

Redshift evolution of the SN stretch distribution

N. Nicolas¹, M. Rigault², R. Graziani², M. Briday¹, Y. Copin¹, and Y. Kim¹

¹ Université de Lyon, F-69622, Lyon, France; Université de Lyon 1, Villeurbanne; CNRS/IN2P3, Institut de Physique des Deux Infinis, Lyon

² Université Clermont Auvergne, CNRS/IN2P3, Laboratoire de Physique de Clermont, F-63000 Clermont-Ferrand, France.

Received 2 November 1992 / Accepted 7 January 1993

ABSTRACT

Context. Type Ia supernovae (SNe Ia) allow for the construction of the Hubble diagram, giving us information about the Universe's expansion and its fundamental components, one of which is dark energy. But systematic uncertainties are now starting to be limiting in our ability to measure those parameters. In particular, the physics of SNe Ia is still mostly unknown, and is thought not to change in time/with the redshift.

Aims. In an attempt to reduce those uncertainties, we try to find an empirical law describing SNe Ia's length of explosion (stretch) evolution with the redshift.

Methods. We started by getting a complete sample representing all of the stretch distribution that Nature can give us, before using LsSFR measurements, an age tracer which evolution with redshift is known, that has been shown to have a strong correlation with the stretch. We compare their AICc, an estimator of the relative quality of statistical models that includes the number of free parameters, to determine which ones describe best the data.

Results. Models with an evolution of the stretch with the redshift have a better AICc than the ones without.

Conclusions. We find that implementing these models allows us to fit the data better than models without stretch evolution.

Key words. Cosmology – Type Ia Supernova – Systematic uncertainties

1. Introduction

Type Ia supernovae (SNe Ia) are powerful cosmological distance indicators that have enabled the discovery of the acceleration of the Universe's expansion [? ?]. They remain today a key cosmological probe to understand the properties of dark energy (DE) as it is the only tool able to precisely map the recent expansion rate $z < 0.5$, when DE is driving it [e.g. ?]. They also are key to directly measure the Hubble Constant (H_0) provided one can calibrate their absolute magnitude [? ?]. Interestingly, the value of H_0 derived when the SNe Ia are anchored on Cepheids [the SH0ES project ? ?] is $\sim 5 \sigma$ higher than what is predicted by cosmic microwave background (CMB) data measured by Planck assuming the standard Λ CDM or when the SN luminosity is anchored at intermediate redshift by the baryon acoustic oscillation (BAO) scale [? ? ?]. While using the tip of the red giant branch technique in place of the Cepheids seem to favor lower values of H_0 [? ?] time delay measurements from strong lensing seem to also favor high H_0 values [?].

The H_0 tension has received a lot of attention as it could be a sign of new fundamental physics. Yet, no simple solution is able to accommodate this H_0 tension when accounting for all other probes and the current most promising scenario appears to be a burst of expansion at the matter-radiation decoupling moment caused by a (fine tuned) early dark energy [?].

Alternatively, systematic effects affecting one or several of the aforementioned analysis could also explain the tension. In [?] we suggested that SNe Ia from the cepheid cali-

brator sample differ significantly to the one from the Hubble flow sample that enables to derive H_0 . Indeed, Cepheid are very young stars and the existence of Cepheids in a galaxy implies that the host is star forming. In [?] we claimed that a more than 90% of the calibrator SNe Ia arise from a young-progenitor population while this population only accounts for about half of the Hubble flow sample. Following [?] and [?], we further showed that young and old progenitor SNe Ia have a different magnitude of about 0.15 mag. This has been confirmed for modern standardization technique [SALT2.4 ? ?] with high significance ($\sim 6\sigma$) in [?] as well as independently by [?] at $\sim 7\sigma$. As detailed in [?], if the magnitude difference between young and old SNe Ia is indeed of 0.15 mag and if SNe Ia from the calibrator sample is fully dominated by young SNe Ia, the effect on H_0 of the existence of these two SNe Ia populations is of 3.5%. Accounting for the fact that another environmental effect (the mass-step) is already included in the SH0ES analysis, the net bias in the SH0ES analysis is expected closer to 3% [see table 6 of ?].

