

Supernovae — a tool for observational cosmology

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Type Ia Supernovae (SNe) are excellent distance indicators in the Universe. Observations of distant SNe Ia led to the discovery of the accelerating expansion of the Universe. The most recent analysis of SNe Ia indicates that considering a flat Λ CDM cosmology, the contribution of dark energy in the total density of the Universe is $\sim 70\%$. Cosmological parameters are estimated from the “luminosity distance-redshift” relation of SNe. Currently a lot of attention is paid to standardization of SNe, i.e. to increase of the accuracy of luminosity distance determination. The uncertainty on the redshift is quite often considered negligible. The redshift most often used corresponds to the one of SN host galaxy relative to CMB frame. In fact the redshift observed on the Earth also includes the contribution from the Doppler effect induced by peculiar velocities related to the Hubble flow. The existing methods to correct redshift for peculiar velocity contribution do not work in clusters of galaxies, the biggest virialized systems in the Universe where peculiar velocities can reach 1000 km s^{-1} . To count for the effect of peculiar velocities in galaxy clusters we studied 145 SNe from the Nearby Supernova Factory and found 11 objects that belong to the clusters. We used the galaxy cluster redshift instead the host galaxy redshift to construct the Hubble diagram. The applied technique allowed to improve the redshift measurements and to decrease the spread on the Hubble diagram. The peculiar velocity correction of galaxies inside galaxy clusters has to be taken into account in future cosmological surveys such as LSST.

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[†]A footnote may follow.

1. Introduction

1.1 A brief story of supernovae

A hundred years ago our conception of the Universe was remarkably different from the modern. The estimations of the Milky Way size spanned from 5 to 300 thousand light years, the location of the Solar System inside the Milky Way remained an open question, and there were no agreement whether spiral nebulae belong to the Milky Way or not. Devoted to these controversies, the Great Debate between Harlow Shapley and Doust Curtis took place in 1920 [1]. Objects, which today are known as novae and supernovae, were prominent actors in this dispute. However, at that time all new stellar-like bright objects, gradually fading in months, were called “novae”. Curtis supported the “Island Universe”, which consisted in the fact that “spirals” — nebulae that were observed in the sky — are other galaxies like ours. Shapley, on the contrary, thought that the Andromeda and other nebulae were only a part of the Milky Way. One of Shapley’s arguments was the fact that in the case of the “Island Universe” luminosity of some novae would reach the luminosity of the Galaxy. The existence of such objects at that time was in serious doubt. Curtis, in turn, based his argument on the fact that taking “spirals” as a part of our galaxy it will be necessary to introduce two classes of novae, because in the “spirals” novae were on an average 7^m dimmer than the others. The idea of the existence of a such duality under otherwise equal characteristics seemed implausible. In order to achieve agreement in absolute magnitudes of novae, it was necessary to put the “spirals” at much greater distances. Noteworthy is that in this case, as noticed by Curtis, the absolute size of the “spirals” matches the size of our galaxy. It turned out that Curtis was right. Finally the “Island Universe” hypothesis was confirmed by Edwin Hubble through observations of Cepheids in nebulae such as Andromeda.

Once the distances to the hosts of novae stars have been determined, it became possible to estimate their absolute magnitudes. It turned out that novae in nebulae are orders of magnitude brighter than others, and astronomers realized that novae should be divided into two subclasses. This division occurred in 1934, when Fritz Zwicky and Walter Baade suggested the term “supernovae”¹ for exceptionally bright novae [2]. In 1938 Baade noticed that supernovae are a more homogeneous class of objects than novae. He found the mean absolute magnitude at maximum light for 18 supernovae to be -14.3^m with a dispersion $\sim 1.1^m$. Thereby supernovae were considered as good distance indicators in the Universe [3, 4, 5]. In 1941 Rudolph Minkowski, obtained and analyzed the first spectra of supernovae, dividing them into two main types [6]. To the Type I he attributed the supernovae which had no hydrogen lines in their spectra and the entire spectrum consisted from broad maxima and minima which were not possible to explain². Type II supernovae, on the contrary, showed presence of hydrogen in their spectra. Over time, a more detailed classification appeared (Fig. 1). Type I supernovae were divided into three subtypes: Ia, Ib and Ic. It was found that the SN Ia phenomenon arises from a thermonuclear explosion of a white dwarf, and SNe II and SNe Ib/c are the core collapse of a massive star at the final stage of its evolution. Thus, SN Ia explosions differ in the origin from the rest of supernovae.

¹It took a couple of years to lose the hyphen.

²Type I SNe spectra were decrypted later by Soviet astronomer Yu.P. Pskovskii [7], however the first who tried to explain the minima in Type I SN spectrum as absorption lines was D. McLaughlin [8].

