Evaluation of Spectral Techniques in Type Ia Supernova Standardisation for Cosmology

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Abstract

Type Ia supernova are valuable cosmic distance measures widely used in observational cosmology, yet current standardisation techniques still remain as a major source of uncertainty. This uncertainty limits cosmological interpretations, decreasing scatter can improve cosmological precision, allowing for better understanding of the evolution and fate of the Universe. A variety of spectra based standardisation techniques aim to reduce this uncertainty. Throughout this review, several techniques are evaluated and compared to the traditional photometric based SALT2 standardisation technique, including the physics motivated line ratio analysis, empirical principle component analysis and spectral matching through "twins". The best performing spectral standardisation, the "Twins" method, obtained a Hubble diagram dispersion of $0.083 \pm 0.012\, mag$ and all spectral methods quantified show an improvement over the traditional SALT2 technique with a typical dispersion of $0.15\, mag$. These results highlight that spectroscopic data analysis in standardisation can reduce uncertainty around type Ia supernova measurements, so it should be central to future surveys. However, it is important to note that spectral analysis in this context introduces a set of new challenges, from observational data requirements to computational limitations.

Contents

1 Introduction

Throughout this review I will evaluate how type IA supernova (SNIa) standardisation methods influence the accuracy of cosmic distance measures which directly influence the cosmological conclusions drawn from SNIa surveys. Technique limitations are highlighted and methods compared with the aim to determine which methods pose promising pathways towards future improved standardisation.

SNIa have played a critical role in cosmological research acting as one of the greatest indicators of cosmic expansion history. Their highly consistent intrinsic luminosity allows for their use as "standardisable candles", with the measurement of SNIa luminosity across redshift resulting in the first compelling observational evidence for accelerated universe expansion in the 1990's [1], [2]. While SNIa remain as a key foundation to observational cosmology, studies are now becoming limited by the uncertainty in SNIa standardisations and understanding of the underlying physics. As standardisations improve further, more complex intrinsic and environmental properties [3] begin to impact the apparent luminosity of observed SNIa. Improved standardisation is vital for the understanding of the universe. With more advanced standardisation techniques distances can be determined more accurately, resulting in tighter and more accurate fits of observed cosmological parameters. This will impose stricter requirements for cosmological models allowing the currently accepted ΛCDM model to be tested [4] and competing models to be distinguished observationally. This work aims to enhance the understanding of the universe's history, evolution and provide a greater insight into one of the most profound questions in physics, what is the ultimate fate of our universe?

This review first provides a background justifying the use of SNIa as standardisable candles in observational cosmology from a physical perspective outlined in Section 2.1 and a discussion of fundamental cosmology, in Section 2.2. Then the current methods are outlined, first the current standardisation technique in Section 3.1 and then how cosmological conclusions can be drawn from standardised SNIa observations in Section 3.2. Observational surveys are then briefly discussed in Section 3.3. Then follows a discussion of emerging standardisation techniques in Section 4, highlighting limitations before concluding the review evaluating the methods outlined and stating future research paths to follow.

2 Background Theory

2.1 Supernova Physics

Supernova are a broad category of stellar explosions, a specific class, SNIa are utilised in observational cosmology due to their consistent luminosity, permitting their use as "standardisable candles". This consistent luminosity is due to the specific stellar evolution resulting in a SNIa.

SNIa spectra indicate an apparent lack of hydrogen emission lines [5], this suggests that the progenitor star is hydrogen deficient, and so the progenitor lacks a hydrogen envelope leaving an exposed core. The leading explanation for SNIa formation is a process involving a carbon and oxygen rich white dwarf formed in a binary system.

From an initial binary stellar system of two main sequence stars, one evolved to a giant. Its increased size exceeded the Roche Lobe [6] therefore initiating mass transfer. If this transfer became unbalanced, the companion star would have been engulfed by the giant creating one common envelope. The increased drag forces caused the giant's core and companion star to spiral inwards, reducing their separation. This loss of orbital energy ejected the envelope leaving an exposed carbon-oxygen core and companion star. This degenerate carbon oxygen core then contracted until the gravitational force and degeneracy pressure balanced, resulting in a carbon-oxygen white dwarf.

At this stage, the companion star began to evolve, expanding and exceeding its Roche Lobe initiating mass transfer. This mass transferred to the white dwarf may fuse to form carbon or oxygen. As the white dwarf's mass increased the Chandrasekhar Limit is approached [7]. Near this mass ($1.4M_{\odot}$ for a non-rotating white dwarf [8]) the core density and temperature favour carbon fusion. Thermal runaway is triggered and the degenerate white dwarf becomes increasingly unstable resulting in a supernova explosion [9].

