STATISTICAL STUDIES OF SUPERNOVAE

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Abstract.
The Sternberg Astronomical Institute Supernova Catalogue was compiled and is regularly updated. The latest version contains data on 930 supernovae (SNe). We also compiled the photometric catalogue of supernovae. Together with the database of Sternberg Institute Supernova search and the plate collection they form the base for our statistical studies of SNe, with major attention on SN frequency, spatial distribution of SNe in the galaxies, distributions of absolute magnitudes and other photometric characteristics of SNe. We present the following recent results. The surface density of SNe decreases with distance from galaxy centers similar to the surface brightness, but distribution of SNe is continuing beyond the optical radius of galaxies, with abrupt change of slope. The radial distribution of type Ia SNe in spiral galaxies is only slightly steeper than the one for SNe II, while SNe Ib/c are more concentrated towards the central regions. SNe Ia in spiral galaxies reveal significant concentration to the spiral arms, similar to the one observed for SNe II and SNe Ib/c. SNe of types Ib/c and II show a strong concentration towards H II regions, while distribution of SNe Ia can be explained by chance superposition. So the progenitors of SNe Ia in spiral galaxies are likely the stars with initial masses range near $4 - 8\ M_\odot$. We present the composite light curve for type Ia SNe based on the data of our catalogues, indicating large scatter of SNe Ia absolute magnitudes.

1. Introduction

Statistical investigations of SNe have been considered as important clue to the nature of SNe precursors. SN rates and spatial distributions in galaxies of different Hubble types are vital for understanding of SNe role in evolution of galaxies, especially history of star formation. Comparison of various distributions of supernovae can be used to estimate selection effects, which affect determination of SNe frequency.

Although significant progress in understanding the nature of SNe of different types has been achieved recently, it is still not exactly known which stellar populations give rise to the three different types of SNe (Type Ia, Type Ib/c, Type II). SNe II and SNe Ib/c (subsequently designated as SNe Ib) are assumed to be due to the explosions of massive, short–lived stars. SNe Ia occur in galaxies of all types, suggesting that their progenitor population is old and evolved. However, the rate of Type Ia SNe in late-type spirals indicates that SNe Ia progenitors in spiral galaxies may be an intermediate-age population, or stars with a range of ages (Oemler and Tinsley 1979, Filippenko 1989, van den Bergh 1990).

2. Radial distribution of SNe in galaxies

We have compiled a catalogue of 930 SNe discovered up to September 1, 1994 (the description of previous version is presented by Tsvetkov and Bartunov, 1993). After rejection of SNe, for which the available data were incomplete, we were able to include 579 SNe into the final sample for the investigation of their radial distribution, among them 104 of type Ia, 21 of type Ib and 126 of type II.

We studied radial distributions of SNe using data on their relative radial distance and absolute radial distances, expressed in kiloparsecs. Relative radii were computed as in Iye and Kodaira (1975). The galaxy diameters D_{25} were taken from RC3 (de Vaucouleurs *et al.* 1991) or reduced to the system of RC3. The relative radial distance $r = 2\rho/D_{25}$, where ρ is the distance of the SN from the center of the galaxy, corrected for the inclination of the galaxy, was computed for every SN from the sample and the dependence of surface density (σ) on radius was then constructed for different samples of SN types and galaxy types. For the galaxies with known radial velocity we were able to obtain absolute radial distance of SN (R), using $H_0 = 75\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$, and then compute surface density (σ^*) of SNe expressed in units kpc^{-2}.

The results are presented in Tables 1 and 2 and in Figs. 1, 2.

The presented data allows following conclusions.

There is a well-defined "tail" in distribution of all SNe in galaxies of all types. The slope of dependence $\log\sigma(r)$ changes abruptly near $r = 1.4$ and remains constant ~ -0.6 until $r = 3.0$–3.5. While for $r < 1.4$ the slope is consistent with surface brightness gradient, there is nothing to compare with the slope of the "tail" and to account for the change of slope near $r = 1.4$. There is also a change of slope on the curve $\log\sigma^*(R)$ near $R = 25$ kpc, but it is not so evident as on the dependence $\log\sigma(r)$.

