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The influence of host galaxy morphology on Type Ia Supernovae standardization and cosmological analysis

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Type Ia Supernovae (SNe Ia) are known to be good distance indicators in the Universe. It becomes possible thanks to the empirical relation between SN light curve parameters and luminosity. However, the Hubble diagram still shows some remaining intrinsic dispersion, which can be related to the effect of supernova environment.

In this work we study how the host galaxy morphology affects SN Ia standardization and cosmological analysis using 330 supernovae from the Pantheon cosmological sample. We reproduce the Pantheon Hubble diagram fit and perform the fit separately for two SN groups according to the morphological type of their host galaxies: early-type and late-type. We found that in passive stellar environment SNe Ia have higher α and smaller β standardization parameters than supernovae hosted by late-type galaxies. The early-type galaxies contain brighter supernovae after stretch and colour corrections. Thus, the host morphology correction do affect the Hubble diagram fit. We also notice that the host mass correction alone is not enough to take the influence of the environment into account. The observed intrinsic scatter in SNe Ia luminosity can still be partially compensated by a more correct consideration of the environmental correction.

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1. Introduction

A supernova (SN) explosion is identified as a sudden increase in the brightness of a star by 9-10^m. Thermonuclear supernovae or Type Ia Supernovae (SNe Ia) appear as a result of explosion of a carbon-oxygen white dwarf that had reached its mass limit — the Chandrasekhar limit — which is accompanied by a huge release of energy. There are several scenarios of the mass increase. The first one is called the single-degenerate scenario; in this case the accretion from a companion star is responsible for the explosion of the white dwarf [1]. Another scenario is called the double-degenerate scenario because it happens in binaries consisting of two white dwarfs [2, 3].

SNe Ia have uniform light curves and similar luminosity at maximum light that makes them good distance indicators and cosmological probes [4, 5]. For example, in the recent cosmological analyses the intrinsic luminosity dispersion of SNe Ia is about 0.05-0.1^m [6, 7]. Due to their huge luminosity ($M_B \simeq -19.5^m$), SNe Ia can be discovered at high distances. Thus, various cosmological models can be tested using the Hubble diagram — the dependence between SN Ia distance modulus and redshifts.

However, before using SNe Ia in distance measurements their light curves should be standardized. Since the pioneering works of B. W. Rust, Yu. Pskovskii, and M. Phillips [8–10], it is known that Type Ia Supernova luminosity depends on the light curve shape. What is more, there is a correlation between SN luminosity and its color [11, 12].

There are different standardization models that are based on parameters extracted from SN light curves and spectra [13–15]. In our work we use the SALT2 standardization model [14] with two light-curve parameters for each SN Ia. These parameters are color — the offset between the maximum brightness in B-band and the mean color value, $c = (B-V)_{MAX} - \langle B-V \rangle$, and stretch x_1 which is responsible for the light-curve shape.

Thus, SNe Ia can be standardized with an empirical relationship between the parameters of the supernova light curve and its absolute magnitude [12]:

$$M_B^{\star} = M_B - \alpha x_1 + \beta c, \tag{1}$$

where M_B is a standardized absolute magnitude of the SNe Ia in B-band for $x_1 = c = 0$; α and β describe, respectively, the stretch and colour law for the whole SN Ia population.

Unfortunately, applying both stretch and color corrections does not lead to a complete standardization of SN luminosity. However, it is turned out that SN luminosity also depends on the environment, i.e. the physical properties of its host galaxy. For this goal different parameters are used, for example, stellar mass, metallicity, age, color, and host morphology. The correlations between various physical parameters of the host and supernova luminosity is well studied in the literature (e.g., [16] and references there).

In this work we reproduce the Pantheon [6] Hubble diagram fit and study the difference in the nuisance parameters M_B, α, β for two sub-groups of SNe Ia: supernovae exploded in late-type and early-type galaxies. In Section 2 we present the data used for the analysis. In Section 3 we reproduce the Pantheon Hubble diagram fit. Section 4 contains the main results of this work — the distance modulus residuals and contour plots for α, β, γ, and M_B parameters for SNe exploded in galaxies of different morphological types. We conclude this work in Section 5.

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2. Data

We use the Pantheon sample which consists of supernovae discovered by the Pan-STARRS1 Medium Deep Survey, SDSS, SNLS, HST and several low-z surveys. In total there are 1047 SNe Ia in the range of $0.01 < z < 2.3$ [6]. For each supernova, its location, $z_{\rm CMB}$, $z_{\rm HD}$, host galaxy mass, stretch and color parameters, distance modulus and all the errors are taken from GitHub[1].

