Nature of star-forming rings in S0 galaxies^{*}

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ABSTRACT

Lenticular galaxies are a morphological class of disc galaxies that in general lacks current star formation and extended gaseous discs. However recent ultraviolet (UV) surveys have revealed extended UV discs and rings even among these 'red and dead' galaxies, and their origin is now still unclear. We have studied the nature of the outer star-forming, UV-detected rings in four unbarred S0 galaxies by undertaking their long-slit spectroscopy with the focal reducer SCORPIO of the Russian 6-m telescope. Gaseous discs in NGC 252 and in NGC 4513 have decoupled kinematics, and the ionized gas of their rings is certainly excited by young stars. Just these two galaxies belong to galaxy groups. Two other, quite isolated S0 galaxies with the UV rings, IC 522 and NGC 446, demonstrate the shock-dominated gas excitation in the UV-detected rings, so their rings may probably have impact origin. However, in all four galaxies the ionized gas reveals the oxygen abundance close to the solar one, so the hypothesis of gas accretion from cosmological filaments seems to be unfavourable. Rather another large galaxy may be a donor of outer gas in the galaxies of our sample.

Key words: stars: formation – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: structure.

1 INTRODUCTION

Lenticular galaxies as a morphological type are characterized by a presence of large-scale stellar discs; however unlike those in spiral galaxies, the stellar discs in S0s look smooth and reddish, without obvious signs of current star formation in their optical-band images. Meantime, contrary to intuitive expectations, the gas presence in the discs of S0s is not rare: for example, Kuijken, Fisher & Merrifield (1996) noted extended ionized gas emission in 58 \pm 9 per cent of their sample S0s, and a persistent study of cold, both atomic and molecular, gas content of lenticular galaxies by Welch, Sage, and their coworkers (Welch & Sage 2003; Sage & Welch 2006; Welch, Sage & Young 2010) has led the authors to the conclusion that the most lenticular galaxies contain cold gas. But Pogge and Eskridge, in their set of papers devoted to exclusively H I-rich SOs (Pogge & Eskridge 1987, 1993; Eskridge & Pogge 1991), found that only less than a half of gas-rich SOs may proceed current star formation in their discs despite the gas presence.

The absence of current star formation in lenticular galaxies does not imply however similarity of their life story to the quiescent evolution of elliptical galaxies, that becomes evident if elliptical and lenticular galaxies are not united into a single class of 'earlytype galaxies' (ETG) but are considered separately. Analysis of nuclear optical-band spectra over a sample of 100 nearby luminous galaxies by Sil'chenko (1993) had shown that while a vast majority, 80 per cent, of nearby elliptical galaxies have typical absorptionline spectra of old stellar populations, the half of nearby lenticulars demonstrate strong Balmer absorptions lines, with the equivalent width of H δ larger than 1 Å and the equivalent widths of H β larger than 2 Å, and so in the nuclei of the half of nearby S0s the stars as young as 1–4 Gyr old dominate in the integrated spectra. Sil'chenko (2006) found the mean age of the stellar populations in the nuclei of nearby S0 galaxies as young as 3 Gyr.

A new aspect of young star presence in lenticular galaxies has been revealed when ultraviolet (UV) imaging of nearby galaxies has been fulfilled by the cosmic telescope Galaxy Evolution Explorer (GALEX). In many disc galaxies extended UV (XUV)bright discs have been discovered, and some of them have been found in lenticular galaxies: the GALEX atlas by Gil de Paz et al. (2007) has presented a lot of spectacular S0s with XUV-bright structures. The morphology of the extended star formation in the discs of S0 galaxies has been studied by several groups of investigators. Marino et al. (2011a) have checked GALEX UV-brightness distributions in 40 S0s with emission lines in the optical-band spectra, and have found rings of recent star formation in seven of them. Salim et al. (2012) have selected instead 29 ETG without optical emission lines, but with strong UV-excess detected by the GALEX, and have mapped them in UV with the Hubble Space Telescope (HST) facilities; almost in all S0s galaxies of their sample large-scale wide or narrow UV rings have been found. Papers by Jeong et al. (2007),

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Marino et al. (2011b), Donovan et al. (2009), Bettoni, Buson & Galletta (2010), Serra et al. (2006) and Thilker et al. (2010) considered individual cases of nearby S0 galaxies with the UV rings.

