

# Ages and abundances in large-scale stellar discs of nearby S0 galaxies<sup>★</sup>

O. K. Sil’chenko,<sup>1,2†</sup> I. S. Proshina,<sup>1</sup> A. P. Shulga<sup>1</sup> and S. E. Koposov<sup>1,3</sup>

<sup>1</sup>*Sternberg Astronomical Institute of the Lomonosov Moscow State University, Moscow, Russia*

<sup>2</sup>*Isaac Newton Institute of Chile, Moscow Branch, Moscow, Russia*

<sup>3</sup>*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA*

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## ABSTRACT

By undertaking deep long-slit spectroscopy with the focal reducer Spectral Camera with Optical Reducer for Photometrical and Interferometrical Observations (SCORPIO) of the Russian 6 m telescope, we studied stellar population properties and their variation with radius in 15 nearby S0 galaxies sampling a wide range of luminosities and environments. For the large-scale stellar discs of S0s, we have measured simple stellar population (SSP)-equivalent metallicities ranging from the solar one down to  $[Z/H] = -0.4$  to  $-0.7$ , rather high magnesium-to-iron ratios,  $[Mg/Fe] \geq +0.2$ , and mostly old SSP-equivalent ages. Nine of 15 ( $60 \pm 13$  per cent) galaxies have large-scale stellar discs older than 10 Gyr, and among those we find all the galaxies which reside in denser environments. The isolated galaxies may have intermediate-age stellar discs which are 7–9 Gyr old. Only two galaxies of our sample, NGC 4111 and NGC 7332, reveal SSP-equivalent ages of their discs of 2–3 Gyr. Just these two young discs appear to be thin, while the other, older discs have scale heights typical for thick stellar discs. The stellar populations in the bulges at radii of  $0.5r_e$  are on the contrary more metal rich than the solar  $Z_{\odot}$ , with the ages homogeneously distributed between 2 and 15 Gyr, being almost always younger than the discs. We conclude that S0 galaxies could not form in groups at  $z \approx 0.4$  as is thought now; a new scenario of the general evolution of disc galaxies is proposed instead.

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

## 1 INTRODUCTION

In the ‘tuning fork’ galaxy classification scheme by Hubble (1936) lenticular galaxies occupied an intermediate position between ellipticals and spirals. They looked homogeneously red and smooth, as ellipticals, implying that they contained an old stellar population, and they had at least two large-scale structural components, centrally concentrated spheroids (bulges) and extended stellar discs, as spirals. Hubble suggested that the morphological-type sequence might be an evolutionary sequence from the simplest shapes to more complex ones because his classification was ‘almost identical with the path of development derived by Jeans from purely theoretical investigations’ (Hubble 1926). Later, the opposite evolution was supposed by the dominant cosmological paradigm: pure discs – late-type spirals? – formed first, and later they merged into spheroids – bulges of early-type disc galaxies or elliptical galaxies. But in all schemes lenticulars remain the secondary products of galaxy evolution. The most common opinion is presently that

lenticular galaxies are former spirals which lost their gas and could not produce more young stars.

The transformation of spirals into lenticulars is thought to be related to dense environments. Indeed, within dense environments lenticulars are the dominant galaxy population (Dressler 1980; Postman & Geller 1984), whereas in the field the fraction of S0s is only about 15 per cent, with spirals being the majority (Naim et al. 1995). Within the typical group environments the fractions of S0s and spirals are comparable, both about 40–45 per cent (Postman & Geller 1984), and in clusters the fraction of S0s may reach 60 per cent (Dressler 1980). The studies of galaxy morphologies with the *Hubble Space Telescope* have shown that the morphological-type balance within dense environments changes abruptly at the redshifts of 0.4–0.5 (Dressler et al. 1997). The fraction of elliptical galaxies in clusters stays constant at  $\sim 20$ –30 per cent between  $z \approx 0.8$  and 0.0, while spiral galaxies, constituting about 50–70 per cent of all galaxies in high-redshift clusters, are replaced by lenticulars at the redshift of 0.4 (Fasano et al. 2000). According to these results, the exact place of S0 formation at  $z = 0.4$  was supposed to be clusters and the proposed mechanisms for this transformation were associated with dense environments via tidal effects and interaction with a hot intracluster medium (Spitzer & Baade 1951; Gunn & Gott 1971; Cowie & Songaila 1977; Larson, Tinsley & Caldwell 1980; Shaya & Tully 1984; Icke 1985; Byrd & Valtonen 1990; Moore et al. 1996;

<sup>★</sup> Based on the observations with the Russian 6 m telescope.

†E-mail: olga@sai.msu.su

Quilis, Moore & Bower 2000). However, recently some additional observational information was presented which gave evidence for the equal presence of lenticulars and spirals in the clusters and in groups at redshifts  $z = 0.4$ – $0.5$ . Wilman et al. (2009) found that at  $z = 0.4$  the fraction of S0s in groups is exactly the same as the fraction of S0s in clusters and exceeds significantly the fraction of S0s in the field, so they concluded that the group and subgroup environments were the main sites of the formation of S0 galaxies, and clusters at  $z = 0.4$  had then to accrete the groups together with their S0s. Moreover, Just et al. (2010) measured the strong evolution of the S0 fraction in massive groups with galaxy velocity dispersions of  $500$ – $750 \text{ km s}^{-1}$  between  $z = 0.4$  and  $0.0$ . So the probable place of the proposed galaxy transformation has shifted now from cluster to groups.

