Lenticular Galaxies with Ultraviolet Rings

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Abstract—Based on GALEX (Galaxy Ultraviolet Explorer) data, we have compiled a list of lenticular galaxies with ultraviolet rings—radially localized star-forming regions. We have analyzed the optical structure of these galaxies using SDSS (Sloan Digital Sky Survey) surface photometry, measured the colors of the rings, and compared the radial localizations of the ring structures in the optical and ultraviolet spectral ranges. Possible scenarios for the formation of ring star-forming regions in lenticular galaxies having no other structural peculiarities and exhibiting a homogeneous old stellar population outside the rings are discussed.

INTRODUCTION

According to Hubble's classification criteria, lenticular galaxies—an intermediate morphological type between elliptical and spiral ones—possess large-scale stellar disks but do not contain any noticeable star-forming regions. These criteria were formulated based on a set of optical galaxy images. However, a recent ultraviolet survey of the morphology of nearby galaxies with the GALEX space telescope (Gil de Paz et al. 2007) has shown that star formation in lenticular galaxies can be detected more often than was assumed previously and a large-scale ring is a typical distribution pattern of star-forming regions.
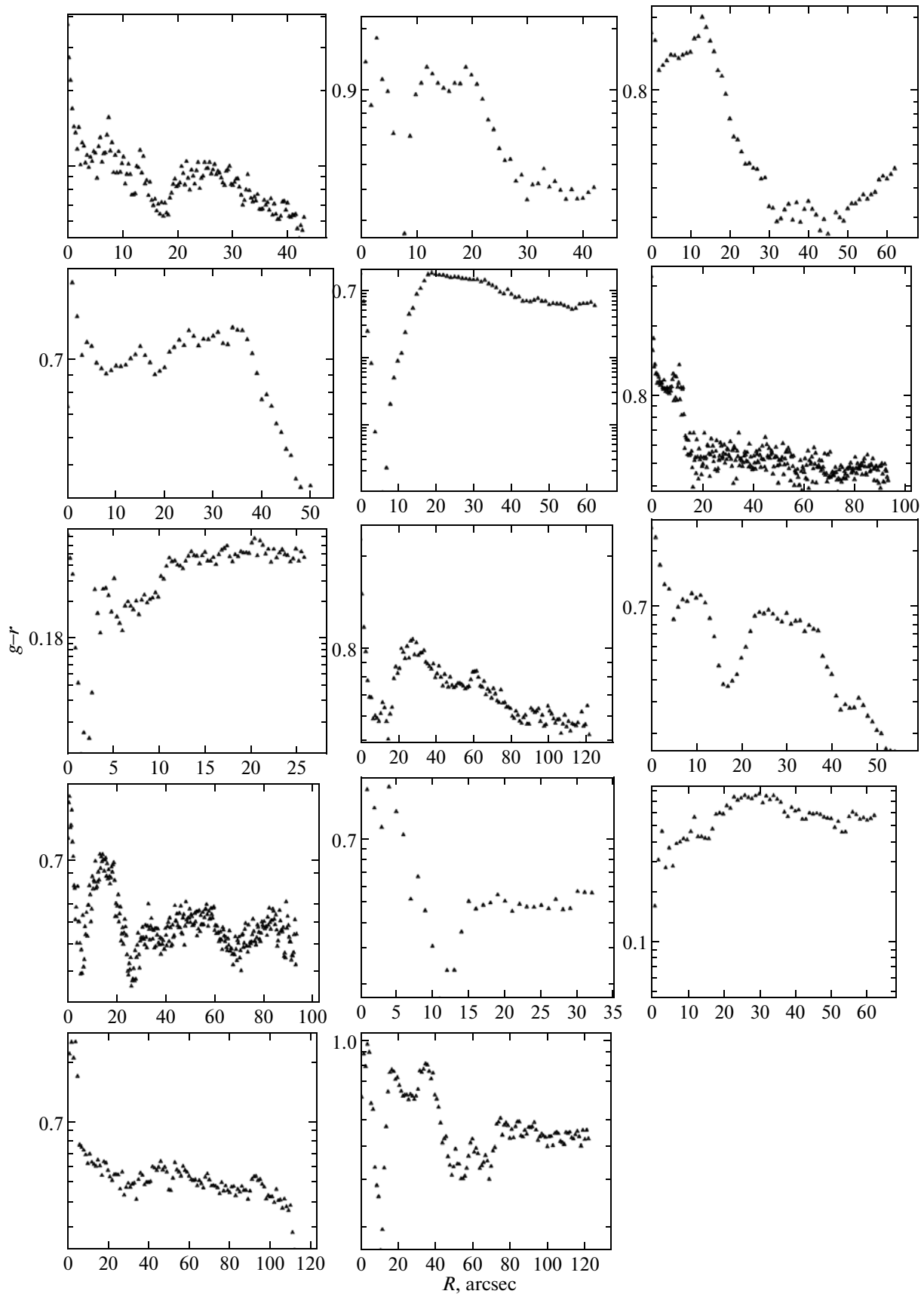
Rings in galaxies are a well-known morphological structure; the classification of rings that was associated with different origins of ring structures has been established long ago. For example, Few and Madore (1986) analyzed a sample of 69 ring galaxies and identified two types: O rings and P rings. The first category includes smooth regular rings with the galactic nucleus at the geometric center; the second category includes rings with a nonuniform surface brightness often with the galactic nucleus shifted relative to the ring center. The counts of satellites—fainter galaxies—around ring galaxies showed that the P category most likely includes collisional rings, because a small neighboring galaxy that probably produced this ring while passing through the disk of a large neighbor could always be detected nearby. The O rings are not always related to interaction and can

