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(ԵՐԵՎԱՆԻ ՖԻԶԻԿԱՅԻ ԻՆՍՏԻՏՈՒՏ)

Բարխուդարյան Լիլիթ Վարդանի

Ia դասի Գերնորերի ծնող աստղերի բազմազանության ուսումնասիրություն

Ա.03.02 - « Աստղաֆիզիկա, ռադիոաստղագիտություն » մասնագիտությամբ ֆիզիկամաթեմատիկական գիտությունների թեկնածուի գիտական աստիճանի հայցման ատենախոսության

ՍԵՂՄԱԳԻՐ

ԵՐԵՎԱՆ – 2023

A. I. ALIKHANYAN NATIONAL SCIENCE LABORATORY

(YEREVAN PHYSICS INSTITUTE)

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Study of the diversity of type Ia supernova progenitors

SYNOPSIS

of Dissertation in 01.03.02 – Astrophysics, radio astronomy presented for the degree of candidate in physical and mathematical sciences

YEREVAN – 2023

Ատենախոսության թեման հաստատվել է Ա. Ի. Ալիխանյանի անվան Ազգային Գիտական Լաբորատորիայի (ԵրՖԻ) գիտական խորհրդում:

Գիտական ղեկավար՝
Ֆիզ.մաթ. գիտ. թեկնածու Արթուր Աշոտի Հակոբյան (ԱԱԳԼ)

Պաշտոնական ընդդիմախոսներ՝
Ֆիզ.մաթ. գիտ. դոկտոր Վահագն Գրիգորի Գուրզադյան (ԱԱԳԼ)
Ֆիզ.մաթ. գիտ. դոկտոր Ժիրայր Սերգեյի Գևորգյան (ԱԱԳԼ)

Առաջատար կազմակերպություն՝
Աստղաֆիզիկայի և տիեզերագիտության ինստիտուտ, Պորտո, Պորտուգալիա
Ատենախոսության պաշտպանությունը կայանալու է 2023 թ. դեկտեմբերի 5-ին ժամը 14:00-ին, ԱԱԳԼ-ում գործող ԲՈԿ-ի 024 «Ֆիզիկայի» մասնագիտական խորհրդում (Երևան, 0036, Ալիխանյան Եղբայրների փ. 2):
Ատենախոսությանը կարելի է ծանոթանալ ԱԱԳԼ-ի գրադարանում:
Սեղմագիրն առաքված է 2023 թ. Հոկտեմբերի 25-ին:

Մասնագիտական խորհրդի գիտական քարտուղար՝
Ֆիզ.մաթ. գիտ. դոկտոր Հրաչյա Մարուքյան

The subject of the dissertation is approved by the scientific council of the A. I. Alikhanyan National Science Laboratory (YerPhI).

Scientific supervisor:
Candidate of ph-math. sciences Artur Hakobyan (AANL)

Official opponents:
Doctor of ph-math. sciences Vahagn Gurzadyan (AANL)
Doctor of ph-math. sciences Zhyrair Gevorkian (AANL)

Leading organization:
Instituto de Astrofísica e Ciências do Espaço, Porto, Portugal
The defence will take place on the 5th of December 2023 at 14:00 during the “Physics” professional council’s session of SCC 024 acting within AANL (2 Alikhanyan Brothers str., 0036, Yerevan).

The dissertation is available at the AANL library.
The synopsis is sent out on the 25th of October, 2023.

Scientific secretary of the special council:
Doctor of ph-math. sciences Hrachya Marukyan

Abstract

The thesis is devoted to the investigation of the diversity of type Ia supernovae (SNe) progenitors. First of all we present an analysis of the height distributions of the different types of SNe from the plane of their host galaxies. We use a well-defined sample of 102 nearby SNe appearing inside high-inclined ($i \geq 85^{\circ}$), morphologically non-disturbed S0–Sd host galaxies from the Sloan Digital Sky Survey. Then, in the next chapter, using spectroscopically classified normal, 91T-, and 91bg-like 197 SNe Ia, we perform an analysis of their height distributions from the disc in edge-on spirals and investigate their light-curve (LC) decline rates (Δm_{15}).

After this, we present an analysis of the LC decline rates of 407 normal and peculiar SNe Ia and global parameters of their host galaxies. Next, we perform an analysis of the galactocentric distributions of the normal and peculiar 91bg-like subclasses of 109 SNe Ia, and study the global parameters of their elliptical hosts.

To perform various comparisons between the properties/numbers of the different subsamples, we use the well-known statistical tests (Kolmogorov-Smirnov and Anderson-Darling tests, etc.) with the implementation of the WOLFRAM MATHEMATICA software and Monte Carlo simulations. In addition to the mentioned tests, we use the *Kendall's* τ and *Spearman's* (ρ) *rank* coefficients/tests to analyse the possible correlations between the physical (intrinsic) properties of SNe Ia (subclass, Δm_{15}, etc.) and their host galaxies (stellar mass, age, etc.).

Our investigation of SNe Ia LC decline rates at different locations within their host galaxies aided in distinguishing between SNe Ia with young progenitors (slow-decliners), corresponding to the "prompt" component with short delay times, and those (fast-decliners) with "older" components exhibiting long delay times. The observational findings are in line with the SN Ia explosion models involving a sub-$M_{\rm Ch}$ mass white dwarf (WD), where the SN LC decline rate serves as a suitable indicator of progenitor population age.

Relevance and motivation

The detailed understanding of the spatial distribution of SNe in galaxies provides important links between the nature of SNe progenitor stars and host galactic stellar populations. These links make it possible to constrain crucial physical parameters of various SN progenitors, such as their masses, ages, and metallicities. Despite numerous excellent studies, the progenitor nature and explosion channels of SNe have been the subject of controversy for decades.

There are many efforts in studying the links between the spectral as well as LC properties of SNe Ia and the global as well as local properties at SN explosion sites of their host galaxies, such as mass, colour, SFR, metallicity, and age of the stellar population. In short, these studies showed that more luminous and slower declining SNe Ia explode, on average, in galaxies with later morphological type, lower mass, higher specific SFR, and younger stellar population age (for SN local environment as well). In [1], recently claimed a significant correlation between the SN Ia luminosity (or LC decline rate) and the stellar population age of its host, at a 99.5% confidence level. They suggested that the previously reported correlations with host morphology, mass, and SFR are originated from the difference in population age. However, SN Ia samples in these studies consist only of spectroscopically normal events with known LC properties, or sometimes include only a tiny portion of peculiar SNe Ia. Therefore, the relations between LC properties of peculiar SNe Ia and the characteristics of their host galaxies have not been explored in such detail as it was done for normal SNe Ia.

