Young Star-Forming Complexes in the Ring of the S0 Galaxy NGC 4324

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Abstract—We present the results of our study of star-forming regions in the lenticular galaxy NGC 4324. During a complex analysis of multiwavelength observational data—the narrow-band emission-line images obtained with the 2.5-m telescope at the Caucasus Mountain Observatory of the Sternberg Astronomical Institute of the Moscow State University and the archival images in the broad photometric bands of the SDSS, GALEX and WISE space telescope surveys—we have detected young star-forming complexes (clumps) located in the inner ring of the lenticular galaxy NGC 4324 and established a regular pattern of their distribution along the ring, which, nevertheless, changes with time (with age of star-forming regions). We suggest several possible evolutionary paths of the lenticular galaxy NGC 4324, of which the swallowing of gas-rich satellites or giant clouds (the so-called minor merging) is the most probable one.

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INTRODUCTION

Lenticular galaxies, by the definition of this morphological type, are generally believed to be disk galaxies without star formation. A deficit of gas in these early-type galaxies is again traditionally mentioned as being responsible for the absence of star formation in the disks of lenticular galaxies. However, deeper surveys in radio lines have recently shown that, in fact, quite often there is a cold gas in lenticular galaxies, both neutral hydrogen (Sage and Welch 2006; Serra et al. 2012) and molecular gas (Welch and Sage 2003; Welch et al. 2010), that can serve as a fuel for star formation. At the same time, the star formation being observed in some gas-rich lenticular galaxies is usually concentrated to ring structures (Pogge and Eskridge 1993; Salim et al. 2012) and, probably, has a different trigger and slightly different physics than does the star formation in the arms of spiral galaxies. There is evidence that the star formation in rings is much more efficient than the star formation in spiral arms (Kormendy and Kennicutt 2004).

The nearby early-type galaxy NGC 4324 being investigated here is remarkable for its bright blue ring (Fig. 1) embedded in a large-scale stellar disk typical for lenticular galaxies—with a reddish color and without structural features, except the ring. The blue color of the ring points to current or recent star formation in it. The galaxy NGC 4324 was included in the sample of the ATLAS-3D project (Cappellari et al. 2011) and was investigated by means of panoramic spectroscopy. There are also photometric surveys that included NGC 4324. In the ARRAKIS atlas (Comerón et al. 2014), where the ring structures noticeable in the 3.6- and 4.5-μm bands are collected, it is classified as a galaxy with an inner ring, (L)SA(r)0+. A bar is felt in the image left after the subtraction of the galaxy model constructed from the parameters derived during the decomposition of the image from the S4G survey (Sheth et al. 2010) given in ARRAKIS, although only the ring is pointed out among the distinguished features in the catalogue. However, the presence of a bar in this galaxy is also noted in the HyperLEDA database. According to this database, the galaxy under study is a member of the NGC 4303 group (Garcia 1993). Basic characteristics of the galaxy being investigated are given in Table 1.

Curiously, a gas is present in this early-type galaxy. For example, an estimate of the molecular hydrogen mass is given in the paper of the ATLAS-3D project by Young et al. (2011): log $M_{H_2} = 7.69 \pm 0.05$, while maps of the CO distribution and kinematics are shown in a detailed study of the molecular gas within the same project (Alatalo et al. 2013): molecular hydrogen is concentrated in a ring closely
following the optically visible ring in morphology and kinematics, and its distribution coincides with the stellar ring and the ionized gas ring. The molecular hydrogen mass in this paper is estimated to be $\log M_{\text{H}_2} = 7.97 \pm 0.02$. The coincident kinematic position angles of the line of nodes of the stellar disk, $\phi_{\text{star}} = 238^\circ \pm 1^\circ$, the molecular, $\phi_{\text{mol}} = 232.0^\circ \pm 1.8^\circ$, and ionized, $\phi_{\text{ion}} = 239.0^\circ \pm 6.8^\circ$, gas obtained in ATLAS-3D (Krajnovi\'c et al. 2011; Davis et al. 2011a) suggest that the morphology and rotation of the molecular and ionized gas and the stellar disk (in the vicinity of the ring) coincide. The normalized surface brightness profile of the molecular gas emission with its peak at a radius of 20\arcsec, almost at the radius of the stellar ring, given the poorer spatial resolution of the CO observations, is shown in Davis et al. (2011b).