The morphological classification of host galaxies for 330 Pantheon supernova is taken from Pruzhinskaya et al., 2020 [17]. They divided all morphological types into 2 groups: early-type galaxies (Early-type, Pa (passive), E, E/S0, S0, S0/a) and late-type galaxies (Sa, Late-type, Sab, Sb, Sbc, Sc, Sb/Sbc/Sc, Scd, Sd, Scd/Ir, Ir, SF (star-forming), Late-type). Thus, 91 SNe from the Pantheon sample exploded in early-type galaxies and 239 SNe have late-type hosts. The authors also found the dependence between the stretch parameter of a supernova light curve and its host type — SNe Ia in early-type galaxies have smaller x_1 than those in late-type galaxies, and no correlation was found for the color parameter. Moreover, according to [17] the mean Hubble diagram residual $\overline{\Delta\mu}$ in the early-type galaxies is smaller than the one in the late-type galaxies. Therefore, SNe Ia in the early-type hosts are brighter after the light-curve corrections than those in the late-type. Since two SN groups have unequal sizes, the significance of the obtained results were verified with the Welch's t-test, a two-sided test for the null hypothesis that two normally distributed populations have equal means [18, 19]. According to it, the difference is significant with the p-value equal to 8.8×10^{-15} and 0.002 for $\overline{x_1}$ and $\overline{\Delta\mu}$ parameters, respectively (see table 4 of [17]).

3. Hubble diagram fit

First of all, to study the influence of such an environmental parameter as host galaxy morphology we have to reproduce the Hubble diagram and compare the results with the original work of Scolnic et al. [6].

Distance modulus μ after standardization is:

$$\mu = m_B - M_B + \alpha x_1 - \beta c + \Delta_M(\gamma) + \Delta_B, \tag{2}$$

where m_B is an apparent magnitude in B band, α, β, M_B are the parameters of the standardization equation, Δ_M is the correction for the host galaxy mass and Δ_B is the correction for the selection effects.

All supernovae from the Pantheon sample were put on the Hubble diagram. To obtain the standardization and cosmological parameters we minimized the following χ^2 using the Python package IMINUIT:

$$\chi^2(\alpha, \beta, \gamma, M_B, \Omega_m) = \Delta\vec{\mu}^T \cdot \mathbf{C}^{-1} \cdot \Delta\vec{\mu}, \tag{3}$$

where $\Delta\vec{\mu} = \vec{\mu} - \vec{\mu}_{\rm model}$, and $\mathbf{C}$ is the covariance uncertainty matrix including both statistical and systematic errors. Theoretical distance modulus $\vec{\mu}_{\rm model} = 5\log_{10} d_L - 5$ is calculated for the flat ΛCDM cosmology ($\Omega_m + \Omega_\Lambda = 1$), where Ω_m is the density of matter, and $\vec{\mu}$ is the observed distance modulus. The iteration stopping criteria is that the difference between the previous and the next

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

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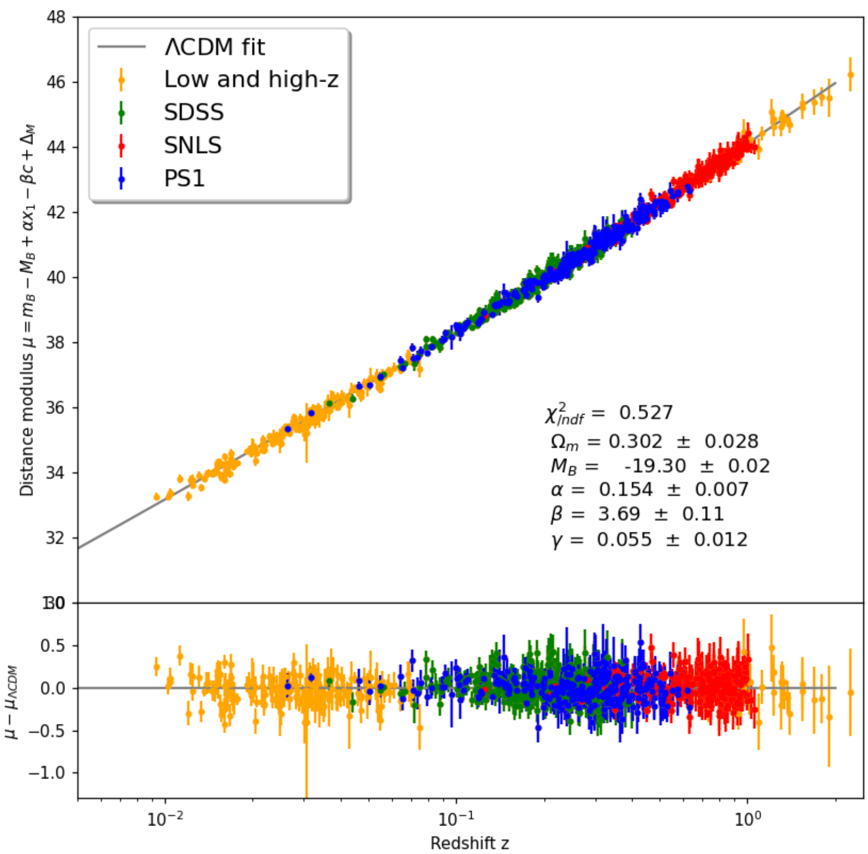

Figure 1: Hubble diagram for the Pantheon SNe Ia sample.