The information on galaxy morphologies at even higher redshifts,  $z > 1$ – $1.5$ , implies another possible way of S0 formation. Deep fields of the *Hubble Space Telescope* have provided high-resolution images of high-redshift galaxies; the statistics of the morphological types at  $z > 1$ – $1.5$  demonstrate the absence of shapes typical for lower redshifts (those of the ‘tuning fork’) and the dominance of clumpy irregular types: chains, nests, ‘head–tails’, etc. (van den Bergh et al. 1996; Elmegreen et al. 2005, 2007). Kinematical studies of gas motions within these chains and nests have shown that these are massive, of  $10^{10}$ – $10^{11} M_{\odot}$ , gravitationally bound discs where star formation proceeds in clumps with typical sizes of about 1 kpc and where the thickness of the discs matches just the clump sizes being 1–1.5 kpc (Genzel et al. 2008; Forster Schreiber et al. 2011). Theoretical considerations confirm that gas-rich discs at  $z > 2$  are gravitationally unstable and should fragment into clumps with typical masses of  $10^9 M_{\odot}$  (Noguchi 1999; Ceverino, Dekel & Bournaud 2010). The observed time-scales of star formation in these clumpy discs are much less than  $10^9 \text{ yr}$  – on average,  $2 \times 10^8 \text{ yr}$ , according to Genzel et al. (2008). It means that at  $z > 2$  we expect fast formation of thick stellar discs via effective consumption of gas by star formation during a few  $10^8 \text{ yr}$  with subsequent feedback (stellar winds of massive stars and supernova explosions), which should clear the discs of remaining gas and would produce S0 galaxies which will be 10–12 Gyr old at  $z = 0$ .

If the bulk of S0 galaxies were spirals at  $z > 0.4$ , or at lookback time of only 4 Gyr according to the modern Universe Lambda Cold Dark Matter (LCDM) time-scale, then star formation proceeded in their discs only 4–5 Gyr ago. In that case their discs should now contain stars as young as 4–5 Gyr and with the solar magnesium-to-iron ratio. Stellar populations in cluster elliptical galaxies are much older than 4 Gyr (Thomas et al. 2005); however, the mean integrated colours of the nearby ellipticals and lenticulars are the same (Buta & Williams 1995). Larson et al. (1980) explained this controversy with the aid of age–metallicity degeneracy: if the younger stellar population of S0s is also more metal rich than the stellar populations of ellipticals, then the colours might be the same. The age–metallicity degeneracy problem can be solved to determine both metallicity and mean age of the stellar populations in S0 discs by using e.g. Lick indices including  $H\beta$  (Worthey 1994) or by combining optical colours with the near-infrared (NIR) data (Bothun & Gregg 1990). There were numerous attempts of doing so, but with controversial results. By combining the optical colours with the NIR data, Bothun & Gregg (1990) found that the S0 discs are younger by 3–5 Gyr than their centres (which they called ‘bulges’), while Peletier & Balcells (1996) did not detect any age difference between the bulges and the discs in their sample of S0s, and MacArthur et al. (2004) found, among a few S0 galaxies, two or three where the centres were prominently younger than the outer discs. The dominant positive

age gradients along the radius up to several effective radii are found for a large sample of field S0 galaxies by Prochaska Chamberlain et al. (2011) from the grJH surface photometry. The similar photometric study of 53 S0 galaxies in the Virgo cluster by Roediger et al. (2011) has revealed zero mean age gradient along the radius and the very old centres of S0s ( $\langle T \rangle = 10.2 \pm 0.7 \text{ Gyr}$ ). The same scatter of conclusions is seen among the studies carried out by using spectral line indices. The early paper by Caldwell (1983), where the centres of S0s were assumed to be old *by definition*, demonstrated bluer  $U - V$  colours of the discs with respect to the  $\text{Mg}-(U - V)$  metallicity sequence for old stellar populations, so the discs were concluded to be younger than the ‘bulges’. Later, with the advent of Lick indices and modern stellar population models, Fisher, Franx & Illingworth (1996) found the discs to be older than the centres in a few nearby S0s. The same conclusion was reached by Bedregal et al. (2011) and Spolaor et al. (2010) for small samples of S0 Fornax members, including dwarfs and giants, while Mehlert et al. (2003), analysing data for Coma cluster member galaxies, did not see any age difference between the centres and the outer parts of the galaxies in their sample. Deep spectral observations of individual nearby S0 galaxies were also published: in NGC 3115 the disc is younger than the bulge (6 versus 12 Gyr) (Norris, Sharples & Kuntschner 2006), and in NGC 3384 the age trend is opposite (Sánchez-Blázquez et al. 2006). However, we would note that most of these studies probed the disc stellar populations at the radii of maximum 1–2 exponential scalelengths; the photometric study by Prochaska Chamberlain et al. (2011) and the study of NGC 3115 are the only ones reaching outer discs of their S0s.