Given the Chandrasekhar limit provides a strict upper bound for white dwarf mass and that the conditions required for SNIa are only present approaching this mass, there is a small mass range for pre-supernova white dwarfs. Additionally, the specific chemical compositions theorised and justified through spectral data from observations points to a consistent pre-supernova white dwarf chemistry. Therefore, the resulting SNIa intrinsic luminosity (or absolute magnitude) can be considered to be relatively consistent independent of distance from the observer and environmental conditions. This theory for SNIa formation also provides physical insight into observed light curves defined by the decay chain [10]:

$$^{56}N\mathrm{i} \rightarrow {}^{56}Co \rightarrow {}^{56}F\mathrm{e} \tag{1}$$

as an explanation for continued luminosity and the model's suggestion that a high mass of ^{56}Ni is produced. The decay of ^{56}Ni is correlated to the peak luminosity and the late time decline rate therefore light curve tail dictated by ^{56}Co decay [11].

However, there are several modern explanations for SNIa formation differing from the traditional Chandrasekhar limit model. Proposed subclasses with differing progenitors, differing white dwarf degeneracy, mass or rotation [12] aim to explain dependencies between SNIa observations. However, this review assumes the traditional Chandrasekhar mass model.

2.2 Dark Energy & Universe Expansion

From the beginning of observational cosmology research, SNIa have played a vital role as distance measures, used to show early observational evidence for the accelerated expansion of the universe [1]. This accelerated expansion is commonly expressed through the Hubble Parameter, H [13],

$$H = \frac{\dot{a}}{a} \tag{2}$$

where a is the scale factor of the universe and $\dot{a}$ its time derivative. Understanding universe expansion provides a deep insight into the history and future of the universe, and a current value for the Hubble parameter H_0 (Hubble constant). The age of the universe can then be estimated through this Hubble parameter using simple approximation $t \approx H_0^{-1}$ or more accurate estimates accounting for expansion history [14]. Since the expansion rate of the universe is linked to the total energy density, ρ, and spacial curvature, k, through the Friedmann equation [13],

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{a^2} \tag{3}$$

understanding the physical properties of the universe allows for a direct interpretation of the universe's evolution.

However, the accelerated expansion of the universe was unexpected so dark energy was theorised to explain this observed acceleration of the universe. The currently accepted ΛCDM cosmological model expresses dark energy in terms of a cosmological constant Λ.

2.2.1 ΛCDM Model

The ΛCDM model is particularly successful as predicted relations from the model closely fit with observations using a variety of techniques across both high and low redshift [15]. The expansion rate, $E(z)$, in a ΛCDM universe can be parametrised in terms of relative energy densities [16],

$$E(z) = \frac{H(z)}{H_0} = \sqrt{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda} \tag{4}$$

where Ω is the relative energy density corresponding to cosmological constant, matter and curvature represented by subscripts Λ, m, k respectively and radiation energy density (Ω_r) is zero.

The ΛCDM model's best fit values are $(\Omega_\Lambda, \Omega_m, \Omega_r, \Omega_k) = (0.7, 0.3, 0, 0)$ [17]. This results in an estimated age of the universe, $t = 13.57\ Gyr$ [18]. Additionally, the fate of a ΛCDM universe is driven by this cosmological constant Λ (or physically dark energy), the influence of dark energy dominates at late times, resulting in continued accelerated expansion pushing any objects unbound by gravity out of each other's cosmological horizons.

2.3 Additional Models

The values of the energy density parametrisations (Ω) in equation 4 have a direct influence on the fate of the universe. For an Einstein deSitter universe $(\Omega_\Lambda, \Omega_m, \Omega_r, \Omega_k) = (0, 1, 0, 0)$ [17] this universe would continue expanding but at a decelerated rate. But crucially any model is restricted by current observations of an accelerating universe, approximately flat curvature and negligible Ω_r at present. Further models propose primordial black holes [19] or dynamic dark energy models [4] in order to explain universe dynamics.

3 Supernova Cosmology

Due to their consistent luminosities, SNIa can be utilised as "standardisable candles" in observational cosmology. If the intrinsic luminosity, L, of a source is known this source can act as a distance measure by measuring the observed flux, F, through relation:

$$F = \frac{L}{4\pi d^2} \tag{5}$$

where d is the distance from the source to the observer. This process enables SNIa to be used as cosmic distance markers, particularly useful in cosmology. This determined distance can be compared to an independently obtained redshift value for the host galaxy. Comparing the two allows constraints on the values of the Hubble constant, H_0 and energy densities, Ω, and the nature of Dark Energy to be determined. This provides a set of requirements that any cosmological model must satisfy to be considered consistent with observations for this universe. However, SNIa are only considered "Standardisable" since the exact luminosity value L is not precisely known. Observational data must therefore be standardised to increase the precision of distance measures allowing cosmology to be determined more precisely.

3.1 Standardisation Techniques

Currently the SALT2 [20] standardisation is widely used, the model compresses SNIa light curve data into three parameters, the peak B-band magnitude (m_B), stretch (x_1) an effective description of light curve width, and the color (c). The standardisation then focusses on the stetch and color, through the empirical SALT2 standardisation:

$$m_B = M + \mu - \alpha x_1 + \beta c \quad (6)$$

where M is the absolute magnitude of an SNIa and values α and β are introduced standardisation parameters. μ is the distance modulus, defined as

$$\mu = 5 \log_{10} \left(\frac{D_L(z)}{10pc} \right) \quad (7)$$

where $D_L(z)$ is the luminosity distance, this corresponds to d in equation 5 for a bolometric flux in place of F. From this luminosity distance, cosmological energy density parameters, in equation 4 can be determined. Assuming flat curvature ($k = 0$)

$$D_L = (1+z)\frac{c}{H_0}\int_0^z \frac{dz'}{E(z')} \quad (8)$$

where z is redshift, c is the speed of light, H_0 the Hubble constant and $E(z)$ is the expansion rate encoding density parameters as shown in equation 4.

