Paired galaxies with different activity levels and their supernovae

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Abstract We investigate the influence of close neighbor galaxies on the properties of supernovae (SNe) and their host galaxies using 56 SNe located in pairs of galaxies with different levels of star formation (SF) and nuclear activity. The statistical study of SN hosts shows that there is no significant difference between morphologies of hosts in our sample and the larger general sample of SN hosts in the Sloan Digital Sky Survey (SDSS) Data Release 8 (DR8). The mean distance of type II SNe from nuclei of hosts is greater by about a factor of 2 than that of type Ibc SNe. The distributions and mean distances of SNe are consistent with previous results compiled with the larger sample. For the first time it is shown that SNe Ibc are located in pairs with significantly smaller difference of radial velocities between components than pairs containing SNe Ia and II. We consider this as a result of higher star formation rate (SFR) of these closer systems of galaxies. SN types are not correlated with the luminosity ratio of host and neighbor galaxies in pairs. The orientation of SNe with respect to the preferred direction toward neighbor galaxy is found to be isotropic and independent of kinematical properties of the galaxy pair.

Keywords supernovae: general • galaxies: fundamental parameters • galaxies: interactions • galaxies: starburst

1 Introduction

Stellar populations and history of SF are crucial parameters that determine the nature of galaxies. Among other triggers, interactions and mergings can play an important role in explaining the origin and processes underlying the active SF phenomena observed in galaxies (e.g., Blanton and Moustakas 2009; Bournaud 2011). Particularly, merging is considered as the mechanism that changes the properties of galaxies dramatically and is able not only to bring additional amount of gas for fueling nuclear activity and starburst, but also to change the efficiency and timescales of SF in galaxies significantly (e.g., Kennicutt 1998; Cox et al. 2008). Connection between interaction/merging and SF has been shown in many observational studies (e.g., Barton et al. 2000; Patton et al. 2011) and theoretically has been modeled and explained in many papers (e.g., Mihos and Hernquist 1996; Di Matteo et al. 2007). According to large-sample statistical studies, in most cases gravitational interaction can be a triggering mechanism for nuclear activity and/or circumnuclear starburst in interacting and merging galaxies (e.g., Ho 2008; Ellison et al. 2011; Liu et al. 2012; Patton et al. 2011, 2013). In several studies enhanced SF was revealed also in tidal arms and in bridges connecting galaxies in interaction (e.g., Smith et al. 2007). There also exists the possibility, that interactions can enhance
SNe are classified into two main types with differences in the nature of progenitors and mechanisms of explosion. Current understanding is that type Ib, Ic and II SNe occur from the gravitational collapse of young massive stellar cores (Hamuy 2003; Smartt 2003), and type Ia SNe from thermonuclear explosions of a white dwarf in close binary systems (Livio 2001; Maoz and Mannucci 2012).

Binary companions in type Ia events have unclear nature (Mannucci et al. 2003; Maoz and Mannucci 2012), whereas CC SNe are connected only with massive young stellar populations with possible differences in masses of progenitors from less massive ones ($M \gtrsim 8 M_\odot$) for type II SNe to more massive ones ($M \gtrsim 20 M_\odot$) for Ib, SNe, with these boundaries depending also on metallicity (e.g., Boissier and Prantzos 2009). While SNe Ia are found in any morphological types of galaxies (van den Bergh et al. 2005), CC SNe are located only in spiral and irregular galaxies with the few exceptions of being found in early-type galaxies, which are in close interaction or are remnants of merging processes (Hakobyan et al. 2008). SN rates of both type Ibc and type II SNe increase from early- to late-type spiral galaxies (e.g., Mannucci et al. 2003; Hakobyan et al. 2011) and are correlated with color and far-infrared (FIR) excess of galaxies (e.g., Cappellaro et al. 1999). The radial distribution of Ibc and II SNe in galactic disks is exponential, being more concentrated for type Ibc SNe (van den Bergh 1976; Hakobyan et al. 2004, hereafter H09; Habergham et al. 2012). CC SNe also are closely associated with spiral arms (e.g., Maza and van den Bergh 1976) and HII regions (e.g., Bartunov et al. 1994; Anderson and James 2008). All observational results mentioned above suggest that CC SNe are tightly connected with recent SF.

