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Spatial distribution of different subtypes of core-collapse and thermonuclear supernovae in the galaxies

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Abstract. The distributions of supernovae of different types and subtypes along the radius and in z coordinate of galaxies have been studied. We show that among SNe Ia in spiral galaxies, SNe Iax and Ia-norm have, respectively, the largest and smallest concentration to the center; the distributions of SNe Ia-91bg and Ia-91T are similar. A strong concentration of SNe Ibc to the central regions has been confirmed. In spiral galaxies, the supernovae of all types strongly concentrate to the galactic plane; the slight differences in scale height correlate with the extent to which the classes of supernovae are associated with star formation.

Keywords. supernovae: general, galaxies: general

1. Introduction

Despite the significantly increased interest in the studies of supernovae (SNe) in recent years and the rapidly growing number of discovered and thoroughly studied SNe, the problem of the nature of SN progenitors still remains unsolved for many classes of SNe. The most efficient method of solving this problem is the identification of SN progenitors in preexplosion images. About 20 SN progenitor stars have been detected in the last 15 years, and upper limits on the luminosity have been established for about 30 objects. Almost all of the detected SN progenitors are type IIP and IIb ones. It has been established that SNe IIP result from the explosions of red supergiants with initial masses from 8 to 15-18 $M_{\odot}$; the most probable precursors for SNe IIb are yellow supergiants, possibly, in binary systems (Smartt 2015).

In addition to the search for SN progenitors, other methods are also used to solve this problem: studies of the stellar population at explosion sites and the large-scale distribution of SNe in their host galaxies (see, e.g., Anderson *et al.* 2015a, Anderson *et al.* 2015b, Kuncarayakti *et al.* 2013a, Kuncarayakti *et al.* 2013b).

Anderson *et al.* (2015a), Anderson *et al.* (2015b) compared the distributions of supernovae of the main types with respect to the star formation rate in spiral galaxies (determined from the Hα flux) and showed SNe Ic to be most closely associated with star formation; the types Ib, IIP, IIn, and Ia follow next in order of decreasing association. The radial distributions of SNe and luminosity in galaxies were also compared. The corresponding distributions for SNe Ia and II turned out to be approximately identical and to show a deficit in the central parts of galaxies; SNe Ibc differ greatly from them and show a strong concentration to the galactic centers. Hakobyan *et al.* (2009) studied the radial distribution of core-collapse supernovae (CCSNe: types II and Ibc) in spiral galaxies. The surface density distribution of all CCSNe was shown to be exponential, with SNe Ibc concentrating more strongly to the galactic centers. No significant differences in the distributions of SNe Ib and Ic were found; there is some deficit of SNe II in the central regions of galaxies.

Although studies of the radial distribution of SNe cannot unambiguously indicate which stars explode as SNe of a certain type, they nevertheless can give important constraints on the nature of the stellar population of SN progenitors. The advantages of this method are a large statistical material and the possibility of a quick comparison of various SN types and subtypes between themselves. New species of SNe, which often become the "progenitors" of new types, are being continuously discovered at present. Note the introduction of subtypes of SNe Ia: types Ia-91bg, Ia-91T (e.g., Leibundgut 2000), the SN Iax type (Foley *et al.* 2013), the discovery of superluminous SNe (SLSNe, brighter than −21 mag) (Quimby *et al.* 2013) and low-luminosity SNe ($M \sim -14$ mag or fainter) (Zampieri *et al.* 2003).

An increase in the volume of observational data makes it possible to study the spatial distribution not only for the main SN types but also for some subtypes: SNe Iax, SNe Ia-91bg, SNe Ia-91T, IIb, and IIn. We have also attempted to compare the distributions of SNe in z coordinate in spiral galaxies for the first time.

2. Selection of input data

We took the samples of SNe to study the radial distributions from the Catalog of Supernovae of the Sternberg Astronomical Institute (Tsvetkov & Bartunov 1993, Tsvetkov *et al.* 2004), its updated version is accessible on the Internet†.