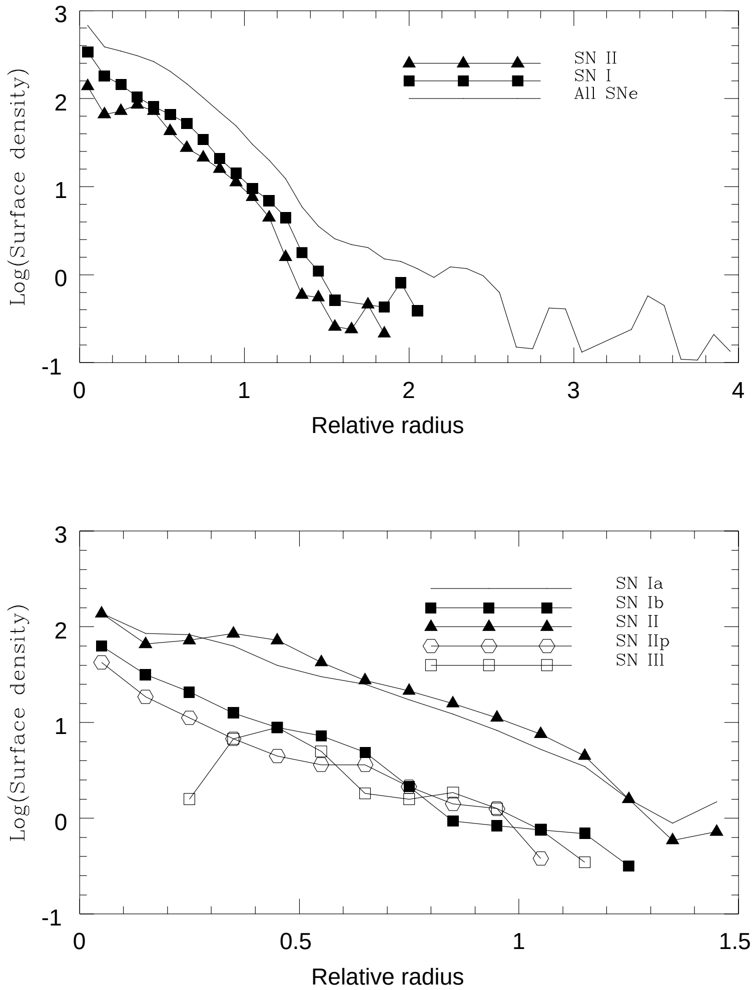

Figure 1. Radial distributions of SNe in all galaxies up to relative radius 4.0 (upper panel); radial distributions for different SNe types in all galaxies (lower panel)

The long "tail" in SNe distribution far outside optical radius of galaxies and change of slope on the dependence of $\log \sigma(r)$ near $r = 1.4$ indicate that SNe can appear in halo population around galaxies. Unfortunately most of these SNe are unclassified. The question of origin of "outlying" SNe deserves special study.

