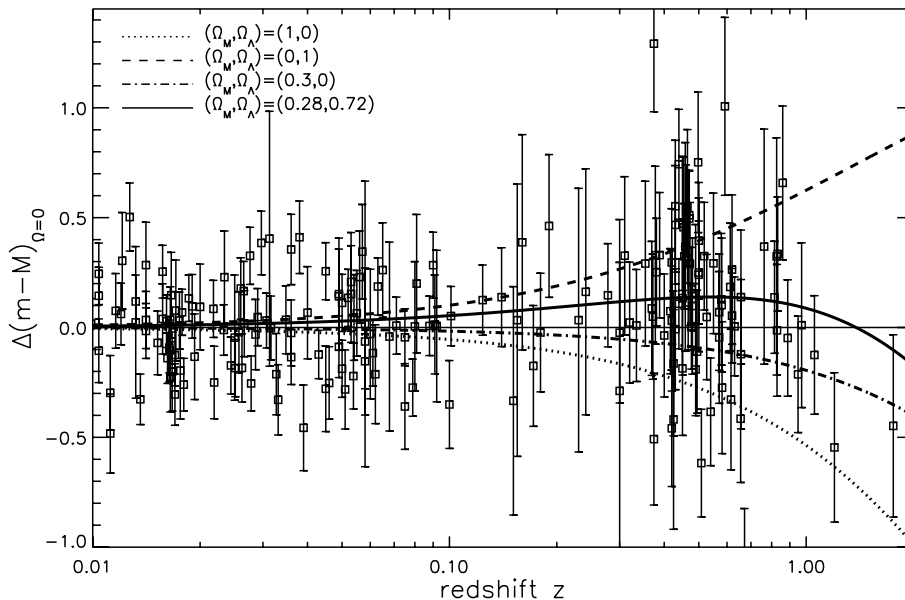


Figure 1: Hubble diagram for 196 SNe Ia in the redshift range $0.01 < z < 0.1$ (data taken from Tonry et al. [3]). The residuals in distance modulus with respect to an empty universe are plotted against redshift for various cosmological models. The error bars show the 1σ statistical errors.

which translates into a 5-8% accuracy in distance determination! If not “standard”, they at least appear to be “standardizeable” (sic).

One can appreciate this in the linear part of the Hubble diagram ($0.01 < z < 0.1$, see Figure 1), where the 102 objects in this range have a residual of $\sim 10\%$ about Hubble’s Law. For $z > 0.1$ we enter a regime in which the relation between distance modulus and redshift is different for different cosmological models. The cosmological claim based on the SN Ia data relies on the measurement of a ~ 0.2 magnitude systematic difference at $z \sim 0.5$, which happens to be of the same order as the scatter in peak luminosity after normalisation. However precise SNe Ia are at determining distances, one is lead to ask whether they are precise *enough*.

Theoretical explosion models of SNe Ia [4] have suggested that not all events can be described using a single parameter. Observationally, very peculiar events have recently been studied: 2000cx, 2001ay and 2002cx are such objects. Their light curves cannot be fit using the standard magnitude-light curve width relation, their spectra reveal an unusual time-evolution sequence and their colours are non standard.

An embarrassing fact confronts the observer of high- z SNe Ia: the local sample comprises $\sim 20\%$ of superluminous events, which are absent from the current magnitude limited high- z sample – where one would expect a significant fraction of superluminous events (i.e. a Malmquist bias). This could be explained via higher extinction towards the high- z objects, poor S/N of both photometry and spectroscopy, an observer bias (observers would “throw away” peculiar events) or an age effect (the signatures of peculiar events tend to disappear around maximum where most of the high- z SN Ia are discovered). In any case this issue remains worrisome and should be seriously addressed in the near future.

A change in the luminosity of SNe Ia as we move to higher redshifts would induce a significant systematic error in our determination of cosmological parameters, however precise these may be. This issue is as complex as it is serious, and before tackling it one must keep in mind two painful facts about SN Ia physics: (1) the progenitors of SNe Ia are not known (2) the explosion physics are not understood. These statements may seem a little extreme, since there are strong reasons to believe the standard SN Ia scenario of a C/O White Dwarf (WD) star accreting matter from a binary companion and undergoing a thermonuclear runaway when reaching the Chandrasekhar limit of $\sim 1.4 M_{\odot}$ (see [5] for a review). However our understanding of the underlying physical phenomena is limited, and theory alone cannot point to or away from the possibility for luminosity evolution.