Moreover, in such studies, SNe Ia host galaxies with various morphological properties, e.g. old ellipticals with spherically-distributed stellar content, lenticulars with an old stellar population in a huge spherical bulge plus a prominent exponential disc, and spirals with old bulge and young star forming disc components are simultaneously included in the samples. In this case, it is difficult to precisely analyse the spatial distribution of SNe, and associate them with a concrete stellar component (bulge or thick/thin discs, old or intermediate/young) in the hosts due to different or unknown projection effects. In addition, E-S0 and spiral host galaxies have had different evolutionary paths through major/minor galaxy-galaxy interaction, and therefore, this important aspect should be clearly distinguished.

Usually, the spatial distribution of SNe in S0-Sm galaxies is studied with the reasonable assumption that all core-collapse (CC) SNe and the vast majority of SNe Ia belong to the disc, rather than the bulge population. Moreover, the distributions of SNe in the disc are studied assuming that the disc is infinitely thin. The height distribution of SNe from the disc plane is mostly neglected when studying the host galaxies with low inclinations (close to face-on orientation) assuming that the exponential scale length of the radial distribution is dozens of times larger in comparison with the exponential scale height of SNe.

Direct measurements of the heights of SNe and estimates of the scales of their vertical distributions in host galaxies with high inclination (close to edge-on orientation) were performed only in a small number of cases. Mainly due to the small number statistics of SNe and inhomogeneous data of their host galaxies, the comparisons of vertical distributions of the different types of SNe resulted in statistically insignificant differences. Therefore, while the detailed study of the vertical distributions in edge-on galaxies has allowed to constrain ages, masses and other physical parameters of their components, the lack of analogous studies on the distribution of various SN subclasses has prevented the determination of their parent populations via the direct comparison with the nearby extragalactic discs and the thick/thin discs of the Milky Way (MW) galaxy.

Aim of the thesis

The main purpose of this PhD thesis is to investigate the vertical distributions of the subclasses of SNe Ia in their edge-on host galactic discs and check the potential correlation between SNe Ia LC decline rates and their heights, which may provide an indication that both parameters are appropriate stellar population age indicators. As well as to properly identify the diversity of SNe Ia, and better constrain the progenitor nature and explosion channels through a comprehensive study of the SN Ia LC decline rates and global properties of their host galaxies (e.g. morphology, stellar mass, colour, and age of stellar population). An additional objective is to investigate the galactocentric distributions of various subclasses of type Ia SNe within elliptical host galaxies.

Novelty of the work

- For the first time, we present an analysis of the height distributions of SNe types, including different subclasses of SNe Ia, from the plane of their host galaxies and investigate their LC decline rates.
- We present an analysis of the LC decline rates of normal and peculiar SNe Ia and global parameters of their host galaxies.
- We discuss the possible explosion channels and present our favoured SN Ia models that have the potential to explain the observed SN–host relations.
- We present an analysis of the galactocentric distributions of the normal and 91bg-like subclasses of SNe Ia, and study the global parameters of their elliptical hosts.

Main points of defence

- The vertical distribution of SNe types, also different subclasses of SNe Ia in different morphological types of edge-on host galaxies are studied.
- SNe Ia progenitors' ages are constrained by their vertical locations.
- Correlation of SN Ia LC decline rates with their heights from the host discs are obtained.
- The radial distributions of SN Ia subclasses, and their host elliptical galaxies' colours and luminosity-weighted ages are compared.

Structure of the thesis

The thesis consists of Introduction, four Chapters, General conclusions and Bibliography. The thesis contains 140 pages, including 31 figures and 31 tables.

Content of the thesis

In the Introduction the main characteristics of type Ia SNe are presented, with the graphical representation of the relationship between the peak *B*-band magnitudes of SNe Ia and their LC decline rates, emphasizing the discernible variations in photometric characteristics across the SNe Ia subclasses. General relations between SNe Ia and properties of host galaxies are presented, as well as LC properties of SNe Ia and the global as well as local properties at SN explosion sites of their host galaxies, such as mass, colour, SFR, metallicity, and age of the stellar population.

The content of the chapters of the thesis is given.

Chapter 1

The first chapter is devoted to the vertical distribution of SNe in disc galaxies. Detailed studies of the vertical distributions of different stellar components in edge-on galaxies allow to constrain their ages, masses, and other physical parameters. The lack of comparable studies on the distribution of various SN types has motivated us to determining their parent populations through direct comparison with nearby extragalactic discs and the thick/thin discs of the MW galaxy. The purpose of this Chapter is to address these questions properly through an investigation of the vertical distributions of the main classes of SNe in a nearby sample of 102 SNe and their well-defined edge-on S0-Sd host galaxies.

We fit *sech*^{2} and *exp* forms of $f(\bar{z})$ profile to the distribution of normalized absolute heights ($|\bar{z}| \equiv |v|/R_{25}$) of SNe, using maximum likelihood estimation (MLE). It immediately becomes clear that in all the subsamples of host galaxies the vertical distribution of CC SNe is about twice closer to the plane of host disc than the distribution of type Ia SNe. In fact, the two-sample Kolmogorov-Smirnov (KS) and Anderson-Darling (AD) tests, shown in Table 1, indicate that this difference is statistically significant[1] in Sa-Sd galaxies, although not significant if only late-type hosts are considered.

Subsample 1				Subsample 2				
Host	SN	N_{SN}		Host	SN	N_{SN}	P_{KS}	P_{AD}
Sa–Sd	Ia	44	versus	Sa–Sd	CC	48	**0.045**	**0.025**
Sa–Sd†	Ia	28	versus	Sa–Sd†	CC	28	**0.011**	**0.003**
Sa–Sbc	Ia	21	versus	Sa–Sbc	CC	21	**0.041**	**0.037**
Sc–Sd	Ia	23	versus	Sc–Sd	CC	27	0.690	0.310
Sa–Sbc	Ia	21	versus	Sc–Sd	Ia	23	0.387	0.440
Sa–Sbc	CC	21	versus	Sc–Sd	CC	27	0.765	0.802
Sb–Sc	Ia	30	versus	Sb–Sc	CC	32	**0.039**	**0.009**
Sb–Sc†	Ia	21	versus	Sb–Sc†	CC	19	**0.013**	**0.001**
Sb–Sc*	Ia	24	versus	Sb–Sc*	CC	31	0.112	**0.028**

Table 1. Comparison of the normalized absolute vertical distributions ($|\bar{z}| \equiv |v|/R_{25}$) of SNe amongst different pairs of subsamples. The P-values are bolded when differences between the distributions are statistically significant.

