The diversity of thick galactic discs

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ABSTRACT
Although thick stellar discs are detected in nearly all edge-on disc galaxies, their formation scenarios still remain a matter of debate. Due to observational difficulties, there is a lack of information about their stellar populations. Using the Russian 6-m telescope BTA we collected deep spectra of thick discs in three edge-on S0-a disc galaxies located in different environments: NGC 4111 in a dense group, NGC 4710 in the Virgo cluster, and NGC 5422 in a sparse group. We see intermediate age (4–5 Gyr) metal rich ([Fe/H] $\sim -0.2\ldots 0.0$ dex) stellar populations in NGC 4111 and NGC 4710. On the other hand, NGC 5422 does not harbour young stars, its disc is thick and old (10 Gyr), without evidence for a second component, and its α-element abundance suggests a 1.5–2 Gyr long formation epoch implying its formation at high redshift. Our results suggest the diversity of thick disc formation scenarios.

Key words: galaxies: evolution – galaxies: stellar content – galaxies: structure.

1 INTRODUCTION

Many important aspects of galaxy evolution remain not fully understood despite the great progress in the astronomical instrumentation and increasing resolution and complexity of numerical simulations. One such unsolved problem is the formation of thick discs, important and widespread structural elements of spiral and lenticular galaxies (Burstein 1979). Manifested by the exponential excess of light in edge-on disc galaxies at large distances above the main disc plane, they are found in most if not all cases (Dalcanton & Bernstein 2002). The Milky Way contains a thick stellar disc component with the scale-height of ∼1 kpc that harbours older and more metal poor stars compared to the star forming thin disc. Lenticular galaxies sometimes possess only old thick discs (McDermid et al. 2015) being consistent with a scenario where they formed thick discs at high redshifts (see details in Sil'chenko et al. 2012) and then have never acquired thin discs and become *normal* spirals in contrast to the formation scenario of the lenticular galaxies through quenching of spirals (Larson, Tinsley & Caldwell 1980).

Several thick disc formation scenarios have been proposed. (i) Thick discs formed rapidly at high redshifts as a result of high density and velocity dispersion of gas in the early Universe (Elmegreen & Elmegreen 2006; Bournaud, Elmegreen & Martig 2009), and thin discs formed consequently by gas accretion from filaments (see Chiappini, Matteucci & Gratton 1997; Combes 2014, and references therein) or minor *wet* mergers (Robertson et al. 2006; Sil'chenko et al. 2011). This scenario should produce old α-enhanced thick discs without notable metallicity gradients. (ii) Thick discs can be formed via secular thin disc flaring as a result of radial migration of stars (Schönrich & Binney 2009; Loebman et al. 2011; Roškar, Debattista & Loebman 2013). Some scenarios predict specific radial and vertical stellar population patterns, for example, a negative radial age gradient above the principal disc plane (Minchev et al. 2015). (iii) Primordially thin discs can get dynamically heated by satellite flybys (Quinn, Hernquist & Fullagar 1993; Qu et al. 2011) and/or minor mergers.

Detailed studies of internal kinematics and stellar populations in thin and thick discs will help us to choose the scenario. In external galaxies which cannot be resolved into stars, integrated light spectroscopy remains the only observational technique for thick disc studies. However, it represents a significant challenge because of typical low surface brightnesses of thick discs.

We carried out deep long-slit spectroscopic observations for a sample of edge-on disc galaxies and derived spatially resolved stellar kinematics and star formation histories. In this *Letter* we present the first results on three S0-a galaxies which, as we show, prove the diversity of the thick disc formation scenarios.

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Table 1. Long-slit spectroscopy of the sample galaxies.

NGC	Date	z-offset arcsec/pc	PA deg	Sp. range Å	T_{exp} sec	Seeing arcsec
4111	21/05/09	0/0	150	4825–5500	8400	1.3
4111	24/04/15	5/364	150	3600–7070	5600	1.0
4710	24/04/15	0/0	27.5	3600–7070	3600	1.2
4710	24/04/15	7/560	27.5	3600–7070	7200	1.1
5422	24/04/12	0/0	151.4	3600–7070	3600	2.5
5422	25/04/15	7/1049	151.4	3600–7070	8400	1.5

2 THE SAMPLE AND THE DATA

2.1 The sample

We chose three edge-on galaxies in different environments: NGC 4111, NGC 4710 and NGC 5422 morphologically classified as *S0-a* by Hyperleda (Makarov et al. 2014).