The effects of the initial composition of the WD progenitor on the nucleosynthesis, light curves and spectra have been carefully studied by Peter Höflich and collaborators [6]. They find that changing

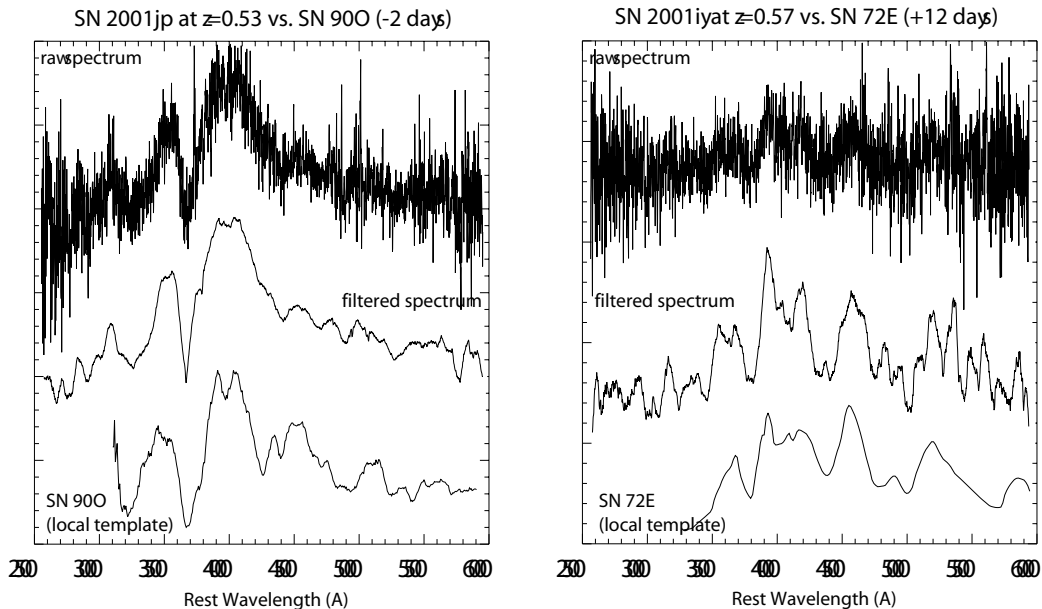


Figure 2: Spectra of high-redshift SNe Ia, from Barris et al. [8]. The poor S/N and the lack of Si II 6150Å absorption render the identification and subsequent analysis of these SNe Ia problematic.

the metallicity Z from Population I to Population II has but a small effect on the resulting rest-frame B and V light curves. However a change of the initial WD C/O ratio by 33% could lead to magnitude differences of $\sim 0.3^m$ for $z \geq 0.2$, comparable to the cosmological signature of a $(\Omega_M, \Omega_\Lambda) = (0.3, 0.7)$ universe at similar redshifts. Again this is problematic and should motivate one to find a coherent physical model for evolutionary effects rather than blindly applying an empirical correlation, however strong it may be.

3 Spectroscopy of High- z SNe Ia

Finding SNe Ia in the local universe is in principle “easy”. With an absolute magnitude of -19.5 (i.e. equivalent to $\sim 5 \cdot 10^9 L_\odot$!), SNe Ia at maximum often outshine their host galaxy. Barring the organisational challenge of coordinating photometric and spectroscopic follow-ups of these transient events, taking spectra and measuring light curves of such objects is a relatively trivial matter. Supernova searches such as the *Calán/Tololo Supernova Search (CTSS)* [7] provided the high- z community with a list of extremely well observed objects in the redshift range $0.01 < z < 0.1$. These SNe Ia are necessary to “anchor” the model curves in the Hubble diagram (see Figure 1) – no claim on cosmological parameters can be made without them.

Finding high- z SNe Ia poses serious technical challenges: the apparent magnitude of such objects is a steep function of redshift (e.g. $m_B(z=1) \sim 25$). For $z \gtrsim 0.4$ the defining Si II (6150Å) feature in SN Ia spectra is redshifted out of the optical into the near-infrared, rendering the identification process extremely tricky. These objects are too faint to be detected from ground-based observatories in this waveband, and so one often relies on shaky cross-correlations of the broad SN Ia features (typically $10,000 - 15,000 \text{ km s}^{-1}$) with local templates to convince oneself of the Ia nature of the observed transient. The S/N of such spectra is often extremely low, making it unfeasible to measure line ratios and fluxes; this is a problem since such measurements would provide valuable tests for evolution in SN Ia spectra.