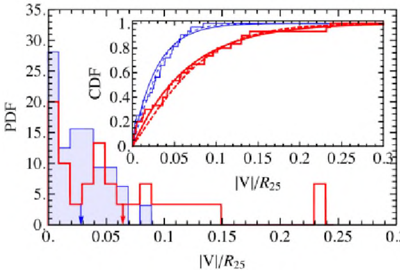

Figure 1. Vertical distributions of type Ia (red thick line) and CC (blue thin line) SNe in Sb–Sc galaxies. The inset presents the cumulative distributions of SNe and fitted sech^2 *(dashed curve) and exp (solid curve) CDFs. The mean values of the distributions are shown by arrows.*

We conclude that the vertical distributions of type Ia and CC SNe in Sb-Sc galaxies can be well fitted by both the *sech*^{2} and *exp* profiles. The vertical distribution of CC SNe is significantly different from that of type Ia SNe, being 2.3±0.5 times more concentrated to the plane of the host disc. In Fig. 1, we present the comparison of vertical distributions as well as the fitted *sech*^{2} and *exp* CDFs between both the types of SNe in Sb-Sc host galaxies.

Interestingly, [2] found that the scale height of a stellar population increases with age, which is also correct for the MW galaxy. They used colour-magnitude diagrams to estimate the ages of resolved stellar populations. The young population in their main-sequence (MS) box of the colour-magnitude diagram is dominated by stars with ages from ~10 up to ~100 Myr, the intermediate population in the asymptotic giant branch

[1] Traditionally, we chose the threshold of 5% for significance levels of the different tests.

(AGB) box is dominated by stars with ages from a few 100Myr up to a few Gyr, while the old population in the red giant branch (RGB) box is dominated by stars with ages from a few Gyr up to ∼10 Gyr. In light of this, we compare in Table 2 the ratios of radial to vertical scales of SNe with those detected from resolved stars in nearby edge-on late-type galaxies [2] and from unresolved populations of extragalactic thick and thin discs estimated using the edge-on surface brightness profiles [3], [4]. Here, to be consistent with the original values from the references, we use the h_{SN}/z_0^{SN} ratios.

Host	h/z_0	Reference
Edge-on Sc galaxies[a] (RGB-box)	1.83 ± 0.99	[2]
SNe Ia (Sb–Sc)	**2.08 ± 0.40**	**This study**
Edge-on Sc galaxies[a] (AGB-box)	2.40 ± 1.30	[2]
Edge-on galaxies[b] (thick+thin disc)	2.67 ± 0.86	[4]
Edge-on Sd galaxies[c] (thick disc)	2.87 ± 0.72	[3]
Edge-on Sc galaxies[a] (MS-box)	3.83 ± 1.79	[2]
SNe CC (Sb–Sc)	**4.76 ± 0.93**	**This study**
Edge-on Sd galaxies[c] (thin disc)	5.48 ± 1.15	[3]

Table 2. Comparison of the length to sech^2 height ratios of type Ia and CC SNe in Sb–Sc galaxies with those detected from resolved stars in nearby edge-on galaxies and from unresolved populations of extragalactic thick and thin discs.

In Table 2, we see that the ratio of scales of the distribution of CC SNe is consistent with those of the resolved MS-box stars in [2] and unresolved stellar population of the thin disc in [3]. On the other hand, the h_{SN}/z_0^{SN} ratio of type Ia SNe is consistent and located between the values of the same ratios of resolved RGB- and AGB-box stars, respectively [2]. In addition, the h_{SN}/z_0^{SN} ratio of type Ia SNe is consistent with those of the unresolved population of the thick disc in [3] and with the thick+thin disc population in [4].

These results are interpreted within the frames of the age-scale height relation of stars in galaxy discs [2], and that type Ia SNe result from stars of different ages (from ∼0.5 up to ∼10 Gyr), with even the shortest lifetime progenitors having much longer lifetime than the progenitors of CC SNe (from a few Myr up to ∼0.2 Gyr).

Chapter 2

In the second chapter, using spectroscopically classified 197 SNe Ia subclasses (normal, 91T- and 91bg-like), we perform an analysis of their height distributions from the disc in edge-on spirals and check the potential correlation between the SN Ia heights from host discs and their LC decline rates, which may provide an indication that both parameters are appropriate stellar population age indicators.

Subsample 1	N_{SN}	versus	Subsample 2	N_{SN}	P_{KS}^{MC}	P_{AD}^{MC}
$\lvert U\rvert/R_{25}$ of Normal	144	versus	$\lvert U\rvert/R_{25}$ of 91bg	23	0.279	0.166
$\lvert U\rvert/R_{25}$ of Normal	144	versus	$\lvert U\rvert/R_{25}$ of 91T	30	0.828	0.835
$\lvert U\rvert/R_{25}$ of 91bg	23	versus	$\lvert U\rvert/R_{25}$ of 91T	30	0.756	0.611
$\lvert V\rvert/R_{25}$ of Normal	144	versus	$\lvert V\rvert/R_{25}$ of 91bg	23	0.079	**0.010**
$\lvert V\rvert/R_{25}$ of Normal	144	versus	$\lvert V\rvert/R_{25}$ of 91T	30	0.685	0.588
$\lvert V\rvert/R_{25}$ of 91bg	23	versus	$\lvert V\rvert/R_{25}$ of 91T	30	**0.033**	**0.022**

Table 3. Comparison of the $|U|/R_{25}$ and $|V|/R_{25}$ distributions between different subclasses of SNe Ia. The P-values are bolded when differences between the distributions are statistically significant.

We compare the projected and normalized radii $|U|/R_{25}$ and the heights $|V|/R_{25}$ between different SN Ia subclasses. In Table 3, the KS and AD tests show that the radial distributions of normal, 91T- and 91bg-like SNe are consistent with one another. In addition, the height distributions of normal and 91T-like SNe are consistent between each other. At the same time, the height distributions of 91T- and 91bg-like SNe are significantly different. The same is happens for the distributions of normal and 91bg-like SNe (with barely KS test significance). Fig. 2 shows a scatterplot of $|V|/R_{25}$ versus $|U|/R_{25}$, and the cumulative distributions of $|V|/R_{25}$ values for different SN Ia subclasses. The mean heights are growing, starting with 91T-like events and progressing through normal and 91bg-like SNe. On the other hand, it is well-known that spiral galaxies have a vertical stellar age gradient, with the age increasing as the vertical distance from the disc plane increases [2], [3]. Therefore, from the perspective of the vertical distribution (an age tracer) it may be deduced that the progenitors of 91T-like and normal SNe Ia are relatively younger than those of 91bg-like events. At least the age differences should be significant for 91T- versus 91bg-like SNe (Table 3, Fig. 2). We emphasize that this study is the first to demonstrate the observational differences in the heights of the SN Ia subclasses.