In this work, we have measured variations of Lick indices along the radius up to 2–4 exponential scalelengths in 15 nearby lenticular galaxies in different environments. By using photometric decomposition, we have extracted the regions where the bulge or disc dominates, and have determined the mean [light-weighted or simple stellar population (SSP)-equivalent] ages, metallicities and magnesium-to-iron abundance ratios for the bulges and for the stellar discs. These data are crucial to evaluate currently available scenarios of formation of S0 galaxies. The paper is organized as follows. Section 2 presents our sample. Section 3 describes the observations and data reduction. Section 4 reviews the details of the photometric structures and gives our own photometric analysis of some moderately inclined galaxies of our sample. Section 5 presents the age and abundance measurements in the bulges and in the large-scale discs of the galaxies under consideration. Sections 6 and 7 contain the discussion and the conclusions, respectively.

## 2 THE SAMPLE

The sample consists of nearby lenticular galaxies for which deep long-slit spectra have been obtained at the Russian 6 m telescope during the last five years as a part of several observational programmes. The main body of the sample is the set of edge-on lenticular galaxies selected for the kinematical study and dynamical modelling by Natalia Sotnikova and observed in the frame of her observational proposal; the kinematical profiles for these galaxies are to be published later. For the purpose of this work we have taken the raw spectral data and have derived Lick index profiles. Four additional moderately inclined S0 galaxies come from our sample of nearby early-type disc galaxies – group members whose central parts have been studied earlier with the Multipupil Fiber Spectrograph of the 6 m telescope; the kinematical and Lick index data for the central parts of these galaxies have been partly published in Sil’chenko (2000), Sil’chenko & Afanasiev (2004) and Sil’chenko

**Table 1.** Global parameters of the galaxies.

Name	Type (NED <sup>a</sup> )	$R_{25}$ (arcsec) (RC3 <sup>b</sup> )	$R_{25}$ (kpc)	$B_T^0$ (RC3)	$M_B$	$M_K^c$	$(B - V)_T^0$ (RC3)	$V_r$ (km s <sup>-1</sup> ) (NED)	$D^d$ (Mpc)	$i_{\text{phot}}$ (LEDA <sup>e</sup> )	$PA_{\text{phot}}$ (RC3)	Environment <sup>f</sup>
N502	SA0 <sup>0</sup> (r)	34	4.9	13.57	-18.8	-22.6	0.95	2489	30	24°	—	1
N524	SA0 <sup>+</sup> (rs)	85	11.5	11.17	-21.1	-25.1	1.05	2379	28	6°	—	2
N1029	S0/a	41	9.3	13.32	-20.0	-23.7	—	3635	46.5	90°	70°	3
N1032	S0/a	97	15.7	12.29	-20.4	-24.3	1.00	2694	34	90°	68°	5
N1184	S0/a	85	12.5	13.44	-19.0	-24.3	—	2342	31	90°	168°	5
N2549	SA0 <sup>0</sup> (r)	117	8.9	12.00	-19.0	-22.9	0.93	1039	15.7	90°	177°	4
N2732	S0	63	8.2	12.85	-19.3	-23.2	0.96	1960	27	90°	67°	4
N3166	SAB(rs)0/a	144	16.2	11.01	-20.8	-24.6	0.87	1345	23	56°	87°	4
N3414	S0pec	106	12.0	11.86	-20.0	-23.9	0.97	1414	23.5	20° <sup>g</sup>	—	2
N4111	SA0 <sup>+</sup> (r):	137	9.5	11.60	-19.2	-23.2	0.89	807	14	84°	150°	0
N4570	S0	114	15.5	11.80	-20.5	-24.55	0.94	1730	28	90°	159°	0
N5308	S0-	112	15.7	12.42	-19.9	-23.95	0.92	2041	29	90°	60°	1
N5353	S0	66	10.8	11.98	-20.7	-25.0	0.97	2325	34	82°	145°	2
N7332	S0pec	122	6.6(13.6)	11.93	-18.3 (-19.9)	-22.2 (-23.8)	0.91	1172	11 (23)	90°	155°	4
I1541	—	23 <sup>e</sup>	8.5 <sup>e</sup>	15.15 <sup>e</sup>	-19.5 <sup>e</sup>	-23.5	1.04 <sup>h</sup>	5926	76	90°	36°	1

<sup>a</sup>NASA/IPAC Extragalactic Database.<sup>b</sup>Third Reference Catalogue of Bright Galaxies.<sup>c</sup> $K_{s,\text{tot}}$ , from 2MASS, are taken from the NED photometry lists.<sup>d</sup>Distances from NED, 'Cosmology corrected' option, except NGC 7332 where in parentheses there is  $D$  from Tonry et al. (2001).<sup>e</sup>Lyon-Meudon Extragalactic Database (LEDA).<sup>f</sup>Environments: 0 – cluster member, 1 – rich-group member, 2 – rich-group centre, 3 – loose-group member, 4 – loose-group centre, 5 – field.<sup>g</sup>An obviously wrong inclination of 77° is given for NGC 3414 in the LEDA.<sup>h</sup>The colour in the central aperture of 3 arcsec, according to Startseva, Sil'chenko & Moiseev (2009).

& Afanasiev (2006). The main global parameters of the galaxies studied in this work are given in Table 1.

