ISSN 1990-3413, Astrophysical Bulletin, 2015, Vol. 70, No. 3, pp. 280–291. © Pleiades Publishing, Ltd., 2015.
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Outer Rings of Early-Type Disk Galaxies

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Received February 16, 2015; in final form, June 11, 2015

Abstract—We have studied the occurrence frequency of the current star formation in the outer stellar rings of early-type disk galaxies based on a representative sample of nearby galaxies from the ARRAKIS catalog. We show that regular rings reveal current star formation with a young stellar population age of less than 200 Myr in about half the cases, while in the pseudorings (open rings), which are only found in spiral galaxies, current star formation is present almost always.

DOI: 10.1134/S1990341315030050

Keywords: *galaxies: structure—galaxies: star formation—galaxies: evolution—galaxies: statistics*

1. INTRODUCTION

Large-scale stellar rings quite often become structural attributes of disk galaxies. Vorontsov-Velyaminov [1, 2] urged to consider them as a part of morphology which is not less important than spirals or bars. Indeed, ring structures of different scales are present in more than a half of disk galaxies [3]. These structures, just like spirals, can have a smooth regular shape or can be clumpy and irregular; they may have the galaxy nucleus in its geometrical center or may be shifted relative to the galactic center [4]. All these features clearly have an evolutionary significance and are related to the origin of the ring. Today, two of the most popular scenarios of the origin of ring structures in galaxies are the resonance and impact scenarios. In the former case, formation of a ring is associated with the presence of a bar in the galaxy: the presence of a non-axisymmetric density perturbation (and, accordingly, the triaxiality of the gravitational potential), which rotates as a solid body with an angular velocity constant along the radius of the disk, leads to dynamical isolation of localized disk zones at a certain distance from the galactic center where the rotation of the bar attains resonance with the quasi-circular differential rotation of gas. In the Lindblad resonance regions, the cloud orbits crowd together, gas gets condensed, triggering the conditions for intense, very efficient star formation, resulting in the formation of radial enhancement in the distribution of stars, in other words, stellar rings [5–8]. The flux tube manifold theory is a modification of the resonance mechanism, where the flux tubes are stable gas orbits around the equilibrium points in the bar-like triaxial potential [9]. The impact mechanism [4, 10–12] involves an external force: it is believed that very contrast rings are formed as a result of an infall of a companion from a highly inclined orbit on the disk of a galaxy near its center. The impact effect results in the disk plane swinging in the vertical direction and generates a ring-shaped density wave running outwards through the galactic disk. If the disk contains gas, intense star formation starts at a distance where the gas is compressed to the critical density, generating an impact stellar ring. However, even in the case of a purely stellar disk, the impact effect may give rise to a transient surface density ring, moving outwards along the radius [13]. It should be noted that the most popular resonance mechanism affects only gas. Importantly, from the dynamical point of view, gas is a collisional system lacking "elasticity" of the stellar component of disks. Gas cannot overcome the regions of chaotic orbits localized in the resonance areas. It "gets stuck" and densifies within a given radius, then followed by star formation. As a result, the gas ring becomes the stellar structure of the disk.

The third possible origin of the outer ring-shaped structures in galaxies, which, as will be shown below, we deem to be the most likely, is accretion of the outer rings from the gas component of a neighboring galaxy through the gravitational tidal effect or from a cosmological filament during hierarchical gravitational clustering of matter. This scenario is not yet very popular among the astronomical community. Once it was actively discussed in light of the discovery of the Hoag

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object [14], as the ring in this galaxy is very massive, and a completely circular (axisymmetric?) early-type galaxy is located at its center. Neither the resonance scenario, nor the impact effect on the suspected own gas disk of the galaxy would produce such an exotic configuration. However, as early as in the survey of Buta and Combes [7], it was noted that no other galaxies similar to the Hoag object were found and that almost everywhere the outer ring is accompanied by a nonaxisymmetric distortion of isophotes in the very center of the galaxy; it was concluded that the vast majority of rings, at least those visibly residing in the main plane of symmetry of the galaxies, have the resonance origin.

