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Triggered star formation in giant HI supershells: ionized gas

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We considered the regions of triggered star formation inside kpc-sized HI supershells in three dwarf galaxies: IC 1613, IC 2574 and Holmberg II. The ionized and neutral gas morphology and kinematics were studied based on our observations with scanning Fabry–Perot interferometer at the SAO RAS 6-m telescope and 21 cm archival data of THINGS and LITTLE THINGS surveys. Qualitative analysis of the observational data was performed in order to highlight two questions: why the star formation occurred very locally in the supershells, and how the ongoing star formation in HI supershells rims influence its evolution? During the investigation we discovered the phenomenon never before observed in galaxies IC 2574 and Holmberg II: we found faint giant (kpc-sized) ionized shells in Hα and [SII]6717,6731 lines inside the supergiant HI shells.

Keywords: Interstellar medium, supershells, star formation, IC 1613, IC 2574, Holmberg II, Holmberg I

1 Introduction

Stellar feedback plays significant role in the regulation of the interstellar medium (ISM) structure and the whole galaxy evolution as well. Stellar winds and supernovae explosions create complexes of shells and supershells of ionized and neutral gas; e.g. Bagetakos et al. (2011) analysed the HI distribution in 20 nearby galaxies and revealed about 1000 cavities in their discs with sizes from 80 pc to 2.6 kpc, expansion velocities from 4 to 64 km/s (mostly 10–20 km/s) and ages from 2 to 150 Myr.

The origin of the largest kpc-sized HI holes and shell-like structures (so-called supergiant shell, SGS) has been the subject of debate for more than two decades. In the standard approach based on the Weaver et al. (1977) model, HI shells result from the cumulative action of multiple stellar winds and supernovae explosions. However

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it was recognized long ago (see e.g. Tenorio-Tagle & Bodenheimer, 1988; Rhode et al., 1999; Kim et al., 1999; Silich et al., 2006) that this scenario cannot explain the origin of SGS since stellar cluster remnants detected are inconsistent with the input of mechanical energy required by the standard multiple winds and supernovae model. Recent studies based on Hubble Space Telescope (HST) observations have found that multiple star formation events over the age of the hole do provide enough energy to drive HI hole formation (see e.g. Weisz et al., 2009a,b; Cannon et al., 2011a,b). A number of SGS exhibit signs of expansion-triggered star formation at their periphery. A special interest consists in a detailed analysis of the interaction of stars and gas in the region of new sites of star formation in the walls of SGS, which can elucidate the process of their evolution.

Dwarf irregular galaxies provide the best environments to study the creation mechanisms of giant HI structures with star-formation episodes in their rims. Because of the slow solid-body rotation and the lack of strong spiral density waves which can destroy the giant shells, they grow to a larger size and live longer compared to such structures in spiral galaxies. The overall gravitational potential of dwarfs is much smaller than that of spiral galaxies, their HI disc scale height is larger and the gas volume density is lower than in spirals. Therefore the same amount of mechanical energy fed to the ISM of dwarf Irr galaxies creates very large long-lived holes with star formation in the walls triggered by their expansion.

During several years we performed the analysis of the ionized and neutral gas structure and kinematics in nearby irregular galaxies: VII Zw 403 (Lozinskaya et al., 2006), IC 10 (Egorov et al., 2010), IC 1613 (Lozinskaya et al., 2003), IC 2574 (Egorov et al., 2014), Holmberg II (Egorov et al. 2016, in preparation). In most of them we had a deal with the star formation ongoing in the rims of the HI supershells. In this work we briefly review the results of our study in the galaxies where the different stages of the SGS evolution are clearly seen: IC 1613, IC 2574 and Holmberg II.