(i) NGC 4111 ($M_J = -22.40$ mag) is a member of the Ursa Major galaxy group that is known to contain a common extended H I envelope (Wolfinger et al. 2013). The distances from NGC 4111 to the nearest neighbours are about 30–40 kpc (Karachentsev, Nasonova & Courtois 2013; Pak et al. 2014). We adopt the distance 15 Mpc that corresponds to the spatial scale 72.7 pc arcsec^{-1} (Tonry et al. 2001).

(ii) NGC 4710 ($M_J = -22.56$ mag) is located in the Virgo cluster outskirts ($d = 16.5$ Mpc by Mei et al. (2007), spatial scale 80.0 pc arcsec^{-1}). Its projected distance to M 87 is about 5.4 deg or 1.6 Mpc (Koopmann, Kenney & Young 2001). A dusty disc is observed in the central 2 kpc region dominated by an X-shaped structure, that is traditionally explained as an edge-on bar (Bureau & Freeman 1999).

(iii) NGC 5422 ($M_J = -22.81$ mag) is a member of the sparse NGC 5485 galaxy group dominated by lenticular galaxies. It is the most luminous and the most distant object in our sample ($d = 30.9$ Mpc by Theureau et al. (2007), spatial scale 150 pc arcsec^{-1}). It possesses a large gaseous disc tilted by some $\sim$5 deg with respect to the stellar disc.

2.2 New observations and archival data

We obtained deep spectroscopic observations of all three galaxies with the universal spectrographs SCORPIO (Afanasiev & Moiseev 2005) and SCORPIO-2 (Afanasiev & Moiseev 2011) at the Russian 6-m BTA telescope using the 1 arcsec wide 6 arcmin long slit. For every galaxy we observed: (i) a major axis in order to get the information on a thin disc for NGC 4111 and NGC 4710, and the mid-plane of the thick disc in NGC 5422 and (ii) a region parallel to the major axis offset by 5–7 arcsec that corresponds to 0.36–1 kpc above the mid-plane in order to probe thick discs. We observed (see Table 1) the mid-plane of NGC 4111 with the SCORPIO in the wavelength range 4800–5600 Å with the spectral resolution $\sim$2.2 Å =55 km s^{-1}. The remaining five data sets were obtained using SCORPIO-2 at slightly lower spectral resolution ($\sim$3.8 Å =95 km s^{-1} at 5100 Å) at the broader wavelength range (3600–7070 Å).

We reduced our spectroscopic observations with our own IDL-based reduction pipeline. We estimated the night sky background from outer slit regions not covered by our target galaxies and an optimized sky subtraction technique that takes into account spectral resolution variations along the slit (Katkov & Chilingarian 2011; Katkov, Sil'chenko & Afanasiev 2014).

All three galaxies were observed with the Infrared Array Camera (IRAC) at *Spitzer Space Telescope* in the imaging mode at wavelengths 3.6 μm and 4.5 μm. We fetched fully reduced 3.6 μm images from the Spitzer Heritage Archive.[1]

2.3 Data analysis

Van der Kruit & Searle (1981) have shown that in case an isothermal disc in the equilibrium state the vertical disc density profiles are described by the law $I = I_0 \operatorname{sech}^2(z/z_0)$, where I_0 is the central intensity and z_0 is the disc scale-height. We fitted vertical profiles obtained by averaging *Spitzer* IRAC images along the radius using models including one and two components. We set central positions of both components to be the same in the case of two-component fitting but left the position itself a free parameter. Our results for NGC 4111 and NGC 5422 quantitatively agree with those presented in the S4G survey (Salo et al. 2015), however the results for NGC 4710 decomposition were not presented there.