An origin of the outer star-forming rings in S0s galaxies otherwise looking 'red and dead', being attributed to the red sequence, is still unclear. Unlike spiral galaxies where outer rings are mostly related to bars and have resonance nature (Buta & Crocker 1993), the lenticular galaxies with the outer star-forming rings can be equally barred or unbarred (Salim et al. 2012). A standard set of hypotheses which is usually considered in every individual case includes gas accretion from another galaxy, gas accretion from intergalactic medium (cosmological filaments), minor merger with a gas-rich satellite and impact disturbance of the own gaseous disc of a (former spiral) galaxy by a head-on collision with another galaxy. To select a dominant process able to provoke star formation in a lenticular galaxy, appropriate statistics on environment and inner structural peculiarities of the S0s with UV rings is needed. Kaviraj et al. (2007, 2009, 2011) argued that since a presence of UV excess is usually accompanied by morphological peculiarities, the main agent of star formation triggering in the ETG is minor merging. On the contrary, the sample of Salim et al. (2012) demonstrates very regular optical and UV morphologies together with the UV excess and XUV discs/rings that allows to the authors to prefer smooth gas accretion from the intergalactic medium as a dominant mechanism of fuelling star formation. Another way to estimate the role of environment in fuelling star formation in lenticulars is to identify the origin of gas there. Indeed, Bertola, Buson & Zeilinger (1992) and Kuijken et al. (1996) fixed the fraction of counter-rotating gas in the discs of nearby S0s, and assuming that if the gas is accreted, the gas accretion proceeded from isotropically distributed external sources, concluded that 40-50 per cent of the S0s with gas have obtained their gas by external accretion. Later, Davis et al. (2011) have divided their ETG sample into two according to be or not to be a member of the Virgo cluster and have found that only non-Virgo galaxies demonstrate decoupled gas kinematics; the conclusion is that the cluster galaxies have their gas being replenished by their own stars, and the field S0s have accreted their gas from external sources in \sim 50 per cent of all cases. So the environment plays certainly, and the origin of star-forming rings in SOs may be different in different environment.

Recently we have collected a list of unbarred S0 galaxies with the outer UV rings (Ilyina & Sil'chenko 2011); the absence of a bar ensures us that the rings are not probably resonance features and that some external events providing their appearance are to be searched for. In the present paper we continue our study of the nature of the outer star-forming rings in S0 galaxies by applying long-slit spectroscopy which reveals a presence of ionized gas emission lines just within the ring's locations. We use spectroscopic data to investigate gaseous and stellar kinematics, gas excitation mechanisms, chemical composition of stars and ionized gas; and by comparing the properties of the gaseous and stellar components of the large-scale discs we hope to derive some ideas about the ring origin.

Here four lenticular (T = -2 to -1) galaxies are considered; their global characteristics assembled over public data bases and literature are given in Table 1, and their Sloan Digital Sky Survey (SDSS)- and *GALEX* views can be inspected in Fig. 1. Though all four are bona fide S0s, red in optical light, some their properties are inhomogeneous. Two of them are isolated and two belong to loose groups consisting of late-type galaxies; three galaxies are luminous S0s and one is less luminous. So we would not surprise to find some differences in their rings' properties and origins. However we hope to catch a range of possible causes for S0s to possess a starforming ring. The layout of the paper is the following. Section 2 describes our observations and data analysis. Section 3 presents the kinematical results. Sections 4 and 5 discuss the gas properties and the properties of the stellar populations, respectively. In Section 6 we conclude.