The sample is small; however, the galaxies are homogeneously distributed over the luminosities, with their blue absolute magnitudes from -19 to -21 and located at different environments. We have one galaxy (NGC 4570) in the Virgo cluster where the intracluster medium influence is unavoidable, and one galaxy (NGC 4111) in the Ursa Major cluster where X-ray gas is not detected. Among group galaxies, NGC 524 and NGC 5353 are central galaxies embedded into X-ray haloes, NGC 5308 is a member galaxy in the X-ray bright group, and NGC 502 and IC 1541 though being members of rich galaxy groups lie outside the X-ray haloes of their groups (Osmond & Ponman (2004), and also some archive ASCA images). NGC 3414 is a central galaxy in the rich group undetected in X-ray. NGC 2732 is a modest host of a few faint satellites. NGC 1029, NGC 2549 and NGC 7332 are in triplets. By using the NASA/IPAC Extragalactic Database (NED) environment searcher, we did not find any galaxies within 300 kpc from NGC 1032 and NGC 1184 so in our Table 1 we characterized them as isolated-field galaxies.

### 3 OBSERVATIONS AND DATA REDUCTION

The long-slit spectral observations were made with the focal reducer SCORPIO<sup>1</sup> (Afanasiev & Moiseev 2005) installed at the prime focus of the Russian 6 m telescope (in the Special Astrophysical Observatory of the Russian Academy of Sciences). As the main goals were stellar kinematics and Lick indices  $H\beta$ , Mgb, Fe5270 and Fe 5335, we observed a quite narrow spectral range rich with absorption lines, 4800–5500 Å, by using the volume-phase grating 2300G. The slit width was 1 arcsec and the spectral resolution

about 2 Å. The CCD 2k × 2k EEV CCD 42–40 and later in 2010 the CCD 2k × 4k E2V CCD 42–90 were used as detectors, and the sampling along the slit was 0.36 arcsec pixel<sup>-1</sup>. The slit length is about 6 arcmin so the data from the edges of the slit were used as the sky background to be subtracted from the galaxy spectra. Inhomogeneities of the optics transmission and spectral resolution along the slit were checked with the high signal-to-noise twilight exposures. Since some of lenticular galaxies reveal weak emission lines in their spectra, and their stellar Lick index  $H\beta$  may be contaminated by the Balmer emission line of the ionized gas, we also obtained spectra of a redder spectral range for these galaxies. This was done using the volume-phase grating 1800R (6100–7100 Å), providing the spectral resolution of ~3 Å, or the grating 1200R (5700–7400 Å), providing the spectral resolution of ~5 Å. These data have been used to calculate the equivalent width of the  $H\alpha$  emission line. In order to do this for the bulge-dominated area, we summed the spectra over 1–3 arcsec intervals near the radius of  $0.5r_e$  for every bulge, and then made Gaussian multicomponent fitting of the  $[N\text{ II}]\lambda\ 6548+6583+H\alpha(\text{emission})+H\alpha(\text{absorption})$  line blend. The derived equivalent widths of the  $H\alpha$  emission line were used to calculate the correction for the  $H\beta$  index as it was described by Sil'chenko (2006). The discs in our sample are mostly emission free. The journal of all long-slit observations is presented in Table 2.

### 4 PHOTOMETRIC STRUCTURE OF THE SAMPLE GALAXIES

In order to match the stellar population properties to particular galaxy components, such as discs and bulges, we have to first of all analyse the light distribution in these galaxies.

The structural parameters of the edge-on sample galaxies are mostly taken from the work by Mosenkov, Sotnikova & Reshetnikov (2010) supplemented by Mosenkov & Sotnikova (private communication) where  $K_s$ -band Two Micron All Sky

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

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

Galaxy	Date	Exposure (min)	PA(slit)	Spectral range (Å)	Seeing (arcsec)
NGC 502	2008 Sept. 03	80	65°	4800–5500	2
NGC 502	2008 Sept. 03	80	155°	4800–5500	2
NGC 524	2007 Aug. 17	40	23°	6100–7100	1.5
NGC 524	2007 Oct. 19	160	127°	4800–5500	2
NGC 524	2008 Sept. 04	45	38°	6100–7100	1.3
NGC 524	2008 Sept. 04	20	115°	6100–7100	1.3
NGC 1029	2010 Nov. 06	90	70°	4650–5730	2.5
NGC 1032	2009 Oct. 16	100	68°	6100–7100	2.1
NGC 1032	2009 Oct. 17	120	68°	4825–5500	2.9
NGC 1184	2009 Oct. 14	120	168°	4825–5500	2.9
NGC 1184	2009 Oct. 15	180	168°	4825–5500	2.3
NGC 2549	2010 Dec. 07	180	177°	4650–5730	2.5
NGC 2549	2010 Dec. 25	150	145°	5700–7400	3
NGC 2732	2009 Oct. 12	120	152°	6100–7100	3
NGC 2732	2009 Oct. 12	120	67°	4825–5500	2.8
NGC 2732	2009 Oct. 15	120	67°	6100–7100	1.7
NGC 3166	2006 Apr. 28	80	86°	4800–5500	2.8
NGC 3414	2009 March 30	45	20°	6100–7100	1.5
NGC 3414	2009 March 31	100	150°	6100–7100	1.3
NGC 3414	2010 April 11	140	150°	4650–5730	3
NGC 4111	2009 March 30	45	150°	6100–7100	2
NGC 4111	2009 May 21	140	150°	4825–5500	1.3
NGC 4111	2009 Dec. 19	105	240°	4825–5500	3.6
NGC 4570	2010 April 08	120	159°	4650–5730	3
NGC 5308	2010 April 10	100	60°	4650–5730	3
NGC 5353	2009 April 05	45	145°	6100–7100	1.7
NGC 5353	2009 May 24	60	145°	4825–5500	3.4
NGC 7332	2009 Oct. 11	180	155°	4825–5500	1.1
NGC 7332	2009 Oct. 11	100	155°	6100–7100	2.5
IC 1541	2008 Sept. 02	30	25°	5700–7400	2.5
IC 1541	2010 Nov. 02	90	35°	4650–5730	1.2

