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How we can account for Type Ia Supernova environment in cosmological analysis*

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Among the other types of supernovae, Type Ia Supernovae (SNe Ia) have less luminosity dispersion at maximum light and show higher optical luminosities. These properties allow to use them as cosmological distance indicators that led to the discovery of the accelerating expansion of the Universe. However, even after the luminosity correction for stretch and colour parameters — “standardisation”, there is a remaining dispersion on the Hubble diagram of ~ 0.11 mag. This dispersion can be due to SN environmental effects — progenitor age, chemical composition, surrounding dust. In this work we study the impact of SN galactocentric distance (376 PANTHEON SNe Ia) and host-galaxy morphology (275 PANTHEON SNe Ia) on the

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light curve parameters. We confirm that the stretch-parameter depends on galactocentric distance and host morphology, but there is no significant correlation for the colour. In the epoch of large transient surveys such as the Vera Rubin Observatory's Legacy Survey of Space and Time, a study of environment and other possible sources of systematical uncertainties in the cosmological analysis is of high priority.

I. INTRODUCTION

Type Ia Supernovae (SNe Ia) are known to be good distance indicators in the Universe. However, we still know a little about their mechanism of explosion and progenitor scenarios. Moreover, we cannot explain the empirical relation between their luminosity and light curve decline rate discovered in the middle of the last century [1, 2]. However, this relation with some modifications is applied to standardise SNe Ia in cosmological analyses [3, 4].

In this paper, we considered one more parameter that affects the SN luminosity, i. e. the environmental correction¹. For describing the environment we used the distance between each supernova and its host galaxy center — galactocentric distance, and morphological type of host galaxy.

II. DATA

The analysis is performed with two data sets:

- (i) Rigault et al., 2015 supernova sample with redshift $0.02 < z < 0.08$ [7].
- (ii) PANTHEON cosmological sample [3] that represents a compilation of Pan-STARRS [8, 9], Sloan Digital Sky Survey [10, 11], SuperNova Legacy Survey [12, 13], various low- z and Hubble Space Telescope supernova samples and consists in total of 1047 SNe Ia ranging from $0.01 < z < 2.3$.

To characterise the SN light curves, we used SALT2 x_1 (stretch) and c (colour) parameters [14]. The x_1 parameter describes the time-stretching of the light curve. The c parameter

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¹ The paper is a continuation of the author's studies of supernova environment, e. g. [5, 6].

is the colour offset with respect to the average at the date of maximum luminosity in B -band, i.e. $c = (B - V)_{max} - \langle B - V \rangle$. We adopted the classical standardisation equation of the distance modulus:

$$\mu = m_B^* - M_B + \alpha x_1 - \beta c, \quad (1)$$

where m_B^* — value of the B -band apparent magnitude at maximum light, M_B is a standardised absolute magnitude of the SNe Ia in B -band for $x_1 = c = 0$; α and β describe, consequently, the stretch and colour law for the whole SN Ia population.

III. ANALYSIS

A. Comparison of environmental parameters

To take into account the effect of the environment on the SN luminosity, different environmental parameters are used. Among them the morphological type [15–19], metallicity [20], stellar mass [16–20], colour [21], star formation rate (SFR; [17, 19, 22]), specific SFR [17, 19] of host galaxy. There are as well the local parameters which are the same physical quantities but characterising the environment in a few kiloparsecs around a supernova, i. e. local colour [21], local SFR [7], and local metallicity [23]. The local parameters offer the advantage of a better description of the supernova nearby environment, while the advantage of the global parameters is their accessibility for measurements at high redshifts.

To study the relation between the local star formation rate, host galaxy morphology, and relative galactocentric distance, i. e. normalised to the size of the host, we took Rigault et al., 2015 [7] supernova sample. The local SFR was obtained by [7] using *GALEX* data and related to the 1 kpc region around SN Ia. The Hubble morphological types of host galaxies were extracted from SIMBAD [24], HyperLEDA [25], and NED [26] astronomical databases. To measure the relative galactocentric distance we calculated the angular separation between the SN position and its host galaxy center; then, we divided this separation by the size of the host characterised by D_{25} parameter which is the length of the projected major axis of a galaxy at the isophotal level 25 mag/arcsec² in the B -band.