The earliest neutral hydrogen mass estimates are given in Krumm and Salpeter (1979) and Giovannardi et al. (1983); they are $6 \times 10^8 M_\odot$ and $5.1 \times 10^8 M_\odot$, respectively. According to Cortese and Hughes (2009), the galaxy under study contains $6.76 \times 10^8 M_\odot$ of neutral hydrogen. As regards the distribution of neutral hydrogen in the galaxy, it is reported in Duprie and Schneider (1996) that neutral hydrogen is detected at distances up to two optical radii, i.e., it is distributed over the disk rather than concentrated only in the ring, consistent with the position–velocity map in Hoffman et al. (1989).

It is not surprising that at such an amount of gas, with 50–100 million solar masses of $\text{H}_2$ being concentrated in a narrow range in radius, young stars are formed in the ring of the galaxy NGC 4324. We have already studied NGC 4324 spectroscopically: these were observations with a long slit at the South African Large Telescope (SALT) (Proshina et al. 2019) and observations with a scanning Fabry–Perot interferometer at the 6-m BTA telescope (Silchenko et al. 2019). Our previous study (Proshina et al. 2019) showed the presence of bright emission lines in the spectrum of this galaxy and nonuniformity of the distribution of...
star-forming sites along the slit; the H\textalpha\, intensity peak falls on the ring at a distance of 23\arcsec from the center. The ring of the galaxy is also excellently seen in the ultraviolet data from the GALEX space telescope survey (Bouquin et al. 2018). We decided to investigate the pattern of star formation in the ring of NGC 4324 by combining the GALEX data and our own panoramic narrow-band photometric observations of the galaxy in the ionized gas H\textalpha\, emission that characterizes the current star formation rates (SFRs) on a timescale up to 10 Myr. In the next section we describe our observations, then list our results on the characteristics of star-forming regions in the ring, and present a discussion of our results and conclusions.

OBSERVATIONS AND DATA ANALYSIS

We decided to take full images of the galaxy NGC 4324 in narrow photometric bands centered on the H\textalpha\, and [N II]λ6583 emission lines with the MaNGaL instrument—a mapper with a tunable filter. A detailed description of the instrument is given in Moiseev et al. (2020). The small bandwidth of the tunable filter, \(~\text{13\,Å}\), allows an image in each emission line to be taken separately. This, in turn, allows us to compare the fluxes in these lines and to determine the gas excitation mechanisms based on diagnostic diagrams. The observations were carried out on April 17, 2018, with the 2.5-m telescope at the Caucasus Mountain Observatory (Shatsky et al. 2020). The total exposure time was 1500 s for the H\textalpha\, image, 3000 s for the [N II]λ6583 line image, and 1500 s for the image in the red continuum adjacent to the lines. The scale of all images was 0.66 arcsec per pixel (2 \times 2 binning); the seeing allowed maps with a spatial resolution of 1.5 arcsec to be constructed. We described the technique for subtracting the continuum images from the narrow-band MaNGaL data to obtain "pure" emission-line images, including the calibration of the observed fluxes in energy units and the correction of the images for the overlapping wings of close emission lines due to the finite spectral resolution of the instrument in Sil'chenko et al. (2020).

In addition, for a more comprehensive analysis of the star formation process we used the ultraviolet (UV) images of the galaxy under study obtained with the GALEX space telescope from the public Mikulski Archive for Space Telescopes (MAST), its optical images from SDSS DR9 (Ahn et al. 2012), and its image in the W4 band at 22 \,\mu m obtained with the WISE space telescope from the public NASA/IPAC archive. Table 2 gives the identifiers of the observing program, the dates of observations, and the exposure times of the UV images used by us.

Compact emission regions in the ring (clumps) are clearly seen on the H\textalpha\, and [N II]λ6583 emission-line intensity maps with the subtracted continuum. The typical size of the clumps turned out to be about 4\arcsec or 0.5 kpc. The emission-line flux was summed in apertures of such a size. Figure 2 (upper row) shows the galaxy’s images in the narrow H\textalpha\, and [N II]λ6583 emission lines with the apertures centered on the clumps and numbered along the ring. The same apertures were also superimposed on the UV images in the FUV and NUV bands and the WISE/W4 image. The fluxes were measured in the specified apertures. For the UV images the fluxes were converted to magnitudes using the calibration equations from Morrissey et al. (2007). The derived magnitudes were corrected for dust absorption in our Galaxy using the photometric absorption indices from the NED (A_B = 0.087). The UV fluxes were corrected for absorption in the galaxy itself using the infrared dust radiation estimates based on WISE data.