These α and β parameters are then determined by simultaneously fitting values to reduce the scatter of the SNIa data, depicted in figure 1.

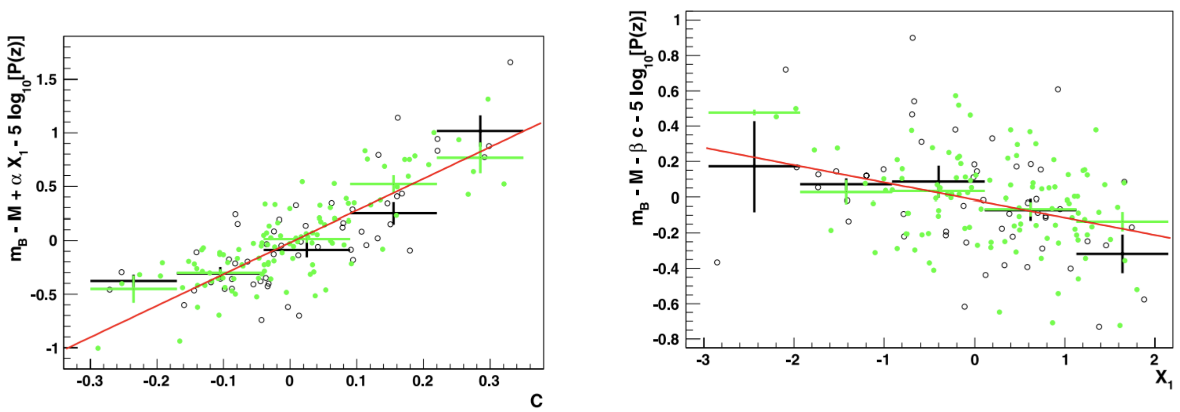

Figure 1: SALT2 simultaneous color (left) and stretch (right) standardisations, fitting linear slopes with gradients corresponding to SALT2 standardisation parameters β (left) and α (right) [20].

This results in an α and β value for the dataset and then the standardisation can be applied to the light curve data for all individual SNIa. This reduces the scatter in peak magnitude values to 0.15 mag [21] and creates a dataset with more consistent absolute magnitude. This ultimately improves distance estimates allowing for further estimation of cosmological parameters allowing further evaluation of models.

This standardisation is strictly empirical with stretch and color parameters inferred from light curve properties. There is strong evidence that the stretch or rate of light curve decline is strongly correlated to the peak magnitude [22] where a wider light curve (larger x_1) produces a larger peak brightness and redder SNIa appear fainter [23]. However this empirical basis can neglect physical processes biasing the standardisation technique.

The method also suffers since the entire light curve is simplified into three parameters, increasing the likelihood of missing further physical processes. The scatter in the SNIa data is also from two major sources, the intrinsic SNIa variability and extrinsic effects, this approach in no way separates these two sources likely reducing the validity of the approach. However, the SALT2 standardisation approach offers a simple and computationally cheap way to reduce scatter in observed SNIa data, particularly well suited to large datasets.

3.2 SNIa as Standard Candles

Once standardisations have been applied, SNIa can be used as standard candles as distance indicators. Plotting the distance modulus (μ), directly correlated to the luminosity distance, shown in equation 7, against independently determines redshift to obtain a Hubble diagram like shown in figure 2, cosmology can be evaluated.

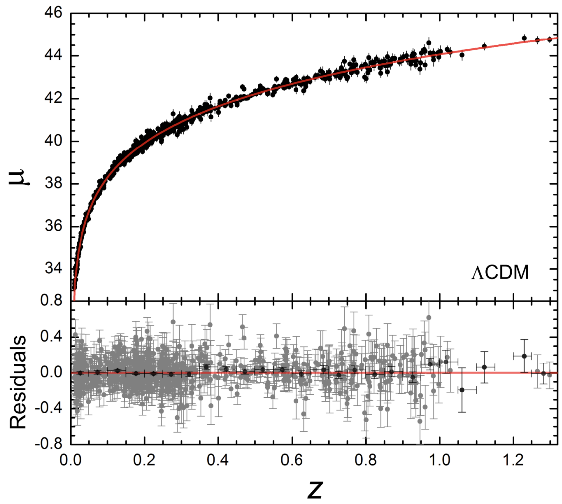

Figure 2: Hubble diagram comparing observed supernova data (black points) to the expected relation from the ΛCDM cosmological model (red line). [24]

The curve shown in figure 2 depicts universe expansion history. The systematic behaviour of the distance modulus over redshift constrain the parameters around any cosmological model including the Hubble parameter and dark energy equation of state (if evaluating a dark energy based model). Models with predicted μ vs z relations vastly differing from observations on a Hubble diagram may therefore be ruled out, like the Einstein deSitter universe model, disproven through supernova cosmology [1], [2]. As shown in figure 2 the currently accepted ΛCDM model fits in good agreement with current observations. Perlmutter et al [25] for example determined a value $\Omega_m^{flat} = 0.28^{+0.09}_{-0.08}$ using this approach, consistent with the ΛCDM model value $\Omega_m = 0.3$. They also provide evidence against a $\Lambda = 0$ cosmology.

