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Regular distribution of star formation regions along the spiral arms and rings of disk galaxies

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Abstract. Recent studies have indicated that the spatial regularity in the distribution of young stellar population along the spiral arms and rings of galaxies, which was previously thought to be uncommon, is actually a fairly common occurrence. Spatial regularity has been found in the spiral arms and rings of galaxies with different morphologies, from lenticular to extremely late-type spiral. The characteristic regularity scale is equal to 350–500 pc or a multiple of that in all the galaxies studied. Theoretical models suggest a scale of instability for the stellar-gas disk around a few kpc, which is larger than what has been observed. Recent magneto-hydrodynamic simulations, however, indicate the formation of regular chains of star formation regions in spiral arms on a scale of 500–700 pc for galaxies similar to the Milky Way. Modern high-quality surveys, like PHANGS–MUSE, provide the necessary observational data (surface densities and velocity dispersions of gas and stellar population) to directly calculate the regularity scales in galaxies, with high spatial resolution and a wide field of view, which is a promising direction for research in this field.

Keywords: HII regions; galaxies: star clusters: general; galaxies: ISM, spiral, star formation

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1 Introduction

Elmegreen & Elmegreen (1983) first brought attention to the fact that neighboring HII regions in the spiral arms of some galaxies are located at equal distances from each other. They noted the rarity of this phenomenon: the only $\approx 10\%$ of the galaxies studied had visually detectable regular chains of HII regions with the characteristic distances λ between neighbouring HII regions of 1–4 kpc in different galaxies. Later, Efremov (2009) found a similar regularity in the distribution of HI superclouds in the Carina and Cygnus spiral arms of the Milky Way with $\lambda = 1.5$ and 1.3 kpc, respectively. He also identified a regular chain of stellar complexes within the north-western arm of M31 with a characteristic distance of 1.1 kpc (Efremov 2010).

The rarity of spatial regularities in the distribution of gas and stellar condensates in spiral arms of galaxies seems quite understandable. Theoretical studies of the gravitational instability of stellar-gas disks (Safronov 1960; Rafikov 2001; Romeo & Falstad et al. 2013) show that the wavelength of the instability depends on a comprehensive set of parameters, including gas and stellar surface densities and their velocity dispersions. The regularity in the distribution of gas clouds and their descendants, star formation regions, requires the constancy of these physical parameters in the stellar-gas disk over a wide range of galactocentric distances. However, such constancy should be a rare phenomenon in classical galactic disks.

Note that considering typical values of the parameters of the stellar and interstellar medium, all theoretical models predict the instability wavelength to be on the order of several kiloparsecs (Marchuk 2018; Inoue et al. 2021a), which is in agreement with the observational results of Elmegreen & Elmegreen (1983) and Efremov (2009, 2010).

In the last decade, however, studies of the regularity of the distribution of the young stellar populations and gas clouds along the spiral arms and rings of galaxies have reshaped our understanding of the prevalence of this phenomenon and its characteristic spatial scales. The aim of this paper is to survey the latest observational and numerical modelling results on the patterns of spatial distribution patterns of the young stellar population and gas clouds along the spiral arms and rings of galaxies of different types. These results have been obtained both by our own research team and by other scientific groups.

2 Review of results

Since 2013, the regular chains of HII regions, HI clouds, and star formation regions have been identified in the spiral arms of NGC 628 (Gusev & Efremov 2013), NGC 4321 (Elmegreen et al. 2018), NGC 895, NGC 5474, NGC 6946 (Gusev et al.