2 Observational data

The observations in the Hα emission line were made at the prime focus of the 6-m telescope of Special Astrophysical Observatory of Russian Academy of Sciences with SCORPIO (Afanasiev & Moiseev, 2005) or SCORPIO-2 (Afanasiev & Moiseev, 2011) multi-mode focal reducers. The data obtained in a scanning Fabry–Perot interferometer (FPI) mode were used for the study of the ionized gas kinematics, while the narrow-band Hα direct images were used for analysis of the ionized gas morphology. Neutral gas distribution and kinematics were studied using the data of archival VLA HI 21 cm observations from THINGS (Walter et al., 2008) and LITTLE THINGS (Hunter et al., 2012) surveys. The detailed description of the observational settings are shown in the corresponding papers for each galaxy discussed there.

3 Triggered star formation in SGSs

We considered three galaxies where the difference in the evolution stage of SGS is most evident. The aim of our analysis was to highlight two questions: what triggers the star

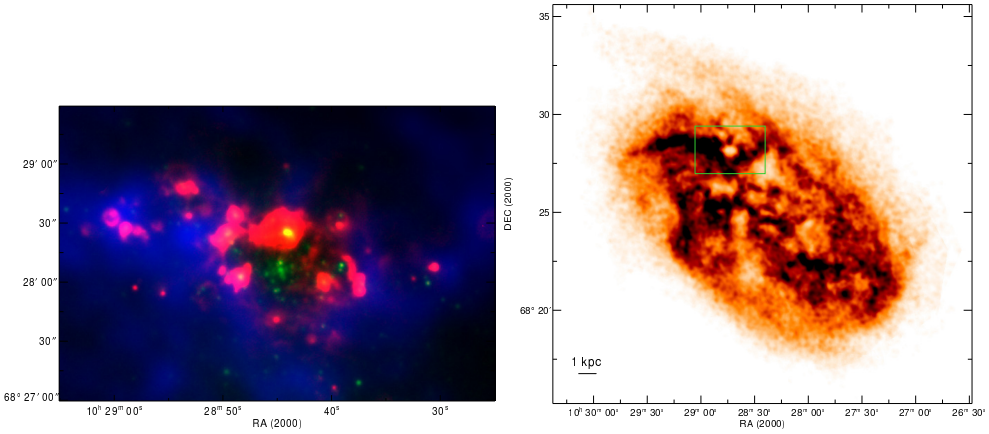


Figure 1 IC 2574. Left: False-color composite image of distribution of Hα emission (red channel) and stellar continuum (green channel) obtained with 6-m telescope of SAO RAS and HI 21 cm emission (THINGS, blue channel). Right: HI distribution according to THINGS data. Green rectangle denotes the region shown in the left panel.

formation at large scales and how the ongoing star formation influences the evolution of the "parent" SGS in a neutral gas? We describe below the most interesting results obtained during the study of each of the selected galaxies and discuss the above questions.

3.1 IC 2574

The well known "supergiant shell" (#35 in the list of Walter & Brinks 1999) in the dwarf Irr galaxy IC 2574 is located at the north-east outskirts of its disc. This SGS surrounding a 1000×500 pc hole in the most prominent region of current and recent star-formation activity in the galaxy represents the impressive example of giant HI shells with triggered SF along rims (see Fig. 1). The analysis of resolved stars based on the HST images (Weisz et al., 2009b) shows that the last most significant episodes of star formation in SGS began $\simeq$100 Myr ago and the recent bursts of star formation along the walls of the shell are as young as 10 Myr. The ages of the younger star-formation events are consistent with those derived from broadband photometry and are younger than the estimated kinematic age of the HI SGS, 14 ± 3 Myr (Walter et al., 1998; Walter & Brinks, 1999; Egorov et al., 2014).

The analysis of the ionized and neutral gas kinematics inside the rim of SGS is presented in Egorov et al. (2014). We showed that for almost all HII complexes studied the energy input from young clusters located inside them is sufficient to drive the formation of observed ionized gas structures. The only exception we found is the shell-like region in the north-west part of the SGS that shows a high expansion velocity (65 km/s). This complex is the youngest in the region and its age is 1 Myr.

In the entire region of the SGS in IC 2574 we detected for the first time the faint diffuse emission in both Hα and [SII] lines. It seems that the source of the emission

observed is the shell-like structure that filled the internal part of the SGS.