\begin{table}[h]
\centering
\caption{Basic characteristics of the galaxy NGC 4324.}
\begin{tabular}{|l|l|}
\hline
Galaxy & NGC 4324	abularnewline
\hline
Morphological type (NED) & SA(r)0^+ \\
R_{25}, arcsec (RC3) & 83 \\
B_T (LEDA) & 12.27m \\
M_H (NED) & -23.43m \\
(B - V)_e (LEDA) & 0.92m \\
PA_{phot} (NED) & 52° \\
Inclination i_{phot} (NED) & 63° \\
V_r, km s^{-1} (NED) & 1667 ± 3 \\
Distance, Mpc & 26.2 \\
M_B & -19.82m \\
Linear scale & 127 pc/arcsec \\
\hline
\end{tabular}
\end{table}

\begin{tablenotes}
\item[1] NASA/IPAC Extragalactic Database.
\item[2] Third Reference Catalogue of Bright Galaxies, de Vaucouleurs et al. (1991).
\item[3] Lyon-Meudon Extragalactic Database.
\item[4] Cosmiclows-2, Tully et al. (2013).
\end{tablenotes}
Table 2. Protocol of the UV observations of the galaxy NGC 4324

| Band | Program identifier | Date of observations | Exposure time, s |
|------|--------------------|----------------------|-----------------|
| FUV  | AIS 228 0001 sg28  | Mar. 31, 2004        | 106.5           |
| NUV  | AIS 228 0001 sg27  | Mar. 31, 2004        | 200             |
| NUV  | MISGCSN1 13360 0229| Apr. 1, 2011         | 1739.7          |
| NUV  | G16001033 GUVICS033| Mar. 18, 2010        | 1668.2          |

Table 3. Characteristics of the emission-line clumps in the ring of NGC 4324

| No. | Flux in Hα, erg s⁻¹ cm⁻² | Σ(Hα), erg s⁻¹ kpc⁻² | EW (Hα), Å | log [N II]6583/Hα | 12 + log (O/H) | Pettini and Pagel (2004) | Marino et al. (2013) |
|-----|--------------------------|----------------------|------------|------------------|----------------|---------------------------|----------------------|
| 1   | 3.60E-15                 | 1.69E+39             | 7.87 ± 0.20| −0.30 ± 0.01     |                |                          |                      |
| 2   | 2.74E-15                 | 1.32E+39             | 5.23 ± 0.20| −0.32 ± 0.01     |                |                          |                      |
| 3   | 1.94E-15                 | 1.05E+39             | 2.62 ± 0.20| −0.35 ± 0.01     |                |                          |                      |
| 4   | 2.17E-15                 | 1.16E+39             | 2.08 ± 0.14| −0.31 ± 0.01     |                |                          |                      |
| 5   | 1.99E-15                 | 1.09E+39             | 1.62 ± 0.10| −0.31 ± 0.01     |                |                          |                      |
| 6   | 2.66E-15                 | 1.36E+39             | 1.85 ± 0.11| −0.54 ± 0.01     |                |                          |                      |
| 7   | 5.34E-15                 | 2.41E+39             | 5.13 ± 0.10| −0.49 ± 0.01     | 8.62           | 8.51                      |                      |
| 8   | 1.87E-15                 | 1.00E+39             | 2.60 ± 0.10| −0.49 ± 0.01     |                |                          |                      |
| 9   | 2.20E-15                 | 1.10E+39             | 5.63 ± 0.15| −0.42 ± 0.01     | 8.66           | 8.55                      |                      |
| 10  | 2.05E-15                 | 0.96E+39             | 8.82 ± 0.20| −0.32 ± 0.01     |                |                          |                      |
| 11  | 2.18E-15                 | 1.04E+39             | 8.63 ± 0.20| −0.41 ± 0.01     | 8.67           | 8.55                      |                      |
| 12  | 2.99E-15                 | 1.43E+39             | 7.69 ± 0.20| −0.40 ± 0.01     |                |                          |                      |
| 13  | 1.44E-14                 | 5.97E+39             | 30.6 ± 0.2 | −0.54 ± 0.005    | 8.59           | 8.49                      |                      |
| 14  | 4.07E-15                 | 1.91E+39             | 6.59 ± 0.16| −0.41 ± 0.01     | 8.67           | 8.55                      |                      |
| 15  | 3.94E-15                 | 1.91E+39             | 4.58 ± 0.10| −0.42 ± 0.01     | 8.66           | 8.55                      |                      |
| 16  | 4.66E-15                 | 2.14E+39             | 5.93 ± 0.20| −0.43 ± 0.01     | 8.65           | 8.54                      |                      |
| 17  | 1.89E-15                 | 1.05E+39             | 2.57 ± 0.10| −0.32 ± 0.01     |                |                          |                      |
| 18  | 2.58E-15                 | 1.30E+39             | 3.69 ± 0.15| −0.22 ± 0.01     |                |                          |                      |
RESULTS

Gas Excitation Diagnostics

Table 3 gives the measured emission-line fluxes and metallicity estimates for the gas in the regions where we detect the dominant contribution of star formation to the gas excitation. The emission-line ratio [N II]λ6583/H\(\alpha\) was corrected for the overlapping of the line wings in the MaNGaL band, according to the calibration from Moiseev et al. (2020).