Several studies have been carried out to investigate rates and distributions of CC SNe located in galaxies showing different levels of nuclear and starburst activity (Petrosian and Turatto 1990; Bressan et al. 2002; Petrov et al. 2005; Hakobyan 2008). Samples included both isolated and paired as well as groups of galaxies (Petrosian and Turatto 1993). Navasardyan et al. 2001). According to these studies, the radial distribution of SNe in active and star-forming galaxies shows a higher concentration toward the center of the active hosts than in normal ones, and this effect is more pronounced for CC SNe (Petrosian et al. 2005), especially for SNe Ibc (Hakobyan 2008). Study of SNe in morphologically disturbed hosts has been carried out also and has showed that fraction of type Ibc SNe in central regions of disturbed hosts is increased compared to that of the undisturbed hosts (Habergham et al. 2012). There is also an indication that SN rates are higher in galaxy pairs compared with that in groups, which can be related to the enhanced SFR in strongly interacting systems (Navasardyan et al. 2001). Studies of SNe in interacting hosts are difficult because of small statistics and many selection effects, but they can provide additional helpful information to understand the influence of interactions on activity and SF processes of galaxies.

The aim of this study is to investigate to what extent gravitational interaction with a close neighbor can be connected with nuclear activity and/or enhanced SF in galaxy pairs, using SNe as tracers of recent SF. For that purpose we selected samples of paired galaxies with different nuclear/starforming activity levels, from AGNs and starburst galaxies to completely passive ones. We examined possible correlations between kinematical properties of pairs of galaxies, integral parameters of SN hosts and their neighbors, as well as SN types and their distributions. Sect. 2 presents the sample of close pairs of galaxies with at least one SN event. Sect. 3 discusses the parameters of SNe, their hosts and close neighbors. Sect. 4 presents the statistical study of the sample and discusses its results. Section 5 is the summary of this study. Throughout this paper, we adopt the Hubble constant $H_0 = 73 \text{km s}^{-1} \text{Mpc}^{-1}$.

2 Sample

The current sample of the study was obtained by cross-matching the catalog of SNe by Hakobyan et al. 2012 (hereafter H12) with the sample of selected pairs of galaxies (see below). SN database H12 contains 3876 SNe located in the area of the sky covered by the SDSS DR8 survey. The database, with the revision of a few SNe (Aramyan et al. 2013), particularly provides SN types, their exact positions in the hosts, as well as homogeneous information about hosts of these SNe (galaxy name, exact coordinates, redshift, morphology, magnitude, angular size etc.) when available.

We used three catalogs of galaxies with different levels of nuclear activity to construct our sample of close pairs of galaxies. These catalogs are the following: (1) the catalog of Markarian (MRK) galaxies (Petrosian et al. 2007, hereafter P07), (2) the Second Byurakan Survey (SBS) galaxies catalog (Gyulzadyan et al. 2011, hereafter G11) and (3) the North Galactic Pole (NGP) galaxy catalog (Petrosian et al. 2008, hereafter P08).

1The notation type Ibc SNe is often used to indicate globally the entire class of stripped-envelope SNe, i.e. Ib, Ic and intermediate cases.
The MRK catalog contains 1545 galaxies having starburst properties and/or active nuclei. In [P07], homogeneously measured parameters of MRK galaxies, such as magnitudes, sizes, positions, redshifts, morphologies are presented. The SBS catalog contains 1676 galaxies, most of which are known to have active nuclei and/or starbursts. Parameters of SBS galaxies are presented in a recent version of the catalog in [G11]. They are measured in the same way as those of the MRK sample. The NGP catalog in [Huchra et al. 1990] contains a complete sample of galaxies down to 15.5 photographic magnitudes within a 6-degree strip passing through the NGP. In [P08], 1093 galaxies of this catalogue were studied, by being grouped into two samples according to their activity level. We named these two samples accordingly as: NGPA – for galaxies with active or star forming nuclei, and NGPN – for normal galaxies. Properties of NGPA and NGPN galaxies were also measured in the same homogeneous way as for MRK and SBS samples. Median redshifts for MRK, SBS and NGP galaxies are 0.02, 0.04 and 0.03 and blue apparent magnitudes with their $\sigma$-s are 15.2 $\pm$ 0.9, 16.7 $\pm$ 0.9 and 15.0 $\pm$ 0.7, respectively. Therefore, the galaxies in three samples are located at similar redshifts and have magnitudes close to each other. It is important to note that, the MRK and SBS samples could bias the total sample toward more active galaxies, both AGN hosts and starburst galaxies. To check it, we conducted a binomial test (comparison of percentages of AGN and starforming hosts) of SN hosts between sub-samples from MRK+SBS and NGP and obtained that the proportions of AGN and starforming hosts are the same for these two sub-samples at $P = 0.08$ and $P = 0.15$ respectively. Thus, MRK and SBS samples do not bias our further statistics.