To derive internal kinematics and stellar population properties (mean ages and metallicities [Fe/H]) of thick and thin discs we first binned our long slit spectra in the spatial direction with the adaptive binning algorithm in order to reach the minimal signal-to-noise ratio $S/N = 30$ per bin per spectral pixel in the middle of the wavelength range. Then, in every bin we applied the NBURSTS full spectral fitting technique (Chilingarian et al. 2007a,b) with a grid of high resolution stellar PEGASE.HR (Le Borgne et al. 2004) simple stellar population (SSP) models based on the ELODIE3.1 empirical stellar library (Prugniel et al. 2007). The NBURSTS technique implements a pixel space χ^2 minimization algorithm where observed spectrum is approximated by a stellar population model broadened with parametric line-of-sight velocity distribution (LOSVD) and multiplied by polynomial continuum (10th degree in our case) to take into account dust attenuation and/or possible flux calibration imperfections in both observations and models. We used Gaussian parametrization of the stellar LOSVD, except our higher resolution mid-plane spectra of NGC 4111 where we exploited the standard Gaussian–Hermite parametrization (van der Marel & Franx 1993).

The [Mg/Fe] abundance ratio which allows one to estimate the duration of the star formation epoch is fixed to the solar value in the PEGASE.HR model grid. Therefore, we measured the Mg*b*, Fe5270/5335 Lick indices (Worthey et al. 1994) and derived [Mg/Fe] ratios in several radial bins along the slit using α-variable models from Thomas, Maraston & Bender (2003).

3 RESULTS AND DISCUSSION

3.1 NGC 4111

In Fig. 1 (left plots) we show the SSP-modelling results of NGC 4111 stellar population and kinematic data. Comerón et al. (2014) have estimated the thin and thick disc masses to be $15 \pm 3 \times 10^9$ M$_\odot$ and $5 \pm 1 \times 10^9$ M$_\odot$ respectively, and Comerón et al. (2012) have demonstrated that the thick disc of NGC 4111 dominates the luminosity at $z > 25.4$ arcsec ($\sim$1.8 kpc) in the inner region. However, according to their models, already at $r = 40$ arcsec the thick disc contribution represents about 80 per cent of the total luminosity fraction in the mid-plane and reaches 90 per cent at $z = 5$ arcsec were we placed the slit. Our data extend out to 6.2 kpc from the centre that corresponds to 10.0 and 2.7 thin and

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[1] http://sha.ipac.caltech.edu/applications/Spitzer/SHA/
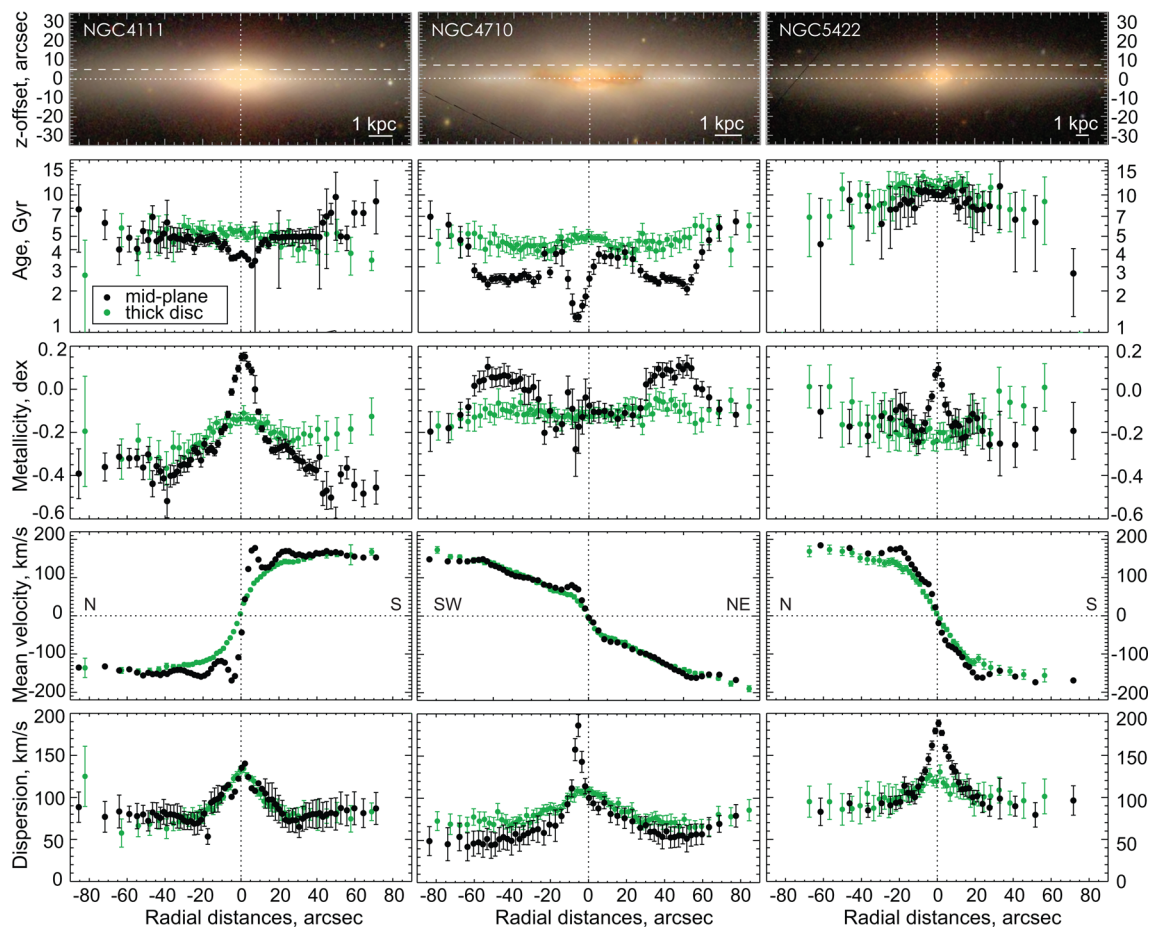
Figure 1. Stellar populations and internal kinematics of three edge-on disc galaxies. Panels (top to bottom): the slit positions overplotted on SDSS colour images, SSP equivalent ages, metallicities, radial velocities and line-of-sight velocity dispersions. Black and green symbols denote mid-planes and thick discs.