be resonant structures in the disks. Schwarz (1984) considered the response of a gaseous disk to the central bar (a nonaxisymmetric potential) in a galaxy and showed that the gas would be gathered into a ring at the outer Lindblad resonance in the course of internal dynamical disk evolution; obviously, gas compression at a certain radius can lead to a ring starburst. Buta and Crocker (1993) investigated the observational statistics of the metric sizes of rings in a sample of several hundred galaxies and confirmed that the rings are genetically related to the bars and their resonances. However, regular rings of star formation are occasionally also encountered in galaxies without bars; each such case requires an individual consideration and, as a rule, ends with the conclusion about minor merging as the cause of the appearance of a ring (Sil'chenko and Moiseev 2006).

After the GALEX survey of the morphology of nearby galaxies in the ultraviolet spectral range, researchers noticed ultraviolet outer rings in some regular lenticular galaxies that are in no way remarkable in the optical band. Marino et al. (2011), Donovan et al. (2009), Bettoni et al. (2010), Thilker et al. (2010), and Serra et al. (2006) published their studies of individual S0 galaxies with resonant and collisional outer rings of star formation (NGC 2962, ESO 381-47, NGC 4262, NGC 404, and IC 4200, respectively), discussing the problem of the origin of these rings in various ways. It seems likely that the appearance of the outer rings of star formation in lenticular galaxies that otherwise are devoid of a considerable amount of gas and young stars is related to the formation event of a lenticular galaxy from a spiral one itself. In this paper, we present the first sample of S0 galaxies with

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The $g - r$ color profiles for the residual galaxy images after the subtraction of the model sum of large-scale disks and bulges from the original SDSS images. The first row: IC 522, MCG 11-22-15, NGC 252; the second row: NGC 446, NGC 809, NGC 934; the third row: NGC 4344, NGC 4513, NGC 6028; the fourth row: NGC 6340, NGC 6534, NGC 7808; the fifth row: UGC 4599, UGC 5936.