SHOULD BE SHORTENED A LOT: However, the importance of this astrophysical bias in the direct measurement of H_0 is still highly debated. We also highlight that it could not explain the high value of H_0 derived by strong lensing. First, [?] did not find any environmental bias when extending the [?] study. It was more recently reported in [?] that indeed local host analysis has significant influence on the SN magnitude but much more importantly than claimed in [?] and with a connection with the progenitor physics and/or a line of sight effect that is unclear. More

importantly, [?] attended to mimic the cepheid sample selection function on the Hubble flow sample by removing SNe Ia from the latter if they classified their host as early-type or non-star forming. They measured that doing so has no effect on the measurement of H_0 .

This paper is part of a series of papers where we test the validity of the two SNe Ia population models developed in [?]. Briday et al. in prep will present how using different environmental tracer is affecting our ability to distinguish the two populations, and Rigault et al. in prep will further study the connection with H_0 . Here we analyze predictions concerning the SNe Ia redshift drifts: (1) that the distribution of the SNIa stretch, a purely intrinsic SNIa property, is evolving as a function of redshift and (2) that this population-drift follows the relation that [?] derived assuming that one population is “young” with a rate proportional to the star formation rate in the Universe and the second is “old” with a rate proportional to the stellar mass.

The concept of the SNe Ia age dichotomy arised when the SNIa rate has first been studied. [?] have shown that the relative SNe Ia rate in galaxies could only be explained if two populations existed, one young, following the host star formation activity, and one old following the host stellar mass (the so called “prompt and delayed” or “A+B” model). In [?] we used the specific star formation rate at the SN location (Local sSFR or LsSFR) to classify which are the prompts (those with a high LsSFR) and which are the delayed (those with low LsSFR). Since the first SNe Ia host analysis, the SN stretch has been known to be strongly correlated with the SN host properties [?] and it has been extensively confirmed since [e.g. ?]. Following the “A+B” model and the connection between SN stretch and host properties, [?] first discussed the potential redshift drift of the SN stretch distribution. In this paper we revisit this analysis with the most recent SNe Ia dataset and we test the validity of the two SNIa age populations model developed in [?].

We present in section ?? the sample we are using for this analysis, which is based on the pantheon dataset [?]. We discuss the importance of obtaining a “complete” sample, i.e. representative of the true underlying SNe Ia distribution, and how we build one from the Pantheon sample. We then present in section ?? our modeling of the distribution of stretch as a function of redshift based on the relative stretch distribution of young and old SNe Ia. Our results are presented in section ?? where we test if the distribution of stretch does evolve as a function of redshift and if the age-model is in good agreement with this evolution. We discuss our results and conclude in section ??.

Throughout the paper we use the Planck 2015 cosmology from the astropy library.

2. Sample

We base our analysis on the latest SNe Ia compilation: the Pantheon catalog from [?]. Using this dataset, we aim at probing the evolution of the distribution of SNe Ia stretch in nature as a function of redshift. Because the observed magnitude of a SN Ia is correlated with its stretch and its color, in a magnitude limited survey such as those constituting most of the Pantheon sample, the distribution of these lightcurve parameters is not representative of the true underlying distribution above a certain limiting redshift. The first SNe Ia that such a survey will miss because they will