We conclude that the observed SGS in IC 2574 is at relatively young stage where the star formation in its walls had been started recently. It is one of the most dynamically active giant HI structures among Irr galaxies. Almost the whole of the rim of the SGS shows the significant increase of star formation rate during the recent 10 Myr. The expansion of the brightest HII region in the north part of SGS rapidly disperses the local HI gas. One can see here the emission features like "horns" located beyond the northern boundary of the SGS. We can suppose that the destruction of the northern wall of the HI supergiant shell due to star formation will result in the growth of the SGS and in its merging with the neighbouring lower sized HI supershells. After several billion years there will be a system of giant adjoining and/or interacting shell-like HI structures similar to those observed in another galaxy we want to draw attention to below – Holmberg II.

3.2 IC 1613

Neutral gas distribution in IC 1613 galaxy shows a highly inhomogeneous structure with a number of HI holes, shells and arc-like structures of different sizes and expansion velocities (see Fig. 2). The only known complex of recent star formation is located in the north-eastern rim of the largest (1 to 1.5 kpc sized) HI "main supershell" in the galaxy. This supershell is older than SGS in IC 2574 – its kinematic age no less than 30 Myr (Silich et al., 2006). Three extended (300–350 pc) neutral shells, with which the brightest ionized shells in the complex of star formation are associated, are observed in the direction of the area of highest HI density in the galaxy. Two of H I shells were found to expand at a velocity of 15–18 km s^{-1} (Lozinskaya et al., 2003). The structure and kinematics of this complex were studied previously in a large number of papers (see, e.g., Lozinskaya et al., 2003; Silich et al., 2006, and references therein).

Figure 2 clearly demonstrates that the Hα emission in IC 1613 coincides well with the walls of three local HI shells mentioned above. The age of observed Hα bubbles are much lower (0.6–2.2 Myr) than the age of the HI shells (5.3–5.6 Myr), that may be an indirect evidence of the triggering of star formation there by the collision of these neutral gas shells. Lozinskaya (2002) proposed that the whole star formation complex in the rim of the "main supershell" is created by the collision of this largest shell with the giant HI supershell to the north.

3.3 Holmberg II

Holmberg II is another example of irregular galaxies that have a non-uniform gas structure with a large amount of shells and holes in the neutral gas distribution (see Fig. 3). Puche et al. (1992) found 51 giant holes and supershells in Holmberg II galaxy; Bagetakos et al. (2011) revealed 39 neutral gas cavities using more strong criteria. Their sizes are from 0.26 to 2.11 kpc and expansion velocity – from 7 to 20 km/s. These values correspond to kinematic age from 10 to 150 Myr. It is necessary to have energy input up to 10^{53} erg for the formation of several SGS.

The object of particular interest is the SGS #17 (according to the list of Bagetakos et al., 2011) – the largest and oldest HI supershell in the galaxy. Optical images in