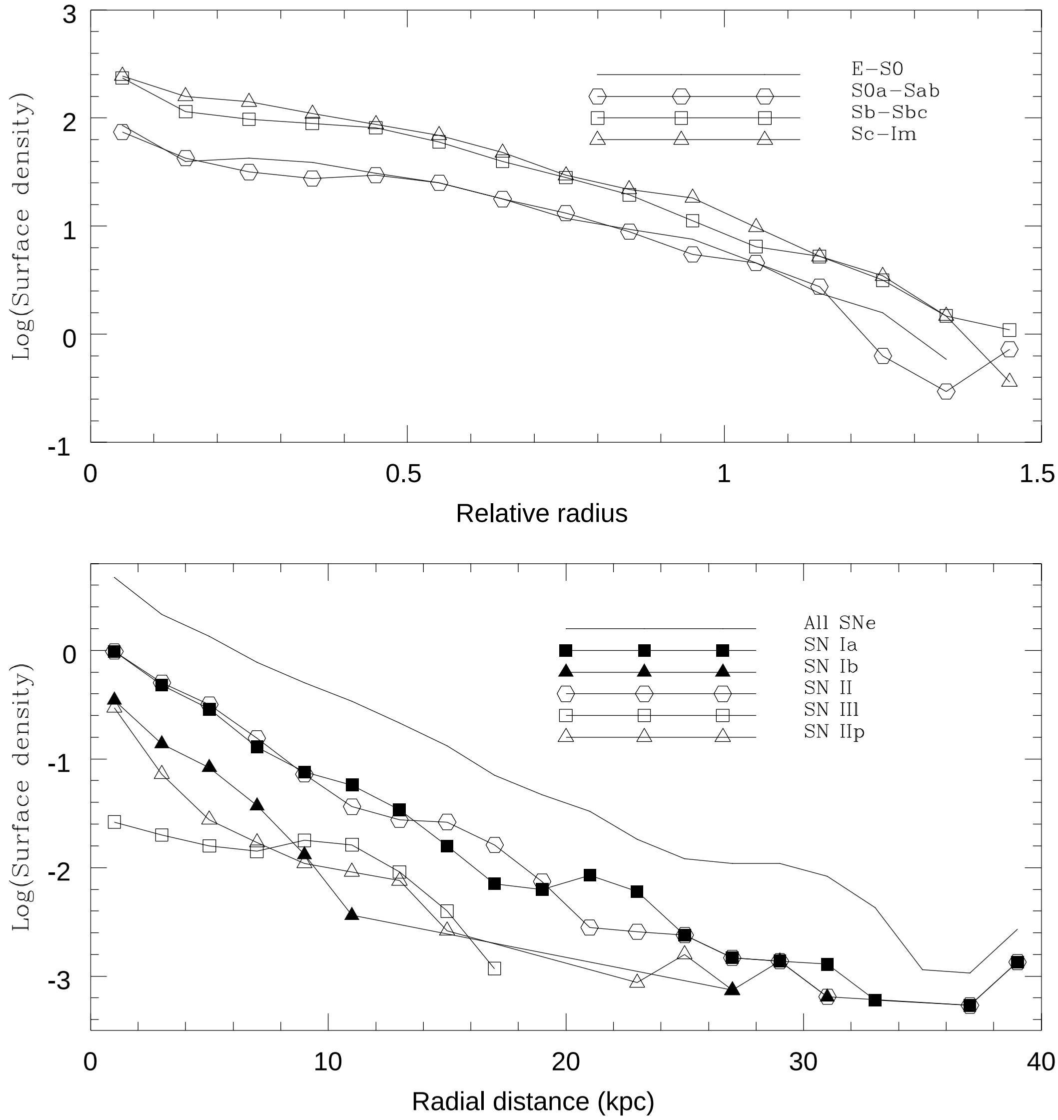

Figure 2. Radial distributions of all SNe in galaxies of different types (upper panel); radial distributions for different types of SNe versus radial distance in kpc (lower panel)

We observed no statistically significant difference between most of the samples representing different types of SNe. Nevertheless we should like to note the steeper decline of $\log\sigma$ and $\log\sigma^*$ for SNe Ib compared to all other SNe types. High concentration of SNe IIP towards central parts of galaxies can also be observed. The density of SNe Ia falls slightly steeper

TABLE 1. Parameters of radial distributions of SNe versus relative radial distance

SN type	Galaxy type	Gradient of $\log\sigma$ $0 < r < 0.5$	$0.5 < r < 1.0$	Number of SNe
All	All	-0.9 ± 0.2	-1.6 ± 0.1	579
-"-	E-S0	-0.9 ± 0.3	-1.3 ± 0.1	78
-"-	S0a-Sab	-1.0 ± 0.3	-1.6 ± 0.1	67
-"-	Sb	-1.2 ± 0.4	-1.7 ± 0.1	78
-"-	Sbc	-0.9 ± 0.3	-1.8 ± 0.1	84
-"-	Sc	-1.1 ± 0.1	-1.6 ± 0.2	100
-"-	Scd-Sd	-0.8 ± 0.4	-1.2 ± 0.1	64
-"-	Sdm-Im	-1.3 ± 0.1	-2.0 ± 0.5	28
Ia	All	-1.2 ± 0.2	-1.4 ± 0.1	104
Ib	-"-	-2.1 ± 0.1	-2.6 ± 0.3	21
II	-"-	-0.5 ± 0.4	-1.4 ± 0.1	126

TABLE 2. Parameters of radial distribution of SNe versus linear radial distance

SN type	galaxy type	Gradient of $\log\sigma^*$ $0 < R < 5$	$5 < R < 20$	Number of SNe
All	All	-0.13 ± 0.024	-0.10 ± 0.01	520
-"-	E-S0	-0.09 ± 0.01	-0.08 ± 0.01	71
-"-	S0a-Sbc	-0.14 ± 0.04	-0.10 ± 0.01	217
-"-	Sc-Im	-0.16 ± 0.01	-0.13 ± 0.01	174
Ia	All	-0.13 ± 0.01	-0.12 ± 0.01	96
Ib	-"-	-0.15 ± 0.02	-0.25 ± 0.02	21
II	-"-	-0.14 ± 0.02	-0.11 ± 0.01	121

than of SNe II. This fact should indicate that their progenitors belong to the same disk population in spiral galaxies and their mean ages do not differ greately. Quite unexpected is high concentration of SNe Ib and SNe IIP to the centers of galaxies, as these types of SNe seem to have the most massive progenitors and therefore should have more flat radial distributions. Although the number of SNe IIP is too small for definite conclusions, for SNe Ib the results seem to be quite reliable.

