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OUTER RINGS IN EARLY-TYPE GALAXIES: FROM VORONTSOV-VELYAMINOV TO PRESENT

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Abstract. ‘Ringed galaxies’, or disk galaxies with prominent outer ring structures, separated visually from the main galactic bodies, were discovered and intensively studied by B. A. Vorontsov-Vel’yaminov whose 110th anniversary is celebrated this year. We discuss progress reached during recent years in understanding outer ring structures of disk galaxies, in particular, the results of our spectroscopic studies on the ring gas kinematics, excitation and chemical composition.

Key words: galaxies: evolution – galaxies: structure – galaxies: kinematics and dynamics – galaxies: elliptical and lenticular

1. INTRODUCTION

This year, we celebrate the 110th anniversary of the pioneer of extragalactic studies in our country, Boris Alexandrovich Vorontsov-Vel’yaminov. One of the favorite targets of his investigations were the so-called ring, or annular, galaxies that he had studied for more than twenty years. Ring galaxies were also considered by him as his important discovery, and later, in the 1980thies, he struggled for the priority of their description. In the SAO/NASA Astrophysics Data System (ADS), we have found his letter addressed to the Editors of the famous astronomical magazine ‘Observatory’, the letter written in 1983 which started with a bitter statement: “Gentlemen, In a paper which I published in 1960 but to which nobody seems to have paid any attention, I presented reproductions of the images of the first 25 ring galaxies discovered by me on the POSS.” It was the time when the ring galaxies were discussed fervently, and almost everybody seemed to be sure that they represented products of galaxy collisions. However, in the Vorontsov-Vel’yaminov (1960) paper and later on (Vorontsov-Vel’yaminov 1976), he argued that a variety of ring morphologies and smooth transitions between them implied regular, intrinsic nature of rings: “...the annular configurations should be looked upon as a structural element on the same level as bars, spiral arms, and discs”. His point of view was then quite original: he proposed a third prong for the Hubble’s fork, parallel to the two others commonly known, along which the third main element of galactic disks, rings, go through from smooth appearance to patchy one, just as spiral arms and bars do along the two other prongs. It is quite clear that Vorontsov-Vel’yaminov considered the rings as structural elements independent of the presence of a bar, so his proper view on their origin was far not only from the collisional hypothesis but also from the 'resonance' ideas developed later. His views were exotic in 1960s–80s; they were also off the mainstream in 1990s and later. Then, it is even more interesting that currently his ideas may overcome all the scenaria discussed up to now.

By now, two main scenaria of the outer ring origin have been considered: the collisional one (Freeman & de Vaucouleurs 1974; Theys & Spiegel 1976; Few & Madore 1986; Athanassoula et al. 1997) and the 'resonance' one (Schommer & Sullivan 1976; Athanassoula et al. 1982; Buta 1995; Buta & Combes 1996). Collisional scenaria suggest a nearly central impact of a dwarf satellite or of a high-velocity gaseous cloud from a strongly inclined orbit; such collisions do not destroy the large-scale disk of the host galaxy but can provoke a radially running shock wave if the gas content of the disk is high enough. 'Resonance' scenaria require violation of axisymmetry of the galactic disk: presence of a bar or even a slight ovality of the central gravitational potential distribution (Jungwiert & Palous 1996) causes radial gas motions such that the gas is assembled at the inner and outer Lindblad resonances of the non-axisymmetric pattern. In both scenaria, gas accumulation at a certain radius is the primary factor, and only subsequent star formation provides such features of the *stellar* surface brightness distributions as the outer rings. Hence, to clarify the nature of the rings in disk galaxies, it is interesting to look at the disk galaxy structures in the UV range; otherwise, to inspect purely stellar, old-population outer rings, one needs data in the near-infrared range. Both directions of investigations have been actively explored recently.

Concerning star formation in S0 galaxies, there is an old paper by Pogge & Eskridge (1993) where it was shown that when a lenticular galaxy exhibited extended star formation, it was organized in rings or ring-like structures. Rich data on the UV morphology of galactic disks has been presented by the GALEX space telescope. Many S0 galaxies were detected in the FUV and/or NUV by the GALEX. For example, Marino et al. (2011) analyzed GALEX images of 40 early-type galaxies having optical emission lines and found five S0s with UV rings among them. Salim et al. (2012) have probed a sample of early-type galaxies, ellipticals and lenticulars, revealing noticeable UV excess in their spectra, with the high-resolution imaging of the Hubble Space Telescope in the FUV. They note weak extended star formation in *all* S0s with the UV excess (representing about 20% of all S0s), and this extended star formation *always* has a ring-like morphology. Salim et al. (2012) distinguish 'wide rings', with a mean radius of 16–20 kpc, 'narrow rings', with a mean radius of 6.5 kpc, 'irregular rings', 'disks with holes' – but they are always *rings*. Well, they are rings and not spiral arms, because galaxies with spiral arms are spirals, not lenticulars. But compact star-forming regions and star-forming nuclei are also rare in UV-bright S0s, they are instead typical attributes of ellipticals. Also, Salim et al. (2012) found no preponderance of the ring presence just in barred galaxies: they find starforming rings in 8 barred and 11 unbarred S0s – the ratio that is close to the general fraction of barred S0s, 35% (Laurikainen et al. 2011, 2013).