Results of a close neighbors search for MRK galaxies within position-redshift space using NASA/IPAC Extragalactic Database (NED) and SDSS DR8 (for current study we added to this list some new objects found only in the 9th data release [Ahn et al. 2012] of SDSS) are already published [Nazaryan et al. 2012, hereafter N12]. In [N12], three criteria were used to select the sample of close neighbors of MRK galaxies. (1) Redshift of MRK galaxy should be more than 0.005. (2) Difference of radial velocities of MRK galaxy and its neighbor should be less than 800 km s$^{-1}$. (3) Projected distance between MRK galaxies and their neighbors should be less than 60 kpc (close systems). According to these criteria, 633 galaxies in close systems containing 274 MRK galaxies were discovered in [N12]. We also conducted the search of neighbors for SBS and NGP galaxies using the same criteria as for MRK galaxies. Identification revealed 380 galaxies in close systems containing 228 SBS galaxies, 365 galaxies in close systems containing 166 NGPN galaxies and 420 galaxies in close systems containing 186 NGPA galaxies. For the current study, only pairs of galaxies were selected from the above mentioned 1798 galaxies in close systems with different multiplicity. The total number of pairs containing at least one MRK, SBS, NGPA or NGPN galaxy is 675. The percentage of pairs that are located within the SDSS area is 87%, 94% and 100% for MRK, SBS and NGP pairs, respectively.

The sample of 675 pairs of galaxies was crossmatched with the list of SN hosts from [H12]. In total 56 SNe in 44 hosts were identified: 18 SNe of them located in 10 MRK, 4 SNe in 4 SBS, 3 SNe in 3 NGP, 11 SNe in 10 NGP hosts, and 20 SNe in 17 neighbors of the aforementioned galaxies. Although the [H12] database contains information about the hosts of SNe, we once more visually inspected all our SNe and host pairs and carefully checked the identification of host galaxies and SN offsets.

3 Measured and collected parameters

In order to obtain homogeneous measurements of parameters of all sample galaxies in pairs, we measured them in the same way as in [P07], [P08], [G11] and [N12]. Table 1 presents the data of SNe, their hosts, and host neighbors, which were used in statistical research. The first four columns of Table 1 present data for SNe. Column 1 contains SN names and Col. 2 contains SN types ([H12]). We grouped SNe into three main classes: type Ia, type II, and type Ibc for statistics. In a few cases, marked by "**", types have been inferred from the light curves. Uncertainties in SN type are marked by ":" and "?" (highly uncertain). Nineteen out of 56 SNe are of type Ia, 12 are of type Ibc, and 15 are of type II. Column 3 contains radial distances of SNe from their host nuclei, normalized to $R_{25}$ of hosts according to [H03]. For CC SNe, we assumed that they are located within the discs of the hosts and corrected their offsets, taking into account galaxy inclination. For SNe of type Ia, the radial distance is the ratio of its angular distance from nuclei to the $R_{25}$ of the host. We did not deproject radial distances for SNe Ia, because 2 out of 19 SNe Ia are located in early-type hosts, 6 SNe are visually located outside the disks of the hosts. Even assuming that some of SNe Ia in spiral hosts belong to the disk population (e.g., [Mannucci et al. 2005, 2006], [Hakobyan et al. 2011]), doing inclination correction to deproject them seems likely to add more errors than
if we do not deproject them. Column 4 presents the position angle (PA) of the SN in its host with respect to the direction toward the neighbor galaxy. It is an angle that has a value from 0° for a SN located toward the neighbor galaxy to 180° for a SN located on the opposite side of the host, independently of the clockwise/anticlockwise direction.