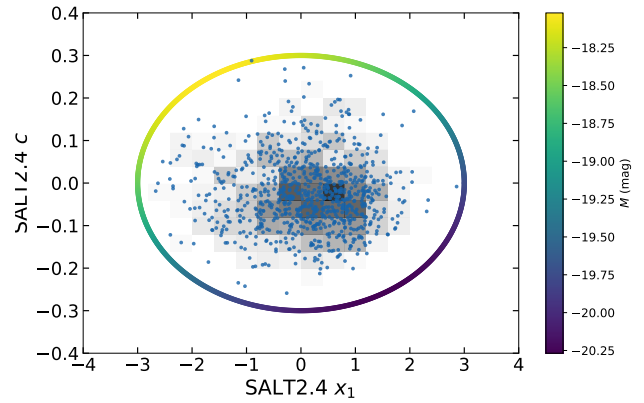


Fig. 1. SALT2.4 stretch and color lightcurve parameters of SNe Ia from the SDSS, PS1 and SNLS samples from the pantheon catalog. The individual SN data are shown as blue dots and a 2D histogram is shown in grey to highlight point density. The ellipse encapsulating all the SN data is displayed colored by the effective standardized absolute magnitude using the α and β standardisation coefficients from [?].

be too faint are indeed the reddest and the lowest-stretch SNe Ia. If such a selection effect is not accounted for, we might confuse true population drift we selection function or conversally.

The figure

The faintest SNIa is that with $x_1 = -1.66$ and $c = 0.25$ and has an absolute **standardized** magnitude at peak in **Bessel-b band** of -18.31 mag, which leads to limiting absolute magnitude of -18.00 if we want to be able to observe it typically a week before and 10 days after peak. Therefore, given the 5σ point source detection magnitude limit of a magnitude limited survey, one can derive the maximum redshift above which the faintest SNe Ia will start to be missed.

SNLS typically acquires SNe Ia in the redshift range $0.4 < z < 0.8$. At these redshifts the rest-frame Bessel-b band roughly corresponds to the SNLS- i filter, that has a 24.8 mag 5σ depth¹. This converts to a $z_{lim} = 0.60$, in perfect agreement with [?] and [?]. Similarly, PS1 observing SNe Ia in the range $0.2 < z < 0.4$, their g -band 5σ depth is 23.1 mag [?], corresponding $z_{lim} = 0.30$. The fig. 6 of [?] suggests a more conservative z_{lim} of 0.27 for the PS1 catalog. In similar redshift range, SDSS has a limiting magnitude of 22.5 [???], which would lead to a $z_{max} = 0.24$. However, the SDSS survey were more sensitive to limited spectroscopic resources. [?] presents that during year-1 of SDSS, SNe Ia with $r - mag < 20.5$ were favored for spectroscopic follow up, corresponding to the redshift cut at 0.15 . For the rest of the SDSS survey, additional spectroscopic resources were used, such that [?] and [?] of show a relative completeness up to $z_{lim} = 0.2$. For the rest of the analysis, we will use $z_{lim} = 0.2$ as baseline magnitude.

In Section ??, we test the impact on using more conservative redshift limits ($z_{lim} = 0.15$ for SDSS, $z_{lim} = 0.27$ for PS and $z_{lim} = 0.55$ for SNLS, following Fig. 14 of ?).

In addition, we use the SNe Ia sample of from the nearby supernovae factory [SNfactory ?] published in [?]. As the SNe search were much deeper than the spectrophotometric follow-up, SNfactory SNe Ia within a redshift range of

¹ CFHT final release website.

Table 1. Origin of the SNeIa in our sample and redshift limit (if applicable) of each surveys.

| Survey | N _{SN} | z _{lim} |
|--------|-----------------|------------------|
| SNf | 141 | – |
| SDSS | 167 | 0.20 |
| PS1 | 160 | 0.30 |
| SNLS | 102 | 0.60 |
| HST | 26 | – |

0.02 < z < 0.09 should also be a random sampling of the underlying SN population. The HST sample from Pantheon follows the same logic and we therefore kept it entirely [?].

Our "complete sample" is therefore made of 656 SNeIa whose composition is detailed in table

CHECK LITERATURE CAN WE USE THE CfA SAMPLES ???