For our study, we selected only classified SNe. In those cases where the explosion occurred in a double or multiple system of galaxies, we selected only those SNe whose host galaxy was determined quite reliably. The intergalactic SNe or SNe without visible host galaxies were not considered. There should have been information about the morphological type, apparent sizes, and radial velocity for the host galaxies. If these data were available in both LEDA‡ and NED¶ preference was given to the former. Just as in our previous papers (Bartunov *et al.* 1992, Tsvetkov *et al.* 2004, Bartunov *et al.* 2007), we calculated the relative distance for each SN, $r = 2(\Delta\alpha^2 + \Delta\delta^2)^{0.5}/D_{25}$, where $\Delta\alpha$ and $\Delta\delta$ are the distances in arcseconds from the galactic center to the SN in right ascension and declination, D_{25} is the diameter of the galaxy to the 25 mag/arcsec^2 isophote. We also calculated the distances normalized to the galaxy's radius along the SN radius vector: $r_c = r/(\cos^2\theta + (b/a)^2 \sin^2\theta)^{0.5}$ where θ is the angle between the SN radius vector and the galaxy's major axis, a and b are the galaxy's apparent major and minor axes. For our study, we selected a total of 2341 SNe; among them there are 1048 SNe Ia, 984 SNe II; and 309 SNe Ibc. They were all discovered before February 16, 2013, with the addition of three 2014 supernovae whose host galaxies are seen exactly edge-on and can be used in considering the distributions in z coordinate. The fraction of supernovae discovered photographically is about 10-15%.

We introduced no radical changes into the technique of studying the radial distributions of SNe compared to our previous papers (Bartunov *et al.* 1992, Tsvetkov *et al.* 2004). We studied the dependence of the logarithm of the SN surface density σ in ring zones along the galactic radius. No smoothing of the data was applied. In those cases where the number of SNe within the ring zones dividing the galactic disk along the radius was

† http://www.sai.msu.su/sn/sncat/
‡ http://leda.univ-lyon1.fr
¶ http://ned.ipac.caltech.edu

not enough to construct the distribution, we increased the size of the corresponding rings beginning from a given radius and further out from the galactic center.

The considerable increase in the number of discovered SNe over the last 10 years has made it possible to study the distributions of SNe not only along the radius but also in a direction perpendicular to the galactic plane, in z coordinate. For this purpose, we selected the SNe that exploded in edge-on spiral galaxies. Our initial selection of galaxies was made according to the condition $i > 85°$, where the inclination i was determined from the formula $i = \arccos(1.04(b/a)^2 - 0.04)^{0.5}$. We then examined the photographs of the selected galaxies and included the galaxies that were undoubtedly seen almost exactly edge-on in our final sample. The sample contains 78 galaxies in which 26 SNe Ia, 44 SNe II, and 8 SNe Ibc exploded. For our study, we took the SN images stored at the "Bright Supernovae" site‖. These images were transformed until they coincided with the images of galaxies from the Digital Sky Survey (DSS)†† in three common stars using the IRAF software package‡‡.

Thus, we can determine the SN explosion site in the galaxy's DSS image. In this image, we drew the straight line corresponding to the galactic plane and determined the angular distances from SN to the galactic plane and from the galactic center to the base of the normal dropped from the SN on the galactic plane. These distances were then expressed in fractions of the galactic radius (z, r_z) or in kiloparsecs (Z, R_z).

3. Results of our study of the radial distribution of SNe

Previous studies showed that the observational selection effects, primarily the losses of SNe in the central parts of galaxies, play an important role in studying the radial distributions (Bartunov *et al.* 1992, Howell *et al.* 2000, Tsvetkov *et al.* 2004). This effect manifest itself most clearly in searching for SNe by the photographic method. However, whereas the fraction of SNe discovered on photographs was significant in previous studies, it is rapidly decreasing at present. It is of interest to estimate whether this effect is retained at present, when all SNe are discovered using CCD surveys. For this purpose, we studied the properties of the samples of SNe with respect to the radial velocities of their host galaxies. Obviously, the influence of selection effects on the results increases as we pass to higher redshifts. This is clearly demonstrated by Fig. 1, which shows the distribution of relative distances r_c as a function of the radial velocities of host galaxies V_r. There is a clear tendency for the minimum distance r_c to increase with V_r.

The influence of selection can also be estimated by dividing the samples of SNe into two parts, with radial velocities larger and smaller than some boundary value. When the boundary value of $V_r = 6000$ km s^{-1} is chosen, the numbers of SNe in the two parts of the samples turned out to be approximately equal. The results are shown in Fig. 1, where the "distant" (with larger radial velocities) and "nearby" (with smaller velocities) samples are denoted by the letters F and N. We may conclude that the influence of observational selection with this choice of the boundary velocity is insignificant for SNe Ia, while it is very large for SNe Ibc and especially for SNe II. Thus, a significant fraction of SNe in the central parts of galaxies are not detected even when searching for SNe with CCD detectors. This should be taken into account both when studying the distributions of SNe and when estimating the rate of SNe, especially when studying the redshift dependence of the SN rate. To completely eliminate the influence of selection, below we constructed

