The Distribution of Supernovae Relative to Spiral Arms of Host Disc Galaxies

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Abstract. Using a sample of 215 supernovae (SNe), we analyse their positions relative to the spiral arms of their host galaxies, distinguishing grand-design (GD) spirals from non-GD (NGD) galaxies. Our results suggest that shocks in spiral arms of GD galaxies trigger star formation in the leading edges of arms affecting the distributions of core-collapse (CC) SNe (known to have short-lived progenitors). The closer locations of SNe Ibc vs. SNe II relative to the leading edges of the arms supports the belief that SNe Ibc have more massive progenitors. SNe Ia having less massive and older progenitors, show symmetric distribution with respect to the peaks of spiral arms.

1. Introduction

It is well known that star forming regions in spiral discs are generally concentrated in spiral arms (e.g. Seigar & James 2002). There are a variety of known structures of spiral galaxies, with different numbers and shapes of their arms (for recent review see Buta 2013). According to their spiral features, spiral galaxies are divided into two broad categories: 1) GD spirals with typically two arms; and 2) NGD spirals with flocculent and/or short arms. Spiral arms in GD galaxies are thought to be density waves that are usually attributed to stellar bars (e.g. Sanders & Huntley 1976; Elmegreen & Elmegreen 1989; Ann & Lee 2013; Roca-Fàbrega et al. 2013), or to the tidal field of a nearby neighbor (e.g. Toomre & Toomre 1972; Kormendy & Norman 1979; Kendall et al. 2011; Casteels et al. 2013). In contrast to GD spiral galaxies, NGD galaxies are likely formed from gravitational instabilities, or are sheared star formation regions (e.g. Seiden & Gerola 1982; Elmegreen et al. 2003).

The distribution of stellar ages in spiral arms have been studied in GD galaxies. Investigating the dynamics of spiral galaxies, Roberts (1969) proposed that the piled up gas in a spiral arm experiences a strong shock that triggers star formation. Then, many studies with contradicting results came out that observationally support or argue the proposed theory.

By this contribution, the fourth study of a series (Hakobyan et al. 2012, 2014, 2016; Aramyan et al. 2016), we present our recent investigation of the distribution of

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different types of SNe relative to spiral arms taking into account the intrinsic properties of arms in order to find links between the distributions of the various SN types and arm’s stellar populations. Moreover, considering possible differences of the distributions of various stellar populations in both types of spirals (e.g. Dobbs & Pringle 2010), we investigate the distribution of SNe in these subsamples of host galaxies.

2. The sample of SNe and their hosts

The sample of this study is drawn from the catalog of Hakobyan et al. (2012), which contains 3876 SNe from the area covered by the Sloan Digital Sky Survey (SDSS) Data Release 8. Since, the analysis of the distribution of SNe relative to spiral arms requires a well-defined sample and high angular resolution images of the SNe hosts, we applied some restrictions and came out with a final sample consisting 215 SNe in 187 host galaxies. The spiral arm classes of all 187 host galaxies were determined visually from the $g$-band SDSS images, following the spiral arm classification of Elmegreen & Elmegreen (1987). Then the galaxies were assigned as GD (classes 9 and 12) or non-GD (NGD, all classes except 9 and 12).

Using the version 2.18.4 of SExtractor software (Bertin & Arnouts 1996), we carried out a procedure to isolate the spiral structure of the galaxies. We first fitted all $g$-band SDSS images of the host galaxies in the sample with bulge+disc models ($r^{1/4}$ bulge and exponential disc profiles are used for all galaxies). The modeled bulge+disc was then subtracted from each original image. Then, the closest segment of spiral arm to SN position is fixed along the radial line passing through the galaxy nucleus and SN location and the radial light profile is obtained. Throughout whole study we used $d_1$ and $d_2$ distances, which indicate the position of SN relative to the edges and peak of spiral arm, respectively. For more details the reader is referred to Aramyan et al. (2016).

3. Results

It is believed that the spiral arms of NGD galaxies corotate with the discs and do not show signs of shocks in their leading edges (see review by Dobbs & Baba 2014). Therefore, one does not expect young stars to be concentrated towards one of the edges of their arms. This scenario also predicts the absence of radial trends for the distributions of SNe Ibc and II inside the spiral arms. In NGD galaxies, we found that CC SNe are more concentrated towards the peaks of spiral arms than SNe Ia. Moreover, despite small number statistics, in NGD galaxies we found different concentration levels for SNe Ibc and II. In particular the mean absolute $d_2$ distance of SNe Ibc is $0.27 \pm 0.08$ ($N = 13$) and for SNe II is $0.49 \pm 0.07$ ($N = 39$). An Anderson-Darling (AD) test shows that the difference between the distributions of absolute distances of SNe Ibc and II from the peaks of spiral arms is barely significant ($P_{AD} = 0.074$). Hence, in NGD galaxies the shortest mean distance to the peak of spiral arm is for SNe Ibc. In addition, the distribution of any SN type inside the spiral arms in NGD galaxies does not show any significant radial trend.