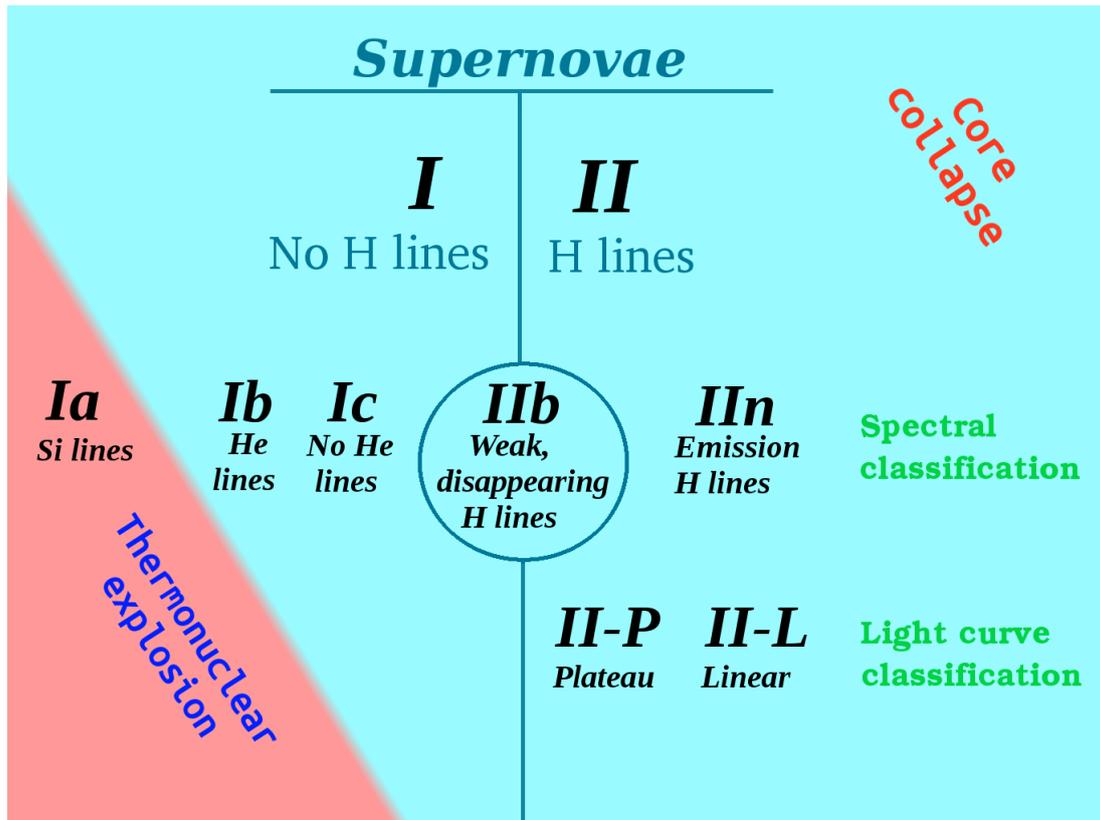


Figure 1: Supernova classification.

Only when SNe were divided into types and subtypes the most homogeneous Type Ia began to be used as cosmological distance indicator. Studies of supernovae led to the one of the greatest discoveries in observational cosmology: the discovery of the accelerating expansion of the Universe. In 1998–1999, two international teams of astronomers, one of which was led by Brian Schmidt and Adam Riess and the other by Saul Perlmutter, reported that the cosmological expansion is accelerating [9, 10]. The most recent analysis of SNe Ia indicates that considering a flat Λ CDM cosmology, our Universe is accelerating with $\Omega_\Lambda = 0.705 \pm 0.034$ [11]. However, this important discovery would not have been possible without another discovery — the discovery of the relation between the peak luminosity of a Type Ia supernova and the shape of its light curve.

1.2 SNe Ia as “standardizable candles”

In the early studies it was widely assumed that SNe Ia have universal light curves and a constant absolute magnitude at maximum (“standard candles”). This was explained by the similarity of the physical processes that lead to the outburst phenomenon. Generally, the outburst is a thermonuclear explosion of a C-O white dwarf whose mass has become close to or larger than the Chandrasekhar mass. In fact, after the detailed observations of a large number of supernovae had been accomplished, it became clear that the absolute magnitude at maximum can vary within 1^m . The reasons of luminosity dispersion could be different. First, the mechanism of mass increase