The observational statistics of ring-shaped structures in galaxies has a rich history. Ronald Buta [15–17] made a lot of effort, comparing the metric properties of rings and bars, and collected arguments in favor of the resonance scenario for the origin of most of considered rings. However, numerous examples are known of the presence of rings, sometimes two or three, at different radii in the galaxies without bars, and often these galaxies are totally isolated, with no companions or signs of interaction. Sil'chenko and Moiseev [18] expressed the belief that the very presence of rings in galaxies without bars and traces of collision with another galaxy indicate that in a broad sense the origin of rings in the galaxies can be diverse, including accretion. Interestingly, along the Hubble morphological sequence, the frequency of occurrence of bars and rings changes at the antiphase. The morphology analysis in the near infrared range at 2–4 μm has shown that in very early-type S0 disk galaxies, the bars are much rarer than even in their nearest neighbors in the classification of early spiral types Sa–Sb ($46 \pm 6\%$ versus 64–93% [19]), while the outer ring-shaped structures, in contrast, exist in 60% of S0 galaxies and only in 20% of Sb galaxies [3]. A large catalog of ring-shaped structures in the disks, called ARRAKIS [3] was recently compiled based on the results of a morphological survey of nearby galaxies with the Spitzer Space Telescope at wavelengths of 3.6 and 4.5 μm. This catalog undoubtedly describes purely stellar structures, as at wavelengths of around 4 μm we see the bulk of the old stellar population. Since all the popular models relate the appearance of ring-shaped structures to the gas condensation and starburst at a certain radius, it is interesting to look how often the stellar ring structures in galaxies reveal the signs of current star formation, especially if such star formation is not present in the rest of the disk (like it would take place in the S0 galaxies by definition). The survey of the nearby galaxy morphology in the ultraviolet (UV) range by the GALEX space telescope provided the necessary observational data to address this problem [20]. In the near UV range, we can only see the stellar population younger than several hundred million years. Thus, the proportion of rings visible in the near UV with respect to the total number of stellar rings gives us a rough estimate of the ring lifetime or the time of their dissipation. Such work has recently been done by Sebastian Comerón [21] for the inner rings in galaxies. He took a sample of the inner rings from the ARRAKIS catalog and searched for them on the GALEX maps and in the data of narrow-band photometry in the emission Hα line. The result of his analysis has shown that in the early-type galaxies (S0–Sab) only 21% (±3%) of rings are not visible in the UV (though in the far UV, at 1500 Å, which reduces the age of the stellar population observed in this band even more). Accordingly, the time of dissipation of the inner rings within the hypothesis of their resonance origin proves to be at least 200 Myr, which approximately corresponds to the time of one orbital period in the central part of the galaxy. In this study we have made a similar analysis of the presence of recent star formation for a sample of outer rings in the early-type disk galaxies from the ARRAKIS catalog.

2. COMPILATION AND ANALYSIS OF THE SAMPLE

A sample of early morphological types of galaxies from S0 to Sb with the outer ring-shaped structures was selected from the ARRAKIS atlas and catalog [3]. To classify and describe the galaxies, this atlas used the images from the Spitzer Survey of Stellar Structure in Galaxies (S4G) [22], which are in public access. The S4G sample of galaxies has the following restrictions: distance $D < 40$ Mpc; galactic latitude $|b| > 30°$; the integrated magnitude corrected for interstellar extinction in the Galaxy, inclination of the disk to the line of sight, and the K-correction $m_{B,\rm corr} < 15.5$; angular diameter to the 25th isophote in B of more than $1'$. The outer ring-shaped feature in ARRAKIS, just like other features in this catalog, was identified from the residual images obtained by subtracting the model image composed of four components (nucleus, bulge, disk, bar) from the infrared galaxy images. All the S4G galaxies were subjected to such pipelining (S4G pipeline 4, P4). We have selected from ARRAKIS the S4G galaxies with the presence of the outer ring feature in the shape of R, RL, R_1, and R_2-type rings. Further, this group of rings will be considered altogether and indicated by the letter R, and, consequently, R$'$ in the case of pseudorings. Because of a small number of selected objects, a more detailed division into the subtypes

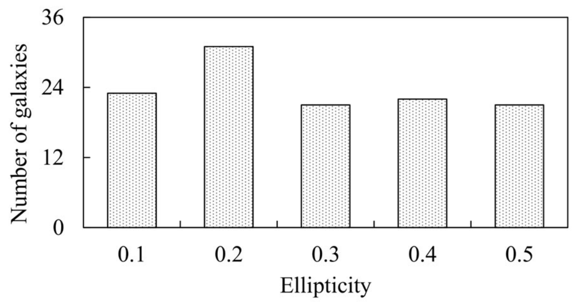

Fig. 1. Distribution of the selected ring-shaped galaxies by the isophote ellipticity value.

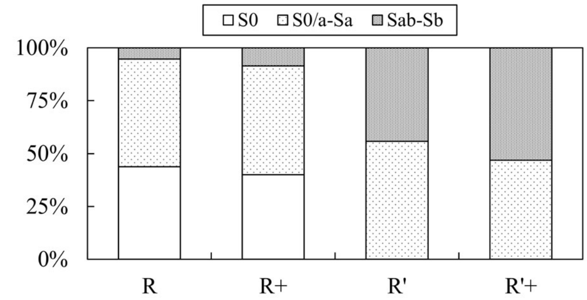

Fig. 2. Fraction of galaxies of different morphological types (S0, S0/a–Sa, Sab–Sb) among the ring-shaped galaxies. R are the ring galaxies, R+ are the ring galaxies with UV radiation in the ring, R′ are the pseudoring galaxies, R′+ are the pseudoring galaxies with UV radiation in the ring.

(R, R_1, R_2, RL) was not conducted. The main difference between the rings and pseudorings is the presence in the former of a closed external feature and a brightness dip between the ring-shaped feature and the more inner part of the galaxy. If in ARRAKIS a galaxy was assigned with two outer ring-shaped structures, this study took into account only the outermost of them. Just like in the ARRAKIS, the S4G galaxies with the isophote ellipticity exceeding 0.5 (disks highly inclined to the line of sight) were not included in the sample due to a large uncertainty in the classification. The S4G includes 2331 galaxies, and according to ARRAKIS, 277 galaxies have an outer ring-shaped feature R or R′ (for 18 of them two outer ring-shaped features in each are noted). After the additional selection by the morphological type (202 galaxies have the S0–Sb morphological types) and ellipticity (less than 0.5), 145 galaxies were left in our sample.