thick disc scale-lengths, respectively. Nevertheless, we do not see significant differences of stellar populations in the outer regions of the NGC 4111 discs. The [Mg/Fe] values for both disc components are about +0.15 dex and consistent within 0.03 dex (Fig. 2, top panel). Stellar ages of the two layers are almost identical ∼5 Gyr. Moreover, the stellar velocity dispersion profiles are similar too. The slight asymmetry of the thick disc stellar population profiles in the outer regions is not statistically significant. With the exception of the central region where our mid-plane data probes the bulge and a kinematically decoupled corotating inner disc (within 10 arcsec), we see a completely flat age profile. Metallicity has a slight negative gradient and decreases from [Fe/H] = −0.2 dex at $r = 15$ arcsec to −0.4 dex in the outer regions of both discs.

3.2 NGC 4710

Our data extends to 85 arcsec (6.8 kpc) and we can identify at least three distinct regions in NGC 4710 by radius: (i) an inner dusty region within 30 arcsec that corresponds to the outer edge of a clearly seen X-shaped structure, (ii) a bright thin blue disc extending to 60 arcsec, and (iii) weaker outer regions. Mid-plane age and metallicity profiles confirm the stepped structure (black points on the centre panels of Fig. 1). A slight asymmetry within the central region corresponds to the bright spot distinctly seen on optical images of NGC 4710 south-west of its centre. It is probably a giant star formation region that shines through unevenly distributed
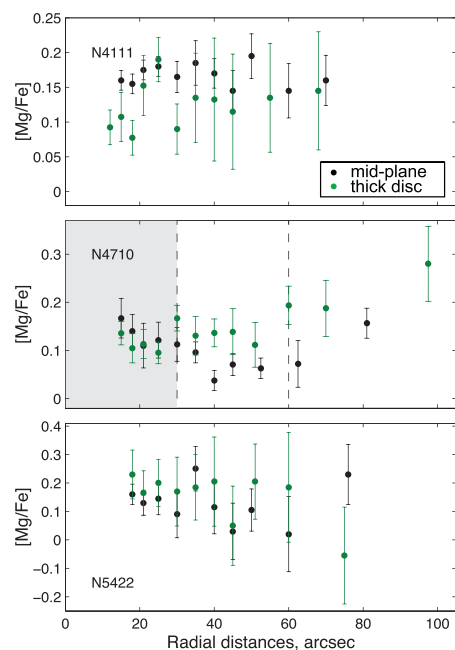
Figure 2. The [Mg/Fe] values averaged in radial bins. Black and green dots are for thin and thick discs, respectively. Dotted lines denote the three regions of NGC 4710, shaded grey is a bar dominated area, then the inner disc at $30 < r < 60$ arcsec, and the thick disc dominated area.
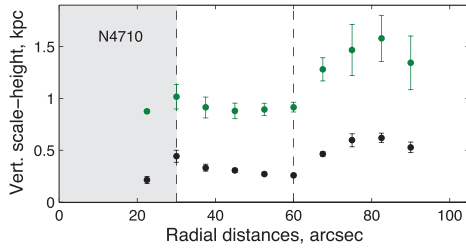
Figure 3. Scale-height radial variations of the NGC 4710 thin and thick discs. The designations are as in Fig. 2.