by white dwarf is not universal: it can be due to the matter accretion on the white dwarf from the companion star (so-called “single-degenerate (SD) scenario” [12]) or the merger of two white dwarfs (“double-degenerate (DD) scenario” or “merging scenario” [13, 14]). Additionally there exist some alternative scenarios, like sub-Chandrasekhar, that is usually associated with weak explosions. These scenarios have internal freedom that results in significant variations in observed light curves of SNe Ia: like point of deflagration-to-detonation transition (for SD scenario), or difference in total mass (for DD scenario). Another important factor which could violate the “standard candle” hypothesis is dust. Dust around the supernovae, as well as in the host galaxy, surely affects light curve behavior. The distribution and properties of dust in host galaxies of supernovae could be different from that in the Milky Way. In addition, the initial chemical composition of the progenitor stars also complicates the picture. A lower metallicity involves an increase of the Chandrasekhar limit and could affect the explosion process. For example, in elliptical galaxies or in halo of spiral galaxies only old, i.e. metal-poor, stars with an age comparable to that of the Universe are located; on the contrary in the star formation regions of spiral galaxies there are young metal-rich stars. The above-listed factors (age, chemical composition of the region around SN, presence of dust) could be considered as environmental effects. In the epoch of large transient surveys, development of observational techniques, and further processing of the data, a study of environment is of high priority.

Fortunately, it was established that supernovae are “standardized candles”. SNe Ia whose luminosity falls down slowly after the maximum light are brighter than supernovae with a fast decline rate (stretch correction; [15, 16, 17]). Later it was shown that their absolute brightness depends on the color as well (color correction; [18, 19]). However, the origin of this relation remains a big mystery of SN science and is not yet reproduced by radiation-hydrodynamical modelling. To take into account stretch and color corrections and, therefore, to determine the absolute magnitude of each SN Ia at maximum, different standardization methods have been developed (the Δm_{15} -method [20, 21], the stretch-factor [22, 9], the Multicolor Light Curve Shape (MLCS) [23, 24], PRES [25], the Spectral Adaptive Light curve Template for type Ia supernova (SALT) [26, 27], the Color-Magnitude Intercept Calibration (CMAGIC) [28], the Supernova Useful Generator and Reconstructor (SUGAR) [29], etc.). These methods improved a lot the accuracy of distance measurements. However, the dispersion on the Hubble diagram still remains. For instance, in the most recent analysis all SNe are standardized with an intrinsic scatter in luminosity about 0.1^m . It could be due to the environmental effects that are not accounted by current standardization methods. Therefore, the SN Ia “standardization” procedure is one of the main sources of systematic uncertainties in the cosmological analysis.

2. Peculiar velocities of SNe Ia in galaxy clusters

Besides the standardization of SN Ia, the Hubble diagram contains another parameter, i.e. the supernova cosmological redshift. This redshift has to be only due to the expansion of the Universe, i.e. the motion within the reference frame defined by the cosmic microwave background radiation (CMB). In fact the redshift observed on the Earth is also affected by peculiar velocities due to the Earth’s rotational and orbital motions, Galactic rotation, peculiar motion of the Galaxy within the Local Group, “infall” of the Local Group toward the center of the Local Super-cluster, host

galaxy peculiar motion etc. The exact contribution of peculiar velocities in the observed redshift is unknown, however it was shown that the peculiar velocities have an impact on the distance measurements and therefore can potentially affect the cosmological analysis [30, 31, 32, 33].

To minimize the influence of poorly constrained peculiar velocities, in some cosmological analyses all SNe with $z < 0.015$ are removed from the Hubble diagram fitting and a 300-400 km s⁻¹ peculiar velocity dispersion is added in quadrature to the redshift uncertainty [34, 35, 36]. In the Union2.1 SN Ia compilation, uncertainties due to host galaxy peculiar velocities were adopted to 300 km s⁻¹. Another way to apply the peculiar velocity correction is to measure the local velocity field assuming linear perturbation theory and then to correct each supernova redshift [37]. [38] estimated the accuracy of this method to be ~ 100 km s⁻¹, [39] adopted the value of 200 km s⁻¹, [40] used 150 km s⁻¹. This approach was used in Joint Light-Curve Analysis (JLA; [11]). However, it was shown that the systematic effect in w , the dark energy equation of state parameter, of different flow models is at the level of ± 0.04 [41].

It has nonetheless been observed that velocity dispersion inside galaxy clusters can exceed 1000 km s⁻¹ [42], i.e. can be greater than it is usually assumed in cosmological analyses and can affect the redshift measurements (see Fig. 2). If we transform the dispersion due to peculiar velocities into a magnitude error

$$\sigma_m = \frac{5\sigma_v}{cz \ln(10)}, \quad (2.1)$$

we will see that for low-redshift region ($z < 0.05$) this error is essentially higher than the one corresponding to 150 km s⁻¹ and 300 km s⁻¹ and it is two times bigger than the intrinsic dispersion of SNe Ia on the Hubble diagram found for the JLA sample (Fig. 3). It means that standard methods to take into account peculiar velocity do not work for the galaxies inside the clusters, and another more accurate method could be developed for these peculiar cases.