Table 1: Comparison between the parameters in the Hubble diagram fit for H_0 = 73.04 km/s/Mpc

Parameter	This work	Scolnic et al., 2018 [6]
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

iterations related to the obtained value should be less than 0.001 for each of the 5 minimization parameters ($\frac{a_i - a_{i-1}}{a_{i-1}} < 0.001$, $a = \alpha, \beta, \gamma, M_B, \Omega_m$). The Hubble constant H_0 is fixed to the value of 73.04 km s^{-1} Mpc^{-1} [20].

The result of the fit is in good agreement with Scolnic et al. [6] (see Table 1). Thus, we conclude that the reproduction of the Hubble diagram was successful and we will use the code in our further research. We present the reproduced Hubble diagram in Fig. 1.

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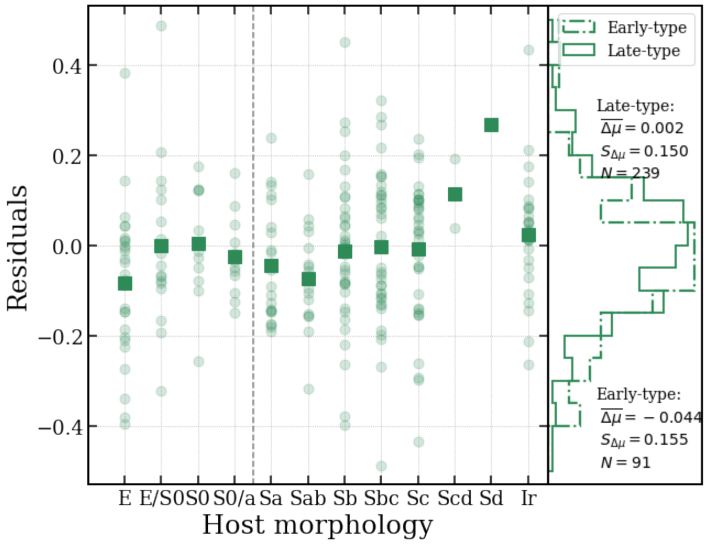

Figure 2: Hubble residuals for Pantheon SNe Ia sample. The squares denote the mean values $\overline{\Delta\mu}$ in each morphological bin. The right subplot is the normalised histogram of $\Delta\mu$ distribution for early-type and late-type morphological groups.

4. Results

To take into account the influence of the supernova environment on the Hubble diagram, the host mass correction (a mass step) is usually included to the cosmological analysis (e.g., [21]). In [6] it is introduced via $\Delta_M(\gamma)$ distance correction, where γ is a parameter of the fit.

In Fig. 2 we show the dependence between the Hubble diagram residuals $\Delta\mu = \mu - \mu_{\rm model}$ and host morphology for the full 5-parameter fit (including γ parameter). For SNe in early-type galaxies (old environment) the value of $\overline{\Delta\mu}$ is slightly smaller than for SNe in late-type galaxies (star-forming environment), which indicates that the mass step correction does not fully account for the environmental effect.

We also performed the Hubble diagram fit separately for 2 sub-groups of SNe Ia divided by the morphological type of their hosts to compare the central values of nuisance parameters α, β, γ, M_B. The density of matter is fixed to the value $\Omega_m = 0.302$ from the Hubble diagram fit of the whole Pantheon sample. We present contour plots as correlations between the minimization parameters in Fig. 3, 4 for the fit with and without host mass correction γ, respectively. We can see that the differences in central values are more than 1-σ, especially for β and M_B parameters. This difference is seen even after the environmental correction for host galaxy mass (Fig. 3). Thus, we conclude that the γ parameter is not enough to take into account the environmental correction.

5. Discussion and conclusions

In this work we reproduced the Pantheon Hubble diagram and studied how the host galaxy morphology affects the distance modulus residuals and nuisance parameters of SN Ia standardisation equation.