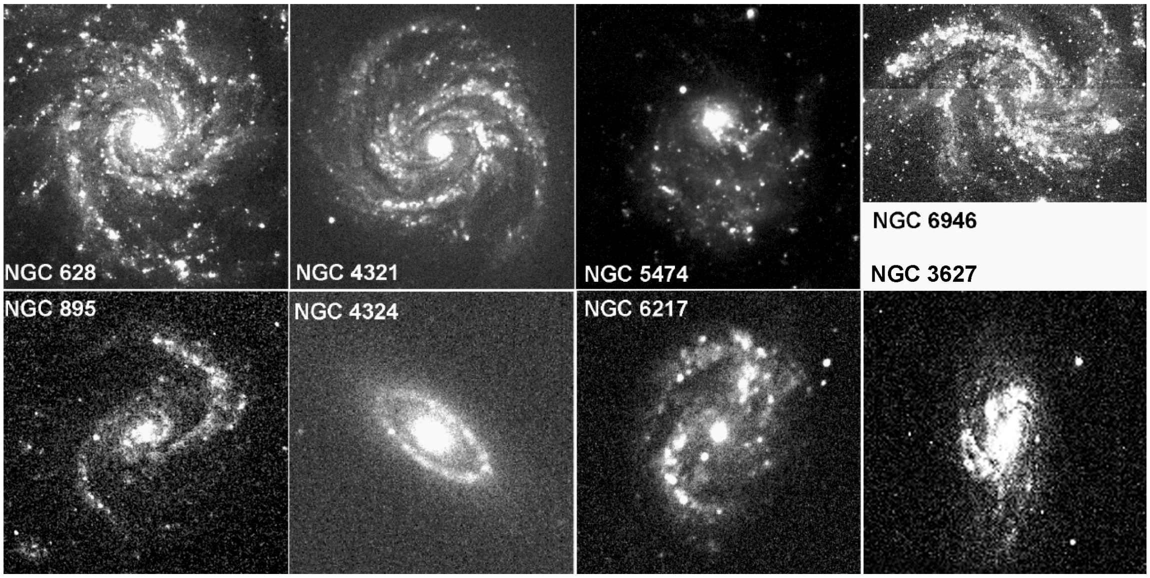

Fig. 1. Images of galaxies with regular chains of star formation regions found in their spiral arms or rings. Images of NGC 3627 and NGC 4324 are from the SDSS *u* band; other galaxies are shown in the *U* band. North is top, east is to the left.

2022), and NGC 3627 (not yet published), as well as in the Carina Arm of the Milky Way (Park et al. 2023) and in the rings of NGC 6217 (Gusev & Shimanovskaya 2020) and NGC 4324 (Proshina et al. 2022). The maps of these galaxies are shown in Fig. 1. The image of NGC 4321 is from the figure obtained in Marcum et al. (2001) and was taken from the NED database.[1] Images of NGC 3627 and NGC 4324 are from the SDSS survey database.[2] Images of other galaxies are based on observations made using the authors' programmes (see Gusev & Efremov 2013; Gusev & Shimanovskaya 2020; Gusev et al. 2022).

The results are derived from the analysis of images of galaxies in the ultraviolet (*GALEX* FUV and NUV bands), optical (UB bands and Hα line), infrared (*Spitzer* 8μm) and radio (21 cm). We present the summary data on the characteristic distances between neighbouring star formation regions (gas clouds, HII regions) in the spiral arms and rings of these galaxies in Fig. 2.

A detailed description of the technique and analysis of the results has been given in the relevant papers and summarized in the survey by Gusev (2023). The only exception is NGC 3627, which has not been previously described. To study the regularities in this galaxy, we used its FUV image obtained by *GALEX* (Gil de Paz

[1] http://ned.ipac.caltech.edu/
[2] http://www.sdss.org/dr13/

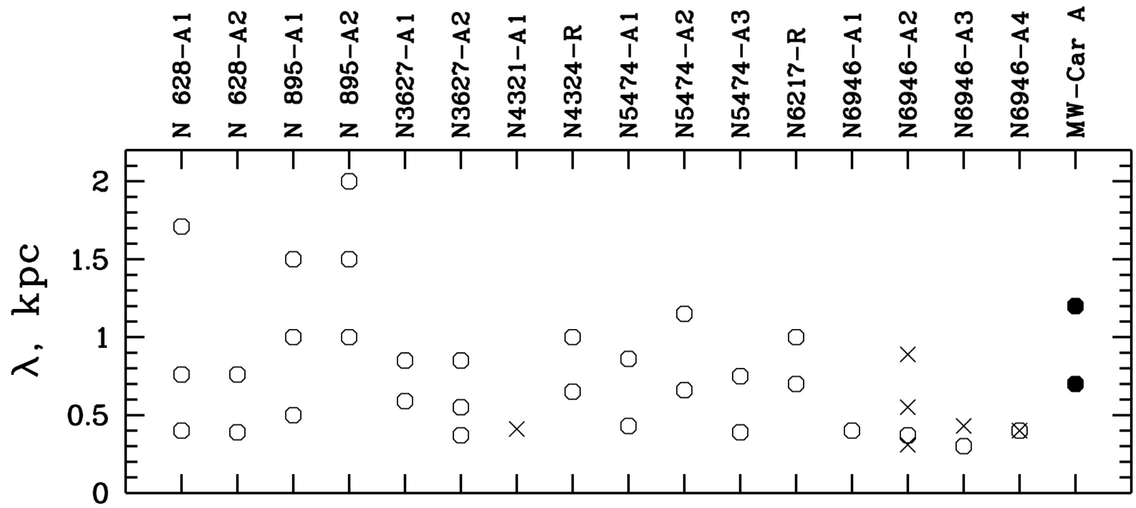

Fig. 2. Characteristic distances λ between neighbouring local brightness maxima in spiral arms and rings of different galaxies, obtained from ultraviolet and optical (open circles), infrared (crosses) and radio data (filled circles).

et al. 2007), the SDSS u image (Brown et al. 2014), and the Hα image from the *SIRTF Nearby Galaxies Survey (SINGS)*[3] (Kennicutt et al. 2003). All images were downloaded from the NED database.