‖ http://www.rochesterastronomy.org
†† http://archive.stsci.edu
‡‡ IRAF is distributed by the NOAO, which is operated by AURA, Inc. under cooperative agreement with the NSF, http://iraf.noao.edu

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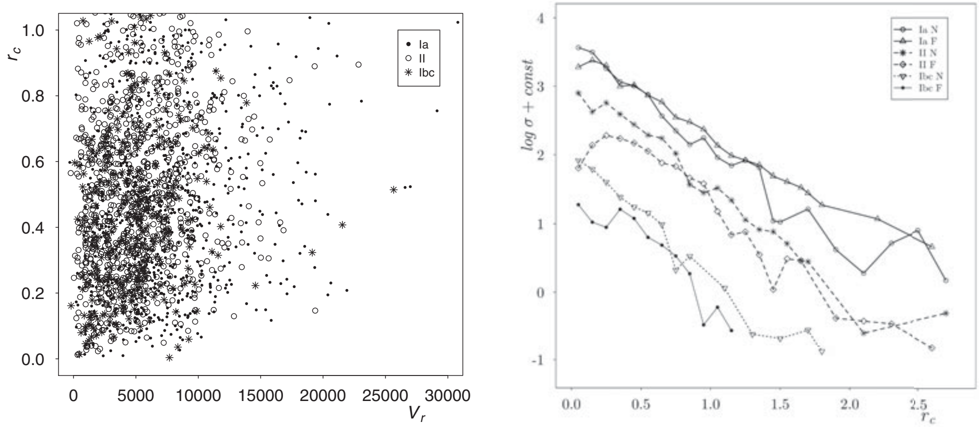

Figure 1. Selection effect on the discovery of SNe. Left panel: distributions of r_c as a function of the radial velocities of the galaxies V_r, right panel: distributions of surface density for "nearby" (N) and "distant" (F) samples.

all distributions with a radial velocity constraint, with the limiting velocity having been taken to be 6000 km s^{-1} for SNe II and Ibc and 8000 km s^{-1} for SNe Ia.

Despite the small number of SNe classified as subtypes of the Ia class, we nevertheless attempted to compare their radial distributions. The samples contained 167 SNe Ia-norm, 10 SNe Ia-91T, 14 SNe Ia-91bg, and 20 SNe Iax. The results for these subtypes are shown in Fig. 2. Probably the most interesting result is a reduced number of SNe Ia-norm in the central parts of galaxies. A strong concentration of SNe Iax to the central regions of galaxies seems quite unexpected. It is also very interesting that the radial distributions of SNe Ia-91bg and SNe Ia-91T agree better with one another than those for SNe Iax and SNe Ia-91T. Of course, these results are not yet quite reliable, and they should be repeated after increasing the sample size. Next, it is worth considering the situation with regard to SNe II and Ibc. The discovery of quite a few new objects has allowed us to separately study the radial distributions for their subtypes: IIP, IIL, IIn, IIb, Ib, and Ic (Fig. 2). Our samples contained 131 SNe IIP, 63 SNe IIn, 41 SNe IIb, 13 SNe IIL, 89 SNe Ib, and 60 SNe Ic. We restricted ourselves only to the SNe exploded in galaxies with radial velocities $V_r < 6000$ km s^{-1}. Given the small number of SNe IIL and the often unambiguous assignment of SNe to this class, we can say that their distributions do not differ significantly from the distribution of SNe IIP. A strong concentration of SNe Ib and Ic to the galactic centers is confirmed, with no difference between SNe Ib and Ic having been revealed. Interestingly, SNe IIb and IIn show a greater similarity to SNe IIP and Ibc, respectively.

4. Results of our study of the distributions of SNe in z coordinate

We constructed both relative and absolute distributions of SNe in z coordinate (Fig. 3). As expected, the SNe of all types strongly concentrate to the galactic plane (see, e.g., Hakobyan *et al.* 2009). The distributions can be fitted by exponentials with scale heights z_0, Z_0. For the relative distributions in z coordinate, $z_0 = 0.030 \pm 0.006$ for SNe Ia, slightly smaller $z_0 = 0.029 \pm 0.005$ for SNe II, and $z_0 = 0.024 \pm 0.006$ for SNe Ibc. Thus, the SNe Ibc are slightly closer to the galactic plane. A similar result is obtained when considering the absolute distributions: $Z_0 = 0.55 \pm 0.11$, 0.50 ± 0.08, and 0.40 ± 0.14 kpc for SNe Ia, II, and Ibc, respectively. We should note that some CCSNe occur at quite