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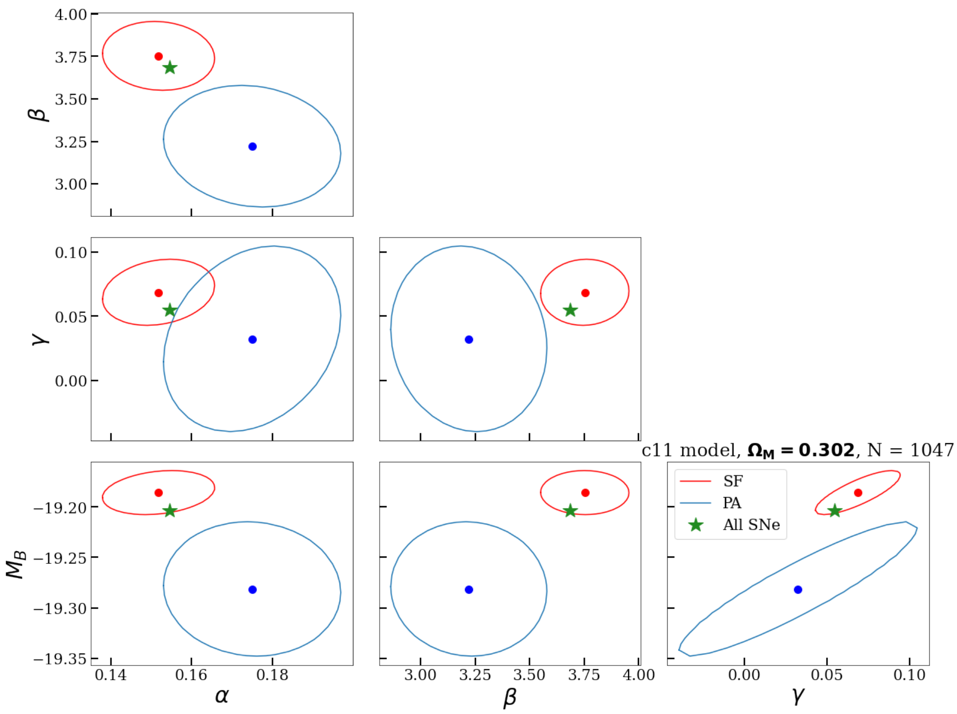

Figure 3: Joint confidence contours (1-σ) in four-parameter plots of α, β, γ, M_B for fits where the SNe are split according to the host galaxy morphology. Red ellipses represent SNe in star-forming environment and blue ellipses represent SNe in passive environment. Dots are the central values for each 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 ($N = 1047$).

We divided the Pantheon supernovae into two groups according to the morphological type of their host galaxies: early-type and late-type. Performing a separate Hubble diagram fit for these groups we found a more than 1-σ difference for β and M_B parameters. Thus, the host morphology correction do affect the Hubble diagram fit.

We also noticed that the host mass correction alone is not enough to take the influence of the environment into account. The observed intrinsic scatter in SNe Ia luminosity can still be partially compensated by a more correct consideration of the environmental correction.

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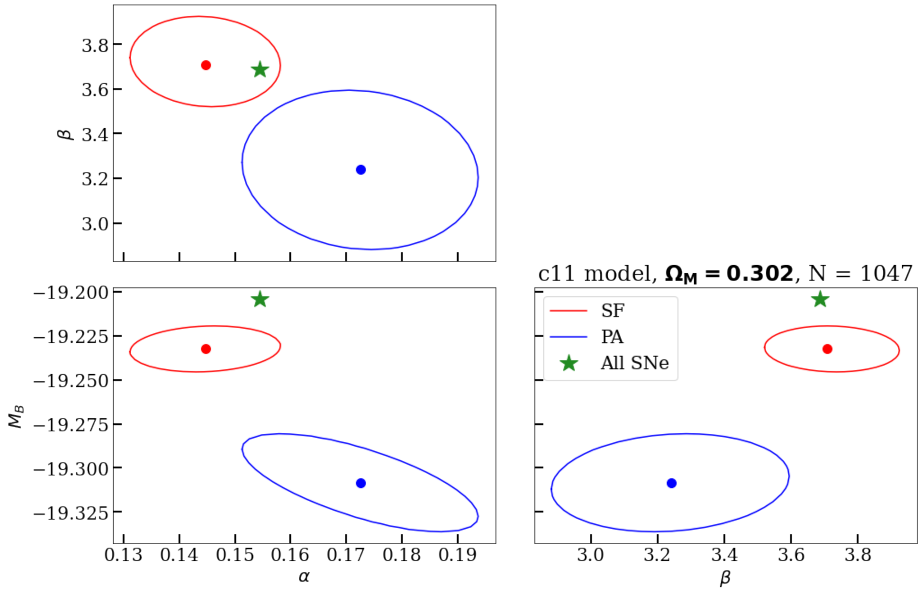

Figure 4: Joint confidence contours (1-σ) in three-parameter plots of α, β, M_B for fits where the SNe are split according to the host galaxy morphology. Red ellipses represent SNe in star-forming environment and blue ellipses represent SNe in passive environment. Dots are the central values for each 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 ($N = 1047$).

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