The latest statistics of outer ring structures in disk galaxies puts some doubts about their close relation to bar structures. Indeed, the ring catalogue ARRAKIS (Comerón et al. 2014) compiled from the data on galaxy imaging by the Spitzer Space Telescope in the 3.6 μm and 4.5 μm passbands reveals a huge preponderance of outer rings among early-type galaxies: among S0s, up to 60% of all galaxies

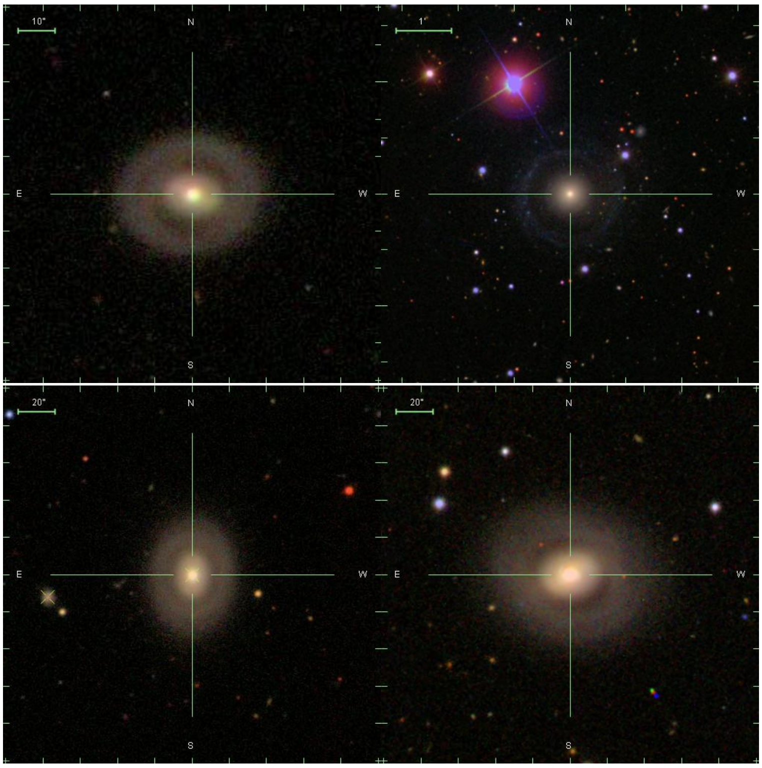

Fig. 1. The SDSS false-color images (combined of three bands) of four S0 galaxies with the UV-bright outer rings seen in the GALEX data: *top left* – PGC 48114, *top right* – UGC 4599, *bottom left* – NGC 809, *bottom right* – NGC 446.

demonstrate outer stellar ring structures, while, among Sb galaxies, this fraction drops to 20%, and to less than 10% among galaxies later than Sbc. And a strictly opposite tendency is observed as concerning the bar frequency in disk galaxies: among spirals, the fraction of barred galaxies in the near-infrared is 80%, while among S0s it drops to 35% (Laurikainen et al. 2011, 2013). Though some fraction of outer rings may have a resonance origin, most rings seem to have a more general nature, related perhaps to the lenticular morphological type as a whole.