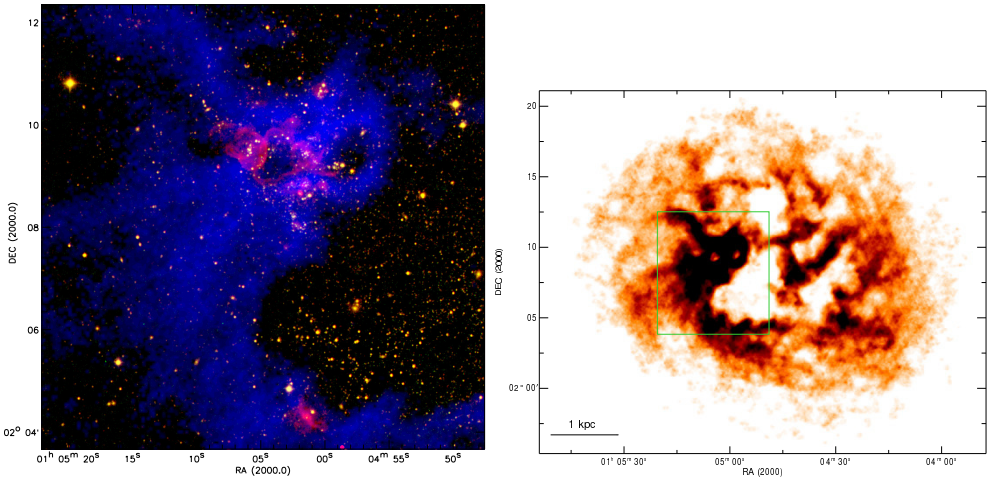


Figure 2 IC 1613. Left: False-color composite image of distribution of Hα (red color) and stellar continuum (yellow color) obtained with the SAO RAS 1-m telescope according to Lozinskaya et al. (2002), and HI 21 cm emission (LITTLE THINGS, blue color). Right: HI distribution obtained by LITTLE THINGS data. Green rectangle denotes the region shown in the left panel.

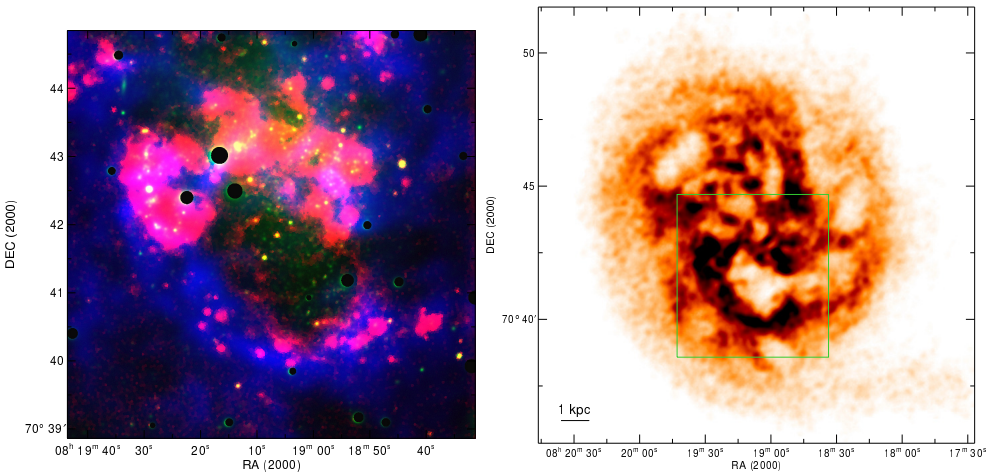


Figure 3 Similar to Fig. 1 for Holmberg II galaxy.

the Hα line reveal the brightest complexes of star formation located in the rim of this SGS. This supershell is much older than the SGS in IC 2574 described above (150 Myr against 14 Myr). Nevertheless, in both cases we observed that the triggered star formation occurred in the walls of SGS. Weisz et al. (2009a) analyzed the stellar population using the data of HST observations and showed that star formation occurs in the north rim of the SGS in Holmberg II about 40 Myr ago and during the last 15 Myr it is observed in the north-east and north-west parts of the shell.

In contrast with the case of SGS in IC 2574, in Holmberg II we observed that triggered intensive star formation occurred not along the full length of the HI supershell rim, but only in one half of them. Why is the Hα emission more intense in the northern part of HI supershell compared with its southern part? Probably, as it was in the case of IC 1613, the interaction and possible collision with two younger and smaller HI supershells to the north from the SGS considered are the reasons for triggering star formation in this region. Indeed, the age of the last starburst episode that occured in the region is in agreement with the estimations of the ages of these two supershells (#16 and #22 in the list of Bagetakos et al. 2011) – 50 and 30 Myr.