In this analysis we considered 70 SNe Ia. In Fig. 1 the relation between the local SFR, galaxy morphology, and relative galactocentric distance is shown. We observe the correlation

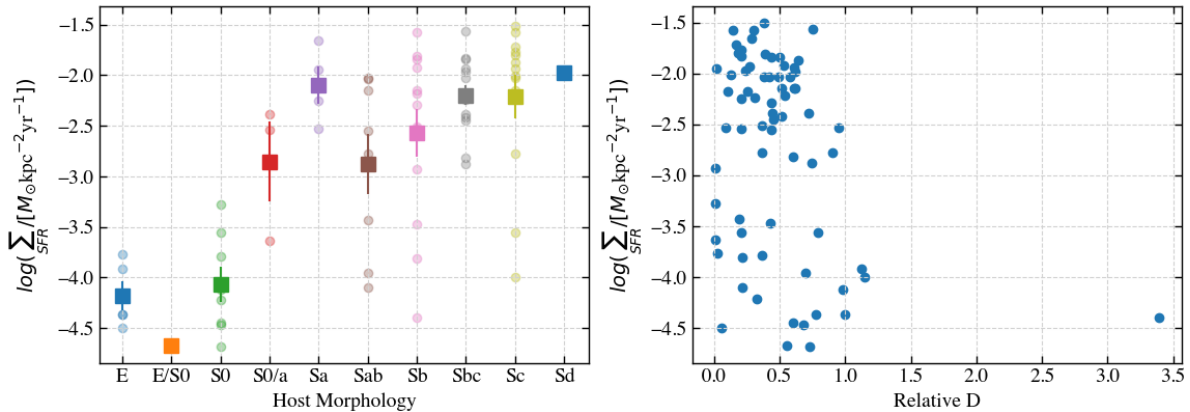


FIG. 1: Local star formation rate in 1 kpc region around SN Ia vs. morphological type of the supernova host galaxies (left subplot) and vs. relative galactocentric distance (right subplot) for the Rigault et al., 2015 [7] supernova sample. Mean values of the data points and associated standard deviations in each morphological bin are marked with squares with error bars.

between the local SFR and galaxy morphology — it is explained by the fact that in elliptical galaxies there is no ongoing star formation and old metal-poor stars are mainly located. Despite the low statistics we also see that the SNe Ia with a relative galactocentric distance $D > 1$ have a lower local SFR.

B. Impact of galactocentric distance on SALT2 parameters

We determined the galactocentric distance for PANTHEON SNe with $z \lesssim 0.2$. Since the PANTHEON sample contains only the supernova coordinates, the host coordinates were extracted from SDSS DR16 [27] and SIMBAD database [24]. The absolute galactocentric distance D for each object was calculated as $D \simeq d_a \times \Theta$. The angle Θ — angle between supernova and the host galaxy center. The angular distance d_a for the flat Λ CDM cosmology with $\Omega_{\Lambda} = 0.7$ and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ is

$$d_a = \frac{c}{H_0 \times (1+z)} \int_0^z \frac{dz'}{\sqrt{(1-\Omega_{\Lambda}) \times (1+z')^3 + \Omega_{\Lambda}}}, \quad (2)$$

where z is the redshift, c is the speed of light. Therefore, we determined the galactocentric distance for 376 PANTHEON supernovae.