2. STAR-FORMING RINGS

We have selected a sample of outer UV-bright rings in lenticular galaxies *without* bars – to tune out of resonance rings. In Ilyina & Silchenko (2011), a list of 14 UV-bright outer rings is published and a comparison of their UV and optical morphologies is made. In all cases, the UV rings have the same radius as the blue optical rings found in the SDSS images (Fig. 1); the only difference of the UV and optical morphologies of these galaxies is the absence, or faintness, of central bulges in the UV. Indeed, *all* these galaxies but one belong to the red sequence, and the only locations inside them where weak star formation proceeds are the rings. The individual levels of the star formation integrated along the rings are of the order of 0.5 solar masses per year. For a half of this sample, we have obtained spectroscopic

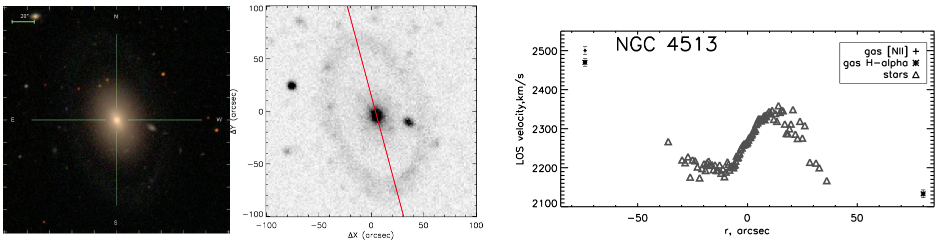

Fig. 2. NGC 4513. *Left*: SDSS color-combined image; *center*: GALEX NUV-image, with the SCORPIO-2 slit overlaid; *right*: line-of-sight velocity profiles for the stellar and ionized-gas components.

data with long-slit spectrographs; in all cases, we have found emission lines in the spectra which reveal the presence of warm ionized gas within these UV-bright, evidently starforming rings. The results for galaxies of the northern sky which have been observed at the Russian 6 m telescope with the SCORPIO-2 spectrograph (Afanasiev & Moiseev 2011) are already published (Ilyina et al. 2014). Among the four galaxies studied, we have found a variety of ionized-gas properties. Half of them demonstrate the gas rotation quite consistent with the rotation of the stellar disk, and in a half of them, the long-slit data reveal decoupled kinematics of the stars and of the ionized gas. We thus confirm the point of view that recently begins to be more and more popular, namely, that the gas in lenticular galaxies is mostly accreted from outside and is often unrelated to the stellar component (Katkov et al. 2014). One of the most striking cases is represented by NGC 4513 (Fig. 2): the outer ring is quite separated from the main galactic body, and its gas rotates in opposite sense with respect to the central part of the galaxy. Interestingly, the outer part of the main stellar body of NGC 4513 demonstrates a smooth decrease of the stellar rotation velocity, as if some part of counterrotating stars, related probably to the outer ring, are added to it.

Besides differing kinematics, the ionized gas in the rings also demonstrates various excitation mechanisms. Although the presence of the UV counterparts at the radii of the outer rings implies current (or quite recent) star formation, only in a half of all cases the ionized gas is excited by young stars; more exactly, the excitation by young stars dominates only in a half of all UV-bright rings. We have constructed the diagnostic BPT-diagrams confronting the line flux ratio of the high-excitation [O III] 5007 Å line to Hβ against the ratios of the low-excitation lines [N II] 6583 Å or [S II] 6717+6730 Å to Hα, and found that a half of all rings demonstrate shock-like excitation. If we consider two possible origins of the gas fuelling star formation in the rings – it may be either the gas accreted from outside or the proper galactic disk gas pushed away and compressed by a vertical satellite impact – both can provide such a variety of the excitation mechanisms. In the former case, the geometry of gas accretion and its rate determine smooth or drastic gas acquisition; in the latter scenario, besides the geometry, the strength of the impact evidently plays its role.

In particular, by accepting the scenario of gas accretion from outside, we immediately need to identify the source of accretion. Such source may be cosmological filaments – features of the large-scale structure of the Universe. In this case, the gas would be primordial and hence metal-poor. Otherwise, the source of external gas accretion may be neighbouring galaxies, and then the gas may be processed

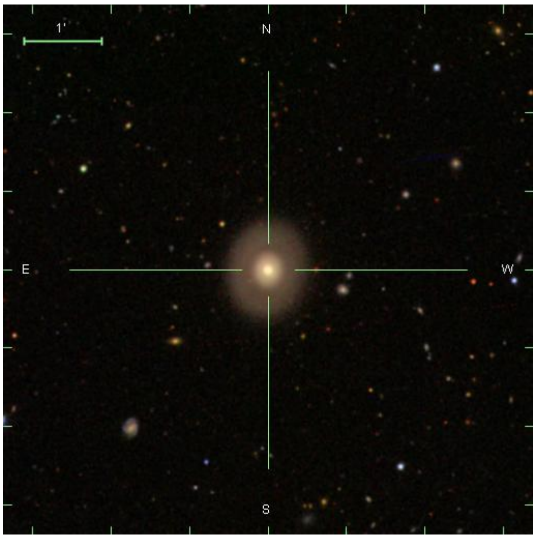

Fig. 3. The SDSS false-color image of NGC 5057; the outer reddish, purely stellar ring with a radius of about 10 kpc is quite prominent.

through stars already and hence be metal-rich. We have succeeded to measure oxygen abundances through the strong emission line calibrations in seven outer rings where the gas was excited by young stars: four galaxies are analyzed in Ilyina et al. (2014) and three more outer rings, in Katkov et al. (2015). In *all* cases, the metallicity of the ionized gas is solar or higher, always much higher than the metallicity of the neighbouring stellar components. Thus, we can exclude the cosmological filaments as a source of the external cold gas accretion in our galaxies.