It is not surprising to detect Hα emission inside the small HI shells in galaxies (see, e.g., LITTLE THINGS survey Hunter et al., 2012), but could giant ionized shells be observed inside the HI SGSs? Up to date only one kpc-sized Hα supershell is known – LMC 4 in Large Magelanic Cloud (Book et al., 2008). Also several supershells of smaller size have been found in that galaxy. We already noticed the detection of diffuse ionized kpc-scale supershell in IC 2574 located inside HI SGS, but there we proposed its shell-like morphology only by kinematics analysis. We found the unique structure in Holmberg II galaxy using the data of FPI and narrow-band imaging observation in Hα line. We clearly detected the giant ionized supershell with resolved shell-like structure that has diameter about 2 kpc and coincides with the internal wall of the examined neutral HI SGS in the galaxy. We should note that this structure has a low brightness (about 10^{-17} erg/s/cm^2/arcsec^2). Bastian et al. (2011) found 126 OB stars in Holmberg II, seven of them are located inside the Hα supershell. These seven OB stars provide enough high energy photons to ionize the internal wall of HI supershell and to create the Hα supershell observed. The detailed study of this structure as well as of the gas kinematics in the star formation regions in Holmberg II will be presented in our forthcoming paper Egorov et al. (2016, in preparation).

Note that the observed parameters of local diffuse ionized gas in the SGS of IC2574 are similar to those of the extra-planar diffuse ionized gas (DIG) in spirals and irregular galaxies. The observed [SII]/Hα and [NII]/Hα line ratios in the DIG are larger compared to classical HII regions. The ionization of DIG in galaxies is traditionally explained by the leakage of ionizing photons from the HII regions as the main source (see, e.g., Seon, 2009; Hidalgo-Gámez, 2006, and references in these papers). Because of this similarity we may propose that faint ionized gas emission observed in the SGSs in IC 2574 and maybe also in Holmberg II galaxies is the result of leakage from the bright HII regions in the SGSs walls. Indeed, all the HII complexes in the walls of studied galaxies have nonuniform, clumpy, or filamentary structure, which allows radiation to leak outside through low-density regions.

4 Conclusions

In this paper we have discussed the nature of triggered star formation complexes located in the rims of the giant (1 kpc and more) HI supershells. These structures are common in nearby irregular galaxies. Here we considered three galaxies: IC 1613, IC 2574 and Holmberg II, that might be best examples of the triggering of star formation in supergiant shells at the different evolution stages. Gas kinematics analysis gave us evidence about the influence of ongoing star formation onto HI supershells.

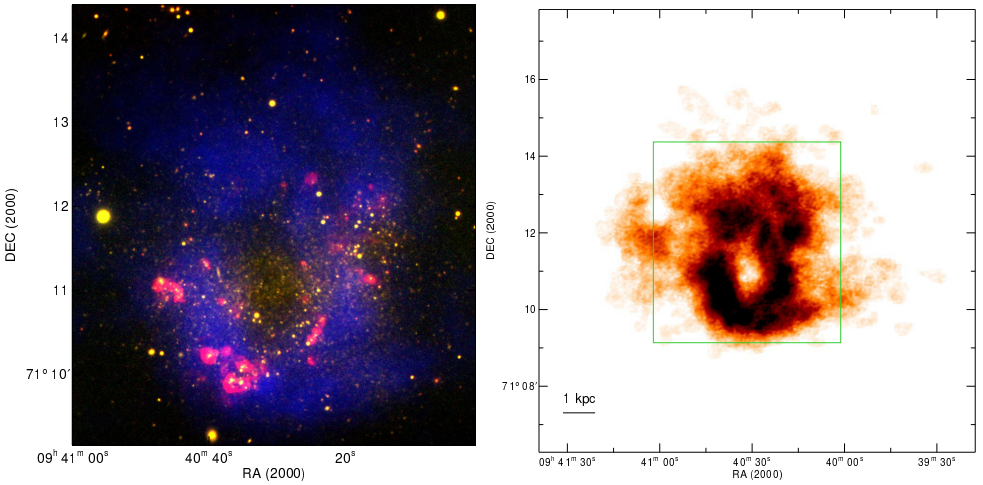


Figure 4 Holmberg I. Left: False-color composite image of distribution of Hα (red color) and stellar continuum (yellow color) obtained with the SAO RAS 6-m telescope, and HI 21 cm emission (LITTLE THINGS, blue color). Right: HI distribution obtained by LITTLE THINGS data. Green rectangle denotes the region shown in the left panel.