Table 1. Global parameters of the program galaxies

Name	Type, NED[1]	V_r, km s^{-1}, NED	D^2, Mpc, NED	R_{25}, arcsec, RC3[3]	m_B, RC3	M_B, LEDA[5]	$g - r$, NED	H I?, NED	Environment, NED
IC 522	S0	5079	71	30	13.97	−20.8	0.84	−	Single + satellite
MCG 11-22-15	−	8064	114	24[5]	15.6[5]	−19.9	−	−	Group member
NGC 252	(R)SA0$^+$(r)	4938	71	45	13.35	−21.3	0.97[6]	+	Group center
NGC 446	(R)SAB0^0	5446	76.5	61	13.35	−21.0	−	+	Pair member
NGC 809	(R)S0$^+$:	5367	74	44	14.66[4]	−19.9	0.78	−	Single + 3 satellites
NGC 934	SAB0$^-$	6353	88	40	14.04	−20.7	0.81	−	Group member
NGC 4344	SB0:	1142	14.5	50	13.34	−18.2	0.58	+	Cluster member
NGC 4513	(R)SA0^0	2304	34	43	14.01	−19.0	0.77	+	Wide pair
NGC 6028	(R)SA0$^+$:	4475	62.5	40	14.35	−20.0	0.89	+	Group center
NGC 6340	SA0/a(s)	1198	20	97	11.87	−20.0	0.82	+	Group center
NGC 6534	S?	8332	117.5	25	15.40	−20.1	−	−	Single
NGC 7808	(R')SA0^0:	8787	122	38	13.48	−21.3	0.78	−	Pair + 5 satellites
UGC 4599	(R)SA0^0	2072	26	60	13.6	−17.5	0.74	+	Group center
UGC 5936	(R)SA0$^+$:	7230	99	39	14.21	−21.0	0.76	−	Triplet center

[1] NASA/IPAC Extragalactic Database.

[2] The distance from NED referred to the center of the Local Group of galaxies.

[3] Third Reference Catalogue of Bright Galaxies, de Vaucouleurs et al. (1991).

[4] Lyon-Meudon Extragalactic Database.

[5] The blue magnitude b_j from the APM survey, Maddox et al. (1990).

[6] The $B - V$ color is given instead of $g - r$ absent NED so far.

ultraviolet rings suitable for a statistical analysis and discuss specific possibilities for the formation of such rings in minor merging events. To tune out the obviously resonant rings that can also be formed without any interaction with another galaxy, we restrict our sample to galaxies without global bars.

COMPILING THE SAMPLE

For our work, we produced a sample of lenticular galaxies without bars whose far- and near-ultraviolet images were primarily presented in the atlas by Gil de Paz et al. (2007) and showed a ring morphology there. In our list, we included only the galaxies for which SDSS (Sloan Digital Sky Survey) data were also available to be able to compare the galaxy morphologies in the ultraviolet and optical spectral ranges. We then analyzed the list of galaxies with an outer ring structure (Kostyuk 1975) compiled by examining the Palomar Atlas and retrieved more

recent, as yet unpublished images from the GALEX site for lenticular galaxies without bars from this list; several bright ultraviolet ring structures were also found among them.

For each galaxy from our list, we searched for the images in the $g(4686$ Å$)$ and $r(6165$ Å$)$ optical filters among the SDSS data available in the well-reduced DR7 release (Abazajian et al. 2009) and in the quite fresh DR8 release opened for public access only in January 2011 for reduction with the goal of finding optical rings and for comparison of the properties of the optical (where they were found) and ultraviolet rings.

As a result of these searches, we selected 14 galaxies whose global properties that we found in extragalactic databases are presented in Table 1.

PHOTOMETRY OF OPTICAL IMAGES

For our purposes, it was necessary to execute several operations on the images: to construct the color