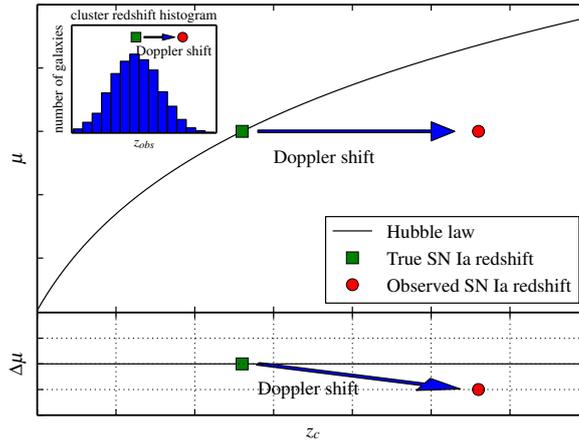


Figure 2: This Hubble diagram demonstrates how large peculiar velocity can affect the measurements of the expansion history of the Universe. The inset plot is a typical velocity distribution of galaxies inside a cluster.

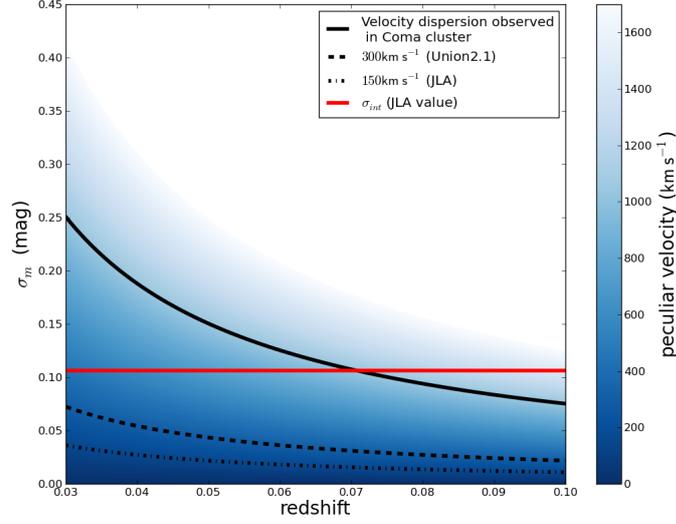


Figure 3: Redshift uncertainties (in magnitude units) due to different levels of peculiar velocities, as a function of the cosmological redshift. The solid line corresponds to the Coma cluster velocity dispersion; the dashed and dash-dotted lines correspond to 300 km s^{-1} and 150 km s^{-1} , respectively. The red line shows the intrinsic dispersion of SNe Ia on the Hubble diagram found for the JLA sample [11].

For a SN in a cluster it is possible to estimate z_c better by using the host galaxy cluster redshift (z_{cl}) instead of the host redshift³ (z_{host}). First, clusters of galaxies are the largest relaxed, virialized systems in the Universe. They provide unique laboratories to study astrophysical processes on a large scale and to probe the galaxy evolution. Second, as it is shown in Fig. 3, the dispersion inside the cluster can be greater than the one usually assumed in cosmological analyses.

The fact that there is additional velocity dispersion of galaxies inside the clusters that should be taken into account has been known for a long time (see for example [43, 44, 45, 46]). Nevertheless, peculiar velocity correction within galaxy cluster has received little attention in SN Ia studies, with the exception of [47]. The redshift correction induced by galaxy clusters is only mentioned briefly in their analysis, as the study’s objective was to measure the bulk flow with SNe Ia. However, at low redshifts this correction is necessary, which is why we focus on it here.

In this paper we identify SNe that appear to reside in known clusters of galaxies. We then estimate the impact of their peculiar velocities by replacing the host redshift by the cluster redshift. As our parent sample we use 145 SNe observed by the Nearby Supernova Factory (SNFACTORY) collaboration between 2004 and 2009 with the SuperNova Integral Field Spectrograph (SNIFS; [48], [49]) installed on the University of Hawaii 2.2-m telescope (Mauna Kea). SNFACTORY is a project devoted to the study of SNe in the nearby Hubble flow ($0.02 < z < 0.1$; Fig. 4; [48]). We perform the fitting of the Hubble diagram and compare the Hubble residuals (HRs) for SNe in galaxy clusters before and after peculiar velocity correction.

³Hereafter, we will call that procedure as peculiar velocity correction.