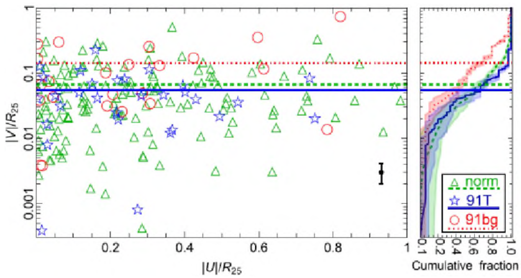

Figure 2. Left-hand panel: Distributions of $|V|/R_{25}$ versus $|U|/R_{25}$ for normal, 91T-, and 91bg-like SNe. The error bar on the right side of the panel shows the characteristic error in the height estimation due to possible inclination floating in 80°–90°. The lines show the mean $|V|/R_{25}$ values for each SN Ia subclass. Right-hand panel: The heights' cumulative distributions for different SNe Ia. The light coloured regions around each curve represent the appropriate spreads considering the uncertainties in height measurements.

With the qualitative age constraints of SN Ia progenitors we add also quantitative ones. The various SN Ia subclasses correspond to different stellar population ages being distributed at the various average heights from the disc [2]. We impose rough numerical constraints on the SN progenitors: 91T-like events arise from progenitors with ages about several 100 Myr, the ages of progenitors of 91bg-like SNe are comparable to ~10 Gyr, while normal SNe Ia arise from progenitors with ages from about one up to ~10 Gyr.

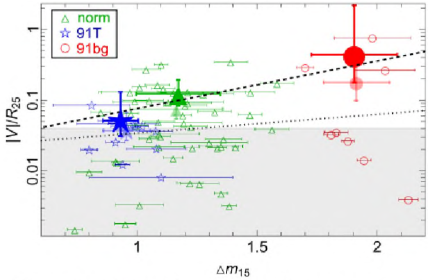

Figure 3. Distributions of $|V|/R_{25}$ versus Δm_{15} for different SN Ia subclasses. The dotted and dashed lines, which encompass all SN Ia subclasses, present the best-fitting lines for entire and dust-truncated (outside the shaded area) discs, respectively.

SN	N_{SN}	$\langle \lvert V \rvert / R_{25} \rangle$	versus	$\langle \Delta m_{15} \rangle$	r_s	P_s^{MC}
All	69	$0.08^{+0.02}_{-0.02}$	versus	1.21 ± 0.32	0.118	0.334
All†	36	$0.14^{+0.06}_{-0.04}$	versus	1.18 ± 0.29	0.471	**0.004**

Table 4. The correlation test for the $|V|/R_{25}$ versus Δm_{15} parameters. The variables are not independent when $P \leq 0.05$ (highlighted in bold).

The correlation between SNe Ia decline rate and the height from the host disc, which is a reliable age indicator of stellar population, has not yet been investigated. Here, we intend to fill this gap. Fig. 3 and the Spearman's rank correlation test in Table 4 show that the trend between $|V|/R_{25}$ and Δm_{15} is positive, but not statistically significant. It should be taken into account that due to the dust extinction in galactic disc the discovery of SNe Ia in edge-on galaxies is complicated and biased against objects at lower heights from the disc. The impact of this effect would be greatest on subluminous SNe (91bg-like events). Therefore, to avoid the possible impact of dust we truncate the heights of SNe with $|V|/R_{25} \geq 0.04$, leaving 36 SNe Ia in our sample. For this dust-truncated sample, the Spearman's rank test reveals a significant positive correlation between the $|V|/R_{25}$ and Δm_{15} parameters (Table 4, Fig. 3). Thus, despite the limited sample size, we demonstrate for the first time a significant correlation between LC decline rates and SNe Ia heights, which is consistent with a sub-M_{Ch} WD explosion models and vertical age gradient of stellar population in discs.

Chapter 3

The third chapter is devoted to the analysis of the LC decline rates (Δm_{15}) of 407 normal and peculiar SNe Ia and global parameters of their host galaxies. With the aim of clarifying the progenitor natures of normal and peculiar (91T-, 91bg-, and 02cx-like) SN Ia subclasses, in this chapter we comparatively study the important relations between the LC decline rates of these SNe Ia and the global properties of the stellar population of their host galaxies with different morphological types.

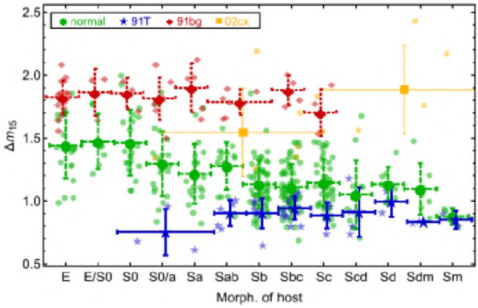

Figure 4. B-band Δm_{15} versus host galaxy morphology for different SNe Ia subclasses, displayed as a scatter plot (smaller symbols) and averaged in bins of morphological type (bigger symbols).

In Fig. 4, we show the distribution of the B-band Δm_{15} values as a function of morphological type of host galaxies, for different SN Ia subclasses. When dividing SNe Ia hosts between E-S0 (galaxies with only old stellar component) and S0/a-Sm morphological types (galaxies with both old and young stellar components), Table 5 shows that the distributions of Δm_{15} values of 91bg-like SNe are not different between the host subsamples, being distributed mainly within old ellipticals/lenticulars and early-type spirals (Fig. 4). In contrast, the Δm_{15} distribution of normal SNe Ia in E-S0 hosts is not consistent with that in S0/a-Sm galaxies.