Table 2. Parameters of the photometric components of the galaxies

Name	Filter	Outer disk		Inner disk		Bulge		
		r_0, arcsec	μ_0, mag arcsec^{-2}	r_0, arcsec	μ_0, mag arcsec^{-2}	r_0, arcsec	μ_0, mag arcsec^{-2}	n
IC 522	r	27.8	23.4	5.9	19.3	2.37	12.7	1.0
IC 522	g	22.3	23.6	5.8	20.1	2.26	13.5	1.0
MCG 11-22-15	r	10.7	26	5.2	23.2	1.51	15.5	1.9
MCG 11-22-15	g	11.0	25.5	4.9	24.3	1.54	16.4	1.9
NGC 252	r	73	24.5	14.9	20.5	3.73	17.4	1.5
NGC 252	g	58	24.7	12.1	21.2	4.13	18.9	1.6
NGC 446	r	23.9	24.9	11.5	22.7	3.32	14.5	1.8
NGC 446	g	23.3	25.4	12.1	23.3	2.9	15.5	1.8
NGC 809	r	18.0	23.8	10.2	19.5	1.4	17.2	1.2
NGC 809	g	20.3	23.1	10.3	20.5	2.33	15.8	1.4
NGC 934	r	35	23.0	7.3	20.7	2.24	15.3	2.1
NGC 934	g	42.6	24.3	7.0	21.4	2.01	16.6	1.8
NGC 4344	r	47.1	22.9	10.3	19.8	−	−	−
NGC 4344	g	62.5	24.4	10.7	20.2	−	−	−
NGC 4513	r	79.3	23.7	8.9	21.3	1.97	15.8	1.5
NGC 4513	g	63	24	10.1	22.3	2.15	16.5	1.6
NGC 6028	r	25	21.8	10.0	19.5	1.77	14.3	2.2
NGC 6028	g	25	22.4	12.4	21.8	1.66	15.1	2.2
NGC 6340	r	50.4	22.2	20.3	20.0	5.17	15.1	1.9
NGC 6340	g	73.3	22.9	22.1	20.8	5.23	15.3	2.0
NGC 6534	r	15.7	21.3	7.6	20.2	1.95	17.2	1.8
NGC 6534	g	14.2	22.9	6.9	20.7	2.31	18.2	1.8
NGC 7808	r	46	24.3	7.6	20.2	2.66	16.2	1.7
NGC 7808	g	63	24.9	8.6	21.3	2.93	17.3	1.7
UGC 4599	r	56.4	23.8	5.5	19.9	2.24	16.5	2.1
UGC 4599	g	50.1	24.3	5.1	20.3	1.59	17.2	2.1
UGC 5936	r	21.4	24	7.7	21.9	1.82	16.1	1.5
UGC 5936	g	23.4	24.8	7.3	22.6	1.82	16.9	1.5

maps of the original images; to decompose the galaxies into structural large-scale elements (disks and bulges); and to construct the color maps of the residuals after the subtraction of the "bulge plus disk(s)" model image obtained in the decomposition from the complete observed galaxy image.

For the first and last operations, we used the software package by Vlasyuk (1993). The photometric calibration data were taken from the SDSS site.

We decomposed each galaxy into its structural elements and then obtained the color profiles of the residuals (see the figure) by means of the GIDRA software package (Moiseev et al. 2004). To describe the derived surface-brightness profiles, we used a model consisting of two exponential disks and a Sérsic bulge. The photometric profiles of all objects, except NGC 4344, agreed satisfactorily with the model for the decomposition in both filters. In contrast, a model consisting of only two exponents was sufficient to describe the surface-brightness profile of NGC 4344; taking into account the structural parameters of the inner component, we interpreted this as the probable absence of a bulge in the galaxy. The decomposition results—the central surface brightnesses and characteristics scales of the component profiles—are collected in Table 2.

RESULTS: RING PARAMETERS

Our reduction revealed the following common properties of the objects being studied:

Table 3. Parameters of the rings in the optical and ultraviolet ranges

Galaxy name	Optical size, arcsec	Ultraviolet size, arcsec	$g-r$
IC 522	11−24	13−26	0.56
MCG 11−22−15	10−22	14−21	0.90 (at the middle) 1.00 (at the edges)
NGC 252	21−30	22−34	0.30
NGC 446	25−42	25−42	0.84
NGC 809	16−34	7−32	1.15
NGC 934	about 57−80	50−88	0.37
NGC 4344	3−12	2.2−11.5	0.35
NGC 4513	about 60−80	69−83	0.70
NGC 6028	23−40	19−39	0.60
NGC 6340	47−64; 25−35; 4−20	up to 66	0.69; 0.41; 0.46
NGC 6534	10−21	11−22	0.30
NGC 7808	18−34	23−36	0.65
UGC 4599	39−60	41−58	0.40
UGC 5936	14−38	18−33	0.64 (at the middle) 0.83 (at the edges)

- the rings of all galaxies, except NGC 809 with a red ring, are most likely blue in the optical spectral range;

- a close coincidence of the optical and ultraviolet ring sizes and positions is observed.

Basic parameters of the rings are presented in Table 3. The ring colors in Table 3 were measured at the central radius for each ring (apart from the central colors, the colors closer to the ring edges are given for UGC 5936 and MCG 11-22-15, because the color at the central radius is appreciably bluer than that of the ring as a whole).