Notice that Kostyuk [23] previously listed 143 ring-shaped galaxies visually selected from the photographic copies of the Palomar Observatory Sky Survey (POSS) maps of the northern sky. If we introduce additional restrictions on size, larger than 1$'$.0, and galactic latitude, $|b| > 30°$, we are left with 51 galaxies. And only 18 galaxies from the list of [23] have radial velocities lower than 3000 km s^{-1}, 11 of which are included in ARRAKIS. We believe that the visual selection concedes to the pipeline reduction, however, the above list includes very interesting galaxies not listed in ARRAKIS, a detailed study of which is planned for the future.

3. CURRENT STAR FORMATION IN THE OUTER RINGS

All the 145 galaxies of the sample have been viewed in the image archive of the GALEX space telescope [1] in the near-UV band (NUV) at 1770–2730 Å on the intensity maps. Relatively massive stars with ages of up to 200 Myr contribute only to the near-UV range [24, 25]. The data for nine galaxies from the list are missing in the GALEX survey. For 16 galaxies the GALEX images clearly reveal a spiral structure outside the outer ring. Bright objects are located next to two galaxies that make it impossible to identify the ring feature. These 18 galaxies were hence excluded from our sample.

In total, the list for studying the UV morphology of the outer rings in the early-type disk galaxies stopped at 118 galaxies. Figure 1 shows the distribution of these ring-shaped galaxies by the values of ellipticity of the external isophotes according to the S4G survey data.[2] This distribution is fairly uniform, and we can deem that there is no selection by the inclination of the galaxy (after excluding the disks inclined at an angle of more than 60°). The fractions of various morphological types among the ring and pseudoring galaxies differ (Fig. 2). Among the galaxies with pseudorings, R′, there are no galaxies of the S0 morphological type. The R galaxies with closed rings, on the contrary, are dominated by the S0 type, and the proportion of the morphological type Sab–Sb is several times smaller than that in the galaxies with pseudorings R′.

We quantitatively estimated the presence or absence of the UV flux in the outer ring of galaxies based on the signal/noise ratio in the image accumulated by the GALEX telescope. An ellipse with major and minor axes D_r and d_r was plotted on the UV image of each galaxy (according to ARRAKIS). They were obtained during the compilation of the ARRAKIS catalog from ellipsoidal approximation of the points belonging to the ring-shaped feature, manually marked on the residual image of the disk. The

[1] http://galex.stsci.edu/GR6/

[2] http://irsa.ipac.caltech.edu/data/SPITZER/S4G/

Table 1. A list of early-type disk galaxies with the outer ring-shaped structures (ARRAKIS)

Galaxy	Type (ARRAKIS)	Ring size (ARRAKIS), arcmin	Disk size (RC3), arcmin	Ring type (ARRAKIS)	Is UV present?	k	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 210	SABab	4.08×2.90	5.01×3.31	$R_2'L$	+	8	2
NGC 254	SAB0	1.59×1.25	2.46×1.52	R	−	−	−
NGC 474	SAB0/a	2.23×2.07	7.08×6.30	R'	−	−	−
NGC 615	SABa	2.26×0.70	3.63×1.45	R_2'	+	4	2
NGC 691	SAab	2.74×1.93	3.47×2.63	R	+	3	2
NGC 718	SABa	1.42×1.09	2.34×2.04	R'	−	−	−
NGC 986	SBab	3.52×2.59	3.89×2.96	R'	+	10	1
NGC 1022	SAB0/a	2.08×1.66	2.40×1.99	RL	−	−	−
NGC 1068	SAa	5.81×4.89	7.08×6.02	R	+	2	2
NGC 1258	SABa:	0.78×0.35	1.35×0.93	R'	+	20	2
NGC 1291	SAB0	8.47×7.08	9.77×8.11	R	+	5	2
NGC 1300	SBb	5.63×4.90	6.17×4.07	R'	+	8	2
NGC 1326	SAB0	2.83×1.87	3.89×2.88	R_1	+	5	2
ESO 548-23	SA0	0.66×0.35	1.05×0.47	RL	+	3	3
NGC 1350	SAB0/a	5.35×2.60	5.25×2.83	R	+	7	2
NGC 1357	SA0/a	2.74×2.20	2.81×1.95	$R'L$	−	−	−
NGC 1398	SBa	4.64×3.17	7.08×5.38	R	+	9	2
NGC 1433	SBa	6.26×4.48	6.46×5.88	R_1'	+	3	1, 2
NGC 1436	SABab	1.59×0.99	2.95×2.01	R'	+	16	2
NGC 1452	SB0/a	2.54×1.43	2.24×1.48	RL	−	−	−
IC 1993	SABab	1.47×1.44	2.46×2.14	R'	+	14	2
NGC 1533	SB0	1.66×1.43	2.76×2.34	RL	+	3	3
NGC 1566	SABb	7.55×6.34	8.32×6.57	R_1'	+	6	2
NGC 1640	SBa	1.74×1.55	2.63×2.05	R'	+	6	2
NGC 1808	SABa	6.38×4.62	6.46×3.87	R_1	+	3	1, 2
NGC 2681	SAB0/a	2.35×2.13	3.63×3.30	R	+	3	3
NGC 2685	S0	4.08×1.80	4.47×2.37	R	−	−	−
NGC 2712	SABab	2.73×1.16	2.88×1.59	R'	+	3	2
NGC 2780	SBa	0.67×0.49	0.89×0.66	R'	+	8	3
NGC 2859	SAB0	3.42×2.73	4.26×3.80	R	+	2	−

Table 1. (Contd.)