dust. Outside the dusty region, between 30 and 60 arcsec, we see a young (~2.5 Gyr) metal-rich (~+ 0.1 dex) component without significant radial stellar population gradients. Outside 60 arcsec the stellar age abruptly becomes significantly older and reaches 6 Gyr while the metallicity decreases to ~− 0.17 dex (e.g. almost half of that inside 60 arcsec). At the same time, the thick disc of NGC 4710 (at 560 pc above the mid-plane) possesses significant gradients neither in age nor in metallicity, which coincide with the values in both outer (>60 arcsec) and inner (<30 arcsec) regions in the mid-plane, $t \approx 4 \ldots 5$ Gyr, [Fe/H] $\approx − 0.15$ dex.

The vertical profile decomposition reveals two components with the scale-height values related as ~1: 3 at all radii outside the bar dominated region. At $r > 60$ arcsec both components are flaring and become twice as thick while their ratio still holds (Fig. 3).

NGC 4710 is the only object in our small sample where we detect statistically significant differences in [Mg/Fe] abundance ratios between the thin and thick disc components and where we see its radial gradients (see Fig. 2, middle panel). While the values coincide at slightly supersolar [Mg/Fe] $\approx + 0.15$ dex inside 30 arcsec, the region dominated by the bar, the thin disc α-enhancement drops to +0.05 dex at $30 < r < 60$ arcsec and then raises again at $r > 70$ arcsec to +0.15 dex, while thick disc stays nearly constant (+0.15. . . 0.20 dex) at all radii.

Also, NGC 4710 is the only galaxy out of three where dust can affect our stellar population analysis. This is true for the inner region ($r < 30$ arcsec) where we see the uneven distribution of dust in the archival optical (*HST*) and far-infrared (*Herschel*) images. However, we do not consider this area in our thick disc analysis. Beyond 30 arcsec, we can neglect the dust effects because it is not detected in any substantial amount on *Herschel* images.

3.3 NGC 5422

NGC 5422 has a single disc component as evident from its vertical density profile analysis. The two-dimensional decomposition by the S4G project reveals a bulge and one *thick* disc with the scale-length and scale-heights 24.3 and 6.7 arcsec (Salo et al. 2015). The disc warp semi-amplitude reaches 110 pc at $r = 3$ kpc. NGC 5422 also possesses a large scale non-star forming gaseous disc slightly inclined at 5° to the main plane manifested by weak emission lines.

For comparison with the mid-plane of NGC 5422 we placed a slit at 7 arcsec (~1050 pc) above it. Our profiles of kinematics and stellar population parameters extend to 70 arcsec (10.5 kpc). We expect that outside $r = 20$ arcsec the bulge influence becomes negligible. Not surprisingly, in those regions our analysis demonstrate stellar population properties and stellar velocity dispersion radial profiles consistent within uncertainties (Fig. 1, right plots). NGC 5422 is the only galaxy were we see an old thick disc ~8. . . 11 Gyr with slightly subsolar ~− 0.2 dex metallicity and a moderate α-enhancement

([Fe/H] ~0.15). The age and metallicity gradients in NGC 5422 are not statistically significant.