With SNIa data for a large redshift range under standard interpretations, two major periods of universe history are depicted in the Hubble diagram. An era of matter dominated universe expansion for redshift above 0.3079 ± 0.0288 [26] and a currently dark energy dominated era for redshift less than 0.3079. The redshift for radiation dominated expansion is too high for observations.

A major limitation of this approach is that most current cosmological models are indistinguishable across small redshift ranges. Therefore, SNIa must be identified across a large redshift range, with a survey extending to $z = 1.5$ required to begin distinguishing dark energy properties [27]. Low redshift SNIa are much easier to obtain observational data for compared to high redshift SNIa. Since they are crucial for distinguishing cosmological models, a major area of research is focussed on high redshift SNIa.

3.3 Observational Surveys

Supernova cosmology is an active research area with large teams publishing vast datasets, consisting of data for thousands of SNIa. Large sky surveys are essential for the understanding of cosmology, one of the most advanced currently used is the Zwicky Transient Facility survey (ZTF), [28] utilising a Palomar 48 inch Schmidt telescope providing a 47 square degree field of view. Generally, SNIa surveys are either photometric (like Zwicky) producing SNIa light curves and spectroscopic observations which aim to infer more data on explosion characteristics, utilised in future methods discussed later.

4 Further Techniques

Although the SALT2 parametrisations are most commonly used to standardise SNIa observations, there is still room to improve the precision of data. One common approach is to add additional terms to the SALT2 parametrisation representing additional physical properties such as host galaxy mass [3] or morphology [29]. Other approaches move away from the simpler SALT2 parametrisation and favour empirical descriptions with more information. However, it is important to note that due to the large scale of the data surveys there are computational (and time) limitations that restrict the usability of certain advanced methods [30].

4.1 Spectral Analysis

One such approach deviating from the traditional parametrisations is to analyse the SNIa spectra. While typically the SNIa are described by a small set of parameters taken from lightcurves (primarily stretch, color and amplitude) The aim with a spectral analysis is to standardise using a higher dimensional description featuring additional information currently lost in SALT2 style compressions.

A method outlined by Bailey et al [31] replaces the typical SALT2 stretch and color parameters with flux ratios from spectroscopic data. It was found that these ratios can have stronger correlation to luminosity than light curve data, most notably the ratio,

$$R_{642/443} = \frac{F(642\,nm)}{F(443\,nm)} \tag{9}$$

where F is the SNIa flux at the indicated wavelength, had a correlation of 0.95. Using this ratio as a correction factor reduced Hubble diagram scatter from $0.161 \pm 0.015\,mag$ [21] using SALT2 stretch, color standardisations to $0.125 \pm 0.011\,mag$. This method requires similar computational power to the SALT2 approach yet provides a physical basis, variation in Fe lines correlate with peak luminosity at the $443\,nm$ line but have little impact around the $642\,nm$ line therefore it can be used as a normalisation parameter. However, high quality spectra near peak supernova luminosity are required and the method is only valid for redshift up to 0.13, beyond this, rest frame corrections shift the spectral features out of the optical band. Using an instrument with a larger wavelength range could extend this limit. Since high redshift SNIa are required for cosmological analysis, this limit reduces the methods practical viability.

This method justifies the use of single line spectral analysis in SNIa standardisation but is not the only technique used, some other approaches link spectral lines to various physical parameters such as ejection velocities [32].

4.2 Spectral Decomposition

Extending to a higher dimensional approach, full spectra can be mathematically decomposed through principal component analysis (PCA) or other similar approaches. PCA based deconstruction has achieved dispersion up to 0.05 mag lower than that of current SALT2 techniques. The aim is to use a full spectrum to capture the physical diversity of the supernovae, addressing SALT2's limitations introduced from relying exclusively on photometry. Saunders et al introduce the PCA based SNEMO models [33].

Figure 3 highlights the ability for even a small number of components to accurately track subtle details in complex spectra. This allows much more information to be extracted compared to traditional methods using light curves. However, the number of components directly influences the fitting accuracy, comparing SNEMO2, 7 & 15 shown in figure 3 for example, SNEMO2 is a simple two parameter decomposition used as a baseline providing an insufficient dispersion reduction to be used in standardisation. While SNEMO15 provides a more comprehensive model, the large number of principal components increases computational requirements, this becomes critical when dealing with large datasets. Therefore, SNEMO7 is the commonly used model for standardisation offering a balance between low computational power, precision and diminishing returns faced by increasing complexity of higher term models.