2 OBSERVATIONS AND DATA REDUCTION

Our long-slit spectral observations were made with the focal reducer SCORPIO1 (Afanasiev & Moiseev 2005, 2011) installed at the prime focus of the Russian 6-m telescope located in the Special Astrophysical Observatory of the Russian Academy of Sciences (Nizhnij Arkhyz). We exposed the full optical spectral range, namely, 3700–7200 Å, by using the volume-phase holographic grating 1200 lines per mm with the maximum efficiency at the $\lambda \approx 5400$ Å. The slit width of 1 arcsec was used, the spectral resolution was about 4 Å. The CCD $2k \times 4k$ E2V CCD42-90 served as a detector, and the scale across the slit was $0.36 \operatorname{arcsec} \operatorname{pixel}^{-1}$. The slit length is about 6 arcmin so at the edges of the slit we take the sky background to subtract from the galaxy spectra. Inhomogeneities of the optics transparency and variations of the spectral resolution along the slit were taken into account by using the high signal-tonoise ratio (S/N) exposures of the twilight spectra. To study the stellar population properties, we calculated the Lick indices $H\beta$, Mgb, Fe5270 and Fe5335; the checking of the Lick index system was maintained as described in Baes et al. (2007). The stellar kinematics was analysed by cross-correlating binned spectra with the spectra of K-giant stars observed the same nights as the galaxies. The emission lines, and the strongest H α and [NII] λ 6583 first of all, were used to derive ionized gas kinematics, by measuring barycentre positions of the lines, and also to calculate variations of the equivalent width of the emission line H α along the slit. For the latter purpose, we binned the spectra along the slit to reach S/N higher than 50-70, and then made Gauss analysis of the line complex [N II] $\lambda 6548 + 6583 + H\alpha$ (emission)+H α (absorption). The derived equivalent widths of the H α emission line were used to calculate the corrections for the H β Lick index as it was described by Sil'chenko (2006). The journal of all the long-slit observations is presented in Table 2.

3 ROTATION OF THE STARS AND IONIZED GAS

The line-of-sight (LOS) velocity profiles measured by us for the stars and ionized gas in all four galaxies are presented in Fig. 2. The main question – has the gas been acquired from any external source - can be answered unambiguously 'YES' only in the cases when the stellar and gaseous kinematics are decoupled; if they are similar, gas can be equally of internal or external origin. By inspecting Fig. 2, we can state an accretion origin of the gas in NGC 252 and NGC 4513. In the former case, the difference in $v_{\rm rot, proj}$ by a factor of 2.5 between the stellar and gaseous components is too large to be explained by asymmetric drift. The conclusion about different inclinations of the stellar and gaseous discs seems unavoidable. Photometric arguments (Ilyina & Sil'chenko 2011) give also evidences for the different inclinations of the main stellar disc and star-forming ring in NGC 252: the south-eastern part of the blue ring is seen better than the north-western part (see the fig. 1 by Ilyina and Sil'chenko), so it is seen projected on to the main disc

¹ For a description of the SCORPIO instrument, see http://www.sao.ru/ hq/moisav/scorpio/scorpio.html.

Parameters	IC 522	NGC 252	NGC 446	NGC 4513
Type (NED) ^a	S0	$(R)SA0^{+}(r):$	(R)SAB0 ⁰	(R)SA0 ⁰
$R_{25}''(\text{RC3})^b$	30	45	61	43
R_{25}^{25} , kpc (NED)	10.2	13.5	20.4	6.8
m_B (RC3)	13.97	13.35	13.35	14.01
$M_H(NED)$	-24.0	-25.2	-24.13	-22.84
(g-r) (SDSS) ^c	0.83	0.84	0.83	0.82
V_r (NED), km s ⁻¹	5079	4938	5446	2304
Distance, ^d Mpc	71	63	70	33
Inclination (LEDA) ^e	40°	51°	46°	59°
PAphot (RC3)	165°	80°	$110^{\circ, e}$	15°
$M_{\rm HI}, 10^9 {\rm M_{\odot}}^{f}$	_	3.4^{1}	2.3^{2}	0.27^{3}
Environmentg	1	2	1	2
	(424, +3.7)	(7, +0.9, 152)	(398, +2.0)	(4, -0.4, 600)

 Table 1. Global parameters of the sample galaxies.

^a NASA/IPAC Extragalactic Database.

^b Third Reference Catalogue of Bright Galaxies (de Vaucouleurs et al. 1991).

^c Sloan Digital Sky Survey, Data Release 8 (Aihara et al. 2011).

^d From NED, 'cosmology-corrected' option.