Subsample 1				Versus	Subsample 2				P_{KS}	P_{AD}	P_{KS}^{MC}	P_{AD}^{MC}
Host	SN subclass	N_{SN}	$\langle\Delta m_{15}\rangle$		Host	SN subclass	N_{SN}	$\langle\Delta m_{15}\rangle$				
E–S0	Normal	47	1.45 ± 0.04	versus	S0/a–Sm	Normal	256	1.15 ± 0.01	**<0.001**	**<0.001**	**<0.001**	**<0.001**
E–S0	91bg	23	1.83 ± 0.03	versus	S0/a–Sm	91bg	27	1.82 ± 0.03	0.876	0.840	0.806	0.842
E–S0	Normal	47	1.45 ± 0.04	versus	S0/a–Sbc	Normal	177	1.16 ± 0.02	**<0.001**	**<0.001**	**<0.001**	**<0.001**
E–S0	Normal	47	1.45 ± 0.04	versus	Sc–Sm	Normal	79	1.11 ± 0.02	**<0.001**	**<0.001**	**<0.001**	**<0.001**
S0/a–Sbc	Normal	177	1.16 ± 0.02	versus	Sc–Sm	Normal	79	1.11 ± 0.02	**0.050**	0.067	**0.048**	0.068
S0/a–Sbc	91T	27	0.91 ± 0.02	versus	Sc–Sm	91T	14	0.89 ± 0.03	0.608	0.322	0.557	0.366
E–S0	91bg	23	1.83 ± 0.03	versus	S0/a–Sbc	91bg	23	1.84 ± 0.03	0.991	0.936	0.931	0.937

Table 5. Comparison of the B-band Δm_{15} distributions of SNe Ia among different subsamples of host morphologies. The P-values are bolded when differences between the distributions are statistically significant.

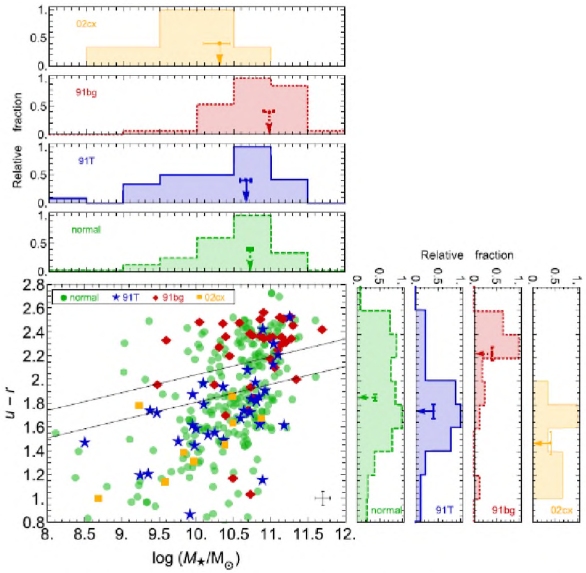

Figure 5. Colour–mass diagram for 326 SNe Ia host galaxies with measured u and r magnitudes, displayed as scatter plots and distributions. In the bottom right corner of the lower left panel, the error bar represents the characteristic errors in our estimations of colours and masses of galaxies. The region between two solid lines marks the Green Valley. For host galaxies of different SN subclasses, the right and upper panels show separately the histograms (distributions of relative fractions) of the colours and masses, respectively. The mean values (with standard errors) of the distributions are shown by arrows (with error bars).

Fig. 5 shows how the host galaxies of different SN Ia subclasses are distributed in the colour-mass diagram. The figure also displays the distributions of *u-r* colours and masses for host galaxies for the different SN subclasses. Host galaxies of 91bg-like SNe are clearly located in the Red Sequence, and most of them have *u-r* colours $\gtrsim$2 mag (i.e. above the Green Valley). In comparison with hosts of normal, 91T-, and 02cx-like SNe, the colour distribution of host galaxies of 91bg-like SNe are significantly redder. Also, the bulk of hosts of 91bg-like SNe are significantly massive ($\log(M_*/M_\odot) > 10.5$). The distribution of host masses is significantly inconsistent with those of the other SN Ia subclasses. At the same time, the colour (respectively, mass) distributions are not statistically different between hosts of normal and 91T-like SNe, spanning almost the entire ranges of host colour (respectively, mass). Finally, although the small number statistics, all the host galaxies of 02cx-like SNe are positioned in the Blue Cloud, mostly below the Green Valley in Fig. 5. Their colour (mass) distribution is significantly bluer (lower) in comparison with that of normal SNe Ia host galaxies, but closer to that of 91T-like SNe hosts.

Chapter 4

In the fourth chapter we present an analysis of the galactocentric distributions of the normal and peculiar 91bg-like subclasses of 109 SNe Ia, and study the global parameters of their elliptical hosts.

To reveal possible differences in global properties of SNe Ia elliptical hosts, in Table 6, using the two-sample KS and AD tests, we compare absolute magnitudes, colours, sizes, elongations, stellar masses, average metallicities and luminosity-weighted ages between the subsamples of host galaxies of normal and 91bg-like SNe. The table shows that the distributions of absolute magnitudes, *g-i* and *r-z* colours, sizes, elongations, stellar masses and average metallicities are not significantly different between host galaxies of normal and 91bg-like SNe. On the other hand, the distributions of *u-r* colours and luminosity-weighted ages of the hosts are significantly inconsistent between the subclasses of SNe Ia. In the histograms of Fig. 6, we show the distributions of host galaxy stellar masses and *u-r* colours. The cumulative distributions of luminosity-weighted ages of the elliptical hosts are presented in Fig. 7. It is clear that, despite their comparable stellar masses, the elliptical host galaxies of normal SNe Ia are on average bluer and younger than those of 91bg-like SNe.

Parameter	normal $\langle$Parameter$\rangle \pm \sigma$	versus	91bg-like $\langle$Parameter$\rangle \pm \sigma$	P_{KS}	P_{AD}
	$\tilde{R}_{SN} \geq 0$ (66 versus 41 hosts)				
M_u (mag)	-19.6 ± 1.0	versus	-19.8 ± 0.9	0.218	0.276
M_g (mag)	-21.2 ± 1.1	versus	-21.5 ± 0.9	0.112	0.137
M_r (mag)	-22.0 ± 1.1	versus	-22.3 ± 0.9	0.113	0.134
M_i (mag)	-22.4 ± 1.1	versus	-22.7 ± 0.9	0.188	0.153
M_z (mag)	-22.6 ± 1.1	versus	-22.9 ± 0.9	0.260	0.156
$u-r$ (mag)	2.4 ± 0.1	versus	2.5 ± 0.1	**0.013**	**0.007**
$g-i$ (mag)	1.2 ± 0.1	versus	1.2 ± 0.1	0.101	0.255
$r-z$ (mag)	0.7 ± 0.05	versus	0.7 ± 0.04	0.107	0.179
R_{25} (kpc)	23.0 ± 12.6	versus	25.6 ± 11.3	0.096	0.142
R_e (kpc)	6.0 ± 3.8	versus	6.0 ± 3.0	0.296	0.345
a/b	1.3 ± 0.2	versus	1.3 ± 0.2	0.766	0.729
$\log(M_*/M_\odot)$	$11.1^{+0.3}_{-1.1}$	versus	$11.2^{+0.2}_{-0.6}$	0.107	0.175
$\log(Z_*/Z_\odot)$	$0.09^{+0.07}_{-0.09}$	versus	$0.11^{+0.06}_{-0.07}$	0.107	0.175
age (Gyr)	$11.7^{+2.3}_{-2.8}$	versus	$12.8^{+1.2}_{-1.8}$	**0.017**	**0.012**

Table 6. Comparison of the distributions of absolute magnitudes, colours, sizes, elongations, stellar masses, average metallicities, and luminosity-weighted ages between the subsamples of host galaxies of normal and 91bg-like SNe. The P-values are bolded when differences between the distributions are statistically significant.