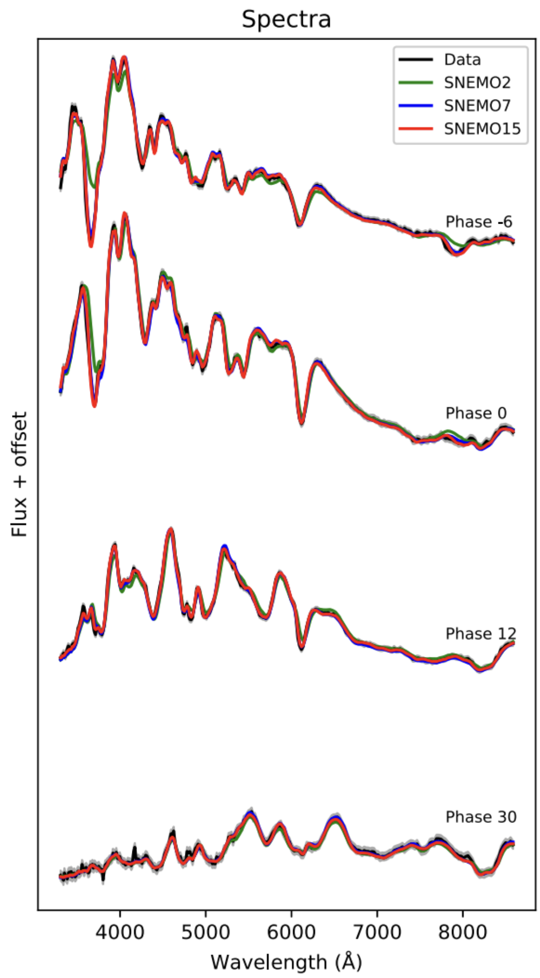

Figure 3: Illustration of PCA based functions, SNEMO2, 7, 15, compared to observed spectra across a variety of phases. Here the number of each "SNEMO" model refers to the number of principal components. [33]

SNEMO7 based standardisation has shown dispersion values of 0.100 mag [33] on training data compared to SALT2 typical values of 0.15 mag [21] demonstrating that PCA and spectral decomposition based standardisation can be used to improve SNIa standardisation.

Spectral decomposition techniques benefit from the possibility of more precise standardisation from a larger data input from spectra. However, high quality spectra are required which are very difficult to obtain especially for high redshift SNIa, so although PCA can capture much more physical diversity than SALT2 the method is currently limited by data availability. Since the SNEMO results outlined use a training set of ideal SNIa, while showing improvement, the model is yet to outperform SALT2 on large, observational datasets and improvements will likely be more conservative. Additionally, spectral decomposition is a purely mathematical process so obtained principle components can represent a number of physical properties.

4.3 Full Spectra Time Series

The SuperNova Empirical MOdels (SNEMO) [33] are not only focussed on light curve peak but across multiple days. In figure 3 the phase corresponds to number of days before (negative) or after (positive) the peak SN luminosity (at Phase 0).

SALT2 methods fail to distinguish intrinsic supernova properties from external effects, both of which are encoded in observational data and cause variation in supernova luminosity. External environmental properties, such as host galaxy contamination on SNIa [34], impact observations too significantly to be neglected in standardisation methods. A prominent environmental cause of spectral variation is reddening caused by dust in the SNIa's host galaxy.

The physical systems causing this variation have very different timescales and evolutions. In principle this allows the intrinsic SNIa properties to be distinguished from interference providing a much more descriptive standardisation. The PCA-based metric approach outlined by Sasdelli et al [35] aims to provide a conceptual framework for separating these intrinsic SNIa and external environmental sources of variation, initially factoring out the host galaxy reddening effects.

This method evaluated spectra across a range of -12.5 to $+17.5\,days$ of peak luminosity in order to accurately distinguish the differing evolutions. A metric space was then established from conducting a PCA of this time series, produced in such a way to be insensitive to reddening effects therefore showing that spectral time series can be used to distinguish intrinsic supernova properties from external effects pre-standardisation. This approach can then be extended to further environmental properties with the aim to isolate intrinsic SNIa properties.

Although this method provides a physically motivated route to SNIa standardisation crucially, it has not yet been fully implemented into standardisation so cannot be quantitatively compared to other methods and instead acts as a proof of concept. If fully realised the approach still suffers limitations, the standardisation process is highly complex, much more so that SALT2, and currently isolates only one external parameter. The computational requirements to fully separate intrinsic supernova properties would likely be too high, especially for large cosmological datasets. The approach is also limited by data availability as several high quality spectra are required for each SNIa.

4.4 Twins Method

Another method aiming to distinguish intrinsic SNIa properties from external variables is the "twins method". This is done through comparing SNIa spectra to identify "twins" from a library of high quality spectrophotometric time series, typically from nearby SNIa using a survey such as Nearby Supernova Factory [36]. Nearby SNIa provide much clearer spectra so are an ideal baseline for comparison. The similarities are quantitatively evaluated through "twinness".
The "twinness", defined by Fakhouri et al. [37], ξ of two SNIa can be quantified using a pseudo-chi squared comparison as

$$\xi(p_i) = \frac{1}{N_{dof}} \times \sum_{\lambda_j} \frac{[f_A(p_i,\lambda_j) - \alpha(\lambda_j) f_B(p_i,\lambda_j)]^2}{\sigma_A^2(p_i,\lambda_j) + \alpha^2(\lambda_j)\sigma_B^2(p_i,\lambda_j) + (\gamma f_A(p_i,\lambda_j))^2} \tag{10}$$

where f_A and f_B are the flux values (from GP-interpolated spectra) of compared supernova A and B at the same wavelength λ_j and phase p_i, and have corresponding variances σ_A and σ_B. N_{dof} is the number of degrees of freedom. Value α is introduced to account for dust extinction and γ represents an error floor. This "twinness" parameter is then used to quantify how spectroscopically consistent two SNIa are illustrated in figure 4 below.