^e Lyon–Meudon Extragalactic Database.

^{*f*} Sources of the H₁ data: ¹Saintonge et al. (2008); ²Eder, Giovanelli & Haynes (1991); ³Tang et al. (2008).

^g The environment types derived from the NED searching are coded: 1 - a pair member (in parentheses – separation in kpc, magnitude difference); 2 - a group member (in parentheses – N gal, magnitude difference with the second(first-)rank galaxy, and separation with it in kpc).

[p]



Figure 1. False-coloured SDSS images (left-hand plots) and the *GALEX* NUV maps with the spectrograph slit position overlapped (right-hand plots) of the galaxies under consideration: IC 522 (upper left), NGC 252 (upper right), NGC 446 (bottom left) and NGC 4513 (bottom right).

Table 2. Long-slit spectroscopy of the sample galaxies.

Galaxy	Date	Exposure (min)	PA (slit) (°)	Seeing (arcsec)
IC 522	08 February 2011	80	165	3.5
NGC 4513	08 February 2011	80	15	3.5
NGC 252	18 November 2011	90	82	1.5
NGC 446	18 November 2011	60	40	1.5

while the north-western part of the ring is probably seen *behind* the main disc. In NGC 4513 the outer gas counter-rotates the inner stellar body, and it is true both for the ionized gas (Fig. 2) and for the neutral hydrogen (Tang et al. 2008). Interestingly, the stellar component in its outer part where we can still measure the LOS velocities, changes its rotation direction starting to match that of the gas. Both galaxies belong to the groups consisting of late-type

spirals any of which can be a source of accretion. In the isolated galaxies IC 522 and NGC 446 the gas rotation seems to match that of the stars; in IC 522 the gas rotation curve continues the stellar rotation curve into more outer parts of the disc.

4 EXCITATION AND METALLICITY OF THE IONIZED GAS IN THE RINGS

Since we have the spectra which are spectrophotometrically calibrated, we can integrate emission-line fluxes over the radial extension of the rings found by us earlier from the photometric analysis (Ilyina & Sil'chenko 2011), and use the line flux ratios to identify a source of gas excitation, whether it is young stars (current star formation) or shock fronts expected in the case of the impact origin of the rings. The estimates of the emission-line flux ratios are given in Table 3.



Figure 2. LOS velocity profiles for the stellar (stars) and gaseous components for the galaxies IC 522 (upper left), NGC 252 (upper right), NGC 446 (bottom left) and NGC 4513 (bottom right), which we have obtained from our SCORPIO long-slit data. In NGC 4513 only the gaseous ring at the radii of -75 and +80 arcsec emits, and it counter-rotates the inner stellar disc.

Table 3. Emission line ratios in the rings with their errors and oxygen abundances in the star-forming rings.

Galaxy	$\log(\frac{[N II]}{H\alpha})$	$\log(\frac{[S II]}{H\alpha})$	$\log(\frac{[OI]}{H\alpha})$	$\log(\frac{[O III]}{H\beta})$	[O/H] from N ₂ (Denicolo et al. 2002)	[O/H] from N ₂ (Pettini & Pagel 2004)	[O/H] from O ₃ N ₂ (Pettini & Pagel 2004)
IC 1522	0.40 ± 0.30	-0.68 ± 0.70	-0.90 ± 0.30	0.70 ± 0.45	_	_	_
NGC 252	-0.25 ± 0.03	-0.11 ± 0.60	-1.26 ± 0.15	-0.20 ± 0.44	+0.03	+0.09	+0.06
NGC 446	0.10 ± 0.25	0.09 ± 0.30	-0.90 ± 0.60	-0.70 ± 0.40	-	-	_
NGC 4513	-0.47 ± 0.43	-0.28 ± 0.33	-0.72 ± 0.62	-0.06 ± 0.03	-0.13	-0.03	-0.06

We have put the emission-line flux ratios measured in the rings of our four galaxies, with their corresponding errors, on to diagnostic diagrams, which are called 'Baldwin–Phillips–Terlevich' (BPT) after Baldwin, Phillips & Terlevich (1981), by applying a method described in Kewley et al. (2006). In Fig. 3 we show one of the BPT diagrams, the [N II]/H α ratio versus [O III]/H β ratio one. The curved solid line corresponds to the theoretical upper limit for starburst models (Kewley et al. 2001). This line may be considered, following Kewley et al. (2001), as a boundary between shock mechanism of gas excitation (to the right and up from the line) and excitation through photoionization by massive blue stars (to the left and down the line). The dashed line is an empirical boundary between star-forming nuclei and active galactic nuclei (AGN; Kewley et al. 2006).