Let us consider the peculiarities of each object being studied in more detail.

IC 522. After the subtraction of the standard model consisting of two disks and a Sérsic bulge, we established the presence of yet another structural element at the galactic center; judging by its red color, it can be interpreted as a circular, most likely de Vaucouleurs bulge. In contrast, the ring is asymmetric both in the ultraviolet and in the optical band. It can also be noted that the galaxy is virtually isolated: NED points out only one faint small object near it.

MCG 11-22-15. This galaxy would be very similar to UGC 5936 in its structural composition (the decomposition of its optical images revealed a fairly regular ring and a circumnuclear bar) were it not

for the fact that the ring has a narrowing in the northwestern region. It is difficult to say whether the ultraviolet ring has the same narrowing, because the object is small (the GALEX spatial resolution is not high enough). The relative redness of the optical ring is also worth noting.

NGC 252. The main difference between the ring of this galaxy and the remaining rings in the sample is that its ring is tilted to the galactic plane. It is worth noting that a spiral pattern is noticeable in the circumnuclear region, suggesting the presence of a circumnuclear disk in the galaxy. The ring appears very blue on the $g-r$ color map.

NGC 446. The ring of this galaxy may be called rather red in the optical band. The galaxy is rich in diffuse matter, as is clearly seen in both optical and ultraviolet images. A structure in the circumnuclear region that can be identified as a circumnuclear disk with a spiral pattern is noticeable in the residual from the decomposition.

NGC 809. The residual from the subtraction of the galaxy's large-scale components contains quite a few interesting features: apart from the red, to all appearances, very dusty ring mentioned above, a bar with an undeveloped spiral pattern was found in the circumnuclear region. The galaxy has ultraviolet and optical rings comparable in brightness.

NGC 934. While the galaxy possesses a bright, though asymmetric, ultraviolet ring, its optical ring is

virtually indistinguishable above the noise level. On the other hand, a circumnuclear disk is excellently seen in both optical and ultraviolet ranges. The galaxy is in a group with a large number of members.

NGC 4344. As its surface-brightness profile showed, this galaxy is devoid of a bulge, which is atypical of lenticular galaxies. Its ring is nonuniform in brightness and consists of individual blue knots, as observed in both optical and ultraviolet ranges. The residual after the decomposition is asymmetric: its southeastern part is appreciably richer in matter than its northwestern part. The galaxy is in the Virgo cluster.

NGC 4513. The decomposition results showed that the ring of this galaxy is similar in nature to the ring in NGC 934: bright in the ultraviolet but faint in the optical range. Interestingly, one more ring with a smaller radius than that observed in the GALEX image can be distinguished on the $g - r$ color map. We did not distinguish it in the ultraviolet, because it sits inside a bright circumnuclear disk.

NGC 6028. The ring in this galaxy has a "tail" noticeable in the southeastern part of the image. The decomposition revealed a circumnuclear bar. Judging by the optical color map, the object located slightly southward of the galactic nucleus may be considered a star.

NGC 6340. This galaxy has already been studied extensively (in particular, by Sil'chenko (2000) and Chilingarian et al. (2009)). For our part, we can add that it possesses several (three) asymmetric rings brighter in the optical band than in the ultraviolet. The galaxy is at the center of a fairly large group.

NGC 6534. This object possesses two rings: the outer, blue one clearly distinguishable in the ultraviolet and the inner, redder one located in the galactic bulge region. It is difficult to say anything about the ultraviolet counterpart of the smaller ring, because its size is small. The rings apparently have different inclinations to the galactic plane.

NGC 7808. When considering the residual from the decomposition, we revealed a nuclear bar in the galaxy and a codirectional structure, most likely a circumnuclear disk. The ring, which is also clearly seen after the decomposition and the construction of the residual color map, is asymmetric and insufficiently bright in both optical and ultraviolet ranges. The galaxy belongs to a small group of only two objects comparable in brightness surrounded by smaller satellites.