There are several criteria by which the gas excitation mechanism can be determined. The first criterion involves the diagnostic diagrams proposed in Baldwin et al. (1981), the so-called BPT diagrams, which allow the mechanisms of gas excitation by shock waves or active nuclei to be separated from the excitation by hard UV radiation from young OB stars based on emission-line intensity ratios. Based on the model calculations of these diagrams from Kewley et al. (2006), we adopted the threshold value of \(\log([\text{N II}]\lambda 6583/\text{H}\alpha) = -0.41\) below which the gas may be deemed to be excited exclusively by radiation from young stars. At the same time, we adopt \(\log([\text{O III}]\lambda 5007/\text{H}\beta) = 0.10\) in the ring, according to the measurement of a long-slit spectrum for NGC 4324 in our previous paper (Proshina et al. 2019). Another criterion proposed in Zhang et al. (2017) is related to the H\(\alpha\) surface brightness at which the emission is assumed to be produced by the gas ionization by radiation from young stars: \(\Sigma(\text{H}\alpha) > 10^{39}\) erg s\(^{-1}\) kpc\(^{-2}\). Yet another criterion for the identification of star-forming regions is related to the equivalent width of the H\(\alpha\) emission line. For example, Binette et al. (1994) and Cid Fernandes et al. (2011) suggested a threshold value of \(\text{EW}(\text{H}\alpha) = 3\) Å; values below 3 Å are deemed typical for diffuse ionized gas (DIG) regions. However, Lacerda et al. (2018) suggested a different threshold value of \(\text{EW}(\text{H}\alpha) = 14\) Å. The ambiguity of this criterion stems from the fact that in the case of projecting the star-forming regions onto a bright underlying structure (for example, when the star-forming regions are not far from the galactic bulge), the contribution of this underlying structure is related to the equivalent width of the H\(\alpha\) emission line. For example, Binette et al. (1994) and Cid Fernandes et al. (2011) suggested a threshold value of \(\text{EW}(\text{H}\alpha) = 3\) Å; values below 3 Å are deemed typical for diffuse ionized gas (DIG) regions. However, Lacerda et al. (2018) suggested a different threshold value of \(\text{EW}(\text{H}\alpha) = 14\) Å. The ambiguity of this criterion stems from the fact that in the case of projecting the star-forming regions onto a bright underlying structure (for example, when the star-forming regions are not far from the galactic bulge), the contribution of this underlying structure is related to the equivalent width of the H\(\alpha\) emission line. For example, Binette et al. (1994) and Cid Fernandes et al. (2011) suggested a threshold value of \(\text{EW}(\text{H}\alpha) = 3\) Å; values below 3 Å are deemed typical for diffuse ionized gas (DIG) regions. However, Lacerda et al. (2018) suggested a different threshold value of \(\text{EW}(\text{H}\alpha) = 14\) Å. The ambiguity of this criterion stems from the fact that in the case of projecting the star-forming regions onto a bright underlying structure (for example, when the star-forming regions are not far from the galactic bulge), the contribution of this underlying structure should be taken into account, which reduces the reliability of assigning the measured emission-line equivalent widths precisely to the distinguished gas emission region. In our case, the ring of NGC 4324 is the inner one, with a radius \(\sim 3\) kpc, and, therefore, the contribution of the underlying stellar population of the galaxy should be taken into account, which we did. For a confident identification of clumps with regions of current star formation we apply all three criteria.
Fig. 3. (Anti-)correlation of the gas metallicity in clumps with the local SFRs: (a) the correlation of the oxygen abundance in the gas, according to the calibration from Pettini and Pagel (2004), with the instantaneous SFRs; (b) metallicity versus SFRs averaged on a timescale of 200 Myr (from the NUV flux). The horizontal dashed line on both panels indicates the solar metallicity.