Galaxy	Type (ARRAKIS)	Ring size (ARRAKIS), arcmin	Disk size (RC3), arcmin	Ring type (ARRAKIS)	Is UV present?	k	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 2893	SAB0	0.87×0.69	1.12×1.02	RL	+	5	1, 2
NGC 2962	SAB0	2.13×1.42	2.63×1.95	R	+	4	2
NGC 3166	SB0	4.11×1.73	4.79×2.35	RL	+	2	3
NGC 3185	SABa	2.51×1.65	2.35×1.59	RL	–	–	–
NGC 3248	SA0	1.77×1.10	2.51×1.56	RL	–	–	–
NGC 3266	SB0	0.79×0.60	1.55×1.32	RL	–	–	–
NGC 3368	SAB0	5.94×3.57	7.58×5.23	RL	+	4	2
NGC 3380	SAB0/a	1.35×1.29	1.70×1.34	RL	+	2	1
NGC 3489	SB0	1.53×0.45	3.55×2.02	R	+	8	2
NGC 3504	SABa	2.03×1.89	2.69×2.10	R'_1	+	6	2
NGC 3507	SABb	2.34×2.11	3.39×2.88	R'	+	8	2
NGC 3583	SABab	1.96×1.04	2.81×1.83	R'	+	13	2
NGC 3637	SB0	1.44×1.12	1.59×1.55	RL	–	–	–
NGC 3675	SAb	2.42×0.89	5.89×3.12	R'	+	10	2
IC 2764	SA0	0.84×0.70	1.62×1.41	R	+	6	2
NGC 3687	SABab	1.43×1.34	1.91×1.91	RL	+	6	2
NGC 3786	SA0/a	1.77×0.79	2.19×1.29	R	–	–	–
NGC 3892	SAB0	2.55×2.20	2.95×2.24	RL	–	–	–
NGC 3941	SB0	1.78×0.94	3.47×2.29	R	+	3	3
NGC 4045	SABab	1.91×0.95	2.69×1.86	R'_1L	+	4	2
NGC 4050	SABa	3.36×2.01	3.09×2.10	RL	–	–	–
NGC 4102	SABab	1.24×0.67	3.02×1.72	R'	+	20	2
IC 3102	SAB0/a	2.76×1.45	2.57×1.36	$R'L$	–	–	–
NGC 4245	SB0	2.65×1.89	2.88×2.19	RL	–	–	–
NGC 4286	SA0	0.78×0.55	1.59×1.00	RL	+	4	3
NGC 4314	SBa	3.72×3.03	4.17×3.71	R'_1	–	–	–
NGC 4355	SAB0/a	0.97×0.49	1.45×0.71	$R'L$	+	2	3
NGC 4369	SB0/a	1.42×1.30	2.09×2.05	R	+	2	3
NGC 4378	SAa	2.93×2.45	2.88×2.68	R'	+	3	2, 3
NGC 4380	SAab	2.02×1.07	3.47×1.91	R	+	7	2, 3

Table 1. (Contd.)

Galaxy	Type (ARRAKIS)	Ring size (ARRAKIS), arcmin	Disk size (RC3), arcmin	Ring type (ARRAKIS)	Is UV present?	k	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 4394	SB0/a	2.74×2.45	3.63×3.23	R	+	9	2
NGC 4405	SABa	1.05×0.66	1.78×1.16	R	+	3	3
NGC 4407	SBab	2.81×1.52	2.35×1.52	R′L	–	–	–
NGC 4424	SB0/a	3.18×1.53	3.63×1.82	R'_2L	–	–	–
NGC 4450	SABa	3.43×2.20	5.25×3.88	R′	+	3	2
NGC 4454	SAB0/a	2.00×1.83	2.00×1.70	RL	–	–	–
NGC 4457	SAB0	4.04×3.76	2.69×2.29	R	–	–	–
NGC 4579	SBa	4.33×3.10	5.89×4.65	RL	–	–	–
NGC 4580	SAa	1.86×1.26	2.09×1.63	R′	–	–	–
NGC 4593	SBa	3.54×2.51	3.89×2.88	R′	+	4	2
NGC 4596	SB0/a	3.40×2.66	3.98×2.95	RL	–	–	–
NGC 4639	SBab	2.36×1.38	2.76×1.87	R′	+	7	2
NGC 4659	SAB0	1.04×0.64	1.74×1.25	R	+	2	3
NGC 4691	S0/a	2.79×2.15	2.81×2.28	R′L	–	–	–
NGC 4698	SA0/a	7.91×2.73	3.98×2.47	R	+	2	–
NGC 4699	SB0/a	1.95×1.48	3.80×2.62	R′	+	7	2
NGC 4736	SABa	10.58×8.68	11.22×9.09	R	+	2	–
NGC 4750	SAa	1.52×1.33	2.04×1.86	R′	+	18	2
NGC 4772	SA0/a	3.85×1.93	3.38×1.69	R′	–	–	–
NGC 4795	SBa	1.38×1.13	1.86×1.58	R′	–	–	–
NGC 4800	SAa	1.22×0.97	1.58×1.17	R′	+	8	3
NGC 4826	SAa	7.17×3.10	10.00×5.40	R′	+	2	3
NGC 4856	SB0	2.44×0.65	4.26×1.19	RL	–	–	–
NGC 4880	SAB0	2.05×1.48	3.16×2.47	RL	–	–	–
NGC 4941	SA0/a	3.33×2.36	3.63×1.96	RL	+	2	1, 2
NGC 4984	SAB0/a	5.07×2.82	2.76×2.18	R′	–	–	–
IC 863	SBb	0.51×0.30	1.82×1.20	R′	+	4	3
IC 4214	SAB0/a	2.03×1.25	2.24×1.28	R_1	+	3	2
NGC 5101	SB0/a	5.31×4.61	5.37×4.56	R'_2	+	2	2
NGC 5134	SAB0/a	3.53×2.99	2.76×1.65	R	–	–	–