3. OLD STELLAR RINGS

Though outer stellar rings are a most common feature of the S0 galaxy structure, they do not always contain gas and current star formation sites. We have recently studied a quite typical giant ($M_B = -20.6$) lenticular galaxy NGC 5057 (Fig. 3) with the SCORPIO-2 spectrograph (Afanasiev & Moiseev 2011) of the 6 m telescope of the Special Astrophysical Observatory (Russian Academy of Sciences). The galaxy possesses a compact bulge with an exponential surface brightness profile and an extended ring or lens, with a flat surface brightness profile which can be traced to $R \approx 13$ kpc from the center. We have found no signs of ionized-gas emission lines anywhere in this galaxy, including the wide ring area. The stellar population of the galaxy is old everywhere along the radius, but the ring (lens) area is distinguished by very low metallicity of the stars, [Z/H]< -0.4, so we cannot estimate its age exactly; the magnesium-to-iron ratio in the lens is nearly solar, in contrast to the bulge (Fig. 4). It seems that star formation proceeded in the ring long ago, that this star formation burst was rather prolonged and started after accretion of metal-poor gas from outside.

Recently we have collected some small statistics on the ages of stellar populations in the rings/lenses of *isolated* lenticular galaxies (Katkov et al. 2015). The isolated lenticular galaxies are characterized by a very wide range of ages of their

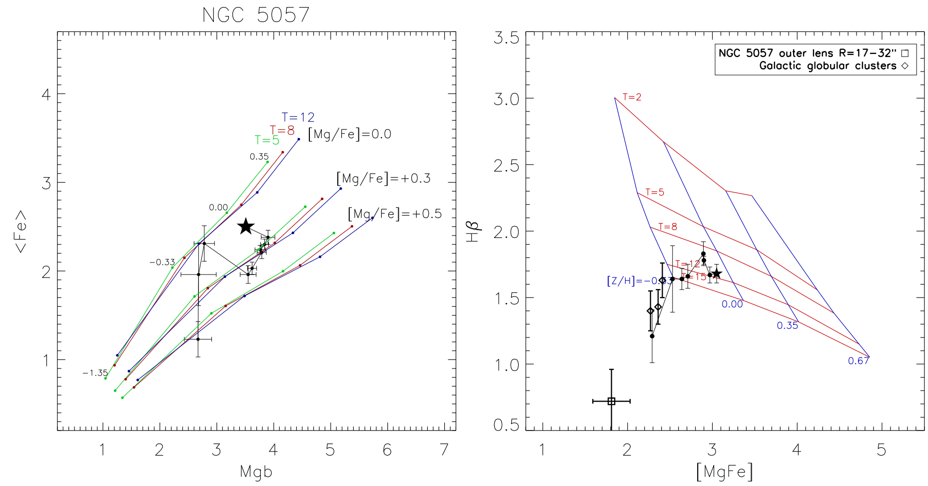

Fig. 4. The diagnostic Lick-index diagrams for NGC 5057. *Left*: the magnesium versus iron diagram demonstrating magnesium overabundance in the bulge and solar magnesium-to-iron ratio in the lens (ring); the black dots are the indices measured along the radius in NGC 5057. The simple stellar population models by Thomas et al. (2003) for three different magnesium-to-iron ratios (0.0, +0.3 and +0.5) and three different ages (5, 8 and 12 Gyr) are plotted as reference. The small signs along the model curves mark the metallicities of +0.35, 0.00, –0.33 and –1.35, if one takes the signs from right to left. *Right*: the age diagnostic diagram. The stellar population models by Thomas et al. (2003) for [Mg/Fe] = +0.3 and five different ages (2, 5, 8, 12 and 15 Gyr, from top to bottom curves) are plotted as reference frame; the blue lines crossing the model metallicity sequences mark the metallicities of +0.67, +0.35, 0.00 and –0.33 from right to left. Three globular clusters of our Galaxy, with intermediate metallicities of [Fe/H] from –0.4 to –0.7, are also plotted by diamonds for comparison; their indices are taken from Beasley et al. (2004).