We observe weak and faint filaments of ionized gas outside HII regions that might be a consequence of the ionizing photons leakage from embedded star formation regions. This process might perturb HI shells and lead to their destruction at the later stage. In the final consequence of that process, the ISM of the irregular galaxy might represent a single neutral supershell with diameter about the disc size and the ongoing star formation in its rim. A picture resembling this is observed in Holmberg I galaxy (see Fig. 4).

Large numbers of HI supershells in galaxy discs is a common picture for nearby irregular galaxies, but the star formation is not distributed uniformly inside them. It seems that the collision of the HI supershells might be one of the main drivers of the star formation triggering on such large scales.

We found for the first time diffuse ionized gas inside the SGS in IC 2574 that shows the signs of the expansion and have size similar to diameter of the SGS. A similar and more confidently detected structure was discovered in Holmberg II galaxy. The structure of the Hα supershell in that galaxy also coincides with the inner wall of the largest HI supershell with active ongoing star formation inside. We considered two mechanisms of the formation of such structures: ionization of the inner wall of neutral supershell by the stellar population inside and/or by the leakage of the ionizing photons from the bright HII complexes.

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References

Afanasiev V.L., Moiseev, A.V., 2005, Astron. Letters, 31, 194
Afanasiev V.L., Moiseev A.V., 2011, Baltic Astronomy, 20, 363
Bagetakos I., Brinks E., Walter F., de Blok W.J.G., Usero A., Leroy A.K., Rich J.W., Kennicutt R.C., 2011, AJ, 141, 2011
Bastian N., 2011, MNRAS, 412, 1539
Book L.G., Chu Y., Gruendl R.A., 2008, ApJSS, 175, 165
Cannon J. M. et al., 2011a, ApJ, 735, 35C
Cannon J. M. et al., 2011b, ApJ, 735, 36C
Egorov O.V., Lozinskaya T.A., Moiseev A.V., 2010, Astron. Reports, 54, 277
Egorov O.V., Lozinskaya T.A., Moiseev A.V., Smirnov-Pinchukov G.V., 2014, MNRAS, 444, 376
Hidalgo-Gámez A.M., 2006, AJ, 131, 2078
Hunter et al., 2012, AJ, 144, 134
Lozinskaya T.A., 2002, Astron.& Astrophys. Tr., 21, 223
Lozinskaya T.A., Arkhipova V. P., Moiseev A.V., Afanasiev V.L., 2002, Astron. Reports, 46, 16
Lozinskaya T.A., Moiseev A.V., Podorvanyuk N.Yu., 2003, Astron. Letters, 29, 77
Lozinskaya T.A., Moiseev A.V., Avdeev V.Yu, Egorov O.V., 2006, Astron. Letters, 32, 361
Puche D., Westpfahl D., Brinks E., Roy J.-R., 1992, AJ, 103, 184
Rhode K.L., Salzer J.J., Westpfahl D., Radice L.A., 1999, AJ, 118, 323
Seon K., 2009, ApJ, 703, 1159
Silich S., Lozinskaya T., Moiseev A., Podorvanyuk N., Rosado M., Borissova J., Valdez-Gutiérrez M., 2006, A&A, 448, 123
Tenorio-Tagle G., Bodenheimer P., 1988, ARA&A, 26, 145
Kim S., Dopita M. A., Stavelet-Smith L., Bessel M., 1999, A&A, 350, 230
Walter F., Brinks E., 1999, AJ, 118, 273
Walter F., Kerp J., Duric N., Brinks E., Klein U., 1998, ApJ, 502, L143
Walter F., Brinks E., de Blok W.J.G., Bigiel F., Kennicutt R.C. Jr, Thornley M.D., Leroy A., 2008, AJ, 136, 2563
Weaver R., McCray R., Castor J., Shapiro P., Moore R., 1977, ApJ, 218, 377
Weisz D.R., Skillman E.D., Cannon J.M., Dolphin A.E., Kennicutt R.C., Lee J., Walter F., 2009a, ApJ, 704, 1538
Weisz D.R., Skillman E.D., Cannon J.M., Walter F., Brinks E., Ott J., Dolphin A.E., 2009b, ApJ, 691, L59