We interpret and summarise our results within an evolutionary (interacting) scenario of SNe Ia elliptical host galaxies. In Fig. 6, the region between two solid lines indicates the location of the Green Valley, i.e. the region between blue star-forming galaxies and the Red Sequence of quiescent E-S0 galaxies. For galaxies with elliptical morphology, this is a transitional state through which blue galaxies evolve into the Red Sequence via major merging processes with morphological transformation from disc to spheroidal shape, and/or a state of galaxies demonstrating some residual star formation via minor merging processes with no global changes in spheroidal structure.

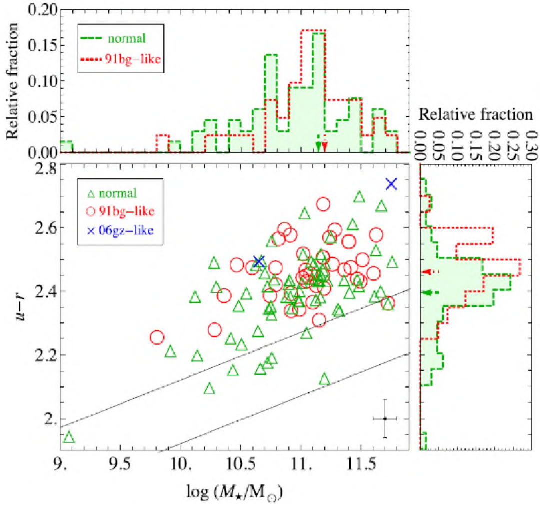

Figure 6. The u – r colour–mass diagram for 109 SNe Ia elliptical host galaxies. Green triangles, red circles, and blue crosses show normal, 91bg-like, and 06gz-like SNe hosts, respectively. The region between two solid lines indicates the Green Valley. The vertical and horizontal error bars, in the bottom right corner, show the characteristic errors in the colour and mass estimations, respectively. For normal (green dashed and filled) and 91bg-like (red dotted) SNe hosts, the right and upper panels represent separately the histograms of the colours and masses, respectively. The mean values of the distributions are shown by arrows.

The rate of SNe Ia can be represented as a linear combination of prompt and delayed components. The prompt component is dependent on the rate of recent star formation, and the delayed component is dependent on the galaxy total stellar mass. In this context, the normal SNe Ia with shorter delay times correspond to the prompt component. The bluer and younger ellipticals (with residual star formation) can also produce 91bg-like events with lower rate, because of long delay times of these SNe, i.e. a delayed component of SN Ia explosions. However, the distribution of host ages (lower age limit of the delay times) of 91bg-like SNe does not extend down to the stellar ages that produce a significant excess of *u-r* colour (i.e. *u*-band flux, see Figs. 6 and 7) - younger stars in elliptical hosts do not produce 91bg-like SNe, i.e. the 91bg-like events have no prompt component. The redder and older elliptical hosts that already exhausted nearly all star formation budget during the evolution may produce significantly less normal SNe Ia with shorter delay times, outnumbered by 91bg-like SNe with long delay times.

Finally, we note that our results favour SN Ia progenitor models such as helium-ignited violent mergers as a unified model for normal (CO WD primary with CO WD companion) and 91bg-like (CO WD primary with He WD companion) SNe that have the potential to explain the different luminosities, delay times, and relative rates of the SN subclasses. In particular, the models predict shorter delay times for normal SNe Ia in agreement with our finding that normal SNe occur in younger stellar population of elliptical hosts. Moreover, the model prediction of very long delay times for 91bg-like SNe ($\gtrsim$ several Gyr) is in good qualitative agreement with our estimation of older ages of host galaxies of these events.

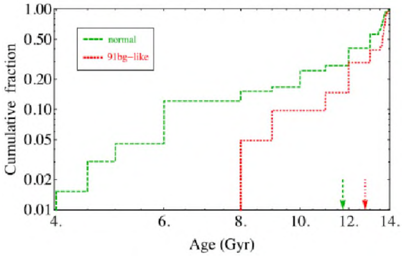

Figure 7. Cumulative distributions of luminosity-weighted ages of elliptical host galaxies of normal (green dashed) and 91bg-like (red dotted) SNe. The mean values of the distributions are shown by arrows.

General Conclusions

The main results of the thesis are:

1. For the first time, we show that in both early- and late-type edge-on spiral galaxies the vertical distribution of CC SNe is about twice more concentrated to the plane of host disc than the distribution of type Ia SNe.
2. When considering early- and late-type spiral galaxies separately, the vertical distribution of type Ia is consistent with both the $sech^2$ and *exp* profiles. In wider morphological bins (S0–Sd or Sa–Sd), the vertical distribution of type Ia SNe is not consistent with $sech^2$ profile, most probably due to the earlier and wider morphological distribution of SNe Ia host galaxies and the systematically thinner vertical distribution of the host stellar population from early- to late-type discs.
3. By narrowing the host morphologies to the most populated Sb–Sc galaxies (close to the MW morphology) of our sample, we exclude the morphological biasing of host galaxies between the SN types and the dependence of scale height of host stellar population on the morphological type. In these galaxies, we find that the $sech^2$ scale height $\tilde{z}_0^{SN}$ of type Ia SNe is 0.096 ± 0.016. The *exp* scale height $\tilde{H}_{SN}$ is 0.065 ± 0.012.
4. In Sb–Sc hosts, the exp scale height (also the h_{SN}/H_{SN} ratio) of SNe Ia is consistent with that of the old population in the thick disc of the MW.

