The influence of environmental effects on Type Ia Supernovae Standardization

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Abstract

Type Ia Supernovae (SNe Ia) are used as reliable cosmic distance indicators and their standardization is necessary for a more accurate measurement of the cosmological parameters of the Universe using the Hubble diagram. However, the Hubble diagram still shows intrinsic dispersion, potentially influenced by the supernova's environment. In this study, we reproduce Hubble fit diagrams for the Pantheon supernovae data, and also investigate the possibility of introducing various standardization equations for supernovae that exploded in early- and late-type galaxies. We analyze 330 SNe Ia from the Pantheon cosmological sample to study how host galaxy morphology affects SN Ia standardization. We find that SNe Ia hosted by early-type galaxies have different standardization parameters compared to those hosted by late-type galaxies. We conclude that correcting for host galaxy morphology significantly impacts the accuracy of the Hubble diagram fit.

Keywords: *supernovae: general; cosmology: observations, cosmological parameters, distance scale*

1. Introduction

Type Ia supernovae (SNe Ia) are known as standard candles or indicators of cosmological distances. In 2011, Saul Perlmutter, Brian Schmidt and Adam Riess received the Nobel Prize in Physics "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae" (Perlmutter et al., 1999, Riess et al., 1998). In fact, it would be more correct to call SNe Ia standardizable objects. As observational data accumulated, Baade (1938) discovered the universality of their light curves: they show a rapid increase to the maximum in 2-3 days and then a drop of $\sim 3^m$ for every $25 - 30$ days.

In the 1970s, B. W. Rust and Yu. P. Pskovskii independently revealed an empirical relationship linking the supernova luminosity with its light curve parameters (Pskovskii, 1977, Rust, 1974). After that, many models of standardization of Type Ia supernovae were proposed using various parameters of the light curve. In our work, we use one of such models called the SALT2 standardization model (Guy et al., 2007) with two light-curve parameters: the color, $c = (B - V)_{MAX} - \langle B - V \rangle$, and the stretch, x_1, of the supernova's light curve. The observed distance modulus μ taking into account the standardization equation is presented as follows:

$$\mu = m_B - M_B + \alpha x_1 - \beta c, \tag{1}$$

where m_B is the apparent magnitude at maximum in B-band, α, β, M_B are the parameters of the standardization equation. In the recent cosmological analysis (Scolnic et al., 2018), host stellar mass correction (Δ_M) and correction for distance biases due to intrinsic scatter and selection effects (Δ_B), are taken into account.

These corrections are suitable yet not ideal as they do not completely get rid of the distance modulus dispersion on the Hubble diagram. There is an intrinsic supernova luminosity dispersion left, which for one of the most recent cosmological analyses is $\sim 0.1^m$ (Brout et al., 2022). We believe this spread may be related to environmental effects.

The goal of this work is to reproduce the Hubble diagram (supernova's distance modulus vs. redshift) for the Pantheon SN sample (Scolnic et al., 2018), as well as to improve the standardization equation taking

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into account the supernova environment. We investigate the possibility of using different standardization equations for two populations of supernovae: those that exploded in galaxies of early (E-S0/a) and late (Sa-Sd, Ir) morphological types.

2. Data and methodology

Our research is based on a comprehensive dataset from the Pantheon sample (Scolnic et al., 2018). This sample consists of 1048 SNe Ia in the range of $0.01 < z < 2.3$ discovered by various surveys including Pan-STARRS1 (PS1; Rest et al. 2014, Scolnic et al. 2014), Sloan Digital Sky Survey (SDSS; Kollmeier et al. 2019, Supernova Legacy Survey (SNLS; Conley et al. 2011, Sullivan et al. 2011) and Hubble Space Telescope surveys (HST; Riess et al. 2007, Suzuki et al. 2012). To ensure transparency and reproducibility, we sourced the data from GitHub[1] and collected coordinates, redshift (z_{CMB}, z_{HD}), host galaxy mass, stretch and color parameters, distance modulus, and associated errors for each supernova. We adopt the morphological classification of host galaxies for 330 supernovae from Pruzhinskaya et al. 2020. All morphological types of hosts are divided into two general groups: early-type galaxies and late-type galaxies. Thus, 91 SNe Ia from Pantheon sample exploded in early-type galaxies and 240 SNe have late-type hosts.