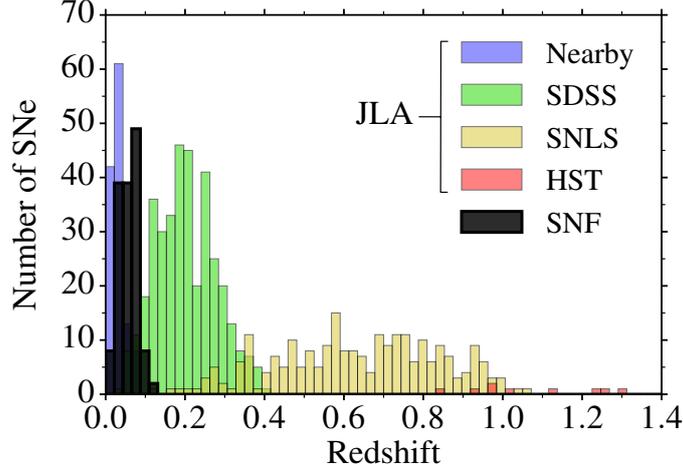


Figure 4: The distribution of redshift for SNe Ia in SNFACTORY [48] and JLA [11].

3. Analysis

3.1 Cluster pre-selection

Using the SIMBAD database [50] we chose all the clusters projected within 2.5 Mpc around the supernovae position and with redshift differing from the supernova one by less than 0.015. We did not consider objects classified as groups of galaxies (GrG), although there is no strong boundary between these and clusters, since groups of galaxies are characterized by smaller mass and therefore smaller velocity dispersion $\sim 300 \text{ km s}^{-1}$ (see fig.5 in [51]). The uncertainty introduced by such velocities is small and below that from intrinsic scatter of SNe Ia.

3.2 Cluster redshift measurement and final matching

To measure the redshift of the cluster it is needed to know which galaxies in the cluster field are its members. First, we took all the galaxies attributed to each cluster in literature sources and added the SNFACTORY host galaxy if it was not among them. Then, these data were combined with the DR13 release database of SDSS [52, 53]. We selected all the galaxies with spectroscopic redshift located in a circle with the center corresponding to the cluster coordinates and projected inside the cluster R_{200} radius — radius where an average interior density of cluster equals to 200 times the critical density of the Universe at redshift z . A redshift cut $5\sigma_V$ was adopted where σ_V is a velocity dispersion inside a cluster⁴.

To estimate the redshift of a cluster we applied so-called bi-weight technique [54]. Bi-weight allows to determine the kinematic properties of galaxy clusters and being resistant in the presence of outliers and robust for a broad range of underlying population with non-Gaussian velocity distributions.

Knowing the redshifts and R_{200} values for each cluster, we performed the final matching. The supernova is considered a cluster member if two conditions are satisfied:

⁴According to the virial theorem, $\sigma_V \simeq \sqrt{\frac{GM_{200}}{R_{200}}}$.

- $D < R_{200}$, where d is a distance between SN and cluster center.
- $|z_{host} - z_{cl}| < 3 \frac{\sigma_v}{c}$

The SNe that did not satisfy these criteria were removed from a further consideration.

Initially we considered everything that is classified as cluster by previous studies (see Sec. 3.1). However, some of these classifications can be false. Since in virialized systems such as clusters the thermal velocity of gas and the velocity of the galaxies are bound by the same gravitational potential, the clusters of galaxies could appear as luminous X-ray emitters, with typical luminosities of $\mathcal{L}_X \sim 10^{43} - 10^{45} \text{ erg s}^{-1}$. While we consider the nearby objects ($z < 0.1$), the X-ray emission has to be resolved by X-ray surveys. Therefore, only candidates with diffuse X-ray emission were kept for further analysis⁵.

The final list of SNFACTORY supernovae in confirmed clusters contains 11 objects.

4. Results

4.1 Impact on the Hubble diagram

Since we have a list of 11 SNe Ia belonging to clusters, we can apply the peculiar velocity correction and study how it affects the Hubble residuals (the difference between observed and theoretical distance modulus). Using only SN Ia outside galaxy cluster⁶, we performed the Hubble diagram fitting and obtained SN Ia nuisance parameters. During the fit cosmology was fixed to $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In order to study the impact of peculiar velocity correction, we compute the Hubble residuals for the supernovae in clusters before and after correction. We used the weighted root mean squared ($wRMS$) as defined in [55] to measure the effect of correction.

We obtained two main results:

- The dispersion of 11 SNe Ia on the Hubble diagram decreases significantly when the peculiar velocities of their hosts inside the clusters are taken into account ($wRMS = 0.130 \pm 0.038 \text{ mag}$). If we are using the redshift of the host instead the redshift of the cluster, the dispersion of these 11 SNe is $wRMS = 0.137 \pm 0.036 \text{ mag}$ (Fig.5).
- Moreover, the $wRMS$ ($0.130 \pm 0.038 \text{ mag}$) we found for SNe inside the clusters before correction is also smaller than $wRMS$ for the SNe in the field ($wRMS = 0.150 \pm 0.009 \text{ mag}$) which could be due to the fact that the intrinsic dispersion in luminosity of SNe Ia inside the galaxy cluster is lower. This effect will be discussed in the Section 4.3.