The next 13 columns of Table I present integral parameters for SN hosts and their neighbors in pairs used in our statistical analysis. Redshifts of galaxies in pairs were obtained from the SDSS DR9 and/or NED. Then, recession velocities were corrected for Virgocentric infall (Terry et al. 2002). The median distance of pairs is 62 Mpc. Coordinates of galaxies were obtained using peak surface brightness from the SDSS images. Names of hosts and their neighbors are presented in Cols. 5 and 6. The SDSS RGB images were used as a primary source for SN hosts and their neighbors’ morphological classification (Cols. 7-10). A detailed description of classification procedure is available in P07. For checking consistency, we compared our SN hosts’ morphological classifications with that of H12. The mean absolute difference in t-types of these two classifications is 0.6 units, and bar detection is different in 17% of cases. To be consistent with P07, P08, G11, N12, magnitudes of the galaxies are measured from the Second Palomar Observatory Sky Survey (POSS-II) and UK Schmidt Telescope (UKST) photographic plates, collected in the Second Digitized Sky Survey (DSS-II). Blue ($J_{pg}$) and red ($F_{pg}$) magnitudes of galaxies were measured from the $J$ and $F$ band images of the objects in a homogeneous way at the isophote corresponding to $\geq 3\sigma$ background noise, which is approximately 25.2 mag arcsec$^{-2}$ (see P07 for details). Absolute magnitudes are corrected for Galactic foreground [Schlafly and Finkbeiner 2011], recalibration of the Schlegel et al. (1998) infrared-based dust map) and target galaxy internal extinctions (Bottinelli et al. 1993) and are presented in Cols. 11 and 12. Linear major diameters of SN hosts and their neighbors are presented in Cols. 13 and 14. They are calculated using angular major diameters measured in a homogeneous way from the DSS-II blue images (see N12 for details).

Pairs of galaxies are described via two parameters describing strength/stage of interacting/merging (e.g., Patton et al. 2000): difference of radial velocities $\Delta v_r$ of SN hosts and their neighbors (Col. 15) and linear projected distance $d_p$ (Col. 16) between pair members. Figure 1 shows the distribution of pairs according to these two parameters. It is noteworthy, that although we cut the initial sample of pairs by $\Delta v_r \leq 800$ km s$^{-1}$, all pairs hosting SNe have $\Delta v_r \lesssim 400$ km s$^{-1}$. The mean error for $\Delta v_r$, which is calculated using available uncertainties from the SDSS and NED, is $\sim 20$ km s$^{-1}$. Pairs of our sample consist of galaxies of comparable luminosities with mean difference of magnitudes $\sim 2$ mag.

In Col. 17 we present BPT (Baldwin et al. 1981) classification types for 25 hosts of SNe presented in SDSS. The pipeline and the way they were measured is described in Brinchmann et al. (2004). For statistical study, we visually inspected whether the nucleus of the galaxy is located within the fiber used to obtain its spectrum and kept only those containing the spectrum of nuclei. We assign to galaxies their SDSS BPT types using numerical codes: (-1) for passive nuclei; (1) for star-forming nuclei; (3) for composite nuclei (data for MRK 171B composite nuclei were added from H12), and (5) for narrow-line Active Galactic Nuclei (AGN). This coding sequence is used to reflect an increasing sequence of equivalent widths of emission-lines.

### 4 Statistics and discussions

#### 4.1 Multivariate factor analysis

The statistical research was conducted in two steps. First, we applied an exploratory multivariate factor analysis (MFA, e.g., Tabachnick and Fidel 2000) to look for correlations between all parameters describing SNe, their hosts and host neighbors, which are collected in Table I. This statistical method is similar to the more commonly used principal component analysis.
Table 1: Data for SNe, their hosts and host neighbors.