UGC 4599. The rings of this object (again, just as in NGC 4513, the inner ring visible in the optical band is only part of the circumnuclear disk in the ultraviolet) have an irregular structure and consist of several arcs. After the subtraction of the standard model of two exponential disks and a Sérsic bulge, the residual from the optical-image decomposition reveals a circular, red, small ($2''$) apparently de Vaucouleurs bulge.

UGC 5936. It has one of the most regular rings in the entire sample that outwardly resembles the ring of NGC 809. A circumnuclear bar can also be distinguished in the residual. The object in the southwestern part of the ring most likely does not belong to the galaxy.

DISCUSSION OF RING FORMATION AND EVOLUTION SCENARIOS

All galaxies of our sample are lenticular ones, i.e., first, disk galaxies having large-scale stellar disks and Sérsic bulges with an index n of about 2 typical of early-type disk galaxies (see the last column in Table 2) and, second, galaxies with an old stellar population belonging to the so-called "red sequence," except NGC 4344 (see the column with the integrated $g - r$ color in Table 1). The first circumstance allows us to delimit our galaxies and Hoag's object having a de Vaucouleurs spheroid (probably an elliptical galaxy) at the ring center; we emphasize that, in our view, Wakamatsu (1990) who investigated NGC 6028 and Finkelman and Brosch (2011) who investigated UGC 4599 call them "Hoag-type galaxies" wrongfully. The galaxies of our sample fill the full spectrum of environment types: they are encountered both in the field and in groups; among them, there are a pair of completely isolated galaxies and one member of the Virgo cluster. One half of the sample galaxies have observationally detected neutral hydrogen (Table 1); in principle, this is consistent with the detection frequency of neutral hydrogen in lenticular galaxies (Eder et al. 1991). However, a careful examination of the data in Table 1 reveals that neutral hydrogen was detected in the half of the sample galaxies that are closer to us, so that the nondetection of H I in the other half of the sample can be an observational selection effect.

Our sample includes only galaxies without global bars (see the morphological types in Table 1; NED gives SB0 for NGC 4344, although a visual inspection of the SDSS images does not reveal any bar in this case either). This implies that we tried to exclude the resonant formation mechanism of the observed rings in all sample galaxies. In contrast, as we noted previously (Ilyina and Sil'chenko 2011), the existing circumnuclear bars are unable to introduce perturbations into the outer structure of the galaxies sufficient for the formation of rings. We conclude that the interaction of galaxies is most likely responsible for the emergence of outer rings of star formation in the sample galaxies. In NGC 7808,

NGC 6340, IC 522, UGC 4599, and NGC 6028, we most likely observe the disruption of the galaxy's satellites by its tidal forces (Helmi et al. 2003). This is suggested by the appearance of the rings: nonuniform in brightness and "wound into a spiral." The rings in NGC 809, NGC 934, NGC 4344, NGC 4513, UGC 5936, MCG 11-22-15, NGC 6534, and NGC 446 were most likely formed due to the passage of satellites through their nuclei (just as in the case of Cartwheel) with small (NGC 809, NGC 934, NGC 4513, UGC 5936, and NGC 446) and slightly larger (NGC 4344 and MCG 11-22-15) impact parameters. This produced a ring density wave (well described, e.g., by Athanassoula and Bosma (1985) and numerically simulated by Mapelli et al. (2008)) that provoked star formation in the ring in the presence of an appreciable amount of gas in the galaxy.

Let us consider several cases in more detail.

As has been noted above, NGC 934 and NGC 4513 have a faint optical ring in the presence of a bright ultraviolet one. This feature should be attributed to the so-called Type 1 XUV disks (Thilker et al. 2007); it can be assumed that here we observe one of the stages (the earliest one?) of collisional-ring evolution.

The ring of NGC 4344 is separated into individual knots; following Athanassoula and Bosma (1985), it can be attributed to the RE type and the cause of such fragmentation is believed to be the absence of a large central stabilizing mass.

Secular evolution effects may probably be considered to be responsible for the formation of two optically observed rings, while only one ring is noticeable in the ultraviolet (NGC 4513 and UGC 4599). The fact (revealed when we compiled our sample) that the presence of a ring in the optical band and a disk at its location in the ultraviolet is a fairly common phenomenon is worth noting.