It is for the clumps, where the gas is excited by young stars, that we estimated the gas metallicity from the ratio of the fluxes in the [N II]λ6583 and Hα emission lines using, for comparison, two calibrations from Pettini and Pagel (2004) and Marino et al. (2013). Figure 3 shows how the gas metallicity changes from clump to clump with SFR. When considering the “instantaneous” SFR determined from the Hα flux, this dependence for SFRs above \(10^{-2} \, M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}\) is the inverse one. When averaging the SFRs on a timescale of hundreds of Myr, using the NUV indicator, this anticorrelation is washed out. This is probably explained by a short duration of local starbursts: as the chemical evolution in the clump advances, the gas is locally depleted, while the gas metallicity reaches saturation (Ascasibar et al. 2015). The solar metallicity is the terminal point of the chemical evolution: the gas metallicity reaches a plateau near the solar value, when the density of the young stellar population locally begins to exceed the gas density (Ascasibar et al. 2015). Note that the clumps with a low SFR in Fig. 3 do not fall on the extension of the above dependence. Most likely, the reason is that, in fact, the emission in them is largely attributable to shock processes, and these clumps were attributed to the star-forming ones formally, because the Hα surface brightness in them exceeds only slightly the critical value of \(10^{39} \, \text{erg s}^{-1} \, \text{kpc}^{-2}\) suggested in Zhang et al. (2017).

**SFR Estimation**

The SFRs used to construct the dependence in Fig. 3 were calculated from the fluxes that we measured based on the MaNGaL map in the Hα emission line using the calibration equations from the review by Kennicutt and Evans (2012) and by taking into account the dust absorption in the galaxy under study; to make the correction for dust, we used the galaxy’s image taken with the WISE space telescope in the W4 (22 μm) band from the open NASA/IPAC archive. The Hα emission is a star formation tracer on a short timescale that does not exceed 10 Myr. The same review by Kennicutt and Evans (2012) also provides the calibrations to calculate the SFRs from the measured UV fluxes, which are SFR tracers on longer timescales—from 100 to 200 Myr. We carried out these calculations using the FUV and NUV images of NGC 4324 from the GALEX space telescope (also by taking into account the UV dust absorption in the galaxy under study using the WISE image in the W4 band). The SFR estimates obtained in the NUV band within three observing programs (AIS, MIS, and GI) agree well between themselves; the availability of three independent measurements in the NUV band allows us both to calculate the mean values and to estimate the errors of the derived SFRs. The plot of the SFR density variation along the ring of NGC 4324 (Fig. 4) turns out to be very curious: a reduced SFR surface density derived from the FUV flux is observed where intense star formation from the flux in the Hα emission line is now observed (clumps 7 and 13). According to the remark by Calzetti (2013), this is typical for a shorter timescale, when the star formation lasts at present no more than 2 Myr. In this case, the calculation using the UV fluxes based on the calibrations by Kennicutt and Evans (2012) should be multiplied by a factor of 3.45. Thus, we conclude that the starbursts in these clumps have begun quite recently (within 10 Myr). The stars that could be formed during a previous starburst (∼200 Myr ago) and could contribute to the FUV luminosity have already exploded or their luminosity peak has shifted to the NUV, leading to the observed dip in the FUV (clumps 7, 13, 16, 17, 18, 1). It is worth noting that the curve tracing the SFRs calculated from the NUV flux is almost horizontal and, therefore, it is better...
Fig. 4. Variation of the SFR density along the ring.

Fig. 5. Ionized gas kinematics from our observations at the 6-m telescope in the Hα emission line. From left to right: the observed radial velocity field, the residual velocity field (after the subtraction of the circular rotation model), and the adopted rotation curve.

Regularity of the Distribution of Clumps along the Ring

To estimate the characteristic separations between clumps in the Hα emission line and between young star complexes in the u band, we deprojected the MaNGaL image of the galaxy in Hα and the SDSS image in the u band. For this purpose, we rotated the original images through an angle of 37° in order that the line of nodes be horizontal and then
de
to determine the mean SFR along the ring precisely from the NUV data. It can be assumed that the star formation began first in clumps 2–3–4, then in 5–6, 14–15, and 8–12, subsequently in 16–17–18–1, then in clump 7 and clump 13—the most recent starburst (possibly a recurrent one, 200 Myr after the previous one).

Orientation of the Gaseous Disk of NGC 4324 from the Ionized Gas Rotation Velocity Field