Survey (2MASS) images are decomposed by means of the BUDDA software (de Souza, Gadotti & dos Anjos 2004): these galaxies are NGC 1029, 1184, 2549, 2732, 4111, 5308, 4570, 5353 and 7332. Since we know the 2MASS images to be rather shallow, we have checked the validity of the disc exponential scalelengths by decomposing the latest Sloan Digital Sky Survey (SDSS) data for the most of these galaxies in the  $r$  band with the GALFIT (Peng et al. 2002); the discrepancy of the found  $r$ -band scalelengths with those in the  $K_s$  band is of the order of a few arcseconds, or within the  $K_s$ -band scalelength estimate accuracy. The bulge effective radius for NGC 1032 is taken from Gorgas, Jablonka & Goudfrooij (2007).

The detailed study of the photometric structures of S0 galaxies IC 1541, NGC 502, NGC 524 and NGC 2732 has been undertaken by us through the  $BV$  and  $R$  imaging with the focal reducer SCORPIO of the 6 m telescope operating in imaging mode. The photometric structure of IC 1541 in the  $BV$  bands has been published by us earlier (Startseva et al. 2009). In face-on NGC 502 and NGC 524 of the NGC 524 group we have found compact bulges and two-tiered (antitruncated) large-scale exponential discs starting to dominate at  $R \approx 15$ –20 arcsec (Ilyina & Sil’chenko 2012).

NGC 3166 is a luminous early-type disc galaxy and the member of a loose group where it is located near the centre being almost as luminous as its nearest neighbour, NGC 3169. The structure of the galaxy is very complex, particularly in its central part. Although the galaxy is inclined to our line of sight (LOS) by at least 60°, with its line of nodes oriented nearly  $E - W$ , the ellipticity of the isophotes drops to zero at the radius of  $\sim 15$ –20 arcsec. Eskridge et al. (2002), using the results of their Ohio State University (OSU)

Nearby Galaxies Survey, identified the low surface brightness bar aligned perpendicular to the line of nodes. There were efforts to decompose the photometric structure of the galaxy: Fisher & Drory (2008) analysed the surface brightness profile in the radius range of 2–45 arcsec and found only a pseudo-bulge with the Sérsic index of  $n = 0.56$ , and Laurikainen et al. (2010) found three (!) bars in the central part of the galaxy though failing to fit the outer disc. We have adopted the bulge effective radius  $r_e = 5.4$  arcsec in the  $K_s$  band from Laurikainen et al. (2010); however, since the galaxy possesses a compact edge-on circumnuclear disc well seen up to  $R = 5$ –6 arcsec, for this galaxy we estimate the bulge stellar population properties *beyond* this circumnuclear disc, at  $R = 7.5$ –9 arcsec and not at  $R = 0.5r_e$ . By decomposing the SDSS  $r$ -band image, we have succeeded to derive parameters of a very extended, low surface brightness large-scale disc of the galaxy; it is the only example of our sample where we have not reached the radius of  $2h$  with our spectral data because its  $h > 5$  kpc.