⁵In order to look for an extended X-ray counterpart the public ROSAT All Sky Survey images for total energy band 0.1-2.4 keV were used, <http://www.xray.mpe.mpg.de/cgi-bin/rosat/rosat-survey>.

⁶taking into account all the SNe Ia does not affect the Hubble diagram fitting because the number of SNe Ia inside galaxy clusters is small.

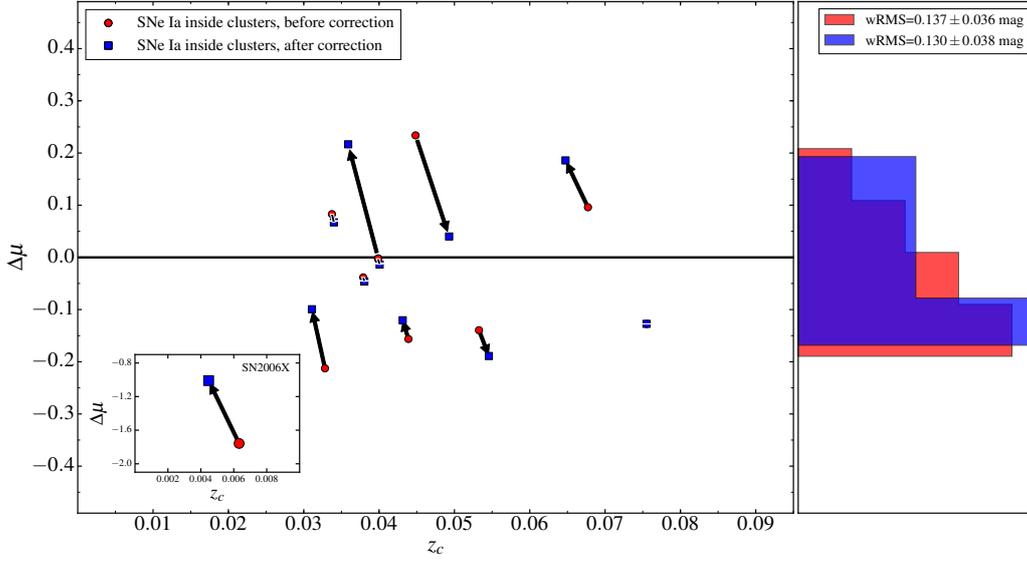


Figure 5: Hubble diagram residuals. For cluster members red circles (blue squares) correspond to residuals for SNe in galaxy clusters before (after) correction for peculiar velocities of the hosts inside their clusters. SN2006X is presented in the inset plot separately from the others due to its very low redshift.

4.2 SN Ia rate in galaxy clusters

Numerous studies of SN Ia rate in clusters have been carried out. The different measurements are summarized in Fig. 6 and Table 1. It is found that for nearby clusters ($z < 0.1$), the explosion rate is $0.042^{+0.022}_{-0.018}$ SNum⁷ [56], whereas the overall explosion rate in the same range of redshift is 0.10 ± 0.02 SNum [57]. Considering that the SN Ia explosion rate is directly related to the star formation rate [58], the obtained result can be explained by lower star formation rate in clusters of galaxies. Indeed, mainly passive elliptical galaxies are located in the central parts of clusters. However, it is interesting to notice that in early-type cluster galaxies SN Ia rate ($0.058^{+0.019}_{-0.015}$ SNum) is higher than in early-type galaxies in the field ($0.019^{+0.013}_{-0.008}$ SNum, [59]). The increased rate may be due to galaxy interactions in clusters, inducing either the formation of young stars or a different evolution of the progenitor binary systems [59].

The explosion rate in clusters is only two times lower than the overall SN Ia explosion rate. Nevertheless, it should be noted that the majority of galaxies in the Universe are not found in galaxy clusters, but in filamentary structures such as the Big wall [68] and therefore SNe Ia in galaxy clusters are rare in untargeted searches as SNFACTORY. To study the SN Ia rate in galaxy clusters a larger sample of supernovae is needed, thus we can not make a strong conclusion about this issue basing on the data we have.