In our previous paper (Sil’chenko et al. 2019) we presented, among a sample of 18 lenticular galaxies, our panoramic spectroscopy for NGC 4324 in the Hα emission line obtained with a scanning Fabry–Perot interferometer. Now, a more detailed analysis of the data presented in Fig. 5 has shown that the gas is mostly involved in circular rotation in a plane inclined to our line of sight at an angle of 65° ± 3° with the line of nodes oriented in the sky at a position angle PA = 235° ± 3° (the radial range for our analysis is 10″–35″). This inclination, in principle, is consistent with the inclination estimated from our isophotal analysis for the inner galactic disk (Proshina et al. 2019), 63°, as it must be in the case of circular gas rotation in the main stellar disk plane. However, emission-line clumps whose velocities differ significantly, up to 70 km s⁻¹, from the model of extrapolated circular rotation with a flat curve V(R) are visible in the outer disk regions and in the immediate vicinity of the galaxy. Below in the Discussion we will use these data to justify the hypothesis of external gas accretion onto NGC 4324.
stretched them vertically by adopting the inclination $i = 65^\circ$, in accordance with the kinematic inclination derived by analyzing the two-dimensional ionized gas velocity field measured with the Fabry–Perot interferometer. We applied the same angles for both images, because the ionized gas observed by us lies in the same plane as do the stars—this is suggested by the consistent kinematics of the gas and stars revealed by us through our spectroscopic long-slit observations (Proshina et al. 2019). Figure 6 shows the deprojected images of NGC 4324 in the Hα emission line and the $u$ band and the separations between the centers of the adjacent clumps extracted from these images. In the deprojected Hα image it can be clearly seen that the gaseous ring under study is intrinsically elliptical, which is typical for resonance rings (Buta 1995), with the resonance rings being predominantly elongated perpendicular to the bar—the so-called R1 type. An interesting manifestation of symmetry is that the localization of the star-forming regions in the ring is pairwise, a half-turn of the galaxy apart (in Fig. 6, left, these pairs are connected by the straight-line segments). Is this a manifestation of the dynamical impact of the bar on the gas compression in the ring and the onset of star formation in the clumps? Figure 7 presents histograms of the distribution of clumps in separations between them. For the image that records the just begun star formation (the map in the Hα emission line) the separations between clumps are grouped to one value, 0.65–0.7 kpc; the second maximum of the histogram (near 1.3 kpc) probably corresponds to twice the characteristic separation or a “missed” clump. On the $u$-band map corresponding to “older” star-forming regions this regularity disappears.

**Fig. 6.** Structure of the ring in the Hα emission line (left) and the $u$ filter (right): top—the deprojected image of the ring; bottom—the separation between adjacent clumps in the Hα emission line and the $u$ filter.
Fig. 7. Histograms of the distribution of separations between adjacent clumps: in Hα (left) and in the u filter (right).

Fig. 8. Comparison of the distributions of star-forming regions visible in the Hα emission line (red circles) and young star complexes visible in the u filter (blue circles); the Hα map and the map in the broadband u filter were constructed from our MaNGaL data and SDSS/DR9 data, respectively.

Figures 8 and 9 show the SDSS images of the galaxy in the u, g, and r bands with the positions of the clumps extracted from the u-band image (blue circles) and the Hα image (red circles) superposed on them. The clumps visible in the u band are basically already formed complexes of star clusters. It can be seen that only clumps 6, 7, and 13 coincided on the Hα and u-band maps. Many of the star complexes, which are bright in the continuum, are visible in the gaps between Hα clumps: for example, 1–2, 4–5, 12–13, 14–15, 15–16, 16–17, and 17–18; or at some distance from them, for example, complex 2–3, while complex 19, which has no analog in the narrow-band Hα and [N II]λ6583 images, is clearly seen in the images in both blue broadband u and g filters. Recall that the most characteristic separation between Hα clumps found by us above is 0.7 kpc, while the characteristic separation between star complexes in the u band is 1.05 and 1.5 kpc (Fig. 7). All of this taken together points to triggered star formation that occurs when the walls of the giant HI shells around young star complexes collide (Efremov and
Elmegreen 1998; Egorov et al. 2015). Since the characteristic separation between clumps is different for different wavelengths and since the "visibility" of star-forming regions at different wavelengths is related to their age (the youngest ones are clearly seen in the Hα emission line, the middle-aged ones are seen in the UV, and by an age of 1–2 Gyr we see the complexes to be bright in u and g), there is the propagation of star formation along the ring that leads to a change in the characteristic separations between star-forming complexes with time, as demonstrated by the histograms in Fig. 7. We cannot present an analogous histogram for the middle-aged star-forming regions, because the GALEX space telescope observations in the NUV band had a spatial resolution of 6′′, which exceeds the sizes of the clumps and is comparable to the expected separations between them in the UV; thus, in the GALEX data the structure of the star-forming ring is washed out.