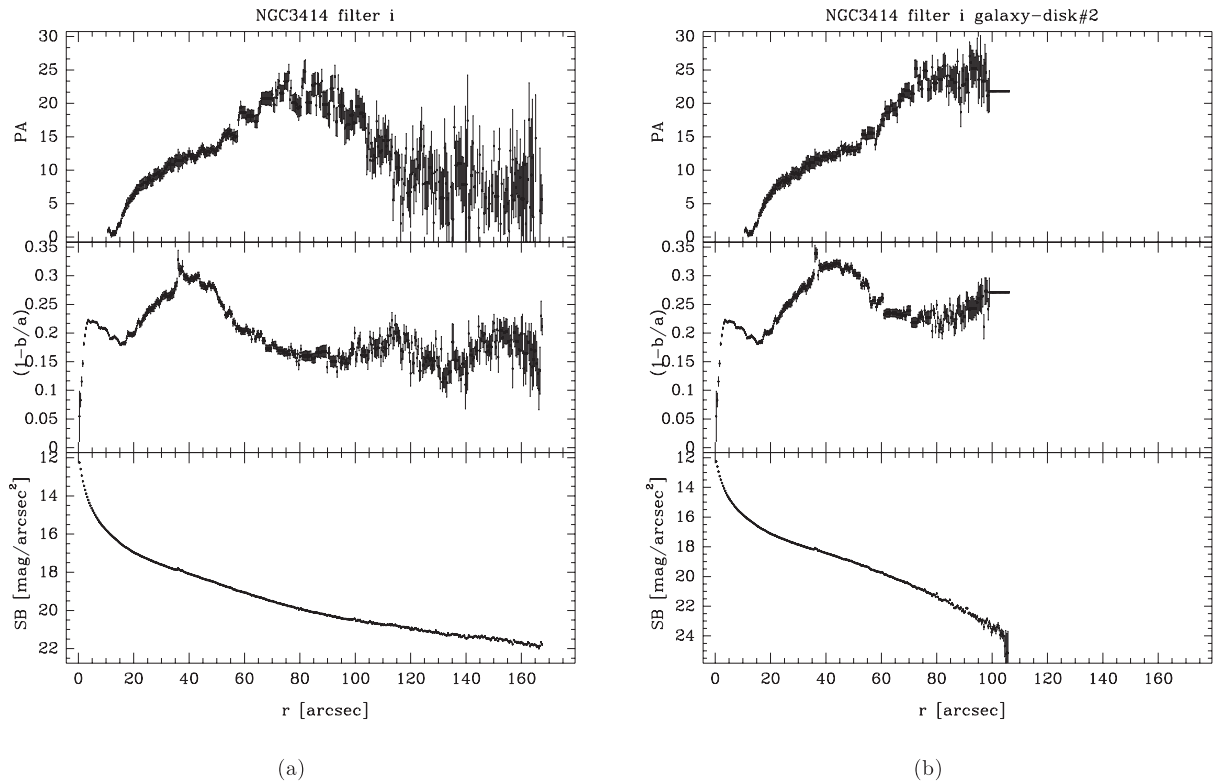
The bulge effective radii in the  $K_s$  band for NGC 524 and NGC 3414 are taken from Laurikainen et al. (2010).

The decomposition results in the optical bands for the moderately inclined sample galaxy NGC 3414 are presented below.

#### 4.1 The global structure of NGC 3414

Due to its peculiar appearance and strong non-axisymmetry, the structure of NGC 3414 requires a careful approach. There are controversial points of view on the 3D orientation of this galaxy: Baggett, Baggett & Anderson (1998) and Chitre & Jog (2002)





**Figure 1.** The results of the isophotal analysis for the *i*-band image of NGC 3414: left – for the full image, right – for the residual image after subtracting the model outer disc. In both plots, top – the position angle of the isophote major axis, middle – the isophote ellipticity, bottom – the azimuthally averaged surface brightness profiles.

consider it as a face-on S0 with a high-contrast thin bar, while Whitmore et al. (1990) and Laurikainen, Salo & Buta (2005) treat it as an edge-on galaxy with a large-scale polar disc.

We analysed a photometric structure of the galaxy by applying the 2D decomposition software *BUDDA* (de Souza et al. 2004) to the data taken from the SDSS/Data Release 7 (DR7) archive (Abazajian et al. 2009). The images were sky-subtracted according to the header notification. The used version of the *BUDDA* allowed us to decompose a galaxy into one exponential disc and a Sérsic bulge. However, we know that the slope of the exponential disc profile may change along the radius – discs may be two tiered, truncated or antitruncated (Pohlen & Trujillo 2006; Erwin, Pohlen & Beckman 2008). To take into account this possibility, we have invented a more complex approach to the galaxy decomposition. Based on isophotal analysis results, we determine an (outer) radius range where the thin disc dominates – it is the (outer) zone with the isophote ellipticity staying constant along the radius at a value corresponding to  $1 - \cos i$  where  $i$  is the disc inclination to the LOS. The isophote analysis has been made in the frame of the *IRAF* software (Fig. 1). After that we masked the inner part of the galaxy and applied the *BUDDA* procedure only to the outer disc-dominated zone. After obtaining the parameters of the outer disc, we constructed a 2D model disc image, subtracted it from the full galaxy image and then applied the *BUDDA* for the second time, this time to the residual image, to derive the parameters of the inner disc and of the bulge. In NGC 3414 the isophote ellipticity comes to a constant level only at  $R > 85$  arcsec, and it is a rather low ellipticity: the outer stellar disc is indeed close to face-on orientation. The inner disc, inside  $R = 80$  arcsec, has a shorter scalelength, a higher visible ellipticity, and contains perhaps a bar (Fig. 1). The full decomposition results in three bands, *gri*, are given in Table 3.