Using photometric profiles along the arms, we found 18 local brightness maxima (condensations of the young stellar population) in each of the spiral arms of NGC 3627. The results of the analysis of the distances between neighbouring young stellar condensations are shown in Fig. 3. In both arms the histogram shows a main peak at 590 ± 30 pc in the western arm (Arm 1) and 550 ± 40 pc in the eastern spiral arm (Arm 2). Half of the star formation regions in each spiral arm have a neighbour at a distance of $\sim$ 550–600 pc. Secondary peaks (at least three separations) are observed at 850 ± 30 pc in Arm 1 and 375 ± 25 and 850 ± 25 pc in Arm 2 (Fig. 3). The main peaks in the arms are also confirmed by the Fourier analysis data, which gives a value of 670 ± 20 pc in Arm 1 and 525 ± 20 pc in Arm 2 (Fig. 3).

Summarizing the observational data, we can conclude that (i) regularity in the spatial distribution of young stellar populations and gas clouds along the spiral arms and rings of galaxies of different morphology and structure is observed more frequently than expected (see Fig. 1); (ii) the characteristic distance between neighbouring zones of concentration of the young stellar population is equal to or a multiple of 350–500 pc; (iii) brighter and larger stellar clusters (gas clouds) are located at greater (multiples) distances from each other than smaller and less massive (Gusev

[3] http://irsa.ipac.caltech.edu

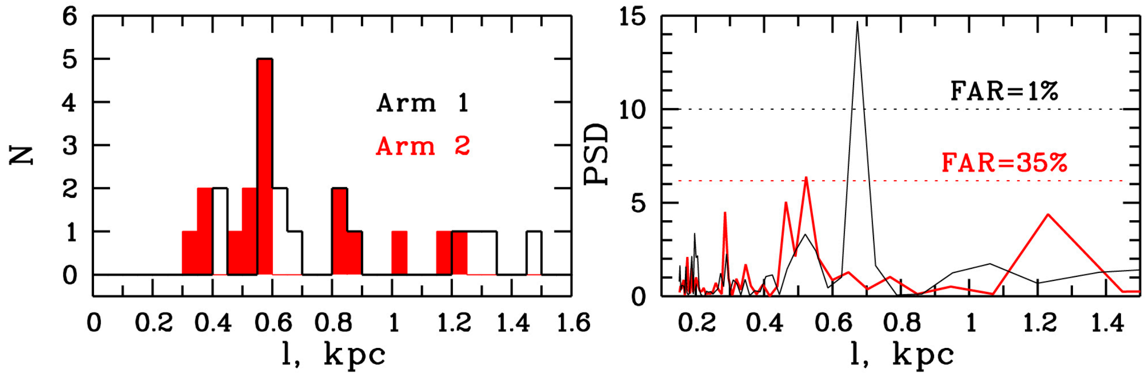

Fig. 3. The number distribution histograms of local brightness maxima by separation between adjacent young stellar condensations along the spiral arms of NGC 3627 (left) and the normalized power spectral density of the function $p(s)$ for the spiral arms in NGC 3627 (right). The function $p(s)$ is a collection of Gaussians on the points of local brightness maxima on the profiles, with a dispersion equal to the peak positioning error; dotted lines are the false-alarm probability (FAP) levels of 1% for Arm 1 and 35% for Arm 2 (see Gusev et al. 2022, for details).

& Efremov 2013; Park et al. 2023); (iv) the presence or absence of shock waves does not affect the formation of regular chains of star formation regions along galactic spirals and rings (Gusev & Efremov 2013; Gusev & Shimanovskaya 2020).

Although theoretical models predicted a scale of the stellar-gas disk instability on the order of a few kpc,Arora et al. (2024) recently used magneto-hydrodynamic simulations in a galaxy like the Milky Way to predict the formation of regular chains of star formation regions in spiral arms on scales of $\sim$ 500 pc in the hydro case (without magnetic field) and $\sim$ 650 pc in the magnetic case.

3 Discussion and conclusions

Despite the simulation of Arora et al. (2024), the question of agreement between the observational data, which show a scale of $\sim$ 350–500 pc, and theoretical models (scale $>$ 1 kpc) remains open. We believe that a promising direction for research in this field is the use of modern high-quality surveys such as PHANGS–MUSE, which provide the necessary observational data (parameters of the gas and stellar populations and kinematics of the disk) for the direct calculation of regularity scales in galaxies with high spatial resolution and wide field of view.

At the same time, the question arises: how accurately do existing theoretical models predict the scale of gas cloud fragmentation? Simulations by Arora et al. (2024) and Inoue et al. (2021b) showed that the separations obtained from numerical simulations turned out to be 1.5–2 times less than the wavelength of the disk instability. A possible explanation for this discrepancy could be the difference between the local physical parameters of the gas disk at the moment of fragmentation and the observed ones. Park et al. (2023) showed that if the observed HI clouds in the Carina Arm were formed by gravitational instabilities in a previously more uniform spiral arm gas, then the velocity dispersion σ in this gas should to be less than or equal to ~ 4 km/s whereas the observed $\sigma = 8$–8.5 km/s. An alternative possibility is the higher surface density of the gas at the moment of fragmentation, caused by shock waves.

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