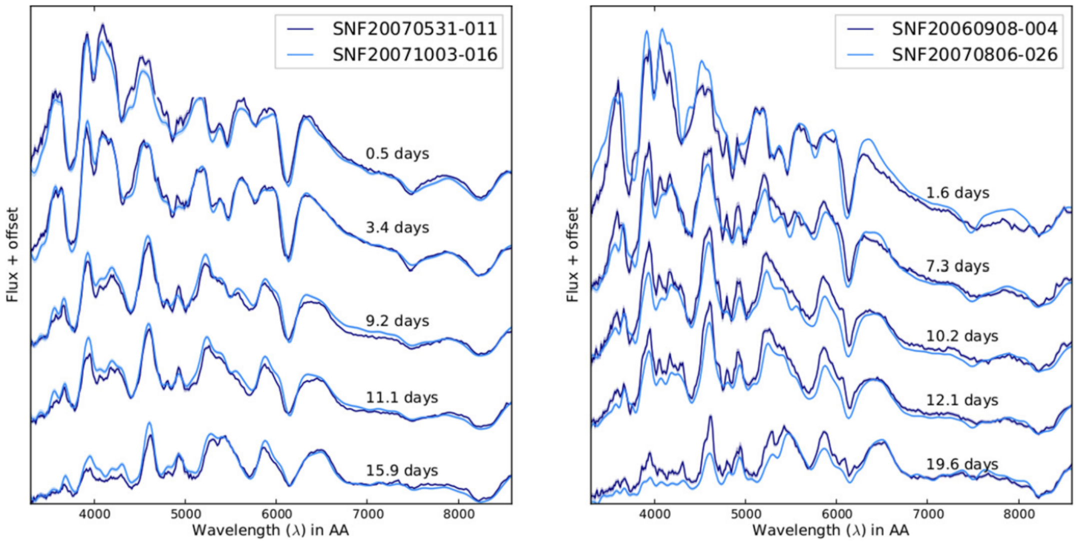

Figure 4: Illustration of good (left) and poor (right) pairs of supernova. The twinness value of the good pair is $\xi = 0.430$ low enough to be used as twins while the twinness of the poor pair is $\xi = 1.755$, too high to be considered as twins [37].

Since the spectra for "twins", such as SNF20070531-011 and SNF20071003-016, are largely identical, it is valid to assume that the underlying physics of the SNIa is the same. Therefore, the pair only differ in absolute luminosity. Value κ represents this overall remaining brightness difference and is encapsulated in coefficient α in equation 10. The difference in absolute magnitude, ΔM can then be determined, as

$$\Delta M = -2.5 \log(\kappa), \tag{11}$$

standardising the pair of twinned SNIa with respect to each other.

This method largely reduces external factors and is scalable as new SNIa can be added to the library providing closer matched twins. In comparison to SALT2's use of two parameters, this approach standardised using high dimensional spectral data. With SNIa standardised to $0.083 \pm 0.012\,mag$ and aims to standardise even high-redshift SNIa within $0.07\,mag$ [37] the method drastically reduces scatter compared to the SALT2 parametrisation with typical dispersion of $0.15\,mag$ [21].

The comparison technique should be explored further as the "twinness" metric utilised a simple pseudo-chi squared statistic but this can be replaced by a machine learning based approach [38], [39].

While the method is predominantly empirical, providing little physical reasoning beyond isolating SNIa intrinsic properties in standardisations and has a high computational cost, the major limitations of this approach are due to data availability. The library used to identify twins must be highly accurate and diverse in order to precisely categorise SNIa. The library used consisted of low redshift SNIa ($0.03 < z < 0.08$ [37]) since their spectra are much more defined (near maximum spectra with a signal-to-noise of 42 per $1000\,km\,s^{-1}$[37]), however this can impose a bias as high redshift SNIa are not represented in the library. High and low redshift environments typically differ in star formation rate and metallicity, and so high redshift environments may be systematically unrepresented in the libraries. Crucially, this model cannot standardise any SNIa without a "twin", this imposes a further cosmological bias against high redshift SNIa and unusual SNIa.

5 Conclusions

SNIa are an essential tool for measuring cosmic distance allowing for universe dynamics to be determined, however, standardisation remains as a major limitation for precise measurements hence accurate cosmological fits. If SNIa are to be continually used as cosmic distance measures, this standardisation issue must be minimised. Throughout this review several spectra based techniques are presented all of which aim to better standardisation.