3. Distribution of SNe relative to spiral arms and H II regions

One way to constrain the possible progenitor population is to consider the local environments of SNe in galaxies of different types. Recently a number of studies have considered the association of SNe with H II regions, which serve as indicators of recent massive star formation. Richter and Rosa (1984), Huang (1987), Van Dyk (1992), Van Dyk et al. (1996) have shown that SNe II and SNe Ib are strongly concentrated towards H II regions in late-type galaxies, while the distribution of SNe Ia relative to H II regions is not different from that expected by chance superposition.

Spiral arms of galaxies also can be considered as sites of recent star formation, although with larger dispersion of ages than H II regions. Maza and van den Bergh (1976) noted a concentration of SNe II towards the spiral arms, but their data were insufficient to make any conclusions on Type I, which was not divided into Types Ia and Ib at that time. With the growing number of classified SNe we have attempted to study the distribution of SNe Ia, Ib and II relative to spiral arms. We also investigated the association of SNe with HII regions, using different approaches and different samples than Huang (1987), Van Dyk (1992) and Van Dyk et al. (1996).

We have selected only classified SNe (SNe I for which the exact type Ia or Ib was unknown, were excluded) from the SAI SN Catalog which occurred in spiral galaxies (types Sa–Sd) with inclination angle $i < 70°$ and diameter $D_{25} > 1'$. This sample consists of 133 SNe. For 126 SNe we have found photographs of their parent galaxies. The main source of photographs was the Palomar Observatory Sky Survey (glass and paper copies). We also used photographs from the Sternberg Institute collection (plates obtained with the 1.25-m and 0.5-m telescopes) and from the literature. Among 126 SNe 95 occurred in a region containing spiral structure, and for 88 of these the quality of the photographs, the inclination of the galaxy and the structure of the spiral arms allowed determination of the distance from the SN to the nearest spiral arm. 18 SNe in our sample occurred in the central bulges, and 13 outside spiral structure. The corresponding data for SNe of different types are presented in Table 3.

For 50 SNe among 88 selected as the final sample we have found photographs in the Sternberg Institute plate collection or in the literature. For these SNe position relative to the spiral structure was determined by combining the photograph with the image of the SN with the photograph on which the spiral structure can be traced. Then we measured the distance from the SN to the ridge line of the nearest spiral arm R in arcseconds, estimated the width of the arm W and the angle ψ between the line, connecting SN with the nearest point on the spiral arm, and the major axis of the galaxy. If no photograph of a SN was found, the position was de-

TABLE 3. Fraction of SNe in different parts of galaxies

	Number and percent of SNe		
	SNe II	SNe Ia	SNe Ib
Region of spiral structure	53 (76%)	30 (75%)	12 (75%)
Central region	8 (11%)	6 (15%)	4 (25%)
Outside spiral structure	9 (13 %)	4 (10%)	0 (0%)

termined using the published offsets from the nucleus of the galaxy. For some SNe we have determined the locations using both the offset and the photograph and found out that the difference between these positions in most cases did not exceed 2–5″.

We expressed the distance between a SN and the middle of the nearest spiral arm in three ways. Following Maza and van den Bergh (1976), we computed the relative distance $R_W = R/W$. However, this estimate of W depends on the quality of the photographs. Therefore we also calculated the scaled distance $R_D = 2R/D_{25}$, where D_{25} is the diameter of the galaxy as given in the RC3 catalog (de Vaucouleurs *et al.* 1991). The linear distance R_P was expressed in parsecs. To compute R_P we used distances of parent galaxies from Tully (1988) or we determined the distance from the radial velocity using H_0=75 km s^{-1}Mpc^{-1} (almost all the galaxies of our sample with velocity $v < 3000$ km s^{-1} have distances from Tully (1988)). For galaxies with $i > 30°$ the distances R_D and R_P were corrected for the inclination of the galaxy, assuming that all objects are confined to the plane of the galaxies, so that

$$R_c = R\sqrt{\sin^2\psi/\cos^2 i + \cos^2\psi}.$$

In this way we obtained corrected distances R_{Dc} and R_{Pc}.

The sample for investigation of SN distribution relative to H II regions consisted of 61 SNe. We calculated the distances from each SN to the nearest H II region expressed in parsecs R_P, and normalized by the radius of the galaxy R_D. We also corrected these distances for the galaxy inclination by means of the same equation in which ψ is the angle between the line, connecting the SN and the nearest H II region, and the major axis of the galaxy.

To make definite conclusions on the presence or absence of a correlation between the locations SNe and sites of star formation (spiral arms, H II regions) we have to compare the observed distributions of distances between SNe and these objects with the ones expected by chance superposition. We constructed the chance distributions of SNe relative to spiral arms and H II regions using the following assumptions and procedures.