It is known from the literature (Audcent-Ross et al., 2020, Lampeitl et al., 2010, Pruzhinskaya et al., 2020, Roman et al., 2018, Sullivan et al., 2003, 2006, 2010) that supernova luminosity depends on the host galaxy parameters (for example, metallicity, stellar mass, star formation rate, local color, galactocentric distance, etc.). In our work we study the influence of host galaxy morphology on the cosmological analysis.
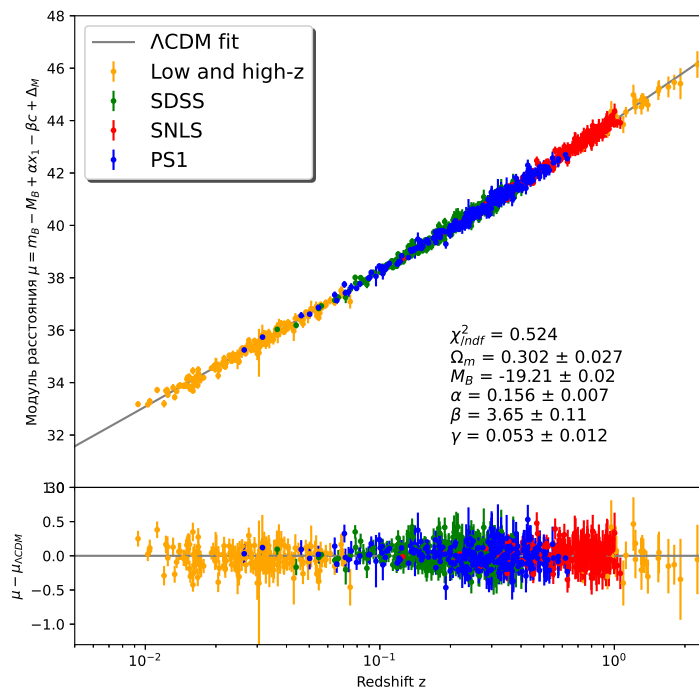
3. Hubble diagram

Figure 1. Hubble diagram plotted with all Pantheon supernovae.

To begin with, it is necessary to reproduce the Pantheon Hubble diagram (see Fig. 1). Assuming the flat ΛCDM cosmology, we found standardization parameters of supernovae (α, β, M_B) and cosmological parameter (Ω_m) by minimizing the Hubble residuals. The value of the Hubble constant corresponds to the one recently measured by Riess et al. (2022): $H_0 = 73.04$ km s^{-1} Mpc^{-1}.

[1] https://github.com/dscolnic/Pantheon

Table 1. Comparison of the obtained values of the free parameters of the Hubble fit diagram with the work Scolnic et al. (2018) for $H_0 = 73.04$ km s^{-1} Mpc^{-1}.

Parameter	This work	Scolnic et al. (2018)
Ω_M	0.302 ± 0.028	0.298 ± 0.022
M_B	-19.204 ± 0.016	—
α	0.155 ± 0.007	0.157 ± 0.005
β	3.687 ± 0.109	3.689 ± 0.089
γ	0.055 ± 0.012	0.054 ± 0.009
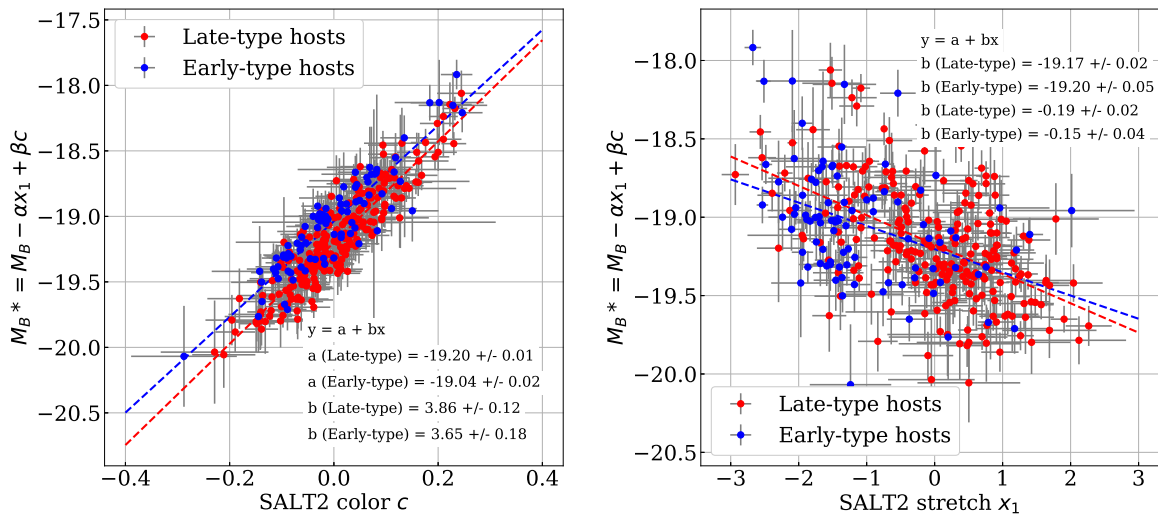
Figure 2. $M_B^\star$ vs. SALT2 parameters. SNe in late-type galaxies are shown with red colour and blue colour represents SNe in early-type galaxies.