4.3 Properties of SNe Ia in galaxy clusters

In Section 4.1 it was shown that $wRMS$ on the Hubble diagram of the supernovae in clusters is less than for supernovae in the field. It could mean that the intrinsic luminosity dispersion of SN Ia

⁷1 SNum $\equiv 1$ SN Ia (100 years $10^{10}M_{\odot}$)⁻¹

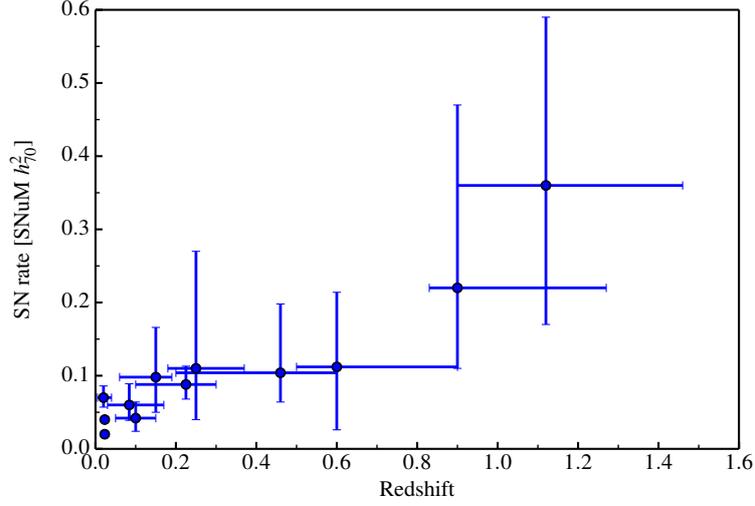


Figure 6: The SN rate in clusters of galaxies provided by different studies [59, 60, 61, 62, 56, 63, 62, 64, 65, 66, 64, 67]. $\text{SNuM} \equiv \text{SNe} (100 \text{ yr } 10^{10} M_{\odot})^{-1}$.

$\langle z \rangle$ (z range)	Rate ($\text{SNuM } h_{70}^2$)	Reference
0.020 (0.005-0.040)	$0.070^{+0.016}_{-0.013}$	[59] ^a
0.023 (0.020-0.026)	~ 0.020	[60]
0.023 (0.020-0.026)	~ 0.040	[61]
0.084 (0.030-0.170)	$0.060^{+0.029}_{-0.021}$	[62]
0.100 (0.050-0.150)	$0.042^{+0.022}_{-0.018}$	[56] ^b
0.150 (0.060-0.190)	$0.098^{+0.068}_{-0.048}$	[63]
0.225 (0.100-0.300)	$0.088^{+0.025}_{-0.020}$	[62]
0.250 (0.180-0.370)	$0.110^{+0.160}_{-0.070}$	[64]
0.460 (0.200-0.600)	$0.104^{+0.094}_{-0.040}$	[65] ^a
0.600 (0.500-0.900)	$0.112^{+0.102}_{-0.086}$	[66]
0.900 (0.830-1.270)	$0.220^{+0.250}_{-0.110}$	[64]
1.120 (0.900-1.460)	$0.360^{+0.230}_{-0.190}$	[67]

Table 1: SN Ia rates in clusters. $\text{SNuM} \equiv \text{SNe} (100 \text{ yr } 10^{10} M_{\odot})^{-1}$. The quoted errors are the sum of statistical and systematic components. ^a The overall cluster SN Ia rate within $D < 1.5 \text{ Mpc}$. ^b The overall cluster SN Ia rate within R_{200} .

in clusters is smaller, i.e. they are more "standard" (see Fig. 5). Unfortunately, the statistical test shows that the significance of this result is low.

Despite of the low significance of the latter result, we could expect some difference between SNe in clusters and outside them, because the properties of the galaxies inside the clusters are known to be different from those in the field. While in the field all morphological types of the galaxies are observed, in the central part of the clusters usually the elliptical galaxies are located. The results of binary star population synthesis together with observational data on the Type Ia SN

rates shows that in elliptical galaxies the overwhelming majority of SNe Ia (99%) form via mergers of binary white dwarfs [69]. Moreover, the oldest, i.e. metal-poor, stars with an age comparable to that of the Universe lie in elliptical/lenticular galaxies as well as in halo of spiral galaxies. And at last, the dust (including grey dust) is almost absent in these regions [70]. The influence of the environmental effects on the supernovae intrinsic luminosity was proved in many works. As a parameter to characterize the environment the galocentric distance, the galaxy morphology, metallicity, mass, specific star formation rate (star formation rate (SFR) per unit galaxy stellar mass), local specific SFR (1-3 kpc around the SN position) were considered. However, it is needed to stress that when we study the environment of SNe the effect of projection is not taken into account, and it can turn out that a SN is projected to the star formation region of spiral host galaxy but in reality it belongs to the halo of this galaxy where metallicity, age of stars and SFR are similar to elliptical passive galaxies.