DISCUSSION AND CONCLUSIONS

Previously, a regular distribution of star-forming regions has already been noted in the linear structures of disk galaxies. It is typical, for example, for the tidal tails of interacting galaxies (Sotnikova and Reshetnikov 1998). It is also encountered in the arms of spiral galaxies (Elmegreen 2010; Gusev and Efremov 2013; Elmegreen et al. 2018). For instance, Efremov (2010) reported on star complexes 0.6 kpc in size distributed in the form of a chain along the northwestern arm of the Andromeda galaxy with a typical spacing of 1.1 kpc, which, in the opinion of the author, is related to a regularity in the distribution of magnetic field lines. While investigating the regular chains of star-forming complexes in the grand-design spiral galaxy NGC 628, Gusev and Efremov (2013) revealed characteristic separations between complexes that are a multiple of 0.4 kpc. Elmegreen et al. (2018) detected a regularity in the distribution of infrared clumps along filaments with a characteristic separation of 0.41 kpc in the dusty spiral galaxy M 100. In their recent paper Gusev and Shimanovskaya (2020) noted such a regularity in the distribution of star-forming regions in the resonance ring of the barred spiral galaxy NGC 6217 with a characteristic separation between star complexes of 0.7 kpc. It is reported in the same paper that this is the first case where a regularity in the distribution of star-forming regions is observed in ring structures. Now we see that this case is not unique. The ring in NGC 4324 may also be a resonance one: although no large-scale bar is seen in the galaxy, our isophotal analysis (Proshina et al. 2019), in particular, the jump in the ellipticity of isophotes at a radius of 13′′−15′′, points to a triaxial structure of the central part of the galaxy elongated approximately along the minor axis of the isophotes. The regularity in the distribution of star-forming complexes in the ring of NGC 4324 suggests that the physical star formation mechanisms on local scales are the same in spiral and lenticular galaxies, while the differences show up when we turn to the analysis of large-scale structures: in spiral galaxies the major star formation occurs in spiral density waves, while in gas-rich lenticular galaxies it is organized into ring structures (Pogge and Eskridge 1993; Salim et al. 2012).

Since we definitely diagnose current and recent star formation in the ring of the lenticular galaxy and since the characteristic distance between the centers of clumps is ∼0.67 kpc, we can probably identify this size with the scale of inhomogeneities during the development of a gravitational instability leading to star formation. It is of interest to estimate the critical gas surface density and to compare it with the observed one. It is found from theoretical calculations

![Diagram](image-url)
Fig. 10. Distribution of the ratio of the [N II]/Hα emission-line fluxes in azimuth along the ring. The typical error of the logarithm of the flux ratio is 0.01. The angle indicated on the horizontal axis is measured from the major axis of the isophotes, the northeastern ending, counterclockwise. The horizontal dashed line demarcates the purely photoionization gas excitation (below the line) from the excitation with an admixture of shock waves. The vertical dashed lines indicate the probable orientation of the triaxial structure at the galactic center.

(Ledoux 1951) that the perturbations with the following wavelengths are unstable:

$$\lambda_{\text{crit}} = \frac{2\pi^2 G \Sigma_{\text{gas}}}{\kappa^2},$$  \hspace{1cm} (1)

where $\kappa$ is the epicyclic frequency. From the ionized gas rotation curve calculated by us (Fig. 5), which is close to the circular velocity of the galactic potential due to the collisional nature of the gaseous subsystem, we see that the galaxy rotates rigidly up to the outer edge of the ring, $\sim 27''$. Under the assumption of rigid rotation, we obtain $\kappa \approx 1.7 \times 10^{-15}$ s$^{-1}$ in the ring. Taking $\lambda_{\text{crit}} = 0.67$ kpc, from Eq. (1) we then obtain $\Sigma_{\text{gas}} \approx 22 M_\odot$ pc$^{-2}$. Let us now calculate the observed molecular gas surface density in the ring by assuming, according to Alatalo et al. (2013), that the radial extent of the ring does not exceed $10''$ and $\log M_{\text{H}_2} = 7.97 \pm 0.02$:

$$\Sigma_{\text{gas}} = \frac{M_{\text{H}_2}}{\pi (R^2 - r^2)} \approx 4.3, \ M_\odot$ pc$^{-2}$.

Since the observed gas surface density is found from our calculations to be lower than its critical value and since we still observe star formation in the ring, this means that, first, apart from the molecular gas, there is neutral hydrogen in the ring that we neglected in our calculations due to the lack of information about its quantitative content precisely in the ring, and, second, additional factors leading to a gravitational instability and the onset of star formation are in action. One of the additional factors may be the so-called feedback from star-forming regions—gas compression by the giant gaseous shells expanding away from the star-forming regions. It is also interesting that the parts of the ring where the ionized gas emission-line clumps show excitation by young stars are close in their azimuthal position to the ends of the oval structure (Fig. 10)—such a configuration may be associated with the so-called ansae, i.e., the regions of enhanced brightness at the ends of the bar. Although it is pointed out in the study by Martinez-Valpuesta et al. (2007) that current star formation is recorded very rarely in ansae, for example, in NGC 4151, which, as NGC 4324, has no bar, but has an oval at the center, the ansae exhibit the blue color and the Hα emission line.