On the observational side, no such evolutionary effects have yet been observed. This does not mean however that they are not present, and one has to keep in mind the poor quality of the high- z SN Ia spectra used in comparison with local templates (see Figure 2). On the basis of inherently qualitative cross-correlations and a lack of a satisfactory physical model for SNe Ia, it is wise to think twice before making any claims about the absence (or presence!) of subtle evolutionary effects in SN Ia spectra.

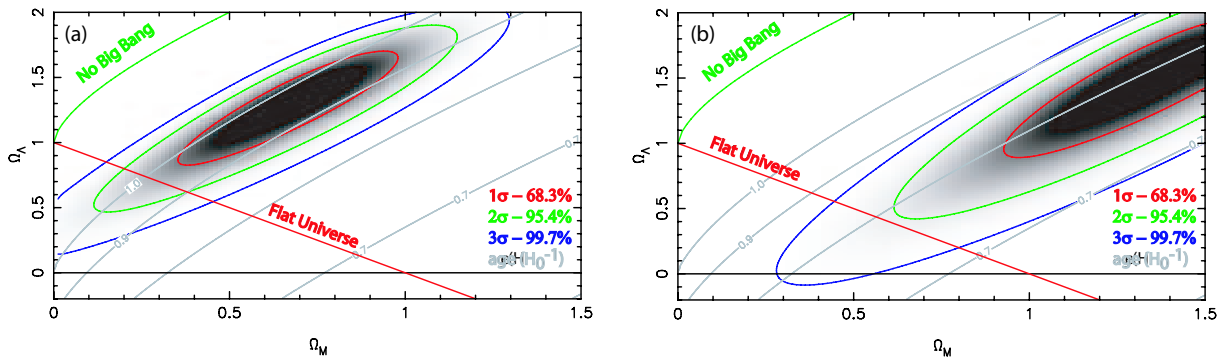


Figure 3: Probability distribution functions (PDF) in the $(\Omega_M, \Omega_\Lambda)$ plane for the current SN Ia data. (a) 172 SNe Ia from Tonry et al. [3] (b) monotonic evolution corresponding to $\Delta(m - M)_{\Omega=0} = 0.4z$.

Examining SN Ia *colours* gives us an altogether different picture: the distant ($z \lesssim 0.5$) objects appear bluer on average than the local ones [9]. If the high- z Ia’s are indeed intrinsically bluer, we have to explain why they also appear dimmer (*intrinsically* dimmer if evolution plays a role), since this is in contradiction with what is found locally (bluer events are also brighter). If evolution is not what causes the bluer colours, this implies that the current SN Ia fitting methods underestimate the extinction to these objects, and hence overestimate their distance from us.

4 Cosmological Implications

However difficult the detection of evolutionary effects may be, one must give credit to both high- z SN Ia teams for their obvious concern for systematic errors in their determination of cosmological parameters due to evolution. In both papers [10, 11] the effects of changes in progenitor populations and environment are investigated. Through statistical analysis, these potential effects are declared to not be important. Paradoxically, this inference relies on the assumption that the high- z SNe Ia can indeed be “normalised” in the same way as their local counterparts, which is exactly the effect one is trying to measure! The issue of the SN Ia environment is easier to get a handle on, since SNe Ia (unlike any other type of SN) occur in early as well as late-type galaxies, and so meaningful comparisons can be made between local and high- z SNe Ia in early-type hosts – such as elliptical galaxies for instance. At all times the concern is whether the *individual* objects have evolved or whether there is simply a change in the *average* properties of the SN Ia population at high redshift.

The SN Ia cosmological results can best be visualised as likelihood contours in the $(\Omega_M, \Omega_\Lambda)$ plane. A set of cosmological models is compared with the SN Ia data, and a probability distribution function (PDF) is derived in the parameter space of concern. These contours are highly degenerate in an orthogonal direction to the flat universe line, and towards higher values of both Ω_M and Ω_Λ . This can readily be understood via a simple analogy: the matter term in the Friedmann equations acts like a “break” on the expansion, whereas the Λ term acts like an “accelerator”. One can imagine obtaining a similar expansion rate by pressing harder on both the break and accelerator, hence the degeneracy in that direction.