The results of the fit are presented in the Table 1 and are in a good agreement with original work of Scolnic et al. (2018).

4. Hypothesis of different standardization equations

Pruzhinskaya et al. (2020) found a dependency between the stretch parameter x_1 and the morphological type of the host galaxy of supernova. It was concluded that supernovae in early-type galaxies were characterized by lower values of the stretch parameter compared to supernovae in late-type galaxies.

It is interesting to see whether the inclination angles of the dependence of $M_B^\star$ (see Eq. 2) – the standardized absolute magnitude – on the color and stretch parameters for the two supernova populations are different. In case of observing a characteristic fracture on the graph, we can conclude that it is worth to introduce various standardization equations for supernovae in various types of galaxies:

$$M_B^\star = M_B - \alpha_1 x_{1,PA} - \alpha_2 x_{1,SF} + \beta_1 c_{PA} + \beta_2 c_{SF} \,, \tag{2}$$

where $\alpha_1 x_{1,PA}$ and $\beta_1 c_{PA}$ are related to early-type galaxies, and $\alpha_2 x_{1,SF}$ and $\beta_2 c_{SF}$ to the late-type ones.

We plotted 330 SNe Ia with known host morphological types on the Fig. 2 of the dependence of $M_B^\star$ on the parameters of color and stretch. The α and β values were taken from the Table 1. The hypothesis is it might be possible to present two different standardization equations for these groups of supernovae and thus we performed linear approximation for them. We do not observe significant differences in the mean values of the slope angle for these two supernova populations. However, on the left subplot we see a shift in magnitudes between two host environments. On the right subplot we do not observe a shift but we can distinguish two clusters, indicating that SNe with smaller x_1 are mainly hosted by early-type galaxies.

5. Supernovae standardization for different groups

Since we are investigating the features of the supernova environment, we separately approximate the Hubble diagrams for supernovae which exploded in early-type galaxies and for ones exploded in late-type galaxies. We perform a Hubble diagram fit for these two subsamples of supernovae without any environmental correction. The cosmological parameter Ω_m is fixed to the value given in the Table 1.

The results in the form of joint confidence contour plots containing correlations of the standardization parameters within 1-σ are presented on the left panel of Fig. 3. The blue color indicates the results of approximation for supernovae in old and passive environment, and red color states for supernovae in young and active environment. Green stars represent standardization parameters obtained for the entire sample of 1048 Pantheon supernovae. At the same time, for two populations, we observe obvious discrepancies in the values of absolute magnitudes M_B depending on color and stretch parameters of the supernovae light curves.
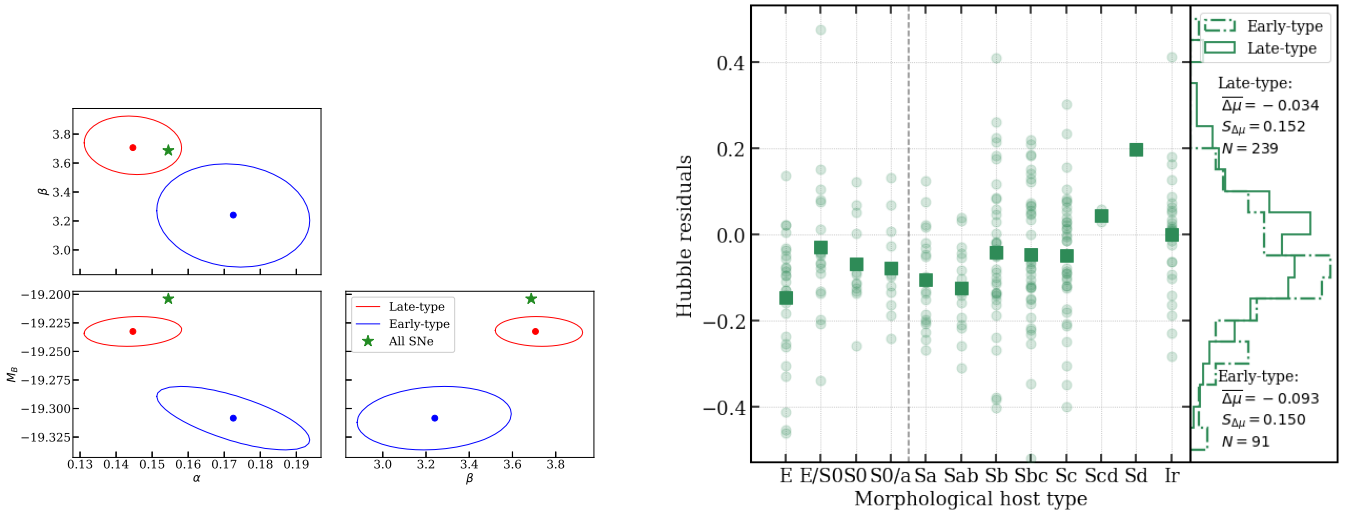