| SN name | Host name | Neig. name | SN type | $R_{SN}/R_{25}$ | $\Delta v_r$ | $d_p$ | Host diam. | Neig. diam. | Host abs. mag | Neig. abs. mag | Host t-type | Host PA | Host bar | Neig. t-type | Neig. bar | Neig. abs. mag | ∆v_r | $d_p$ |
|---------|-----------|------------|---------|----------------|-------------|--------|------------|-------------|---------------|---------------|-------------|----------|---------|-------------|----------|---------------|-------|-------|
| 1960I   | Ia        | 0.42       | 66      | 0.82           | 0.02        | 1.00   | 0.30       | 0.30        | -0.03         | -0.03         | 0.07        | 0.07     | 1.00    | 0.07        | 0.07     | 0.07           | 1.00  | 1.00  |
| 1960J   | Ia        | 0.96       | 107     | 0.33           | 0.33        | 0.33   | 0.33       | 0.33        | -0.03         | -0.03         | 0.07        | 0.07     | 1.00    | 0.07        | 0.07     | 0.07           | 1.00  | 1.00  |
| 1960M   | Ia        | 0.67       | 116     | 0.67           | 0.67        | 0.67   | 0.67       | 0.67        | -0.03         | -0.03         | 0.07        | 0.07     | 1.00    | 0.07        | 0.07     | 0.07           | 1.00  | 1.00  |
| 1961D   | Ia        | 0.71       | 142     | 0.71           | 0.71        | 0.71   | 0.71       | 0.71        | -0.03         | -0.03         | 0.07        | 0.07     | 1.00    | 0.07        | 0.07     | 0.07           | 1.00  | 1.00  |
| 1972C   | Ia        | 0.18       | 41      | 0.18           | 0.18        | 0.18   | 0.18       | 0.18        | -0.03         | -0.03         | 0.07        | 0.07     | 1.00    | 0.07        | 0.07     | 0.07           | 1.00  | 1.00  |
| 1972L   | Ia        | 1.83       | 33      | 1.83           | 1.83        | 1.83   | 1.83       | 1.83        | -0.03         | -0.03         | 0.07        | 0.07     | 1.00    | 0.07        | 0.07     | 0.07           | 1.00  | 1.00  |
| 1973A   | Ia        | 0.30       | 104     | 0.30           | 0.30        | 0.30   | 0.30       | 0.30        | -0.03         | -0.03         | 0.07        | 0.07     | 1.00    | 0.07        | 0.07     | 0.07           | 1.00  | 1.00  |
| 1973E   | Ia        | 0.67       | 175     | 0.67           | 0.67        | 0.67   | 0.67       | 0.67        | -0.03         | -0.03         | 0.07        | 0.07     | 1.00    | 0.07        | 0.07     | 0.07           | 1.00  | 1.00  |

Note: Only 10 entries are shown. Full Table 1 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/cgi-bin/qcat?J/other/ApSS/000.000. A portion is shown here for guidance regarding its form and content.

Table 2: Varimax rotated normalized orthogonal factor loadings. Data for 46 SNe sample.

| Variable                  | $F_1$ | $F_2$ | $F_3$ |
|---------------------------|-------|-------|-------|
| SN type                   | 0.16  | -0.71 | 0.00  |
| $R_{SN}/R_{25}$           | 0.33  | 0.40  | 0.35  |
| SN PA                     | 0.03  | 0.06  | -0.26 |
| Host t-type               | 0.47  | -0.46 | 0.43  |
| Host bar                  | 0.14  | -0.02 | 0.83  |
| Host abs. mag             | -0.56 | 0.16  | 0.50  |
| Neig. t-type              | 0.34  | -0.70 | 0.21  |
| Neig. bar                 | 0.71  | 0.00  | 0.10  |
| Neig. abs. mag            | -0.76 | -0.05 | 0.37  |
| $\Delta v_r$             | 0.18  | 0.72  | -0.05 |
| $d_p$                     | -0.67 | 0.14  | -0.25 |
| Accum. variance           | 21%   | 39%   | 53%   |

Note: Only 10 entries are shown. Full Table 2 is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsarc.u-strasbg.fr/cgi-bin/qcat?J/other/ApSS/000.000. A portion is shown here for guidance regarding its form and content.

(The PCA). The MFA describes the interdependence and grouping patterns of variables in terms of factors. Factor loadings are measures of involvement of variables in factor patterns and can be interpreted like correlation coefficients. The square of the loading is the variation that a variable has in common with the factor pattern. The percent of total variance carried by a factor is the mean of squared loadings for a factor. Applying MFA, we chose as initial variables all the parameters of Table 1 assigning to SN types following coding: 1 to Ia, 2 to II, and 3 to Ibc. This order is chosen not to shade the suggested age sequence for SN progenitors from older to younger (e.g., Livio 2001; Heger et al. 2003; Eldridge and Tout 2004). To increase confidence on the obtained results, analysis was conducted for two data sets. First, we run MFA for all initial variables of Table 1 excluding SN host BPT classes only. In this case, the total number of SNe in the statistics is 46 in 40 hosts. Then, we run MFA including also host BPT classes as the initial variable. In this case, the total number of SNe in the statistics is reduced to 21 in 16 hosts (see Table 1). In order to simplify the interpretation of the results, we only present the rotated varimax normalized orthogonal values for the three most significant factors, with highlighted values above 0.5 correlation threshold. Table 2 shows the factor loadings, i.e., the correlation coefficients between the initial variables and the factors for the $N = 46$ SNe sample with all initial variables of Table 1 excluding BPT classes of hosts. Table 3 shows factor loadings for the $N = 21$ SNe sample with all initial variables of Table 1 including.
Table 3  Varimax rotated normalized orthogonal factor loadings. Data for 21 SNe sample.