Assuming that 1) the $g$-band profiles of spiral arms represent the distribution of young stars, and 2) the peaks of spiral arms of NGD galaxies are the most suitable sites of the star formation, we propose that when the concentration of a given type of SNe towards the arm peak is higher, their progenitors are younger (more massive
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in the context of single-star evolution). Thus, a mass sequence Ia–II–Ibc for the SN progenitors is expected, in agreement with those from the literature obtained by the association of various SN types with the Hα emission of the host galaxy (e.g. James & Anderson 2006; Anderson & James 2008; Anderson et al. 2012).

The distribution of SNe inside the spiral arms of GD galaxies is quiet different. In particular, in GD galaxies we found a significant shift between the distributions of distances of CC and Ia SNe from the peaks of spiral arms. This is probably the reflection of the offset between B- and I-band light profiles of spiral arms with strong density waves reported by del Rio & Cepa (1998). The mentioned effect is schematically illustrated in fig. 1 of Martínez-García et al. (2009). It is probably also reflected on the corresponding distributions of CC SNe versus SNe Ia in GD galaxies.

In addition, in GD hosts, there is a statistically significant positive correlation for arm SNe II between $d_2$ and $R_{SN}/R_{25}$ (galactocentric distance of SN normalized to $R_{25}$ radius of the galaxy).\textsuperscript{1} The same correlation is found for SNe Ibc, with an even higher slope, but not significant because of small number statistics. The positions of both types of SNe beyond $R_{SN}/R_{25} \approx 0.45$ (roughly the mean corotation radius) are now typically outside the peaks of the arms through the radius vector, while at smaller radii the positions of SNe are typically inside the peaks of the arms. Similar trends for star-forming regions are observed in some GD galaxies (e.g. Cedrés et al. 2013).

Adopting an average corotation radius of 0.45 $R_{25}$, the mean distances ($d_1$ inside and $1 - d_1$ outside the corotation radius, respectively) of SNe Ibc and II from leading edges of spiral arms are 0.25±0.07 and 0.44±0.03, respectively. AD test shows that the difference between the distributions of SNe Ibc and II relative to leading edges of spiral arms is statistically significant ($P_{AD} = 0.011$). According to the dynamical simulations by Dobbs & Pringle (2010), the observed concentration sequence towards the leading edges of spiral arms indicates a lifetime sequence (see the top-left panel of fig. 4 in Dobbs & Pringle 2010) for their progenitors (from youngest to oldest). Hence, the greater the mean distance from the leading edge, the longer is the progenitor’s lifetime.

The scheme of star formation in a model of a GD galaxy with two spiral arms with the directions and relative sizes of drifts from birth places up to the explosion for various SNe is given in the Fig. 1. Inside the corotation radius (dashed circle), star formation processes generally occur in a shock front at the inner (leading) edges of spiral arms. Since the disc rotates faster than the spiral arms inside the corotation radius, newborn stars near inner edges move towards the outer edges of spiral arms. On the contrary, outside the corotation radius, stars are caught up by the spiral arms, hence move from the outer edges of the arms towards the inner edges of spiral arms. In the corotation zone, there are no triggering mechanisms of star formation, such as spiral shocks. The main mechanism of star formation in this region (dotted surface of arms) is gravitation instability (as in NGD galaxies). Therefore, in this region, the distribution of SNe inside the spiral arms should have the same behavior as in NGD galaxies. Moreover, because of the absence of spiral shocks in this region, star formation (e.g. Elmegreen et al. 1992), hence the number of CC SNe, should exhibit a drop. Since more massive stars live shorter than less massive ones, their explosion sites are, on average, closer to the leading edges of arms where they born. The observed significantly shorter distances of SNe Ibc from the leading edges of spiral arms show that their progenitors are younger

\textsuperscript{1}The $R_{25}$ is the SDSS g-band 25\textsuperscript{th} magnitude isophotal semimajor axis of SN host galaxy.
Figure 1. The scheme of star formation distribution in a model of two armed GD galaxy with the directions and relative sizes of drifts from birth places up to the explosion for SNe Ibc (blue arrow) and II (green arrow). For better visualization, the directions of drifts are shown with a significant radial component.

(more massive) than those of SNe II. This result is in agreement with the single-star progenitor scenario of SNe Ibc.

To sum-up, the reported results show that the distribution of SNe relative to spiral arms is a powerful tool to constrain the lifetimes (masses) of their progenitors and to better understand the star formation processes in various types of spiral galaxies.

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