The distribution of SNe within each parent galaxy was assumed to have the radial surface density distribution reported by Bartunov *et al.* (1992): $\sigma = \sigma_0 10^{-1.8r}$, where σ is the surface density of SNe, r the distance from galaxy nucleus normalized by the galaxy radius $D_{25}/2$. 1000 points, representing SNe, were randomly distributed with this density dependence in the interval of $0.2 < r < 1$.

The model galaxy had two spiral arms described by the relation $r = r_0 e^{0.3\phi}$ where ϕ is the polar angle, and we adopted $r_0 = 0.2$ and a length of the arms $\approx 300°$ in polar coordinates.

To simulate the distribution of SNe relative to H II regions, we used the observed distribution of H II regions in the face-on galaxy NGC 3184 (Hodge and Kennicutt 1983) and also models, where H II regions were represented by 40 and 60 randomly distributed points.

The distributions of SNe relative to spiral arms and H II regions are shown in Figs. 3–5. We present only distributions over the corrected distances R_{Dc} and R_{Pc}, the distributions over R_D and R_P are similar to them.

The results of Kolmogorov–Smirnov test – the probabilities P, that two distributions are drawn from the same parent population, are reported in Tables 4 and 5. The pairs of SN types for which the distributions are compared are given in the first column of Table 4. The kinds of distributions which are used for comparison are presented in the column headings of this Table: the objects they are related to (spiral arms or H II regions) and the type of distance (R_{Dc}, R_{Pc} or R_W).

Table 5 shows the results of a comparison between models with chance distribution of SNe and the observed distributions (only with the distance R_{Dc}) for different SN types. We used three models of distribution of H II regions for calculation of chance distributions, as described in previous section. They are referred to as "NGC 3184", "40" and "60" in the column headings of Table 5. The results of comparison with the described above model of chance distribution relative to spiral arms are shown in the column "Spiral arm".

The results reported in Table 3 show that the fraction of SNe which occur in the region of spiral structure is similar for all types of SNe. SNe Ia and SNe II have a similar frequency of occurrence in the outer and inner parts of galaxies, while SNe Ib show a greater concentration towards the galaxy center. These data confirm our results reported in previous section.

The data plotted in Figs. 3, 4 indicate that SNe of all types are concentrated towards spiral arms. We can calculate the percentage of SNe which occurred in spiral arms (i.e. those with $-0.5 < R_W < 0.5$): 50% for SNe II, 46% for SNe Ia and 67% for SNe Ib. This is confirmed by the results

TABLE 4. Kolmogorov–Smirnov probability that two distributions were drawn from the same parent population

SN type	HII (R_{Dc})	HII (R_{Pc})	Sp.arm (R_{Dc})	Sp.arm (R_{Pc})	Sp.arm (R_W)
Ia – Ib	$9 \cdot 10^{-3}$	$9 \cdot 10^{-3}$	0.35	0.67	0.50
Ia – II	$2 \cdot 10^{-4}$	$4 \cdot 10^{-3}$	0.12	0.31	0.34
Ib – II	0.93	0.93	0.95	0.84	0.69

TABLE 5. Kolmogorov–Smirnov probability of agreement between observed SN distributions and models with chance superposition

SN type	NGC 3184	40	60	Spiral arm
Ia	$8 \cdot 10^{-4}$	0.67	0.30	0.10
Ib	$4 \cdot 10^{-3}$	$5 \cdot 10^{-6}$	$1.3 \cdot 10^{-5}$	0.09
II	10^{-7}	$3 \cdot 10^{-14}$	$1.7 \cdot 10^{-13}$	$2 \cdot 10^{-4}$

presented in Tables 4 and 5. The values of P show that there is no significant difference between distributions of three types of SNe relative to spiral arms, and that the probability of chance superposition is low for SNe II and Ib and only slightly higher for SNe Ia.

The data reported in Fig. 5 and Tables 4, 5 reveal that the distribution of SNe Ia relative to H II regions is different from those for SNe II and Ib. The values of P in Table 5 allow to conclude that the location of SNe Ia is not correlated with that of H II regions. The distributions of SNe Ib and SNe II relative to H II regions are strikingly similar and the probability that these distributions are due to chance superposition is extremely low.

Our results confirm the conclusions of Richter and Rosa (1984), Huang (1987), Van Dyk (1992) and Van Dyk et al. (1996) that SNe II are strongly concentrated towards H II regions, and also the results of Maza and van den Bergh (1976) on the correlation of SNe II with the spiral arms. Van Dyk's (1992) results on the distributions of SNe Ib and Ia relative to H II regions are also confirmed.