| Variable             | $F_1$  | $F_2$  | $F_3$  |
|----------------------|--------|--------|--------|
| SN type              | -0.18  | 0.84   | 0.18   |
| $R_{SN}/R_{25}$      | 0.70   | -0.30  | -0.13  |
| SN PA                | 0.03   | 0.08   | -0.42  |
| Host t-type          | 0.54   | 0.74   | 0.08   |
| Host bar             | 0.72   | 0.09   | -0.09  |
| Host abs. mag        | -0.19  | -0.15  | -0.76  |
| Neig. t-type         | 0.27   | 0.83   | 0.01   |
| Neig. bar            | 0.67   | 0.26   | 0.46   |
| Neig. abs. mag       | -0.58  | -0.12  | -0.66  |
| $\Delta v_r$         | 0.07   | -0.61  | 0.58   |
| $d_p$                | -0.73  | -0.45  | -0.22  |
| Host BPT type        | -0.17  | 0.20   | 0.83   |
| Accum. variance      | 23%    | 46%    | 67%    |

In Table 2, the first factor ($F_1$), which accounts for about 21% of the common variance, is the combination of the hosts and its neighbors absolute magnitudes, existence of bar of neighbor and linear projected distance between galaxies in pairs. Galaxies located in closer pairs have higher luminosities with preferable existence of bar. Factor $F_2$, which accounts for about 18% of the common variance, is the combination of velocity difference between galaxies in pairs, host and its neighbor morphologies and SN types. Members of pairs with smaller velocity differences are galaxies of later morphological types, and discovered SNe in these pairs are preferably CC with higher rates of Ibc SNe. Factor $F_3$, which accounts for about 14% of the common variance, is the combination of host absolute magnitudes and the existence of a bar.

In Table 3, the first factor ($F_1$), which accounts for about 23% of the common variance, is the combination of SN relative distance from host nuclei, host morphological types and existence of bar, as well as linear projected distance between galaxies in pairs. Closer located galaxies in pairs have relatively later morphological types and prominent bars. In such pairs, SNe in their hosts are discovered at larger distances from the nuclei. Factor $F_2$, which accounts for about 23% of the common variance, corresponds to the factor $F_2$ of the first MFA and combines the same parameters. Factor $F_3$, which accounts for about 21% of the common variance, combines BPT classes of host galaxies, hosts and neighbors absolute magnitudes and velocity difference between galaxies in pairs.

Combining the results of both MFA analyses, presented in Tables 2 and 3, first we can conclude that change of number of SNe as well as change of used initial variable sets does not significantly affect most of the obtained results. Most conclusions repeat each other in different factors of these MFA analyses. Summarizing the results, we can make the following conclusions. Nuclear activity level correlates with host galaxy luminosity. This is a well known fact proven with many observations (e.g., Meurs and Wilson 1984). More luminous galaxies located in closer pairs have a higher percentage of bars, probably triggered by interactions (e.g., Méndez-Abreu et al. 2012). MFA does not show any correlation between PA and any physical parameters of the pair and the SN. Comparing the distribution of SNe by angle describing their orientation with respect to the neighbor galaxy, we find that it is statistically the same as an isotropic distribution, and is independent of the $\Delta v_r$ and $d_p$ of the pair. This result is in agreement with Petrosian and Turatto (1992) and Navasardyan et al. (2001), and it can be explained by different distributions of dynamical timescales of interacting/merging galaxies in pairs. Another important result of MFA is that the difference of radial velocities correlates well with type of SNe located in these pairs, this result is discussed below.

4.2 Morphologies of hosts and neighbors

We study the most prominent grouped parameters in detail by exploring one-to-one correlations. The first row of Table 4 shows mean morphological $t$-types of our paired sample hosts for SNe of different types. The errors correspond to the standard error of the mean. It is obvious that hosts of type Ibc and II SNe are of later morphological classes than those of type Ia in accordance with MFA. This is well known observational result (e.g., Cappellaro et al. 1999; van den Bergh et al. 2003). For comparison, in the second row of Table 4 mean morphologies of the unbiased sample of 1021 nearby ($\leq 100$ Mpc) hosts of different types SNe from H12 are presented. As is seen from the results of the Kolmogorov-Smirnov (KS) test for paired hosts of our sample and from sample of H12, there is no statistically significant difference between our and H12 $t$-types. In agreement with MFA, SN hosts of our sample tend to form pairs with neighbors (data of which are presented in the third row of Table 4) with similar morphologies. However, if we compare the distributions of $t$-types of all hosts and all neighbors irrespectively of SN types, a KS test shows a statistically significant difference between them. This probably reflects the fact that the KS test rarely rejects the null hypothesis in small samples. According to Table 4 the percentage of barred galaxies among our hosts is larger ($\sim 2\sigma$) than that in the general sample of hosts from H12. Since H12 general sample contains both paired and isolated hosts, but our
Table 4  Morphological classification of SN hosts and their neighbors.