3. Method

We used the LsSFR and stretch measurements from the SNf sample. The LsSFR has an evolution with the redshift that is analytically known: calling the fraction of young stars and the fraction of old ones, Rigault 2018 et + find

$$\frac{\delta}{\psi} \equiv \text{LsSFR} = K \times 1 + z^\varphi \quad (1)$$

with $\varphi = 2.8$, and knowing $\psi = 1$:

$$\delta = K^{-1} \times 1 + z^{-1} + 1^{-1} \quad (2)$$

$$\psi = K \times 1 + z^+ + 1 \quad (3)$$

The goal is to find how the stretch depends on the LsSFR, distinguishing old and young SNe which fractions evolve with the redshift, in order to have an analytical law for the mean redshift evolution of the stretch. The measured data on which we based our first model is plotted in figure ??; based of the shape of the x_1 vs LsSFR cloud, we implemented the following model:

- **young**: a gaussian of mean μ_1 and standard deviation σ_1 , namely $\mu_1 \equiv \mu_1$;
- **old**: a linear combination between μ_1 and another gaussian $\mu_2 \equiv \mu_2$

As such, the probability to observe a young SNe Ia labeled "i" with a stretch x_1^i and error \bar{x}_1^i is

$$p(x_1^i, \bar{x}_1^i | \mu_1, \sigma_1) = \frac{1}{\sigma_1} \exp\left(-\frac{(x_1^i - \mu_1)^2}{2\sigma_1^2}\right) \quad (4)$$

and for an old one:

$$p(x_1^i, \bar{x}_1^i | \mu_1, \sigma_1, \mu_2, \sigma_2, a) = a \times \frac{1}{\sigma_1} \exp\left(-\frac{(x_1^i - \mu_1)^2}{2\sigma_1^2}\right) + (1 - a) \times \frac{1}{\sigma_2} \exp\left(-\frac{(x_1^i - \mu_2)^2}{2\sigma_2^2}\right), \quad (5)$$

where a is the relative amplitude between the two gaussians. Finally, the normalized stretch distribution at a given z $x_1|z$ is the weighed sum of both young and old stretch distributions given their relative fraction :

$$x_1|z = \mu_1 + (1 - a) \times \mu_2 \quad (6)$$

We fitted it on SNf data, giving the results table

We implemented and compared 10 models in total, 4 of which have an evolution with the redshift from $z = 0$, and 6 don't ($f = \text{cst}$). The ones with and evolution are:

- 3G2M2S, the one we described (but fitted on all the data);
- 3G2M1S, where this time $\mu_1 \equiv \mu_2$;
- 2G2M2S, model taken from HOWELL 2009 where we added ;
- 3G3M3S, with three independent gaussians.

The ones without a stretch evolution are the same ones but with an "F" implying we set $f = \text{cst}$, and two others:

- 1G1M1S, where there is no distinction between old and young SNe;
- 1G1M2S, taken from KESLLER 2017 and used in recent cosmological analysis SCOLNIC 2018. It's an asymmetric model where

$$p(x_1^i, \bar{x}_1^i | \mu, \sigma, f) = \begin{cases} \mathcal{N}(\mu, \sqrt{\sigma^2 + \bar{x}_1^i{}^2}) & \text{if } x_1^i \geq \mu \\ \mathcal{N}(\mu, \sqrt{\sigma^2 + \bar{x}_1^i{}^2}) & \text{else} \end{cases} \quad (7)$$

The fitted parameters are showed table

4. Results

To compare all these models, we use the Akaike Information Criterion corrected for sample size (BURNHAM 2002), that penalises the increase of free parameters in order to discourage overfitting:

$$\text{AICc} = \text{AIC} + 2kk + 1n - k - 1 \quad (8)$$

with $\text{AIC} = 2k - 2 \ln \mathcal{L}$, where k is the number of free parameters and the likelihood. The probability for a model to be as representative as the "best" one is given by:

$$p(\text{other} > \text{best}) = \exp \text{AICc}/2 \quad (9)$$

The results are showed table

5. Conclusion

Stretch evolution with the redshift is a thing. Need to see if it has an impact on the cosmology though.