Table 1. (Contd.)

Galaxy	Type (ARRAKIS)	Ring size (ARRAKIS), arcmin	Disk size (RC3), arcmin	Ring type (ARRAKIS)	Is UV present?	k	Notes
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
NGC 5375	SBa	2.24 × 1.82	3.24 × 2.75	R′	+	4	2
NGC 5377	SAB0/a	4.05 × 2.03	3.72 × 2.08	R_1	+	2	2
NGC 5534	SBa	1.21 × 0.83	1.41 × 0.83	R′L	+	6	2
NGC 5602	SA0	1.05 × 0.54	1.45 × 0.77	RL	−	−	−
NGC 5678	SAb	2.31 × 1.17	3.31 × 1.62	R′	+	6	2
NGC 5701	SB0/a	3.21 × 2.72	4.27 × 4.05	R'_1	+	9	2
NGC 5713	SBab:	1.67 × 1.48	2.76 × 2.45	R′	+	2	3
NGC 5728	SB0/a	3.61 × 2.34	3.09 × 1.76	R_1	−	−	−
NGC 5750	SAB0/a	2.70 × 1.30	3.02 × 1.60	RL	−	−	−
NGC 5757	SBab	1.35 × 1.19	2.00 × 1.62	R'_2	+	3	2
NGC 5806	SABab	2.68 × 1.46	3.09 × 1.58	R′	+	2	2
NGC 5850	SBab	4.00 × 3.31	4.27 × 3.71	R′	+	2	2
NGC 5957	SBa	2.38 × 2.08	2.82 × 2.62	R′	+	3	2
NGC 6012	SBab	2.57 × 2.32	2.09 × 1.50	R′	+	4	2
NGC 6217	SBb	2.72 × 2.46	3.02 × 2.51	R′	+	3	1
NGC 6340	SA0/a	1.80 × 1.52	3.24 × 2.94	R	+	2	−
NGC 7051	SABb	1.12 × 0.97	1.32 × 1.09	R'_2	+	2	1
NGC 7098	SAB0/a	3.63 × 2.26	4.07 × 2.65	R	+	3	2
NGC 7140	SABab	3.72 × 2.60	4.17 × 3.00	R′	+	2	2
NGC 7191	SABb	0.83 × 0.37	1.59 × 0.55	R′	+	8	2
NGC 7219	SABa	1.36 × 0.83	1.74 × 1.04	R'_2	+	10	2
IC 1438	SAB0/a	1.77 × 1.32	2.40 × 2.04	R_1	+	3	2
NGC 7421	SBab	1.68 × 1.54	2.04 × 1.82	R′	+	6	2
IC 5267	SA0/a	4.65 × 3.31	5.25 × 3.88	RL	+	3	2
NGC 7479	SBb	2.77 × 2.13	4.07 × 3.10	R′	+	20	2
NGC 7552	SBa	3.08 × 2.52	3.39 × 2.68	R'_1	+	10	2
NGC 7724	SABa	0.88 × 0.54	1.45 × 1.00	R′	+	5	2
NGC 7731	SABa	1.09 × 0.85	1.41 × 1.12	R'_2	+	2	2

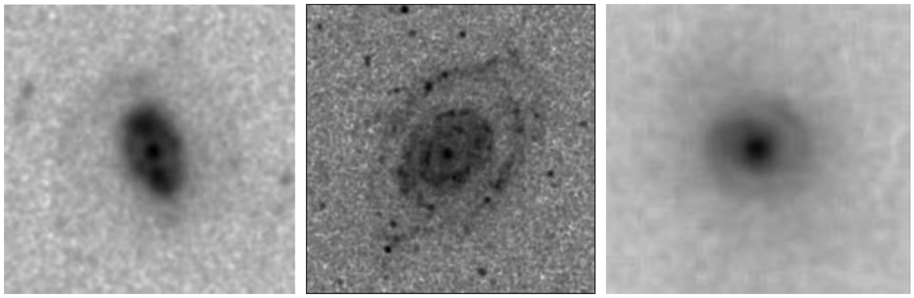

Fig. 3. Examples of the GALEX images, NUV filter, for the galaxies with ring structures R, which correspond to different types marked in the last column of Table 1. The left panel: ring type 1, unclosed (NGC 3380, the field size is $2\overset{\prime}{.}5$); at the center: ring type 2, clumpy (IC 5267, the field size is $8'$); the right panel: ring type 3, a filled disk (NGC 2681, the field size is $2'$).