|   | All SNe | Ia | Ibc | II |
|---|---------|----|-----|----|
| 1 | Our host mean t-type | 3.4±0.4 | 2.0±0.6 | 4.2±0.7 | 5.3±0.7 |
| 2 | H12 host sample, mean t-type | 3.9±0.1 | 2.3±0.2 | 4.5±0.2 | 5.0±0.1 |
| 3 | Our neighbor mean t-type | 4.1±0.5 | 2.5±0.5 | 5.9±0.9 | 4.7±1.1 |
| 4 | p value KS test for rows 1 & 2 | 0.43 | 0.74 | 0.43 | 0.89 |
| 5 | p value KS test for rows 1 & 3 | 0.00 | 0.14 | 0.71 | 0.46 |
| 6 | Our host bar (in %) | 45±7 | 42±12 | 50±15 | 47±13 |
| 7 | H12 host bar (in %) | 30±1 | 27±3 | 28±4 | 31±2 |
| 8 | Our neighbor bar (in %) | 32±6 | 26±10 | 42±15 | 33±13 |

The sample consists of paired hosts only, the excess of bars in our sample is expected (e.g., Méndez-Abreu et al. 2012).

Fig. 2  Normalized histograms of radial distributions of types Ia (red solid), Ibc (blue dotted), and II (green dashed) SNe. The error bars assume a Poisson distribution (with ±1 object if none is found). Top-right: surface density profiles (with arbitrary normalization) of all CC SNe: Ibc (blue dotted), and II (green dashed). The lines show the maximum likelihood exponential surface density profiles of CC SNe. The observational deficit of SNe in the central regions is due to the Shaw (1979) effect.

4.3 Radial distributions

The radial distribution of SNe is shown in Fig. 2. The mean value of $R_{SN}/R_{25}$ is 0.53 ± 0.10 for type Ia. The mean normalized distance $R_{SN}/R_{25}$ of SNe II, at 0.74 ± 0.09 is roughly double that of SNe Ibc at 0.38 ± 0.06. The significance of more concentrated Ibc SNe relative to II SNe is 3.35σ. The mean values of normalized distances of Ia SNe agree with the results of Fig. 4 in van den Bergh (1997) calculated in the same way without deprojecting. Our mean values for CC SNe within estimated errors are in agreement with those of H09, where values 0.62 ± 0.03 for type II and 0.45 ± 0.04 for type Ibc SNe were reported. The higher II to Ibc ratio of mean normalized distances in our sample is marginally significant (1.54σ) than that in the H09 general larger sample.

In addition, we calculated surface densities of type Ibc and II SNe, assuming that they are located within discs of spiral hosts, as is shown in top-right corner of Fig. 2. Wang et al. (2010) measured number and surface density distributions of type II SNe in their hosts and indicated that SNe detected in SF hosts follow an exponential law, but the distribution of type II SNe in AGN hosts (which are in general thought to be more disturbed) significantly deviates from exponential law. Moreover, Habergham et al. (2012) found a remarkable excess of Ibc SNe within central regions of disturbed galaxies, i.e. mainly in galaxies showing signs of merger-triggered starbursts in their nuclei. To check consistency of surface density distributions of CC SNe with an exponential model, we generated exponential distributions with the corresponding scale lengths using maximum likelihood fitting according to H09 and compared real SNe distributions with them by means of a KS test. We found a deviation from the exponential density fall for SNe Ibc. To figure out the nature of the deviation, we removed all the SNe within $R_{SN}/R_{25} < 0.25$ bin, generated new exponential distributions and performed a KS test again. The deviation vanished. Therefore, the SNe located closer to the nuclei are responsible for the deviation from exponential distribution. The surface densities shown in Fig. 2 suggest that the observational deficit of SNe in the central regions is due to the Shaw (1979) effect as the main source of the deviation.