Then, we analysed how the SALT2 parameters, x_1 and c , are distributed as a function of galactocentric distance. We divided our sample into two supernova groups: those with

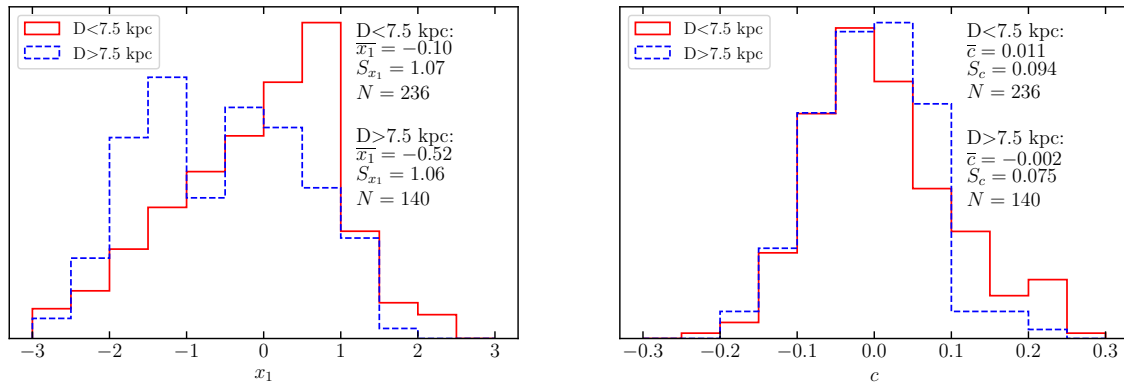


FIG. 2: Normalised distribution of x_1 (left subplot) and c (right subplot) SALT2 parameters for two groups of supernovae: those with $D < 7.5$ kpc and those with $D > 7.5$ kpc.

$D < 7.5$ kpc and those with $D > 7.5$ kpc. The quantitative criteria of such separation is taken from [28]. As we can see from Fig. 2, the difference in the stretch mean values is $\Delta_{\bar{x}_1} = 0.42$ with a significance $> 3\sigma$. For more distant supernovae the average stretch value is smaller, which means that they are dimmer before stretch correction (see Equation 1). As for the colour parameter, we do not observe any significant difference between two groups.

C. Impact of host morphology on SALT2 parameters

In this section we analysed how another parameter of environment, i. e. host galaxy morphology affects the SALT2 parameters.

Using SIMBAD, HyperLEDA, and NED astronomical databases, we determined the host morphological type for 275 Pantheon SNe². Since the number of SNe Ia that exploded in galaxies with different morphological type is not the same, we also combined the “close” morphological types in three groups: “Early-type”, “Late-type”, and “Irregular” (see Table I). To the ‘Early-type’ galaxies we assigned [E-S0/a] Hubble types, to the “Late-type” — [Sa-Sd], and to the “Irregular” — [Ir] as well as those with uncertain classification [Scd/Ir].

The distribution of stretch and colour SALT2 parameters depending on host galaxy

² The detailed list of Pantheon SNe with host galaxies and their morphological types is given in Pruzhinskaya et al., 2020 [6]. The total number of studied SNe in [6] is higher (330 objects) since the galaxies classified as star-forming were also included to the analysis. Here, we considered three different groups instead of two as it was done in [6], and we can assign the star-forming galaxies to none of these groups.

TABLE I: Three groups of 275 Pantheon Type Ia Supernovae divided according to their host morphology with the number of supernovae in each group (N), mean and standard deviation of the SALT2 x_1 and c light-curve parameters, and the Hubble residuals $\Delta\mu$.

Morph. group	N	$\overline{x_1}$	S_{x_1}	\overline{c}	S_c	$\overline{\Delta\mu}$	$S_{\Delta\mu}$
Early-type	91	-1.05 ± 0.10	0.99	-0.003 ± 0.010	0.093	-0.092 ± 0.016	0.149
Late-type	153	-0.23 ± 0.08	1.03	0.018 ± 0.007	0.088	-0.057 ± 0.012	0.153
Irregular	31	0.23 ± 0.13	0.73	-0.026 ± 0.013	0.073	0.001 ± 0.023	0.129