outer rings are generally faint features of galaxies. The galaxies in which an external, with respect to the ring, continuation of the disk without structure is visible in the UV were not excluded from our sample. To estimate the brightness of the ring in the ultraviolet, the GALEX image of the galaxy was smoothed by the 5–10-pixel window. If the average smoothed count value in the pixel of the ring-shaped feature region exceeded two or more values of the surrounding background, then the galaxy was marked as having UV radiation in its outer ring-shaped feature.

Our estimates of the sky background on the GALEX intensity maps in the vicinity of 117 galaxies of the list give an average value of 0.00274 cts s^{-1} in one pixel, which corresponds to the average surface brightness of $27\overset{m}{.}36/\square''$ in the NUV band in the AB system. The sky background values around different galaxies vary in the range of 0.0020–0.0042 cts s^{-1}, the sample standard deviation is 0.00049 cts s^{-1}. One galaxy (NGC 1068) was not included in the background estimation sample, since only for this galaxy from our list the value of the sky background is 0.0070 cts s^{-1}. For 36 galaxies from the list with faint (at least three values of sky background) ring-shaped features the average background is 0.00278 cts s^{-1} in one pixel at the same range of values and standard deviation, as indicated above for the whole sample. This corresponds to the sky surface brightness in the NUV filter of $27\overset{m}{.}35/\square''$.

The list of 118 galaxies with the outer ring-shaped structures we studied is shown in Table 1. The table lists successively in columns as follows: the name of the galaxy; the galaxy classification from ARRAKIS without details; major and minor axes of the outer ring-shaped structure D_r and d_r in arcminutes (from ARRAKIS); the major $2a$ and minor $2b$ axes of isophotes of the galactic disk at the surface brightness level of $25^{m}/\square''$ in the B-band (from the RC3 catalog [26]); the type of the ring-shaped structure from ARRAKIS; the presence or absence of a ring-shaped UV radiation structure in the NUV band according to the GALEX (marked with "+" or "−" respectively); the k coefficient, an approximate average value of the UV flux in the ring in one pixel in the units of the ambient background according to the GALEX (if $k < 2$, a minus is marked in this column); the notes to the form of the ring-shaped structure in the UV: 1—incomplete, 2—clumpy, 3—a filled disk. Thus, the galaxy without notes and with the "+" sign in column 6 has a rather uniform ring-shaped structure in the UV, visible at all position angles. Figures 3 and 4 show the examples of all the kinds of ring-shaped structures described in the notes of Table 1.

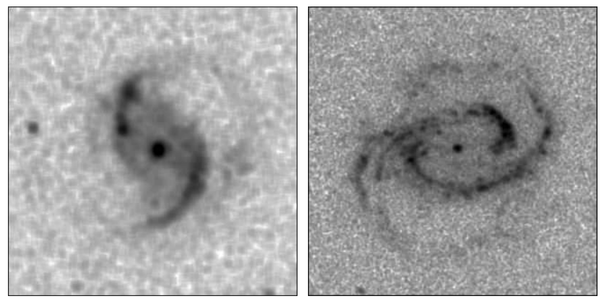

Fig. 4. Examples of the GALEX images, NUV filter, for the galaxies with pseudoring structures R', which correspond to different types marked in the last column of Table 1. The left panel: ring type 1, unclosed (NGC 986, the field size is $5'$); the right panel: ring type 2, clumpy (NGC 1300, the field size is $8'$).

Table 2 summarizes the data on the number of ring-shaped galaxies from the list depending on the morphological type and the presence of UV radiation in the ring. Our list has only 24 galaxies without bars (SA type, marked in the second column of Table 1) and 94 barred galaxies (SB and SAB types). Although according to Table 2 the number of galaxies with bars and rings is four times greater than galaxies with rings but without bars, we conclude that the presence of a bar in the galaxy does not affect how

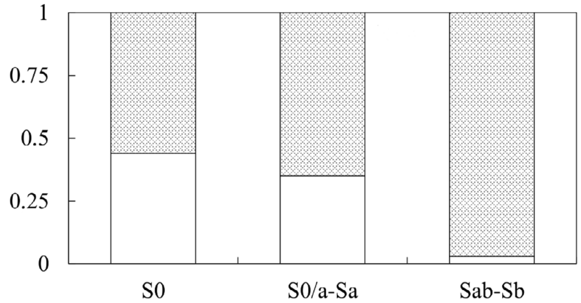

Fig. 5. Proportion of galaxies with ultraviolet radiation in the ring (shaded) for different morphological types of all R+R′ ring-shaped galaxies. The total number of R+R′ galaxies in each morphological type is normalized to unity.