5. For the first time, we show that the ratio of scale lengths to scale heights (h_{SN}/z_0^{SN}) of the distribution of type Ia SNe is consistent and located between the values of the same ratios of the two populations of resolved stars with ages from a few 100 Myr up to a few Gyr and from a few Gyr up to $\sim$10 Gyr, as well as with the unresolved population of the thick disc of nearby edge-on galaxies.
6. For the first time, we demonstrate that 91T- and 91bg-like subclasses of SNe Ia are distributed differently toward the plane of their host edge-on disc. On average, the SN heights are rising, beginning with 91T-like events and progressing through normal and 91bg-like SNe Ia.
7. We roughly estimate that 91T-like events originate from relatively younger progenitors with ages of about several 100 Myr, the ages of progenitors of normal SNe Ia are from about one up to $\sim$10 Gyr, and 91bg-like SNe Ia arise from progenitors with significantly older ages $\sim$10 Gyr.
8. We show that the SN Ia LC decline rates correlate with their heights from the host disc, after excluding the selection effects brought by dust extinction, which means the correlation between Δm_{15} and ages of SNe progenitors.
9. In general, the B–band Δm_{15} distribution of SNe Ia seems to be bimodal, with the second (weaker) mode mostly distributed within $\sim$1.5-2.1 mag. This faster declining range is generally occupied by 91bg-like (subluminous) events, while the Δm_{15} of 91T-like (overluminous) SNe are distributed only within the first mode at slower declining range ($\Delta m_{15} \lesssim 1.1$ mag).
10. The host galaxies of normal, 91T-, and 91bg-like SNe Ia have morphological type distributions that are significantly inconsistent between one another.
11. As for galaxies in general, the distribution of SNe Ia hosts in the u–r colour-mass diagram is bimodal. The hosts of 91bg-like SNe are located in the Red Sequence of the diagram, most of them have u–r colours $\gtrsim$ 2 mag (i.e. above the Green Valley). In comparison with hosts of normal, 91T-, and 02cx-like SNe, the colour distribution of hosts of 91bg-like SNe are significantly redder. Importantly, the bulk of hosts of 91bg-like SNe are significantly massive ($\log(M_*/M_\odot) > 10.5$) and old (more than 10 Gyr). The hosts' mass (age) distribution is significantly inconsistent with those of the other SN Ia subclasses.
12. As previously shown with smaller nearby SN Ia samples, there is a significant correlation between normal SNe Ia LC decline rates and global ages (morphologies, colours, and masses) of their host galaxies. On average, those normal SNe Ia that are in galaxies above the Green Valley, i.e. in early-type, red, massive, and old hosts, have faster declining LCs in comparison with those in galaxies below the Green Valley, i.e. in late-type, blue, less massive, and younger hosts.

13. For the first time, we show that the LC decline rates of 91bg-like SNe and 91T-like events do not show dependencies on the host galaxy morphology and colour. The distribution of hosts on the colour-mass diagram confirms the known tendency for 91bg-like SNe to occur in globally red/old galaxies (from halo/bulge and old disc components) while 91T-like events prefer blue/younger hosts (related to star-forming component).
14. We show that the distributions of projected galactocentric radii (with different normalizations) of normal and 91bg-like SNe in elliptical galaxies follow the de Vaucouleurs model, except in the central region of ellipticals where the different SN surveys are biased against the discovery of the events.
15. We show that the distributions of absolute magnitudes, stellar masses and average metallicities are not significantly different between host galaxies of normal and 91bg-like SNe.
16. We show that the distributions of $u-r$ colours and luminosity-weighted ages are inconsistent significantly between the elliptical host galaxies of different SN Ia subclasses: the hosts of normal SNe Ia are on average bluer and younger than those of 91bg-like SNe.
17. The distribution of host ages (lower age limit of the delay times) of 91bg-like SNe does not extend down to the stellar ages that produce a significant excess of $u-r$ colour (i.e. u-band flux) - younger stars in elliptical hosts do not produce 91bg-like SNe, i.e. the 91bg-like events have no prompt component. The redder and older elliptical hosts that already exhausted nearly all star formation budget during the evolution may produce significantly less normal SNe Ia with shorter delay times, outnumbered by 91bg-like SNe with long delay times.
18. Our results favour SN Ia progenitor models such as helium-ignited violent mergers as a unified model for normal (CO WD primary with CO WD companion) and 91bg-like (CO WD primary with He WD companion) SNe that have the potential to explain the different luminosities, delay times, and relative rates of the SN subclasses.

Bibliography

[1] Kang, Y. and et al., "Early-type Host Galaxies of Type Ia Supernovae. II. Evidence for Luminosity Evolution in Supernova Cosmology," *The Astrophysical Journal,* vol. 889, p. id.8/23, 2020.

[2] Seth, A. C., Dalcanton, J. J. and de Jong, R. S., "A Study of Edge-On Galaxies with the Hubble Space Telescope Advanced Camera for Surveys. II. Vertical Distribution of the Resolved Stellar Population," *The Astronomical Journal,* vol. 130, pp. 1574-1592, 2005.

[3] Yoachim, P. and Dalcanton, J. J., "Structural Parameters of Thin and Thick Disks in Edge-on Disk Galaxies," *The Astronomical Journal,* vol. 131, pp. 226-249, 2006.

[4] Bizyaev, D. V. and et al., "The Catalog of Edge-on Disk Galaxies from SDSS. I. The," *The Astrophysical Journal,* vol. 787, p. id.24/12, 2014.

List of Thesis Publications

1. Hakobyan A.A., **Barkhudaryan L.V.**, Karapetyan A.G., Mamon G.A., Kunth D., Adibekyan V., Aramyan L.S., Petrosian A.R., Turatto M., *"Supernovae and their host galaxies - V. The vertical distribution of supernovae in disc galaxies",* Monthly Notices of the Royal Astronomical Society, 2017, Volume 471, Issue 2, pp. 1390-1400.

2. **Barkhudaryan L.V.**, Hakobyan A.A., Karapetyan A.G., Mamon G.A., Kunth D., Adibekyan V., Turatto M., *"Supernovae and their host galaxies - VI. Normal Type Ia and 91bg-like supernovae in ellipticals"*, Monthly Notices of the Royal Astronomical Society, 2019, Volume 490, Issue 1, pp. 718-732.

3. Hakobyan A.A., **Barkhudaryan L.V.**, Karapetyan A.G., Gevorgyan M.H., Mamon G.A., Kunth D., Adibekyan V., Turatto M., *"Supernovae and their host galaxies - VII. The diversity of Type Ia supernova progenitors"*, Monthly Notices of the Royal Astronomical Society, 2020, Volume 499, Issue 1, pp. 1424-1440.