From our results in Fig. 3 the rings of three galaxies (NGC 252, NGC 446 and NGC 4513) may belong to the area of young-star photoionization within the limits of the flux-ratio errors, and only the ring of IC 522 belongs certainly to the area of shock excitation. However, the positions of NGC 446 at the BPT diagrams are, on one hand, beyond the main cloud of the SDSS galaxy distribution which involves two excitation mechanisms, namely photoionization by young stars and by an active nucleus over a range of parameters. On the other hand, the theoretical boundary between the photoionization is reachable for this galaxy taking

into account the flux-ratio errors. So we conclude that the probable mechanism for the gas excitation in the ring of NGC 446 may be a shock wave. By using the empirical calibration formulae allowing to estimated gas oxygen abundances from the strong emission-line ratios N₂ and O₃N₂ for the gas excited by young stars (Denicolo, Terlevich & Terlevich 2002; Pettini & Pagel 2004), we have estimated the gas oxygen abundances in the rings of NGC 252 and NGC 4513; they are found to be close to the solar value and included also into the Table 3. We have also estimated the star formation rate (SFR) in the rings by applying the formula relating the H α emission-line flux to SFR from Kennicutt (1998). The SFR is of order of 10^{-10} – 10^{-9} M $_{\odot}$ yr⁻¹ pc⁻², or, if being integrated over the whole rings under the assumption of homogeneous SFR distribution, equal or less than 0.1 M $_{\odot}$ yr⁻¹.

For the final choice of gas excitation mechanism acting within the emission-line rings of the galaxies studied here, and in order to estimate ring's gas metallicities, we have carried out fitting of the line flux ratios by exploring the IDL widget tool named the IDL Tool for Emission-line Ratio Analysis (ITERA) by Groves & Allen (2010), which contains theoretical ratios of many strong emission lines as determined by standard photoionization and shock models. The metallicities found by this fitting are in general close to the solar value, slightly higher in IC 522 and slightly below the solar value in NGC 4513. The comparison of the models with our observations



Figure 3. The diagnostic BPT diagram comparing emission-line flux ratios of the sample of SDSS galaxies with S/N > 3 plotted by dots (Kewley et al. 2006) and our results for the emission-line rings in the S0 galaxies (IC 522 – diamond; NGC 252 – square; NGC 446 – triangle; NGC 4513 – asterisk).

is shown in Figs 4 and 5. Into every plot we have placed a model, which describes our results best of all, and at the same plot, for comparison – models, which correspond to the same mechanism of gas excitation, but with a different metallicity. For the all the cases we have used the comparative models, which metallicity refers to the Small Magellanic Cloud (SMC; one-fifth of the solar metallicity).

Below we discuss properties of the investigated rings in detail.

IC 522. To recover a mechanism of gas excitation within the galactic ring we have used a shock model in two versions, that of 'shock only' and that of 'shock+precursor' (for more details see Allen et al. 2008). The most successful result has been reached when using the first variant. The ring of this galaxy is located closer to the centre than the rings of other galaxies: the mean radius is only 6 kpc. From the data of Table 3 we are able to conclude that this ring has the highest line ratio $[N II]/H\alpha$ among the objects investigated. Both facts have allowed us to assume that the ring of IC 522 may be metal rich and to apply a model with the metallicity equal to two solar ones and with a pre-shock density of 1 cm^{-1} . Since the grids of the best-fitting model and the SMC model are generally overlapped, for more clarity of presentation in Fig. 5 we vary the shock front velocity and the value of the pre-shock transverse magnetic field B separately. The plots of Fig. 5 demonstrate that the metal-poor (SMC) model can be excluded at the level more than 2σ .