Table 2. Valeurs des paramètres pour différents modèles. En rouge les données aberrantes.

| Model | a | f | 1 | 1 | 2 | 2 |
|-----------------------|-----------------|---------------|-----------------|-----------------|------------------|-----------------|
| 3G2M2S _{SNf} | 0.48 ± 0.07 | none | 0.39 ± 0.07 | 0.56 ± 0.05 | -1.5 ± 0.1 | 0.52 ± 0.09 |
| 3G2M2S | 0.48 ± 0.17 | none | 0.36 ± 0.08 | 0.61 ± 0.05 | -1.3 ± 0.2 | 0.60 ± 0.12 |
| 3G2M2SF | 0.1 ± 0.6 | 0.2 ± 0.6 | -0.9 ± 0.7 | 0.7 ± 0.3 | 0.5 ± 0.2 | 0.6 ± 0.1 |
| 3G2M1S | 0.47 ± 0.07 | none | 0.35 ± 0.04 | 0.61 ± 0.03 | -1.25 ± 0.10 | 1 |
| 3G2M1SF | 0.2 ± 0.9 | 0.7 ± 0.3 | 0.36 ± 0.04 | 0.60 ± 0.03 | -1.23 ± 0.10 | 1 |
| 2G2M2S | none | none | 0.49 ± 0.04 | 0.54 ± 0.03 | -0.72 ± 0.08 | 0.83 ± 0.07 |
| 2G2M2SF | none | 0.3 ± 0.2 | -0.9 ± 0.6 | 0.7 ± 0.2 | 0.5 ± 0.2 | 0.56 ± 0.09 |

| Model |
|--|
| 1G1M1S 0.01 ± 0.04 0.90 ± 0.03 |

| Model | - | + |
|------------------------------|-----------------|-----------------|
| 1G1M2S 0.16617 ± 0.00004 | 1.07 ± 0.04 | 0.69 ± 0.03 |

| Model | a | f | 1 | 1 | 2 | 2 | m_3 | 3 |
|---------|-----------------|-----------------|-----------------|-----------------|----------------|-----------------|------------------|-----------------|
| 3G3M3S | 0.14 ± 0.08 | none | 0.51 ± 0.06 | 0.54 ± 0.04 | -1.9 ± 0.2 | 0.29 ± 0.11 | -0.55 ± 0.12 | 0.67 ± 0.15 |
| 3G3M3SF | 0.2 ± 0.2 | 0.10 ± 0.04 | -1.7 ± 0.2 | 0.4 ± 0.1 | 0.9 ± 0.1 | 0.3 ± 0.2 | 0.0 ± 0.2 | 0.7 ± 0.1 |

Table 3. Comparaison des modèles. NR représente les modèles implémentés durant ce stage. (F) indique les modèles pour lesquels il n’y a pas d’évolution de la fraction de SNe Ia jeunes et vieilles en fonction du redshift.

| Name | Description | Free param | $\ln \mathcal{L}$ | AIC_c | AIC_c | Proba |
|---------|--------------|------------|-------------------|---------|---------|-----------------------|
| 3G2M1S | NR 1S | 4 | 1815 | 1823 | 0.0 | 1.0 |
| 3G2M2S | NR 2S | 5 | 1815 | 1825 | -2.0 | 3.6×10^{-1} |
| 2G2M2S | Howell | 4 | 1818 | 1826 | -3.4 | 1.8×10^{-1} |
| 3G3M3S | NR 3S | 7 | 1812 | 1826 | -3.6 | 1.6×10^{-1} |
| 3G3M3SF | NR 3S (F) | 8 | 1813 | 1829 | -6.3 | 4.3×10^{-2} |
| 2G2M2SF | Howell (F) | 5 | 1823 | 1833 | -9.9 | 7.0×10^{-3} |
| 3G2M1SF | NR 1S (F) | 5 | 1823 | 1833 | -10.4 | 5.5×10^{-3} |
| 3G2M2SF | NR 2S (F) | 6 | 1823 | 1835 | -12.0 | 2.5×10^{-3} |
| 1G1M2S | Kessler (F) | 3 | 1837 | 1843 | -20.2 | 4.1×10^{-5} |
| 1G1M1S | 1 gauss. (F) | 2 | 1872 | 1876 | -53.5 | 2.4×10^{-12} |