The baseline SALT2 standardisation produces a scatter after standardisation of $0.15\,mag$, all spectral methods reduce this, with flux ratios reducing scatter to $0.125 \pm 0.011\,mag$, the SNEMO7 model achieving $0.100\,mag$ scatter and the twins method decreasing scatter to $0.083 \pm 0.012\,mag$ with aims to achieve dispersion within $0.07\,mag$.

One major limitation to any standardisation process is computational cost, single line spectral analysis and line ratios require similar, low computational power to SALT2. SNEMO and time series methods however introduce a much higher computational cost reducing practicality. The twins method faces even larger practical limitations, once a large SNIa library is introduced power requirements will become very high.

Another limitation to all spectral methods in comparison to SALT2 is the data requirements. While spectral analysis requires only one spectra near peak luminosity, this is still much harder to obtain than a light curve for SALT2. Both SNEMO and Twins methods require a time series of SNIa spectra, this limits these methods significantly due to data availability. Through the use of spectra all methods factor higher dimensional information than SALT2, particularly time series spectra capturing SNIa evolution. Spectral analysis methods provide a unique advantage since they are physically motivated as opposed to the other strictly empirical methods.

Extrinsic properties significantly increase scatter, the Twins method directly isolates intrinsic SNIa properties and Sasdelli et al provides a valuable conceptual framework to remove external effects. SALT2 or spectral decomposition methods cannot distinguish these effects without further analysis and flux ratios rely on empirical correlations so components are not directly separated.

Overall, these methods prove that using higher dimensional spectral information instead of photometric data provides a path to improved standardisations. The viability of this will ultimately be determined by data availability and computational requirements currently limiting their viability in observational cosmology. Future work should focus on streamlining techniques to reduce computational power and decrease spectral quality requirements to increase the practical viability of the methods outlined.

References

[1] Riess AG, Filippenko AV, Challis P, Clocchiatti A, Diercks A, Garnavich PM, et al. Observational Evidence for an Accelerating Universe and a Cosmological Constant. The Astronomical Journal. 1998;116(3):1009-38.

[2] Perlmutter S, Aldering G, Boyle BJ, Castro PG, Couch WJ, Deustua S, et al. Measurements of Omega and Lambda from 42 High-Redshift Supernovae. In: Paul J, Montmerle T, Aubourg E, editors. 19th Texas Symposium on Relativistic Astrophysics and Cosmology; 1998. p. 146.

[3] Jones DO, Kenworthy WD, Dai M, Foley RJ, Kessler R, Pierel JDR, et al. A Spectroscopic Model of the Type Ia Supernova-Host-galaxy Mass Correlation from SALT3. Astrophysical Journal. 2023 Jul;951(1):22.

[4] Chaudhary H, Capozziello S, Praharaj S, Pacif SKJ, Mustafa G. Is the ΛCDM model in crisis? Journal of High Energy Astrophysics. 2026 Feb;50:100507.

[5] Filippenko AV. Optical Spectra of Supernovae. Annual Review of Astronomy and Astrophysics. 1997 Jan;35:309-55.

[6] Eggleton PP. Aproximations to the radii of Roche lobes. Astrophysical Journal. 1983 May;268:368-9.

[7] Chandrasekhar S. The Maximum Mass of Ideal White Dwarfs. Astrophysical Journal. 1931 Jul;74:81.

[8] Carroll BW, Ostlie DA. An Introduction to Modern Astrophysics. 2nd ed. San Francisco, CA: Addison-Wesley; 2007.

[9] Woosley SE, Weaver TA. The physics of supernova explosions. Annual Review of Astronomy and Astrophysics. 1986 Jan;24:205-53.

[10] Colgate SA, McKee C. Early Supernova Luminosity. Astrophysical Journal. 1969 Aug;157:623.

[11] Anderson JP. A meta-analysis of core-collapse supernova ^{56}Ni masses. Astronomy & Astrophysics. 2019 Aug;628:A7.

[12] Maoz D, Mannucci F, Nelemans G. Observational Clues to the Progenitors of Type Ia Supernovae. Annual Review of Astronomy and Astrophysics. 2014 Aug;52:107-70.

[13] Dimopoulos K. Introduction to Cosmic Inflation and Dark Energy. CRC Press; 2020.

[14] Jimenez R, Cimatti A, Verde L, Moresco M, Wandelt B. The local and distant Universe: stellar ages and H0. Journal of Cosmology and Astroparticle Physics. 2019 Mar;2019(03):043–043. Available from: `http://dx.doi.org/10.1088/1475-7516/2019/03/043`.

[15] Di Valentino ED. Challenges of the Standard Cosmological Model. Universe. 2022 Jul;8(8):399.

[16] Hogg DW. Distance measures in cosmology; 2000. Available from: `https://arxiv.org/abs/astro-ph/9905116`.

[17] Jackson N. The Hubble Constant. Living Reviews in Relativity. 2007;10(1):4. Available from: `https://doi.org/10.12942/lrr-2007-4`.

[18] Valcin D, Jimenez R, Seljak U, Verde L. The Age of the Universe with Globular Clusters III: Gaia distances and hierarchical modeling; 2025. Available from: https://arxiv.org/abs/2503.19481.