3.4 The diverse origin of thick discs

Several processes may act simultaneously during the formation of structures that we observe how as thick discs. When we extend our sample, our high quality observational data will allow us to evaluate the significance of every particular thick disc formation scenario not only for specific objects but also for different galaxy types. Presently, all three objects we describe are classified as S0-a galaxies, which certainly cannot give a full picture of the thick disc formation in late type spiral galaxies. Nevertheless, the assumption that S0s may be disc systems depleted their gas by star formation (see e.g. Larson et al. 1980) implies a possible evolutionary link between thick discs across the Hubble sequence.

According to theoretical predictions, we do not expect that in lenticular galaxies without strong spiral arms, the radial migration should play an important role. Given our very limited sample, it is difficult to test the relevance of the radial migration scenario from observations. One of the reasons is that depending on the initial distribution of the radial metallicity, very different radial profiles of stellar population parameters can emerge (see e.g. Curir et al. 2012). Nevertheless, the models by Minchev et al. (2015) predict a notable negative age gradient in thick discs because younger stars migrate further from the disc plane at larger radii. Our data extend substantially further in terms of surface brightness and, consequently, radial distances than in previous studies (Yoachim & Dalcanton 2008; Comerón et al. 2015), therefore the flat radial age profiles which we observe can rule out this formation model. On the other hand, this situation may occur if the radial migration was strong enough to flatten radial stellar population gradients in both thin and thick discs.

The rapid turbulent thick disc formation by Bournaud et al. (2009) looks plausible only for NGC 5422. This galaxy has a moderately α-enhanced very old stellar population in its disc that correspond to the duration of the star formation epoch of 1.5–2 Gyr (Thomas et al. 2005), if it had started to form at $z \approx 3$ and was finished by $z \approx 1.5$.

At the same time, we cannot clearly assess the importance of other thick disc formation mechanisms, such as minor mergers or accretion events, for all three galaxies. For example, very moderate negative or flat metallicity gradients in our thick and thin discs support the scenario of the disc thickening by minor mergers, because such events are expected to flatten metallicity gradients as demonstrated by numerical simulations (Qu et al. 2011) available in the GALMER data base (Chilingarian et al. 2010).

In addition to the above, we emphasize some environment related aspects, which may explain the formation and evolution features of disc subsystems under consideration.

The apparent multi-component structure in the mid-plane of NGC 4710 suggests a complex evolution history. We have to keep in mind that this galaxy belongs to the Virgo cluster. Despite of the fact that it is nowadays located at a significant distance from M 87 (~1.6 Mpc), we have a reason to believe that NGC 4710 already passed the cluster centre in the past. According to Koopmann et al. (2001), there is an abrupt truncation of *GALEX* UV and H$_\alpha$ fluxes, tracers of recent and ongoing star formation, beyond $r = 60$ arcsec. Moreover, the map of atomic hydrogen demonstrates the truncated profile and H I (as well as dust) is detected only within the inner 60 arcsec (Serra et al. 2012). We believe that we should see a similar end-product, if an initially thick disc had been forming

and growing until low redshift ($z = 0.5$ in this case) similarly to NGC 4111, and then the thin disc growth was fueled by additional gas in much larger amounts than in NGC 4111, which caused intense star formation and self-enrichment. Later, the ram pressure stripping (Gunn & Gott 1972) by the hot intracluster gas near the Virgo cluster centre strips the outer part ($r > 60$ arcsec) of the thin gaseous disc and quenches the star formation. The disc flaring would quickly occur beyond this radius because there will be no more gas and dynamically cold stars forming in the mid-plane – exactly as we observe in NGC 4710.

NGC 5422 does not have a young stellar component at all. It is a member of the sparse NGC 5485 group where at least four out of five other luminous galaxies are lenticulars with discs older than $t > 10$ Gyr (Peletier & Balcells 1996; Peletier et al. 1999). They all might have formed at $z = 2...3$ as *normal* discs and then exhausted their gas reservoirs around $z = 1$ and stopped forming stars. Since then, the group must have been evolving only by dry mergers. The NGC 5422 disc looks very similar to the face-on lenticular galaxy NGC 6340 (Chilingarian et al. 2009) that also lives in a sparse group.

After all, the three examples of edge-on thick discs revealed the diversity of properties that suggest a broad spectrum of their formation scenarios. Further clarifications on preferred scenarios will be obtained when our sample of deep spectroscopic observations extends.

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