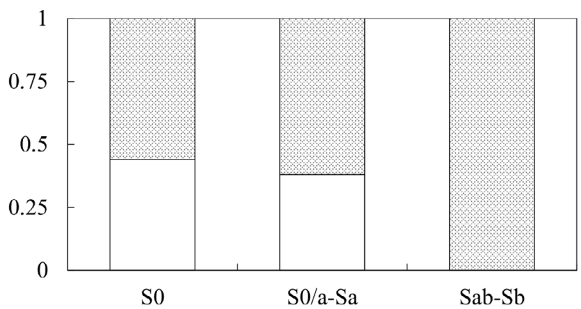

Fig. 6. Proportion of galaxies with ultraviolet radiation in the ring (shaded) for different morphological types among the ring R galaxies. The total number of galaxies in each morphological type is normalized to unity.

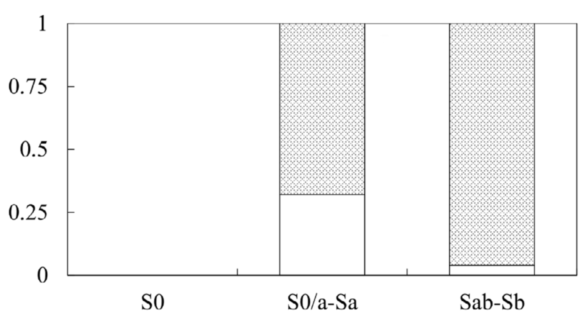

Fig. 7. Proportion of galaxies with ultraviolet radiation in the ring (shaded) for different morphological types among the pseudoring R′ galaxies. The total number of R′ galaxies in each morphological type is normalized to unity. S0 galaxies do not possess pseudorings.

often the UV radiation would be detected in the ring of the galaxy, i.e., how often the current star formation occurs in the rings. In the following discussion, we do not make a division of galaxies with and without a bar.

Figures 5–7 present the histograms at which the proportions of galaxies with UV radiation in the ring (the shaded portion of the column) among all R+R′ ring-shaped galaxies, and also separately for the ring R and pseudoring R′ galaxies among different morphological types. All types of ring-shaped structures are characterized by an increase in this proportion in the transition from the S0 to Sb galaxies. But even at the minimum, for S0 galaxies, it reaches 56%, which is about a half of all rings. Almost all the spiral Sab–Sb galaxies (29 of 30) possess UV radiation in their ring-shaped feature.

The average ratio of the major axis of the ring D_r (the third column of Table 1) according to ARRAKIS to the major axis of the outer isophote of the galactic disk according to the RC3 data (the fourth column of Table 1) is 0.81 with a dispersion of 0.25. Seventy percent of the galaxies of the list fall within the ratio interval of 0.6–1.0. Among the list galaxies with UV radiation in the ring-shaped structure (84 galaxies), type 2, which is a clumpy structure, is the most common (the eighth column of Table 1, 61 galaxies). Interestingly, this is true for all the morphological types of galaxies. The average value of the k coefficient (the seventh column in Table 1) is near 6, and it increases from S0 to Sb. Among the ultraviolet ring types, mentioned in the eighth column of Table 1, clumpy rings, type 2, have an average k coefficient almost two times larger than the other types.

4. DISCUSSION

We have investigated the occurrence frequency of current star formation in the outer rings of early-type disk galaxies on the material of a sufficiently representative sample (more than 100 objects) from the ARRAKIS catalog [3], containing a list of galaxies with *old stellar* rings, selected from the images at 4 μm. It was found that regular stellar rings of the S0 galaxies contain young stars in about half the cases, while the pseudorings of spiral galaxies contain them almost always.

Although lenticular galaxies are considered (by definition of this morphological type) to be devoid of large-scale star formation in the disk, in fact, at a closer look, is not so. In 21% of S0 galaxies the GALEX space telescope observes the presence of an extended signal, which indicates extended regions of current star formation [27]. The morphology of this extended star formation is quite curious. Recently, Salim et al. [27] examined a sample of early-type galaxies with ultraviolet excess at the Hubble Space Telescope and constructed UV images with high spatial resolution. The type of morphology of the UV images got strictly divided: in six ellipticals it proved to be concentrated in a small volume, whereas in 15 of 17 S0 galaxies extended star formation was noticed, and in all 15 cases, the starburst morphology is ring-shaped. The rings may be of different size:

Table 2. Distribution of ring galaxies by the type of the ring-shaped feature (R are rings, R′ are pseudorings) and the galaxy morphological type

Type	All			Among them, those having "+" in the UV column		
	R + R′	R	R′	R + R′	R	R′
S0	25	25	0	14 (56% ± 10%)	14 (56% ± 10%)	0
Among them, SB	19	19	0	11 (58% ± 11%)	11 (58% ± 11%)	0
Among them, SA	6	6	0	3 (50% ± 20%)	3 (50% ± 20%)	0
S0/a-Sa	63	29	34	41 (65% ± 6%)	18 (62% ± 9%)	23 (68% ± 8%)
Among them, SB	49	23	26	32 (65% ± 7%)	13 (56% ± 10%)	19 (73% ± 9%)
Among them, SA	14	6	8	9 (64% ± 13%)	5 (83% ± 15%)	4 (50% ± 18%)
Sab–Sb	30	3	27	29 (97% ± 3%)	3 (100%)	26 (96% ± 4%)
Among them, SB	26	1	25	25 (96% ± 4%)	1 (100%)	24 (96% ± 4%)
Among them, SA	4	2	2	4 (100%)	2 (100%)	2 (100%)
All	118	57	61	84 (71% ± 4%)	35 (61% ± 6%)	49 (80% ± 5%)
Among them, SB	94	43	51	68 (72% ± 5%)	25 (58% ± 6%)	43 (84% ± 5%)
Among them, SA	24	14	10	16 (67% ± 10%)	10 (71% ± 12%)	6 (60% ± 16%)