## 5 AGE AND METALLICITY ALONG THE RADIUS

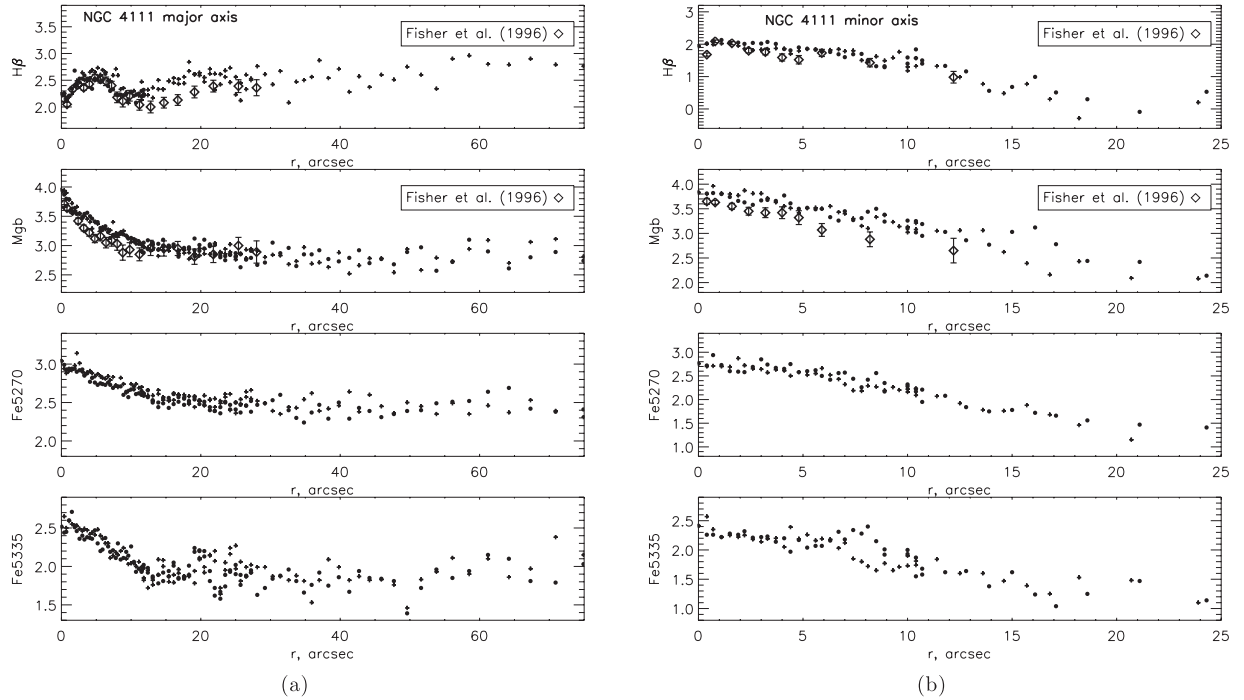
Focusing on  $H\beta$ , Mgb, Fe5270 and Fe5335, we have measured the Lick index profiles up to large distances from the galaxy centres exceeding two exponential scalelengths in almost all cases. The Lick index system was controlled for every observational run with a sample of standard Lick stars (Worthey et al. 1994) in the way described by Baes et al. (2007).

In Fig. 2 we show the Lick index profiles measured along the major and minor axes in NGC 4111. The comparison to the previous measurements of Mgb and  $H\beta$  along the major and minor axes done for this galaxy by Fisher et al. (1996) shows that our profiles are twice as extended. Two halves of the profiles, the northern and southern ones, are in good agreement with each other, with the exception of the  $H\beta$  profile where we have not been able to measure the northern part because of the low recession velocity of the stellar component resulting in a cutoff of the blue-continuum band of the  $H\beta$  index. The low point-to-point scatter till the last measured radii gives evidence for the high accuracy of the Lick index measurements even in the outer part of the disc.

Fig. 3 presents four more examples of our Lick index profiles measured along the major axes of the edge-on lenticular galaxies. One can see very compact central parts with rapid variations of the Lick indices; these are the bulge-dominated zones. Outside these zones, the Lick index profiles look rather flat. For the outer parts, we have binned index measurements in radial ranges of 5–10 arcsec; the errors shown are standard errors of the means. As a comparison to our data, in Fig. 3 we have also plotted the results of Gorgas et al. (2007) and Proctor & Sansom (2002) obtained from long-slit spectra along the *minor* axes of the galaxies. Their studies were

**Table 3.** NGC 3414: parameters of the brightness profile fitting by a three-component Sérsic model.

Component	Radius range of fitting (arcsec)	$n$	$PA_0$	$1 - bla$	$h_0$ (arcsec)	$h_0$ (kpc)	$r_e$ (arcsec)
NGC 3414, $i$ band							
Outer disc	$>85$	1	$3^\circ$	$0.05 \pm 0.03$	$56 \pm 14$	$6.4 \pm 1.6$	–
Inner disc	20–70	1	$25^\circ \pm 4^\circ$	$0.27 \pm 0.05$	$18 \pm 2$	$2.0 \pm 0.2$	–
Central bulge	$<15$	$2.1 \pm 0.4$	$10^\circ \pm 8^\circ$	$0.18 \pm 0.05$	–	–	$3.8 \pm 0.4$
NGC 3414, $r$ band							
Outer disc	$>85$	1	$3^\circ$	$0.08 \pm 0.05$	$63 \pm 19$	$7.2 \pm 2.2$	–
Inner disc	20–70	1	$25^\circ \pm 4^\circ$	$0.26 \pm 0.05$	$17 \pm 2$	$1.9 \pm 0.2$	–
Central bulge	$<15$	$2.1 \pm 0.4$	$10^\circ \pm 7^\circ$	$0.18 \pm 0.05$	–	–	$3.5 \pm 0.3$
NGC 3414, $g$ band							
Outer disc	$>85$	1	$3^\circ$	$0.06 \pm 0.04$	$48 \pm 16$	$5.5 \pm 1.8$	–
Inner disc	20–70	1	$25^\circ \pm 5^\circ$	$0.31 \pm 0.07$	$17 \pm 2$	$1.9 \pm 0.2$	–
Central bulge	$<15$	$2.2 \pm 0.9$	$10^\circ \pm 11^\circ$	$0.15 \pm 0.05$	–	–	$3.0 \pm 0.4$

**Figure 2.** Radial profiles of the Lick indices  $H\beta$ ,  $Mgb$ ,  $Fe5270$  and  $Fe5335$  as measured from the SCORPIO spectral data along the major (a) and minor (b) axes of NGC 4111. The dots and crosses refer to different sides of the slit with respect to the centre; the data by Fisher et al. (1996) are overlotted for comparison.