The most interesting new result is the concentration of SNe Ia towards spiral arms. We can also see that SNe Ia and SNe II occur preferentially on the outer edges of the spiral arms. For SNe Ib the number of objects is too small for definite conclusions on such details of distribution.

It is interesting to note that according to Li *et al.* (1991) the most probable fraction of Galactic supernova remnants in spiral arms is 0.4–0.6,

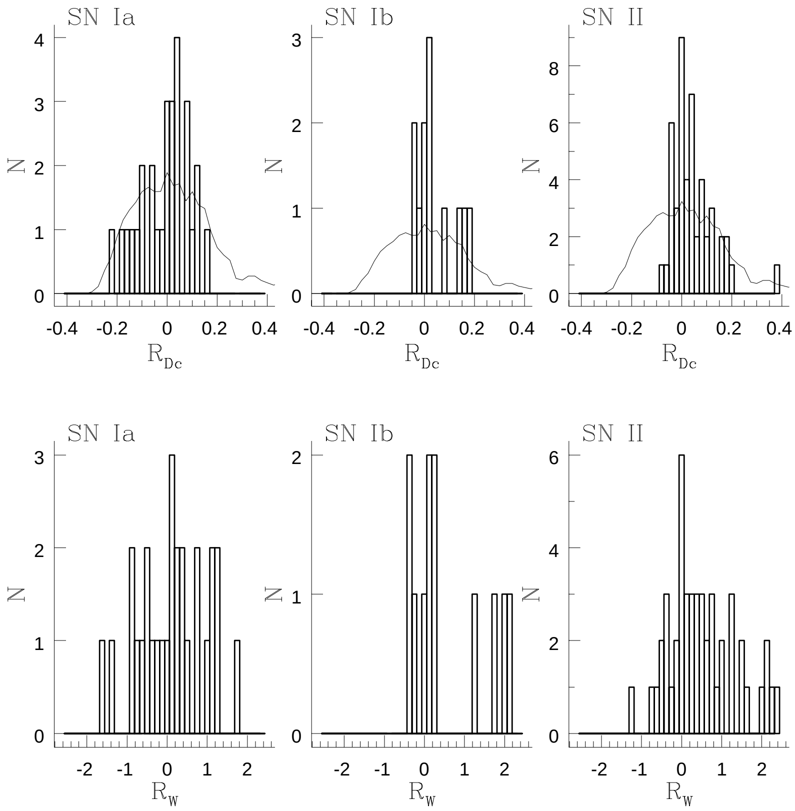

Figure 3. Distributions of SNe relative to spiral arms over the distance R_{Dc} from the SN to the spiral arm, normalized by the apparent radius of the galaxy and corrected for the inclination. The distribution expected for chance superposition of SNe and spiral arms is plotted by solid line (upper panel); distributions of SNe relative to spiral arms over the distance R_W from the SN to the spiral arm, normalized by the width of the spiral arm (lower panel)

which agrees with our data for SNe reported above.

Our results suggest that SNe II and Ib belong to massive stellar populations, and that their progenitors have similar age and initial mass. But there is a possibility that SNe Ib show greater preference for the central regions of the galaxies than do SNe II, which might indicate difference in the evolution of presupernovae of Types Ib and II.

SNe Ia occur in the spiral arms with a frequency very similar to that for SNe II. We can also conclude that most of their progenitors in spiral galaxies cannot belong to an old, evolved population. They are very likely stars of

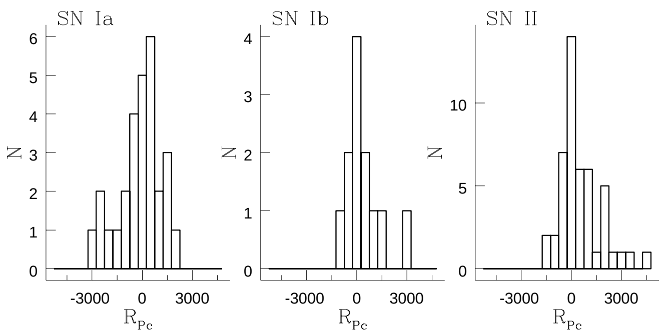

Figure 4. Distributions of SNe relative to spiral arms over the distance R_{Pc} from the SN to the spiral arm, expressed in parsecs and corrected for the inclination of the galaxy

intermediate age (> few times 10^7 years) and mass in the range 4–8 $M_\odot$. There is a possibility that SNe Ia in spiral and elliptical galaxies may have different origin. To clarify this question an investigation of the locations of SNe Ia in early–type galaxies is needed, together with a comparison of photometric and spectroscopic data.