Figure 3 shows the effects of evolutionary effects on the derived PDFs from the SN Ia data, and hence on the inferred cosmological parameters. The sample of 172 SNe Ia for which $z > 0.01$ and $A_V < 0.5$ (to avoid highly extinguished objects dominated by peculiar velocities) largely favours a positive Ω_Λ term, though clearly excludes the flat universe line at the 1σ level. This is in contradiction with results from measurements of primordial temperature fluctuations in the cosmic microwave background (CMB) data, which strongly favour $\Omega_{\text{tot}} \sim 1$ (c.f. 1.02 ± 0.02 from the latest WMAP results [12]), and could point to an uncontrolled source of systematic errors. Though one must be careful in making claims on the inferred cosmology when lacking a feasible physical model for the luminosity evolution, one can see that such effects would dramatically affect our determination of cosmological parameters from SN Ia data, even when combined with other experiments (CMB or large scale structure measurements). The problem with such simplistic models – or other systematic effects that scale with $(1 + z)$ such as “grey dust” [13] – is that they fail to reproduce the nonmonotonic behaviour of

the $z > 1$ SNe Ia. To mimic such a turnover in the Hubble diagram would require an extraordinary amount of dubious fine tuning.

5 Conclusions

To this day, all statistical tests and observational data have failed to disprove the $\Omega_\Lambda \neq 0$ cosmology indicated by the SN Ia data. However our lack of a complete physical model to describe the Type Ia supernova phenomenon (progenitor systems as well as explosion physics) render us prone to systematic errors in the determination of cosmological parameters. Though we have not yet found direct evidence for luminosity evolution in the high- z sample, there are concerns about events in the local sample that do not fit the one-parameter normalisation scheme. Even for those objects that *do* obey the empirical magnitude-decline rate relation, the statistical uncertainty in magnitude after the correction is applied is of the order of the cosmological effect we are trying to detect.

For this very reason we need a better hold on systematic errors. These could be due to faulty corrections for host galaxy extinction, a Malmquist bias (though no superluminous events have been detected in the high- z sample), absorption by intergalactic “grey” dust (though this fails to reproduce the nonmonotonic behaviour in the Hubble diagram), weak gravitational lensing (especially important for the $z > 1$ sample), or simply an observer bias and measurement errors. One must not be blinded with the hope of increasing our physical understanding of SNe Ia by going number hunting: already in 1998 Riess et al. [10] were dominated by *systematic* errors, and this with a sample of only 16 high- z SNe Ia.

The current efforts in carefully examining the Ia results are of crucial importance to modern cosmology. However exciting these results may be they point to an embarrassing gap in our current understanding of fundamental physics. To the dark matter which makes up 80% of the matter energy density we must add another “dark” component with negative pressure that makes up $2/3$ of the total energy density of the universe. Thus we are left with a “concordance” universe for which 95% of the energy content is unaccounted for. As said by Sir Arthur Eddington (originally a comment on Heisenberg’s uncertainty principle): “Something unknown is doing we don’t know what.”

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References

- [1] Tammann, G.A., & Sandage, A., ApJ, 1995, 452, 16
- [2] Philipps, M.M., ApJ, 1993, 413, L105
- [3] Tonry, J., et al., 2003, astro-ph/0305008
- [4] Höflich, P., & Khokhlov, A., 1996, ApJ, 457, 528
- [5] Hillebrandt, W., & Niemeyer, J., 2000, ARA&A, 38 , 191
- [6] Höflich, P., Wheeler, J.C., & Thielemann, F.K., 1998, ApJ, 495, 617
- [7] Hamuy, M., et al., 1993, AJ, 106, 2392
- [8] Barris, B., et al., 2003, ApJ, in prep.
- [9] Leibundgut, B., 2001, ARA&A, 39, 67
- [10] Riess, A., et al., 1998, AJ, 116, 1009
- [11] Perlmutter, S., et al., 1999, ApJ, 517, 565
- [12] Spergel, D.N., et al., 2003, astro-ph/0302209
- [13] Aguirre, A., & Haiman, Z., 2000, ApJ, 532, 28