stellar disks, from 1 to 15 Gyr; but the ages of their rings/lenses are confined to a rather narrow range of 2–5 Gyr. We note the resemblance of the star formation epoch in the rings/lenses of isolated lenticular galaxies and the epoch of appearance of Butcher-Oemler effect in the group and cluster lenticular galaxies, $z = 0.4$ (Wilman et al. 2009). Evidently, the epoch of secondary star formation in the rings and disks of lenticular galaxies had its maximum some 4 Gyr ago, and we can only guess what could be the cause. For example, we can refer to the theoretical prediction that strong bars appeared in disk galaxies only at $z < 1$ when the stellar disks became dynamically cold enough (Kraljic et al. 2012), and then the numerous star-forming rings might form 4–5 Gyr ago as a resonance response to the bar appearance. However, in lenticular galaxies there remains a problem of gas supply for the star formation ignition, so the appearance of bars and accretion of gas from outside had to act together. Perhaps, the former could be the result of the latter because accretion of a large amount of cold gas had to cool the disks and to provide conditions for developing bar-like instabilities in the disks.

4. CONCLUSIONS

Outer rings are common structures in early-type, mostly lenticular galaxies. Moreover, current (secondary) star formation in lenticular galaxies is commonly organized as rings. Unlike spiral galaxies, lenticular galaxies with rings are unbarred in a half of all cases, so their ring structures need not be of resonance origin within the tumbling non-axisymmetric gravitational potential. We suggest that the outer ring structures in S0 galaxies have been formed mostly through accretion of the outer cold gas; perhaps, the peculiar geometry of such accretion betraying itself by frequent shock-like gas excitation in the rings is the cause of the S0 morphology and of the absence of spiral arms in these galaxies. Interestingly, the metallicity of the ring gas is found to be nearly solar, so the source of the gas accretion cannot be cosmological filaments feeding galactic disks with primary gas. We think that typically minor merging of gas-rich satellites may be the cold-gas source for disk galaxies.

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REFERENCES

Afanasiev V. L., Moiseev A. V. 2011, Baltic Astronomy, 20, 363
Athanassoula E., Bosma A., Creze M., Schwarz M. P. 1982, A&A, 107, 101
Athanassoula E., Puerari I., Bosma A. 1997, MNRAS, 286, 284
Beasley M., Brodie J. P., Strader J. et al. 2004, AJ, 128, 1623
Buta R. 1995, PASP, 105, 654
Buta R., Combes F. 1996, Fundamentals of Cosmic Physics, Vol. 17, p. 95
Comerón S., Salo H., Laurikainen E. et al. 2014, A&A, 562, A121
Few J. M. A., Madore B. F. 1986, MNRAS, 222, 673
Freeman K. C., de Vaucouleurs G. 1974, ApJ, 194, 569
Jungwiert B., Palous J. 1996, A&A, 311, 397
Katkov I. Yu., Sil'chenko O. K., Afanasiev V. L. 2014, MNRAS, 438, 2798
Katkov I. Yu., Kniazev A. Y., Sil'chenko O. K. 2015, AJ, submitted
Kraljic K., Bournaud F., Martig M. 2012, ApJ, 757, 60
Ilyina M. A., Sil'chenko O. K. 2011, Astron. Letters, 37, 589
Ilyina M. A., Sil'chenko O. K., Afanasiev V. L. 2014, MNRAS, 439, 334
Laurikainen E., Salo H., Buta R., Knapen J. H. 2011, MNRAS, 418, 1452
Laurikainen E., Salo H., Athanassoula E. et al. 2013, MNRAS, 430, 3489
Marino A., Rampazzo R., Bianchi L. et al. 2011, MNRAS, 411, 311
Pogge R. W., Eskridge P. B. 1993, AJ, 106, 1405
Salim S., Fang J. J., Rich R. M. et al. 2012, ApJ, 755, 105
Schommer R. A., Sullivan W. T. III, 1976, Aph. Lett., 17, 191
Theys J. C., Spiegel E. A. 1976, ApJ, 208, 650
Thomas D., Maraston C., Bender R. 2003, MNRAS, 339, 897
Vorontsov-Vel'yaminov B. A. 1960, AZh, 37, 381
Vorontsov-Vel'yaminov B. A. 1976, Pis'ma v AZh, 2, 520
Wilman D. J., Oemler A., Mulchaey J. S. et al. 2009, ApJ, 692, 298