We can estimate the mass of the star complexes using the SDSS images in the $u$ and $g$ bands as well as the calibration equation and its coefficients from Bell et al. (2003). Since the ring is the inner one, the contribution of the underlying disk should be taken into account in the aperture photometry of star-forming regions. For example, clump 13 is, in our view, the most suitable object for estimating the mass by the method described above, because this clump is youngest and most compact, as was seen from the above analysis. We measured the fluxes in the $u$ and $g$ bands, converted them to magnitudes, and corrected them for extinction in our Galaxy using the extinctions from the NED for the SDSS photometric bands: $A_u = 0.102$ and $A_g = 0.08$. For clump 13 the color was found to be $(u - g) = 0.19$. Next, using Table 7 from Bell et al. (2003), we determine the coefficients for the equation and find that the ratio $M/L_g = 0.75$ and the mass of the young star complex is $\sim 7 \times 10^6 M_\odot$. Several more largest clumps (7, 1–
2, 14–15) also have a stellar mass $\sim 10^7 M_\odot$. Such a mass of the star complexes is consistent with their size of 0.5 kpc when considering the gravitational instability of a gas (Cowie 1981).

The question about the origin of the gas observed in the ring of this galaxy remains open: whether it is the gas that was returned by evolved stars in this galaxy or it has an accretional (external) origin. The consistent kinematics of the stellar and gaseous components argues for the first assumption. The mechanisms for the transfer of evolved gas from the galactic center to the periphery are considered in Marinacci et al. (2010). As regards the interaction with the environment, in the paper by Morales et al. (2018), which is devoted to searching for tidal features in nearby galaxies, NGC 4324 was assigned to the galaxies in which such features were detected. However, there is also another variant of accretion—minor mergers. If the gas-rich satellites of the galaxy had an orbital spin aligned with its rotation and if they fell in the plane of the stellar disk of NGC 4324, then this pattern of motion of the satellites could lead to gas accumulation in the disk of the galaxy under study and without any apparent signatures of interaction. The thus inflowing gas is accumulated in the ring having a resonant nature associated with the rotation of the triaxial structure at the galactic center (whose presence is suggested by the circumstantial evidence given above). Moreover, our additional analysis of the gas radial velocity map in the H$\alpha$ line from Sil'chenko et al. (2019) presented above shows the presence of HII regions located far from the ring and rotating in the same plane and with velocities that more or less correspond to the galactic rotation at these radii. Our long-slit spectroscopic study (Proshina et al. 2019) showed bursts of emission in the H$\alpha$ and [NII] line at great distances from the center, up to 12 kpc, with the gas velocities lying on a “plateau,” i.e., coinciding with the velocity of the main galactic disk. At the same time, deviations from the circular flat–disk rotation model are also observed for three of the four outer HII regions that do not lie on the major axis of the isophotes—on the line of nodes of the disk (Fig. 5, middle). This most likely points to some inclination of the outer orbits of gaseous clouds—a warp of the gaseous disk probably associated with the capture of material from a plane that is not exactly coplanar to the stellar disk. Out of the outer H$\alpha$ regions, region $A$ (Fig. 5) is also seen in the continuum in the galaxy’s blue images from SDSS with an absolute magnitude $M_g = -9.6$; it is probably an irregular, gas-rich satellite of NGC 4324. According to our MaNGaL data, the nitrogen to H$\alpha$ line ratio allows the oxygen abundance in the gas to be estimated: with the calibrations from Pettini and Pagel (2004) and Marino et al. (2013) this estimate is $12 + \log(O/H) = 8.44 \pm 0.04$, i.e., half the solar one and lower than the estimates for the outer NE and SW HII regions belonging to the galactic disk ($\sim 8.56$).

All of this observational evidence confirms the hypothesis about the possible feeding of the disk in the lenticular galaxy with gas through the fall of gas-rich satellites and/or giant clouds. This aligned pattern of accretion of the satellites contributes to the star formation in the accreted gas, as was noted previously in Sil’chenko et al. (2019). Clumps are formed in the ring due to the gravitational instability, in which star formation begins. The subsequent star formation triggers in the gaseous ring are already the shock waves from evolving complexes of massive OB stars—the first formed clusters of young stars in gaseous clumps. In addition, the fall of a satellite or a giant gas cloud onto the galactic disk can serve as a trigger of another starburst. Thus, the chain of “gaseous clumps—star complexes” observed by us is a chain of the propagation of star formation both in space (in the ring) and in time. To clarify the question about the origin of the gas, we need a detailed mapping of NGC 4324 in the 21-cm H I line for both the galaxy itself and its environment.

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