In the Fig. 7 we show how the peculiar velocity correction ($c|\Delta z|$) before and after correction depend on supernova parameters (X_1, C), host properties (sSFR, stellar mass, morphological type, RS residuals, [71, 72]), relative SN position inside the cluster and cluster mass M_{200} . The $c|\Delta z|$ plot shows that most of the SNe whose redshifts change have $X_1 \simeq 0$, hosted by blue spiral galaxies, with high sSFR, smaller $M_{stellar}, r/R_{200} \simeq 0.7$ (see Fig. 7). This is consistent with the distribution of galaxies in the cluster where the massive/elliptical/passive galaxies are located in the center but outer region contains spiral galaxies as well and with velocity profiles inside the clusters (see fig. 15 in [73]).

The low statistics do not allow us to perform the cosmological fit separately for the supernovae inside and outside galaxy clusters and to study the behavior of the supernova light curve parameters in both subsamples. However, it is necessary to perform such kind of analysis using the larger sample of SNe Ia because the variation of the light curve parameters, especially the luminosity, influences the cosmological analysis (e.g., [74, 75]).

5. Conclusions

By now several realizations of the idea of SN Ia “standardization” are developed. These methods are contiguously improving with time, however, the intrinsic dispersion on the Hubble diagram still remains. The possible solution can be the including of environmental factor to the standardization procedure.

Besides the standardization of SNe Ia, the Hubble diagram contains another parameter, i.e. the supernova cosmological redshift. The redshift observed on the Earth is affected by peculiar velocities that are unknown and introduce an additional uncertainty on the Hubble diagram. In galaxy clusters a contribution of peculiar velocities can be large. For SNe Ia in clusters we propose a technique that allowed to improve the redshift measurements for low and intermediate redshifts ($z < 0.1$) and to decrease the spread on the Hubble diagram. We also found that the dispersion on the Hubble diagram of 11 SNe Ia that belong to clusters is smaller than the one of SNe in the field. Nevertheless, this result is not statistically significant. The environmental studies of larger sample of SNe Ia in clusters are needed. The difference in SN light curve parameters inside and outside the clusters can be crucial for future cosmological analysis where all supernovae are described by one standardization model.

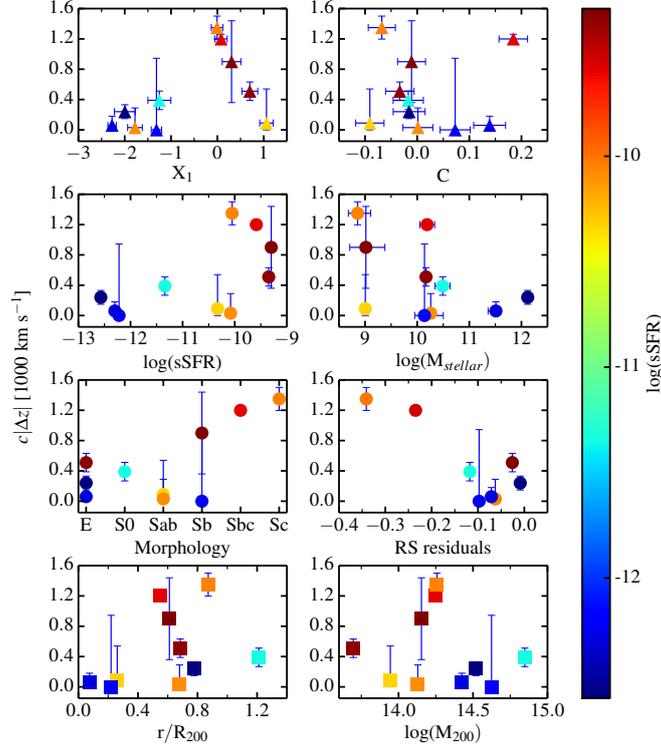


Figure 7: The peculiar velocity correction ($c|\Delta z|$) for supernovae that belong to clusters as a function of supernova parameters (X_1 , C ; triangles), host properties (specific SFR [yr^{-1}], stellar mass [M_\odot], morphological type, RS residuals [$(g-r) - (g-r)_{RS}$]; circles, [71, 72]), relative SN position inside the cluster and cluster mass M_{200} [M_\odot] (squares). The colorbar shows the corresponding specific SFR.

The impact of peculiar velocities decreases with distance and becomes negligible at cosmological redshifts. However, for the future surveys such as LSST [76], to perform very precise distance measurements such effects have to be taken into account.

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DISCUSSION

G.S. BISNOVATYI-KOGAN: What is the percent of galaxies which do not belong to any galaxy cluster?

M.V. PRUZHINSKAYA: I think nobody knows exactly. I can tell only that the majority of galaxies in the Universe are found in filamentary structures such as the Big wall and not in galaxy clusters.

L. AMATI What about using only SNe Ia in clusters to measure H_0 ? Does this reconciles the estimate of H_0 from SNe and CMB?

M.V. PRUZHINSKAYA: This is interesting but we still do not have enough SNe in clusters to do a sensitive analysis. We will do it in the next future.