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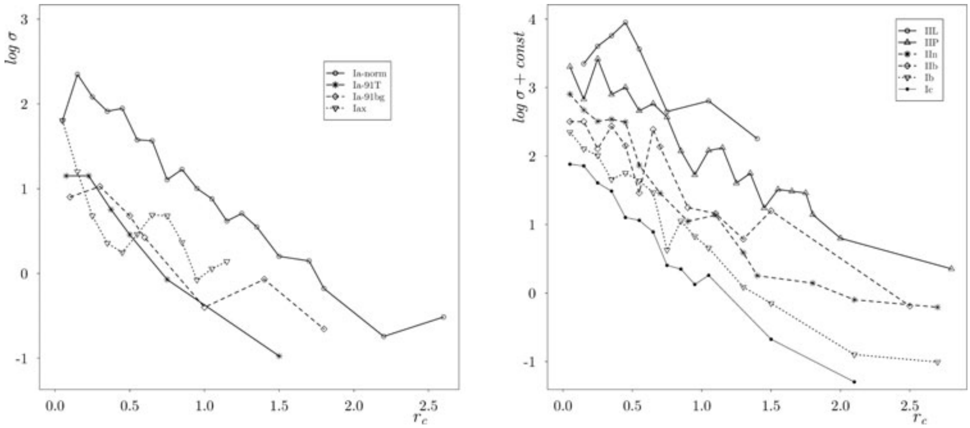

Figure 2. Radial distributions of subtypes of thermonuclear SNe (left panel) and CCSNe (right panel).

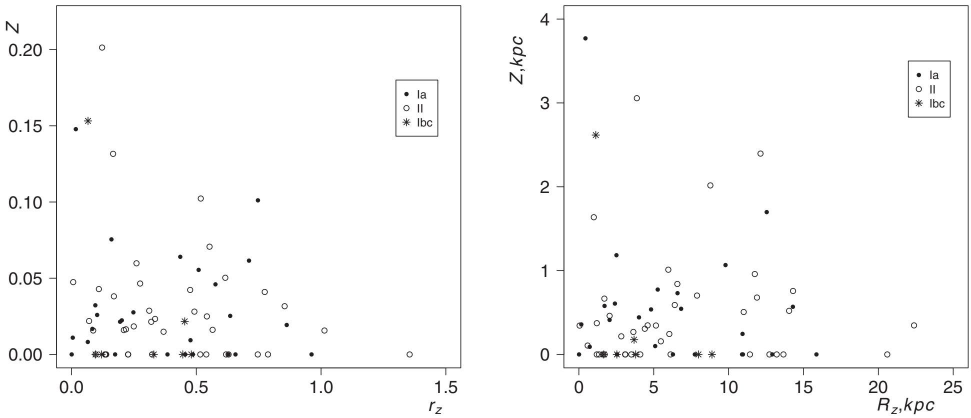

Figure 3. Distributions of SNe Ia, II and Ibc in z coordinate. Left panel: relative distributions, right panel: distributions of distances expressed in kiloparsecs.

high $Z \sim 3$kpc and there is a trend for SNe with high Z to be located in the central parts of the galaxies.

5. Conclusions

Based on data from the SN Catalog of the Sternberg Astronomical Institute, we studied the radial distributions of SNe in their host galaxies, with the radial distributions for subtypes of the main SN classes (Iax, Ia-91bg, Ia-91T, IIn, IIb, IIL, and IIP) having been compared for the first time. The distributions of SNe Ia, II, and Ibc in z coordinate have been studied for the first time. We showed a significant fraction of SNe in the central parts of galaxies to be lost for galaxies with $V_r > 10000$ km s^{-1} . The distributions of SNe Ia-91bg and Ia-91T in spiral galaxies turned out to be similar and different from those of SNe Ia-norm and Iax. SNe Iax show a strong concentration to the central regions of galaxies. We confirmed a stronger concentration of SNe Ib and Ic to the galactic centers than that for other types of core-collapse supernovae, with no difference between SNe Ib and Ic having been revealed. Our study of the distributions in z coordinate confirms a strong concentration of SNe of all types to the planes of spiral galaxies, but some CCSN

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are located quite high above the plane. The slight differences in scale heights agree with the extent to which the supernovae of these classes are associated with regions of recent star formation.

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