NGC 252. The most successful result of simulation for this galaxy was achieved with the models which were generated by the PEGASE v2.0 code (Kewley et al. 2001). For comparison we have placed three models (Kewley et al. 2001) in Fig. 4: those corresponding to instantaneous zero-age starburst model (dash–dotted line), continuous starburst model (dashed line) for 4 Myr age with the same metallicity and electron density, namely, solar metallicity and $n_e = 10 \text{ cm}^{-1}$ found in the most successful simulation, and a comparative model of instantaneous zero-age starburst for the SMC

chemistry (solid line). By comparing the models and our observational data, we have found that our observations of the NGC 252 ring correspond better to the model of continuous starburst: while it can be fitted by the model of instantaneous starburst at the [N II]/H α versus [O III]/H β diagram, it is closer to the model of continuous starburst at the [S II]/H α versus [O III]/H β diagrams.

NGC 4513. By acting similarly as with the previous galaxy, in Fig. 4 we have plotted three models generated by the PEGASE v2.0 code (Kewley et al. 2001) on to the corresponding pictures: instantaneous zero-age starburst model (dash–dotted line), continuous starburst model (dashed line) for the 4 Myr age with the similar metallicity and electron density, namely, the half-solar metallicity and $n_e = 10 \text{ cm}^{-1}$, and the model of continuous starburst for the SMC metallicity (solid line). According to all the diagrams, the continuous starburst model succeeds.

NGC 446. As we have noticed above, the nature of the UV-bright emission-line ring in NGC 446 has appeared to be too complicated for understanding: the BPT diagnostic diagrams have led us to some ambiguity. The scrupulous simulation has resolved the problem: a model that describes the results of observations best of all is a model of shock-dominated excitation in the version 'shock only' (Allen et al. 2008) with the solar metallicity and pre-shock density of 10 cm^{-1} .

5 CHEMICAL COMPOSITION AND AGE OF THE STELLAR DISCS NEIGHBOURING THE GASEOUS RINGS

We have calculated Lick indices $H\beta$, Mgb, Fe5270 and Fe5335 along the radii in the galaxies under consideration up to the disc-dominated area and have determined SSP equivalent ages,



Figure 4. Simulations of the line ratios $[N II]/H\alpha$ versus $[O III]/H\beta$ (left) and $[S II]/H\alpha$ versus $[O III]/H\beta$ (right) for the galaxies with the ring gas excited by young stars. Model grids are taken from Allen et al. (2008) and Kewley et al. (2001), the ionization parameter *q* (maximum velocity of ionization front in cm s⁻¹) is coloured in a logarithmic scale, solid line is corresponding to the SMC chemistry models, dashed and dash–dotted lines corresponding to the models with the best-fitting metallicity (see the detailed discussion of the individual galaxies in the text.)

metallicities and magnesium-to-iron ratios by confronting the measured indices to the evolutionary synthesis models by Thomas, Maraston & Bender (2003). The goal was to compare stellar metallicities in the discs to the gas oxygen abundance, to check if the gas is metal poor and, consequently, primordial, recently accreted from a cosmological filament, or has come with a dwarf gas-rich satellite in a minor merger. However, in NGC 446 and NGC 4513 we could only probe the disc regions well inside the ring radii, though in NGC 4513 the disc stellar population probed at R = 20-32 arcsec is counter-rotating with respect to the galaxy central part and so is genetically related to the more outer gas.

Figs 6 and 7 present the results for three galaxies which we could probe over rather extended radial area. Even within this very small sample, the gas–star relations are quite various. While in the centres of the galaxies the magnesium-to-iron ratios are homogeneously close to +0.1 to +0.2, the discs of IC 522 and NGC 4513 have solar [Z/H] and [Mg/Fe], while in NGC 252 the disc is strongly magnesium overabundant, [Mg/Fe] = +0.4 to +0.5, and very metal poor beyond the ring radius, [Z/H] \approx -1.3. Let us remind that the gas oxygen abundance in the ring of this galaxy is solar. In NGC 446 where only the very *inner* stellar disc, $R \approx$ 7–10 arcsec is probed, the stars are also metal poor unless the gas: [Z/H]_{*} = -0.3 versus solar oxygen abundance in the gas. So we can conclude that the ionized gas in the rings has come from a rather massive neighbour, and/or it may be of intrinsic origin and is chemically processed during a rather long period.