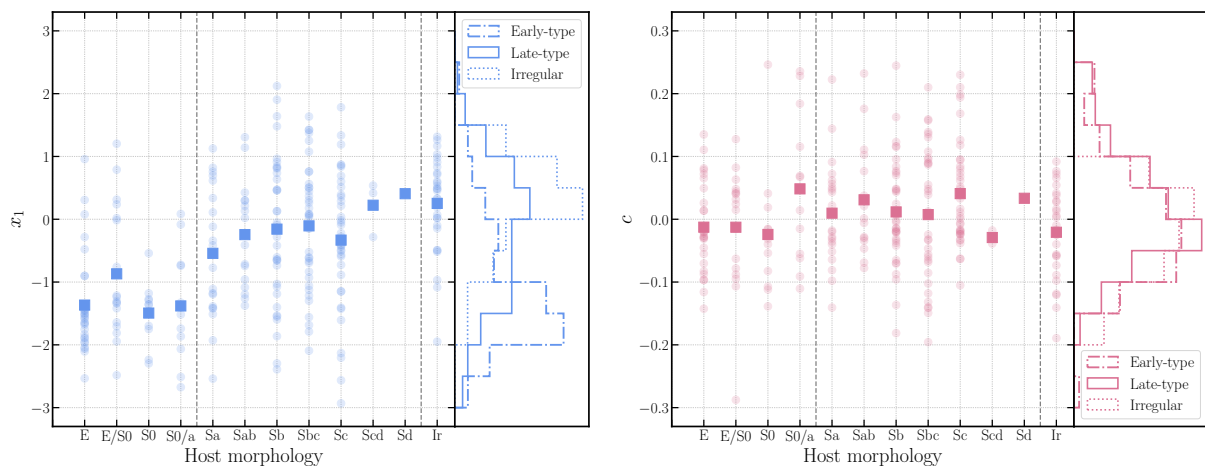


FIG. 3: Distribution of x_1 (left) and c (right) SALT2 parameters depending on host galaxy morphology. The right-hand subplots are the normalised histograms of x_1 and c distributions for three morphological groups of galaxies, respectively. Dashed black lines denote the borders between different morphological groups, i. e. “Early-type”, “Late-type”, “Irregular”.

morphology is given in Fig. 3. In the left subplots each circle corresponds to a supernova and the squares are the mean values of the parameters for each morphological type. In the right subplots the normalised histograms of x_1 and c distributions for three morphological groups of galaxies are given. As we can see from Fig. 3, the SNe from the early-type galaxies tend to have the smaller values of x_1 , the SNe in the irregular galaxies — the higher x_1 values, and the SNe in late-type galaxies have x_1 -distribution with a mean value in between both (see also Table I). However, we do not observe the difference for the colour parameter, the most significant difference ($\sim 2.9\sigma$) is seen between the supernovae hosted by late-type and irregular galaxies.

IV. DISCUSSION

A. Hubble diagram residuals

The dependencies between the SALT2 parameters and host morphology suggest that SNe Ia can be physically different in old metal-poor and young star-forming environment. To investigate the impact of this effect on the Hubble diagram, we reproduced the Hubble diagram from the PANTHEON analysis for the flat Λ CDM cosmology and considered the distance modulus residuals depending on host galaxy morphology (Fig. 4). The observational distance modulus were calculated with account taken of stretch and colour correction. However, we removed from the distance modulus the host stellar mass correction (see e. g. [29, 30]), that is responsible for the environmental correction in the PANTHEON cosmological analysis.

The distribution of the Hubble diagram residuals depending on host galaxy morphology is shown in Fig. 4. It can be noticed that the mean residuals increase from the “Early-type” group to “Irregular” one. For instance, it means that SNe Ia in the early-type hosts are brighter after the stretch and colour corrections than those in the late-type. Therefore, the including of the host galaxy term to the standardisation procedure of SNe Ia is important for the accurate cosmological analysis.