4. Composite SN light curves

We have compiled the catalog of photometric observations of SNe, which at present includes data for 120 SNe. For SNe with well defined maximum light we can plot the composite light curves, which is shown in Fig. 6. For SNe with known distance to the parent galaxy and interstellar extinction we can construct the light curve in absolute magnitudes, they are presented in Fig. 7 for SNe Ia.

We can see that the light curves for type Ia SNe have similar shapes, but with quite large scatter of rates of brightness decline past maximum and the

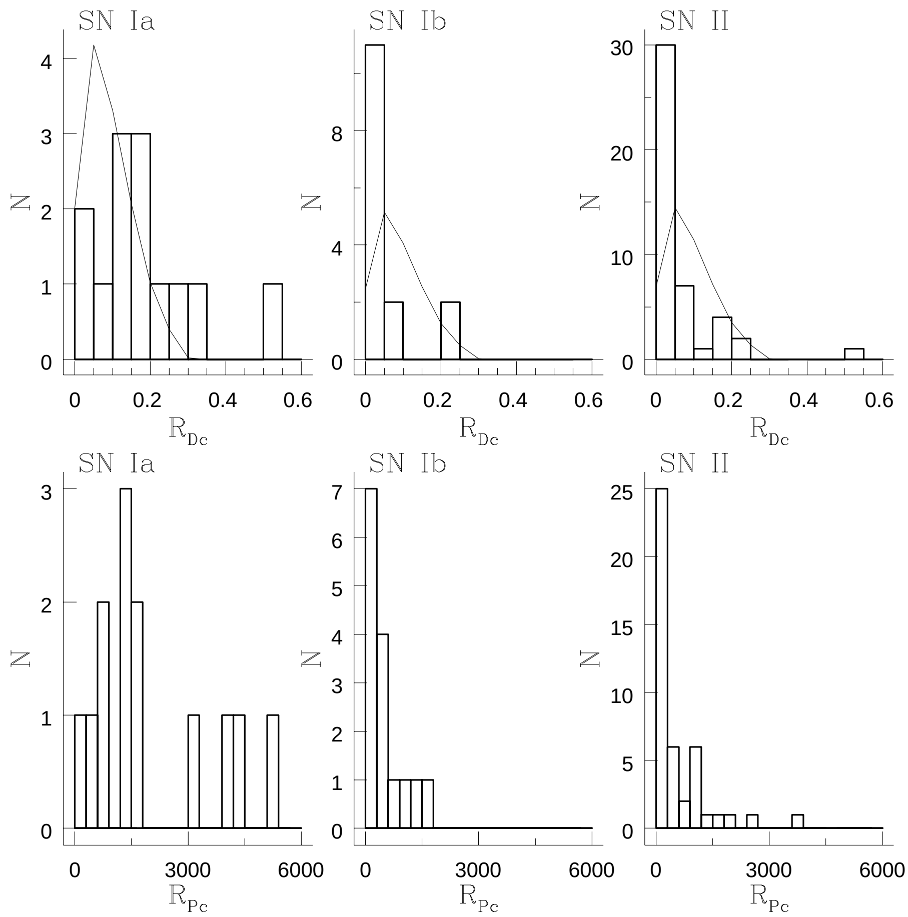

Figure 5. Distributions of SNe relative to H II regions over the distance R_{Dc} from the SN to the H II region, normalized by the apparent radius of the galaxy and corrected for the inclination. The distribution expected for chance superposition of SNe and H II regions is plotted for the model with 60 H II regions by solid line (upper panel); distributions of SNe relative to H II regions over the distance R_{Pc} from the SN to the H II region, expressed in parsecs and corrected for the inclination of the galaxy (lower panel)

interval between maximum and inflection point. There is well pronounced ridge line, corresponding to 'average' SNe Ia. Fig. 7 shows large scatter of SNe Ia absolute magnitudes, which is larger than 4^m. The most bright and faint SNe Ia are the peculiar objects SN 1991T and SN 1991bg, but even for 'normal' type Ia SNe the range of absolute magnitudes is larger than 2^m.