The existence of a bluer midline of the rings in UGC 5936 and MCG 11-22-15 than the main color of the ring can most likely be also attributed to the action of secular evolution.

In contrast, judging by its inhomogeneity and asymmetry in the optical band, the tilted ring in NGC 252 was formed through the accretion of a companion galaxy from an inclined orbit onto this galaxy (Athanassoula and Bosma 1985).

CONCLUSIONS

Based on GALEX data, we compiled and photometrically studied a sample of 14 lenticular galaxies with ultraviolet rings (outer rings of star formation). We calculated the color profiles and the ring colors in the optical band from SDSS data.

We also analyzed possible formation mechanisms of the rings being studied by comparing our (morphological and photometric) results with numerical simulations. Their good agreement within the framework of the hypothesis of collisional or tidal formation of outer rings in the galaxies of our sample is worth noting.

REFERENCES

1. K. N. Abazajian, J. K. Adelman-McCarthy, M. A. Agueros, et al., Astrophys. J. Suppl. Ser. **182**, 543 (2009).
2. E. Athanassoula and A. Bosma, Ann. Rev. Astron. Astrophys. **23**, 147 (1985)
3. D. Bettoni, L. M. Buson, and G. Galletta, Astron. Astrophys. **519**, 72 (2010).
4. R. Buta and D. A. Crocker, Astron. J. **105**, 1344 (1993).
5. I. V. Chilingarian, A. P. Novikova, V. Cayatte, et al., Astron. Astrophys. **504**, 389 (2009).
6. J. L. Donovan, P. Serra, J. H. van Gorkom, et al., Astron. J. **137**, 5037 (2009).
7. J. Eder, R. Giovanelli, and M. P. Haynes, Astron. J. **102**, 572 (1991).
8. J. M. A. Few and B. F. Madore, Mon. Not. R. Astron. Soc. **222**, 673 (1986).
9. I. Finkelman and N. Brosch, Mon. Not. R. Astron. Soc. **413**, 2621 (2011).
10. A. Gil de Paz, S. Boissier, B. F. Madore, et al., Astrophys. J. Suppl. Ser. **173**, 185 (2007).
11. A. Helmi, J. F. Navarro, A. Meza, et al., Astrophys. J. **592**, L25 (2003).
12. M. A. Ilyina and O. K. Sil'chenko, Astron. Astrophys. Trans. (2011, in press); arXiv:1012.1499.
13. I. P. Kostyuk, Soobshch. SAO AN SSSR **13**, 45 (1975).
14. S. J. Maddox, G. Efstathiou, and W. J. Sutherland, Mon. Not. R. Astron. Soc. **246**, 433 (1990).
15. M. Mapelli, B. Moore, E. Ripamonti, et al., Mon. Not. R. Astron. Soc. **383**, 1223 (2008).
16. A. Marino, R. Rampazzo, L. Bianchi, et al., Mon. Not. R. Astron. Soc. **411**, 311 (2011).
17. A. V. Moiseev, J. R. Valdés, and V. H. Chavushyan, Astron. Astrophys. **421**, 433 (2004).

18. M. P. Schwarz, Astron. Soc. Austral. Proc. **5**, 464 (1984).

19. P. Serra, S. C. Trager, J. M. van der Hulst, et al., Astron. Astrophys. **453**, 493 (2006).

20. O. K. Sil'chenko, Astron. J. **120**, 741 (2000).

21. O. K. Sil'chenko and A. V. Moiseev, Astron. J. **131**, 1336 (2006).

22. D. A. Thilker, L. Bianchi, G. Meurer, et al., Astrophys. J. Suppl. Ser. **173**, 538 (2007).

23. D. A. Thilker, L. Bianchi, D. Schiminovich, et al., Astrophys. J. **714**, L171 (2010).

24. G. de Vaucouleurs, A. de Vaucouleurs, H. G. Corwin, Jr., et al., *Third Reference Catalogue of Bright Galaxies* (Springer, Berlin, Heidelberg, New York, 1991), p. 2069.

25. V. V. Vlasyuk, Astrofiz. Issled. (Izv. SAO RAN) **36**, 107 (1993).

26. K.-I. Wakamatsu, Astrophys. J. **348**, 448 (1990).

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