Figure 3. *Left panel:* Joint confidence contours (1-σ) in three-parameter plots of α, β, M_B for fits where the supernovae are split according to the host galaxy morphology. Red ellipses represent SNe in star-forming environment and blue ellipses represent SNe in passive environment. Dots are the central values for each subsample and green stars represent values for the whole Pantheon fit. The density of matter is fixed to the value $\Omega_m = 0.302$ for the full Pantheon fit ($N_{SNe} = 1048$).
Right panel: Hubble residuals for 330 SNe with known host morphology types from Pantheon SNe Ia sample. The squares denote the mean values $\overline{\Delta\mu}$ in each morphological bin. The right subplot is the normalised histogram of $\Delta\mu$ distribution for early-type and late-type morphological supernovae groups.

Thus, we state that without any additional environmental correction the standardization procedure is incomplete. This can also be seen on the Hubble residuals plot. On the right panel of Figure 3 we show the dependence between the Hubble diagram residuals $\Delta\mu = \mu - \mu_{\mathrm{model}}$ and host morphology. SNe in early-type galaxies (old environment) possess slightly smaller values of $\overline{\Delta\mu}$ compared to SNe in late-type galaxies (star-forming environment), which indicates that environmental effects need to be taken into account to fulfil the intrinsic dispersion.

6. Discussion and conclusions

In the course of our study, we successfully approximated the Hubble diagram for the Pantheon sample of 1048 Type Ia supernovae. This was done both for the entire sample as a whole and for individual groups of supernovae, depending on the type of environment – star-forming or passive.

However, the question of introducing various standardization parameters that take into account supernovae environment remains open. The figures showed that the average absolute value of the luminosity of supernovae at the maximum differ depending on the host galaxy type. In particular, supernovae in late-type galaxies have large values of the stretch parameter compared to supernovae in the passive environment. This leads to a shift depending on the color (see Fig. 2). In the future, we plan to continue exploring the possibility of introducing various standardization equations for different populations of supernovae: not only

the host galaxy morphological type, but also the galactocentric distance can be considered as a criterion for attribution to a particular population.

We confirm that environmental correction should be introduced in order to minimize the luminosity dispersion on the Hubble diagram.

The code to perform the described analysis is availavle at `GitHub`[2].

References

Audcent-Ross F. M., Meurer G. R., Audcent J. R., Ryder S. D., Wong O. I., Phan J., Williamson A., Kim J. H., 2020, Mon. Not. R. Astron. Soc. , 492, 848

Baade W., 1938, Astrophys. J. , 88, 285

Brout D., et al., 2022, Astrophys. J. , 938, 110

Conley A., et al., 2011, Astrophys. J. Suppl. Ser. , 192, 1

Guy J., et al., 2007, Astron. Astrophys. , 466, 11

Guy J., et al., 2010, Astron. Astrophys. , 523, A7

Kollmeier J., et al., 2019, in Bulletin of the American Astronomical Society. p. 274

Lampeitl H., et al., 2010, Astrophys. J. , 722, 566

Perlmutter S., et al., 1999, Astrophys. J. , 517, 565

Pruzhinskaya M. V., Novinskaya A. K., Pauna N., Rosnet P., 2020, Mon. Not. R. Astron. Soc. , 499, 5121

Pskovskii I. P., 1977, , 21, 675

Rest A., et al., 2014, Astrophys. J. , 795, 44

Riess A. G., et al., 1998, Astron. J. , 116, 1009

Riess A. G., et al., 2007, Astrophys. J. , 659, 98

Riess A. G., et al., 2022, Astrophys. J. Lett. , 934, L7

Roman M., et al., 2018, Astron. Astrophys. , 615, A68

Rust B. W., 1974, PhD thesis, Oak Ridge National Laboratory, Tennessee

Scolnic D., et al., 2014, Astrophys. J. , 795, 45

Scolnic D. M., et al., 2018, Astrophys. J. , 859, 101

Sullivan M., et al., 2003, Mon. Not. R. Astron. Soc. , 340, 1057

Sullivan M., et al., 2006, Astrophys. J. , 648, 868

Sullivan M., et al., 2010, Mon. Not. R. Astron. Soc. , 406, 782

Sullivan M., et al., 2011, Astrophys. J. , 737, 102

Suzuki N., et al., 2012, Astrophys. J. , 746, 85

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[2]https://github.com/pruzhinskaya/SN_environment