6 CONCLUSIONS AND DISCUSSION

We have studied the nature of star-forming, UV-detected rings in four unbarred S0 galaxies by undertaking long-slit spectroscopy with the focal reducer SCORPIO of the 6-m telescope. Two of four gaseous rings, in NGC 252 and in NGC 4513, have decoupled gaseous kinematics, and the ionized gas of the rings is certainly excited by young stars. Just these two galaxies belong to galaxy groups. Two other, quite isolated S0 galaxies with UV rings, IC 522 and NGC 446, demonstrate the gas excitation in the rings which is dominated by shock, so we suggest that their rings have probably impact origin. However, in all the galaxies the ionized gas reveals the oxygen abundance close to the solar one or higher.

By analysing the results obtained for our small sample of lenticular galaxies with extended gaseous subsystems and UV-detected outer rings, we can conclude that star-forming rings, which are rather common features in lenticular galaxies and are not always related to the bar resonances, may be of various origin that may depend probably on environment conditions. The UV rings in isolated galaxies IC 522 and NGC 446 may represent the consequences of central impact by a satellite from a highly inclined orbit. The gas which is a fuel for star formation in similar cases may be the own gas of large galaxy impacted which is compressed by radially running shock wave produced by the impact. In agreement with this scenario, the ionized gas rotation in IC 522 and NGC 446 matches indeed the rotation of the stellar discs. For S0 galaxies in groups,



Figure 5. Shock excitation models for IC 522 and NGC 446 based on the calculations by Allen et al. (2008); the top row plots present the models with the transverse component of the pre-shock magnetic field fixed at $B = 5 \mu$ G for IC 522 (left) and at $B = 0.1 \mu$ G for NGC 446 (right) and varying shock velocity coded by colour, the bottom row presents the models with the fixed shock velocity and varying *B*. The best-fitting models (see the text) at all plots are those where the squares are connected by dashed lines. The comparison models at the top row – the models with the gas metallicity of 20 per cent of the solar one. At the bottom row, besides the best-fitting models, we plot the comparison models with close parameters (the squares connected by solid lines) – they are $v = 1000 \text{ km s}^{-1}$ and [Z/H] = 0.0 – and also the full set of models for the SMC ([Z/H] = -0.7) to show that our data for IC 522 and NGC 446 exclude such low metallicity of the gas. Correspondingly, the colour bar for the magnetic field *B* below the bottom row plots refers only to the SMC models, the colours of the squares correspond to the shock velocity (the right-hand colour bar).



Figure 6. The diagnostic index-index diagrams, Mgb versus $\langle Fe \rangle \equiv (Fe5270 + Fe5335)/2$, for the Lick indices measured in IC 522, NGC 252 and NGC 4513 along their radii starting from the nuclei (big stars) towards the disc-dominated area. 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.



Figure 7. The age–diagnostic diagrams for the stellar populations along the radius in IC 522, NGC 252 and NGC 4513 starting from the nuclei (big stars) towards the disc-dominated area. The SSP models by Thomas et al. (2003) for 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.

such as NGC 252 and NGC 4513, there are much more possibilities to accrete gas smoothly - in particular, from another large galaxy during the close passage. There are late-type neighbours, NGC 258 and NGC 260, near NGC 252 which are to be gas-rich galaxies and which could be gas donors for NGC 252. The rotation momentum of the accreted gas then would be related to the orbital motion of a companion galaxy and may be decoupled from the rotation momentum of the large-scale stellar discs of the galaxies recipients. Independently on the origin of the gas, we can suggest that after a brief event of gas accretion and/or its compression into a ring, the subsequent star formation is a rather prolonged process because the gas oxygen abundance in three cases is larger than the stellar metallicity in the neighbouring regions of the stellar discs, and in NGC 4513 where the ring is well beyond the optical radius of the galactic disc the counter-rotating stellar component related genetically to the outer accreted gas demonstrates the solar magnesium-to-iron ratio.

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