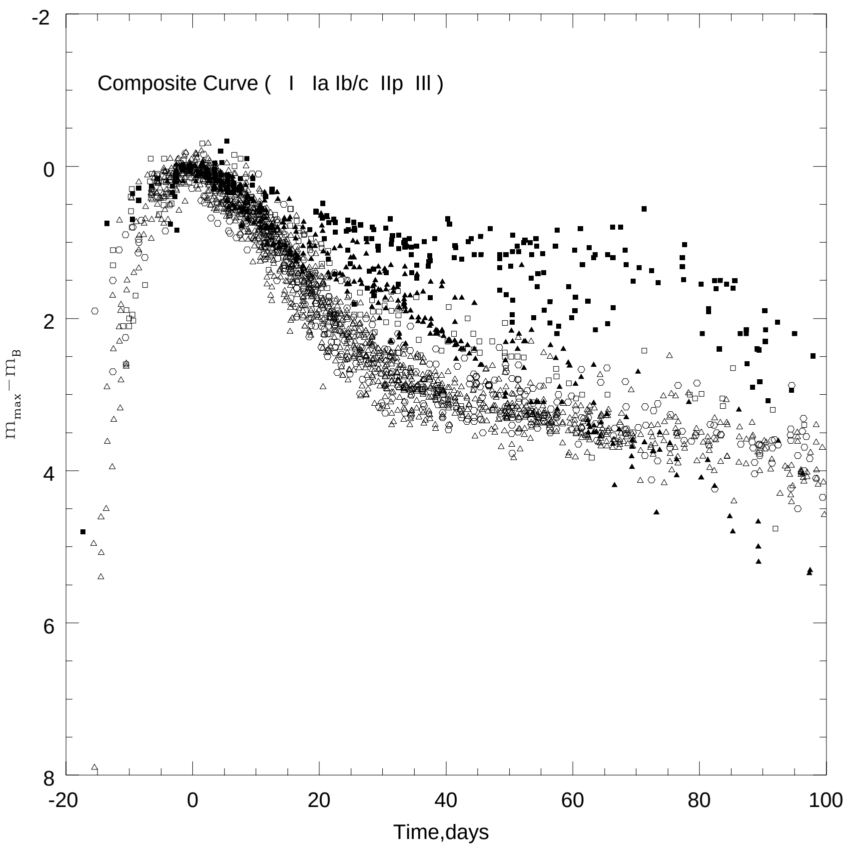

Figure 6. Composite B light curve for SNe of all types

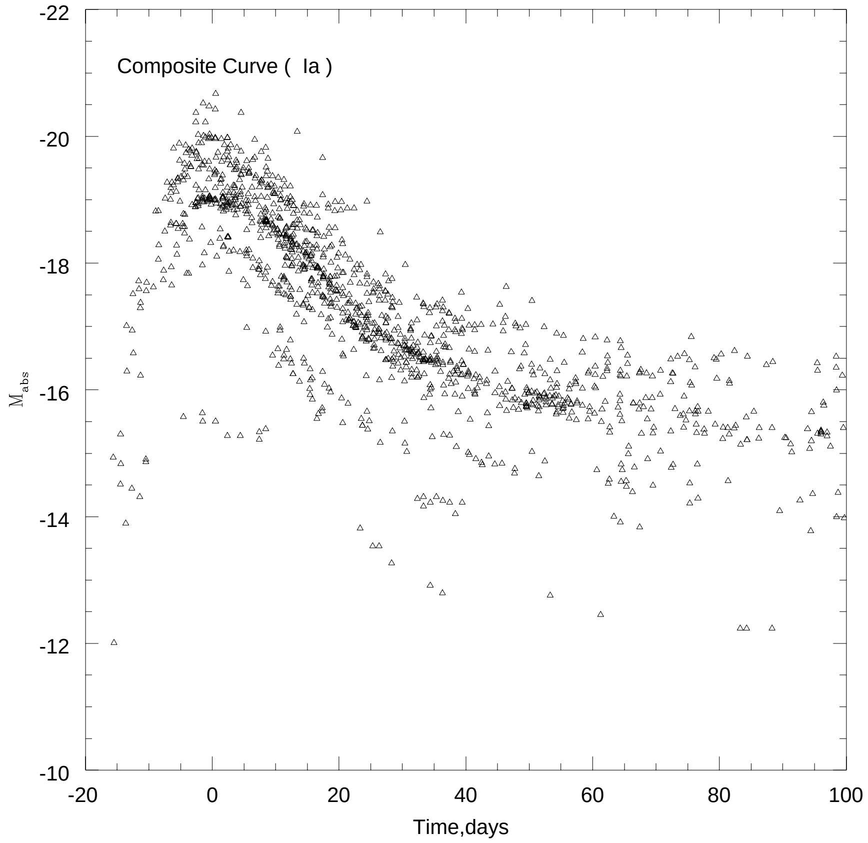

Figure 7. Absolute B light curves for SNe Ia

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