There is non-significant excess of Ibc SNe in central regions of hosts of our sample in comparison with those of H09 sample. This result, not reproducing that of Habergham et al. (2012), can be explained by large number of disturbed galaxies in our sample, hence less accurate measurements of $R_{25}$ and less secure inclination corrections of SN distances.
We also checked how kinematical properties of pairs, such as $\Delta v_r$ and $d_p$, describing strength/stage of interacting/merging, affect the distribution of SNe within their hosts. We divided our pairs sample for each SN type into two subsamples, with larger and smaller $\Delta v_r$, and we checked whether SNe in pairs with small $\Delta v_r$ have different radial distances from centers of their hosts. For CC SNe, we found this difference insignificant. For Ia SNe, there is no difference at all. The similar procedure was done for $d_p$ with the same results.

4.4 Pair properties

In addition, we analyzed subsamples of pairs with SNe of different types, with the main results presented in Table 5. A KS test shows that the distribution of $\Delta v_r$ of pairs containing SNe Ia and II is the same with practically consistent mean values. In contrast, the same distributions of pairs with Ibc and II SNe (also of pairs with SNe Ibc and non-Ibc) are significantly different (3.2$\sigma$) with smaller mean $\Delta v_r$ for Ibc. This means that Ibc SNe explode preferably in pairs with stronger interaction (e.g., Patton et al. 2000). We consider this as an important result needing a physical interpretation. The same results were qualitatively obtained using MFA. It is worth noting, that there is no significant difference between mean values of $d_p$ of pairs with SNe of different types as is seen in Table 5. Assuming that sizes of galaxies can bias dependence of pair properties on $d_p$, we also normalized projected separations to sizes of pair members ($d_p/\Sigma R_{25}$). This normalization does not add any statistical change to all the correlations with $d_p$. Since distance may be an important factor biasing dependence of SFR indicators on $\Delta v_r$, is stronger than that on $d_p$, as was shown in Barton et al. (2000, 2005; Boissier and Prantzos 2009). In this respect, we expect a relatively larger amount of star-forming galaxies, especially with smaller $\Delta v_r$ and $d_p$, in our sample of paired hosts due to interaction-triggered starbursts. Therefore, excess of Ibc SNe compared to II SNe in the pairs with smaller $\Delta v_r$ and $d_p$ can be a result of higher SFR. In close environments of galaxies ($d_p < 60$ kpc) dependence of SFR indicators on $\Delta v_r$ is stronger than that on $d_p$, as shown in van den Bergh (1997) and H09. The ratio of mean $\Delta v_r$ is higher than in the general sample of SN hosts.

Table 5 The mean values of parameters of pairs containing SNe of different types.

| SN type | Number of SNe | Mean $\Delta v_r$ (km s$^{-1}$) | Mean $d_p$ (kpc) |
|---------|---------------|-------------------------------|-----------------|
| Ia      | 19            | 134±27                        | 34±4            |
| Ibc     | 12            | 56±14                         | 28±5            |
| II      | 15            | 129±18                        | 32±6            |
| All (including unclassified) | 56 | 117±9 | 33±3 |

5 Summary

We have studied 56 SNe located in pairs of galaxies and analyzed the dependence of SN properties on the host and neighbor properties. The main results are:

1. SN hosts as well as their neighbors in our sample have statistically the same morphological classification as hosts from the general sample of SNe ($\leq 100$ Mpc) from H12. Our sample contains only paired galaxies, therefore the amount of barred hosts in our sample is higher than in the general sample of SN hosts.

2. Mean radial distances obtained for our sample of SN hosts are in agreement with those reported in van den Bergh (1997) and H09. The ratio of mean radial distances of type II and Ibc SNe is about 2. Radial distributions of CC SNe in our sample of paired galaxies are difficult to fit into a model with
exponentially falling surface density because of the observational deficit of SNe in regions located close to nuclei.

3. SNe of type Ibc are located in pairs having smaller $\Delta v_r$ than pairs containing type II and Ia SNe. This difference is significant at the 3.2$\sigma$ level. We suggest that this result is because of higher SFR in closer pairs, resulting in a higher rate of Ibc SNe compared to II SNe. A similar trend is found considering $d_p$ of pairs, although it is significantly weaker.

4. The luminosity ratio of galaxies in pairs does not display any correlation with the SN types.

5. The orientation of SNe with respect to the preferred direction is found to be isotropic, independent of $\Delta v_r$ and $d_p$.

As a conclusion, we consider that close environment of galaxies can have some observable effect on SN production due to the impact on SF of galaxies.

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