[19] Lorenzoni DL, Geller SR, Kaiser DI, McDonough E. Primordial Black Holes from Inflation with a Spectator Field. arXiv e-prints. 2025 Dec:arXiv:2512.04199.

[20] Bazin G, Ruhlmann-Kleider V, Palanque-Delabrouille N, Rich J, Aubourg E, Astier P, et al. Photometric selection of Type Ia supernovae in the Supernova Legacy Survey. Astronomy & Astrophysics. 2011 Oct;534:A43.

[21] Rigault M, Smith M, Goobar A, Maguire K, Dimitriadis G, Burgaz U, et al.. ZTF SN Ia DR2: Overview; 2024. Available from: https://arxiv.org/abs/2409.04346.

[22] Phillips MM. On the Inhomogeneous Nature of Type IA Supernovae. In: American Astronomical Society Meeting Abstracts #182. vol. 182 of American Astronomical Society Meeting Abstracts; 1993. p. 29.07.

[23] Tripp R. A two-parameter luminosity correction for Type IA supernovae. Astronomy & Astrophysics. 1998 Mar;331:815-20.

[24] Melia F, Wei JJ, Maier RS, Wu XF. Cosmological tests with the joint lightcurve analysis. EPL (Europhysics Letters). 2018 Sep;123(5):59002.

[25] Perlmutter S, Aldering G, Goldhaber G, Knop RA, Nugent P, Castro PG, et al. Measurements of Ω and Λ from 42 High-Redshift Supernovae. The Astrophysical Journal. 1999 Jun;517(2):565–586. Available from: http://dx.doi.org/10.1086/307221.

[26] Cahill K. The eras of radiation, matter, and dark energy: new information from the Planck Collaboration. arXiv e-prints. 2016 Jun:arXiv:1606.08865.

[27] Linder EV. Understanding the Optimal Redshift Range for the Supernovae Hubble Diagram. arXiv e-prints. 2001 Aug:astro-ph/0108280.

[28] Bellm EC, Kulkarni SR, Graham MJ, Dekany R, Smith RM, Riddle R, et al. The Zwicky Transient Facility: System Overview, Performance, and First Results. Publications of the Astronomical Society of the Pacific. 2019 Jan;131(995):018002.

[29] Pruzhinskaya MV, Novinskaya AK, Pauna N, Rosnet P. The dependence of Type Ia Supernovae SALT2 light-curve parameters on host galaxy morphology. Monthly Notices of the Royal Astronomical Society. 2020 Dec;499(4):5121-35.

[30] Magee MR, Siebenaler L, Maguire K, Ackley K, Killestein T. Quantitative modelling of type Ia supernovae spectral time series: Constraining the explosion physics; 2024. Available from: https://arxiv.org/abs/2403.16889.

[31] Bailey S, Aldering G, Antilogus P, Aragon C, Baltay C, Bongard S, et al. Using spectral flux ratios to standardize SN Ia luminosities. Astronomy & Astrophysics. 2009 Jun;500(2):L17-20.

[32] Foley RJ, Kasen D. Measuring Ejecta Velocity Improves Type Ia Supernova Distances. Astrophysical Journal. 2011 Mar;729(1):55.

[33] Saunders C, Aldering G, Antilogus P, Bailey S, Baltay C, Barbary K, et al. SNEMO: Improved Empirical Models for Type Ia Supernovae. Astrophysical Journal. 2018 Dec;869(2):167.

[34] Burgaz U, Maguire K, Dimitriadis G, Harvey L, Senzel R, Sollerman J, et al. ZTF SN Ia DR2: The spectral diversity of Type Ia supernovae in a volume-limited sample. Astronomy & Astrophysics. 2025 Feb;694:A9.

[35] Sasdelli M, Ishida EEO, Hillebrandt W, Ashall C, Mazzali PA, Prentice SJ. Breaking the colour-reddening degeneracy in Type Ia supernovae. Monthly Notices of the Royal Astronomical Society. 2016 Jul;460(1):373-82.

[36] Wood-Vasey WM, Aldering G, Howell AD, Nugent P, Perlmutter S, Quimby R, et al. The Nearby Supernova Factory. In: American Astronomical Society Meeting Abstracts. vol. 199 of American Astronomical Society Meeting Abstracts; 2001. p. 64.08.

[37] Fakhouri HK, Boone K, Aldering G, Antilogus P, Aragon C, Bailey S, et al. Improving Cosmological Distance Measurements Using Twin Type Ia Supernovae. Astrophysical Journal. 2015 Dec;815(1):58.

[38] Boone K, Aldering G, Antilogus P, Aragon C, Bailey S, Baltay C, et al. The Twins Embedding of Type Ia Supernovae. I. The Diversity of Spectra at Maximum Light. Astrophysical Journal. 2021 May;912(1):70.

[39] Boone K, Aldering G, Antilogus P, Aragon C, Bailey S, Baltay C, et al. The Twins Embedding of Type Ia Supernovae. II. Improving Cosmological Distance Estimates. Astrophysical Journal. 2021 May;912(1):71.