4. **Barkhudaryan L.V.**, *"Constraining Type Ia supernovae through their heights in edge-on galaxies"*, Monthly Notices of the Royal Astronomical Society: Letters, 2023, Volume 520, Issue 1, pp. L21-L27.

Լիլիթ Վարդանի Բարխուդարյան

Ia դասի Գերնորերի ծնող աստղերի բազմազանության ուսումնասիրություն

Ամփոփագիր

Ատենախոսությունը նվիրված է Ia դասի Գերնոր աստղերի (ԳԱ-երի) նախազերնորերի բազմազանության ուսումնասիրությանը: Նախ և առաջ ներկայացվել են տարբեր դասի ԳԱ-երի բարձրությունների բաշխումների ուսումնասիրությունները դրանց մայր գալակտիկաների սկավառակի հարթության նկատմամբ: Օգտագործվել է մոտ Տիեզերքում գտնվող 102 ԳԱ-երի ընտրանք: Այդ ԳԱ-երը հայտնաբերվել են մեծ թեքվածություն ունեցող ($i \geq 85°$), չձևախեղված S0–Sd մայր գալակտիկաներում Երկնակամարի Սլոնյան Թվային Շրջահայության տիրույթից: Այնուհետև հաջորդ գլխում օգտագործելով սպեկտրային դասակարգված նորմալ, 91T- և 91bg-նման 197 Ia դասի ԳԱ-երը, կատարվել է դրանց բարձրությունների բաշխումների ուսումնասիրություն կողքից դիտվող պարուրաձև գալակտիկաների սկավառակի հարթության նկատմանբ և ուսումնասիրվել են դրանց պայծառության կորերի անկման տեմպերը (Δm_{15}):

Այնուհետև, ներկայացվել է նորմալ և պեկուլյար 407 Ia դասի ԳԱ-երի պայծառության կորի անկման տեմպերի և դրանց մայր գալակտիկաների գլոբար պարամետրերի ուսումնասիրությունը: Որից հետո կատարվել է նորմալ և 91bg-նման 109 Ia ԳԱ-երի ենթադասերի շառավղային բաշխումների ուսումնասիրություն, ինչպես նաև ուսումնասիրվել են դրանց էլիպսաձև մայր գալակտիկաների գլոբալ պարամետրերը:

Տարբեր ենթադասերի ԳԱ-երի պարամետրերի/քանակների միջև տարբեր համեմատություններ անցկացնելու նպատակով օգտագործվել են հայտնի վիճակագրական թեստեր (Kolmogorov-Smirnov և Anderson-Darling և այլ թեստեր) Վոլֆրամ մաթեմատիկա (WOLFRAM MATHEMATICA) համակարգչային միջավայրում և Monte Carlo մոդելավորմամբ: Ի հավելումն նշված վիճակագրական թեստերի, ԳԱ-երի ֆիզիկական (սեփական) հատկությունների (ենթադաս, Δm_{15} և այլն) և դրանց մայր գալակտիկաների պարամետրերի (աստղային զանգված, տարիք և այլն) միջև կորելացիաները գնահատելու համար օգտագործվել են *Kendall's* τ և *Spearman's* (ρ) *rank* թեստերի բնութագրերը:

Ia դասի ԳԱ-երի պայծառության կորի անկման տեմպերի ուսումնասիրությունը դրանց մայր գալակտիկաների տարբեր դիրքերում թույլ է տվել զանազանել երիտասարդ նախազերնորերից առաջացած ԳԱ-երը (դանդաղ նվազողներ), որոնք համապատասխանում են կարճ կյանքի տևողությամբ «prompt» բաղադրիչին, և այն ԳԱ-երը (արագ նվազողներ), որոնք առաջացել են ծեր բաղադրիչից՝ երկար կյանքի տևողությամբ: Այս դիտողական արդյունքը լավ նկարագրվում է սպիտակ թզուկ աստղի մինչև 1.4 $M_{\text{Արեգակ}}$ զանգվածով (sub-M_{Ch}) պայթյունի մոդելով, որում Δm_{15}-ը հանդիսանում է նախազերնորի տարիքի ցուցիչ:

Лилит Вардановна Бархударян

Исследование разнообразия родительских звезд сверхновых типа Ia

Резюме

Диссертация посвящена исследованию разнообразия родительских звезд сверхновых типа Ia. Прежде всего, представлен анализ вертикальных распределений различных типов сверхновых Ia относительно плоскости их родительских галактик. Была использована выборка из 102 близких сверхновых типа Ia, обнаруженных в галактиках с большим наклоном диска ($i \geq 85°$) и морфологически не нарушенных типов S0–Sd из Слоановского цифрового обзора неба. Затем, в следующей главе, используя спектроскопически классифицированные 197 нормальные сверхновые типа Ia, а также 91T- и 91bg-подобные сверхновые, был проведен анализ их вертикальных распределений относительно диска в спиральных галактиках видимые с ребра и были исследованы скорости падения кривых блеска (Δm_{15}).

После этого представлен анализ скоростей падения кривых блеска 407 нормальных и пекулярных сверхновых типа Ia и глобальных параметров их родительских галактик. Затем, был проведен анализ галактоцентрических распределений нормальных и пекулярных (91bg-подобных) подклассов из 109 сверхновых типа Ia и были исследованы глобальные параметры их эллиптических родительских галактик.

Для проведения различных сравнений между свойствами/количеством различных подвыборок использовались хорошо известные статистические тесты

(тесты Колмогорова-Смирнова и Андерсона-Дарлинга и др.) с использованием программного обеспечения WOLFRAM MATHEMATICA и моделирования Монте-Карло для симуляций. В дополнение к упомянутым тестам, использовались коэффициенты/тесты Кендалла (τ) и Спирмена (ρ) для анализа возможных корреляций между физическими (собственными) характеристиками сверхновых типа Ia (подкласс, Δm_{15} и др.) и их родительскими галактиками (звёздная масса, возраст и др.).

Исследование скорости падения кривых блеска сверхновых типа Ia в разных местах внутри их родительских галактик помогло различить сверхновые типа Ia с молодыми предсверхновыми (медленно убывающие), соответствующим "prompt" (быстрому) компоненту с короткими временами жизни, и сверхновые (быстро убывающие) со «старым» компонентом, проявляющими большие времена жизни. Наблюдательные результаты соответствуют моделям взрыва сверхновой Ia, включающим белых карликов с массой ниже массы Чандрасекара (sub-M_{Ch}), где скорость падения кривой блеска сверхновой служит подходящим индикатором возраста предсверхновой звезды.