for the narrow rings of star formation, the authors of [27] obtained the mean radius of 6.5 kpc, for wide rings—16–20 kpc. There still exists a rare morphological subtype "a disk with a hole," however, these are actually rings with a large outer radius. Among the S0 and Sa early-type disk galaxies, possessing rings of star formation, the sample of [27] proved to have approximately an equal number of galaxies with and without bars (8 and 11 objects respectively), so that the resonance nature of most of these rings is not quite obvious. We have to say that the conclusion about the dominance of the ring morphology in the distribution of star-forming regions in lenticular galaxies has already been proposed earlier. As early as in 1993, Pogge and Eskridge [28] noted that during a deep search for the Hα emission in disks of lenticular galaxies rich in neutral hydrogen, star formation could be detected in half the cases, and it was always organized in rings. It took the authors by surprise that the presence or absence of star formation is not related with the amount of fuel for star formation (the amount of hydrogen), and that it is probably triggered by some (kinematic?) factor quite different from the gravitational instabilities, controlling star formation in thin disks of late-type spiral galaxies. Certain statements on the presence of star formation in the outer rings, which in terms of dynamics of the gas component should in theory be stable against the processes of fragmentation, came from the results of a detailed study of outer rings in disks of early-type spiral galaxies [29]. The most natural additional mechanism triggering star formation in gas with *mean* density under the Kennicutt threshold value [30] would attract shock waves. This leads us to the assumption of the accretion of cold gas from the outside, perhaps from inclined orbits (to provide a compression shock wave in the gas) as the dominant mechanism of formation of regular outer rings of star formation in the disks of early-type galaxies, where the surface density of gas, as known (see, for example [31, 32]) is significantly smaller than that in the late-type galaxies, and is as a rule insufficient to support star formation on its own. At the same time, the distribution of neutral hydrogen in the early-type galaxies (with the presence of neutral hydrogen) is much more extended than that in the spiral galaxies: regular H I structures in S0 can be up to 200 kpc in diameter [33]. Based on multicolor photometry, Afanasiev and Kostyuk [34] have shown that the ring-shaped galaxies from the list of [23] belong to the early morphological types, which resonates with the conclusions of Comerón et al. [3]. However, in [34] it was also noted that the galaxies with rings have more extended stellar disks than the galaxies without rings, and it is a stronger indication of the further construction of the outer parts of disks through stimulated star formation in the outer rings as a result of accretion of the outer cold gas.

It is possible that the outer pseudorings of the early-type spiral galaxies, where star formation is taking part in almost 100% of cases are genetically related to the phenomenon of the so-called XUV disks (eXtended UltraViolet disks [35, 36]), observed in approximately 20–30% of all disk galaxies of the nearby universe. Broken (unclosed) pseudorings may well be spiral density waves with a tight swirl, spreading outward into an extended gas disk from the inner regions of the stellar disk. These are also shock waves capable of stimulating star formation in a gaseous medium of low density [37, 38]. However, the origin of the XUV disks, which are equally often met both in late-type spiral galaxies and in massive galaxies that inhabit the "red sequence" and "green valley" [39], is lately also linked with the acts of recent accretion of cold external gas [36, 40, 41]. Hence, both for the pseudorings, the external scenario of the formation through the accretion of cold gas with a high rotation momentum to the periphery of the disk of the galaxy remains to be the most attractive. Perhaps more preferable for these structures is a slow, smooth accretion close to the galactic disk symmetry plane.

Finally, on the lifetime of rings with star formation. Given the average age of the stellar population of rings, detected in the near UV range of at least 200 Myr and the period of revolution of the external regions of disk galaxies, which is equal to about 800 Myr both in giant and dwarf disk galaxies [42], it is clear that star formation in the rings would not survive even one period. This explains the dominance of clumpy morphology of the rings in our results (Type 2 in the last column of Table 1). Star formation lacks time to spread over the complete azimuthal angle. Judging from the fact that an approximately equal number of regular rings reveals and does not reveal the signal in the near UV, the characteristic time of star formation in the rings is at least 200 Myr. This is consistent with the idea of very effective star formation in the ring structures. For example, for star formation in the circumnuclear rings, Kormendy and Kennicutt [43] also give the characteristic time scale of a few hundred millions of years and point out that it is much shorter than the typical time scale of star formation in the disks of spiral galaxies (in the spiral arms).

ACKNOWLEDGMENTS

We have made use of the data from the NASA/IPAC Extragalactic Database (NED) and the Spitzer Space Telescope which are operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA. Some data (NASA GALEX mission) were obtained from the Mikulski Archive for Space Telescopes (MAST), which is supported by the NASA Office of Space Science via grant NNX09AF08G and by other grants and contracts. This study has been performed at the expense of the Russian Science Foundation (project No. 14-22-00041).

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Translated by A. Zyazeva