B. The optimal parameters

It is needed to stress that the galactocentric distance we used in Section III B is the absolute distance and therefore can not serve as a good parameter to distinguish the old and young stellar environment. The galaxies have different sizes and what is far for a one is not necessary far for another. The use of the relative distance is more appropriate [31]. The host morphology parameter also can be debated. In the elliptical galaxies the stellar population is mostly old and metal-poor, while in the spiral galaxies there are both, old (halo) and young stars (star formation regions in the disk). Therefore, in the further studies we plan to use the information about the relative galactocentric distance and host morphology. In our opinion the combination of both can be an effective parameter of environment.

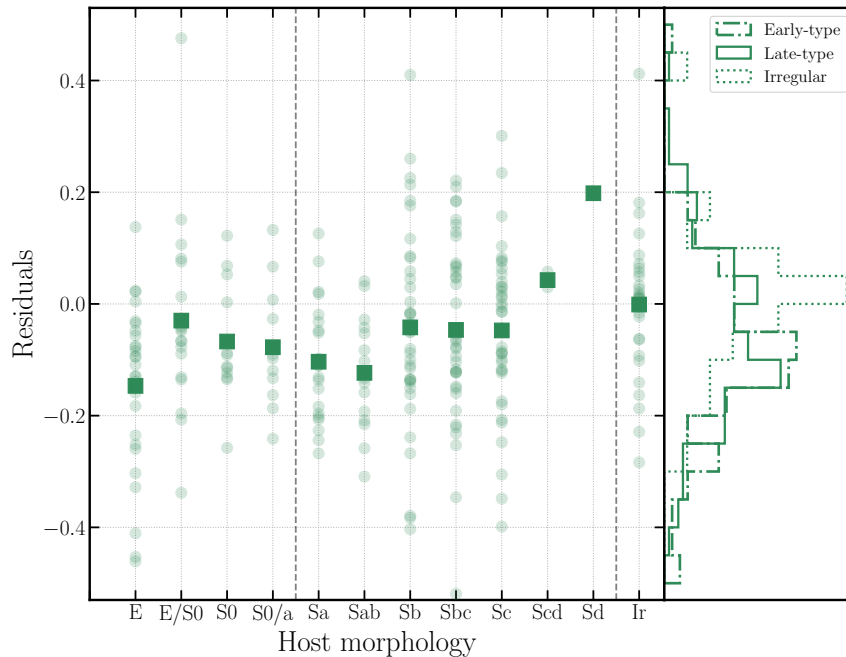


FIG. 4: Distribution of the Hubble diagram residuals depending on host galaxy morphology. The right-hand subplot is the normalised histograms of $\Delta\mu$ distribution for three morphological groups of galaxies. Dashed black lines denote the borders between different morphological groups, i. e. “Early-type”, “Late-type”, “Irregular”.

V. CONCLUSIONS

Using the PANTHEON cosmological sample of SNe Ia we studied the influence of galactocentric distance and host galaxy morphology on SALT2 light curves parameters and distance modulus residuals on the Hubble diagram.

- We confirm that the stretch parameter of SNe Ia significantly depends on the host morphology and galactocentric distance. The supernovae with lower stretch are hosted mainly by elliptical and lenticular galaxies or far from the center of host galaxies.
- No significant correlation for the SALT2 colour parameter is found neither for separation by the galactocentric distance nor by the morphological groups.
- The host galaxy morphology affects the residual dispersion on the Hubble diagram. The mean distance modulus residual in early-type galaxies is smaller than the one in

late-type or irregular galaxies, which means that early-type galaxies contain brighter supernovae after stretch and colour corrections.

- As an optimal parameter to characterise the supernova environment we suggest to use a combination of the relative galactocentric distance and the host morphology.

Our results are consistent with previous studies, e. g. [6, 19, 32]. We confirm the importance of including a host galaxy parameter into the standardisation procedure of SNe Ia for future measurements of cosmological parameters.

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