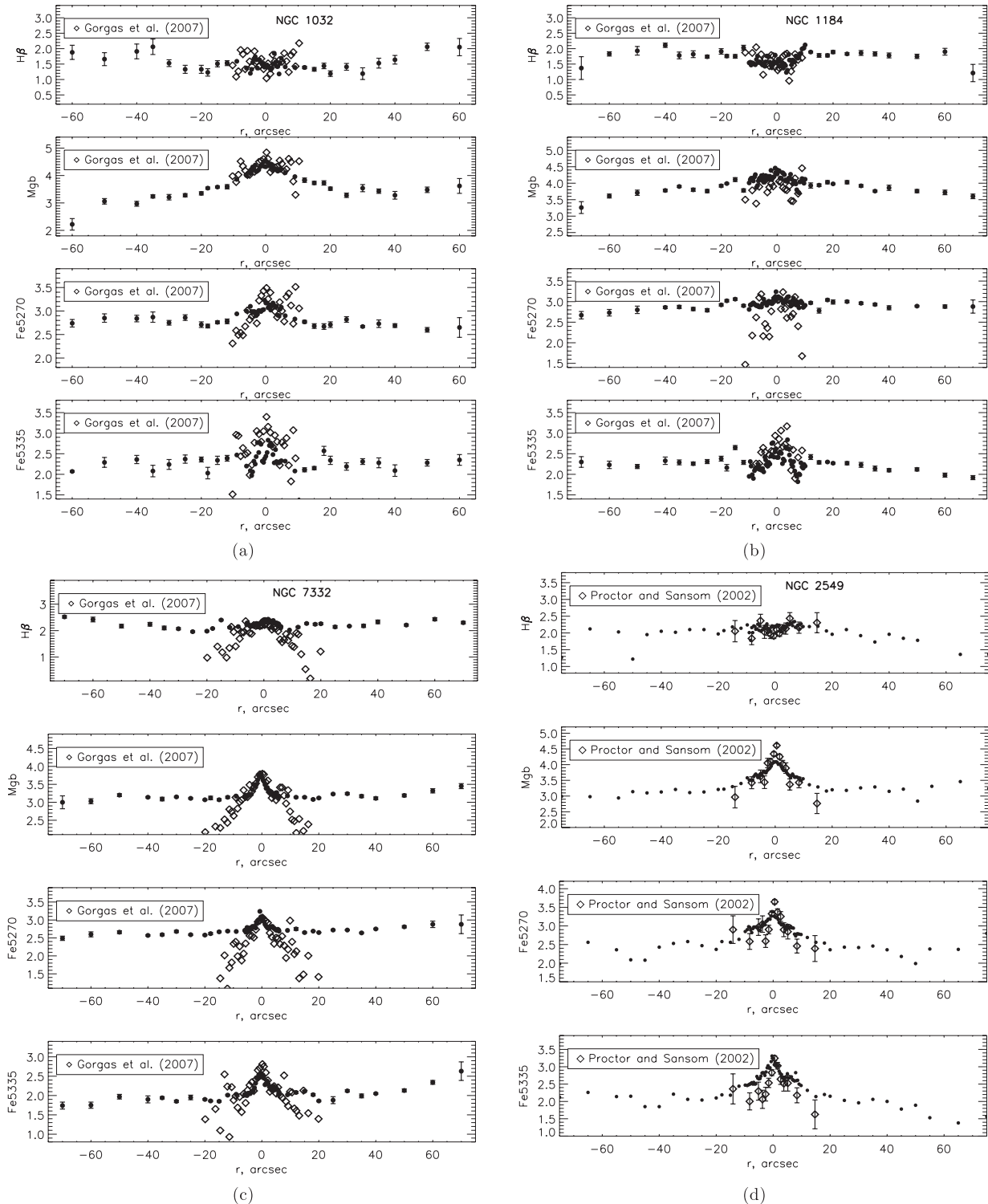
concentrated exclusively on the bulges. In the centres of the profiles the agreement with our data is almost perfect which confirms our good calibration on to the standard Lick index system and insignificant contributions of the discs into the spectra along the major axes at  $R < 5\text{--}10$  arcsec.

Let us consider separately the bulges and the discs of the galaxies in our total sample.

### 5.1 The bulges

In order to characterize the bulges, we have decided to probe their stellar population properties at the radii of  $0.5r_e$  where  $r_e$  refers to the effective radii of the bulges *after* the surface brightness profile decomposition. Since we have photometric decomposition results for all our galaxies, we have estimated the contribution of the discs to the surface brightness at  $R = 0.5r_e$  by extrapolating the outer exponential disc profiles towards the centres of the galaxies. These

estimates can be used to correct the bulge Lick indices measured at  $R = 0.5r_e$  for the disc contributions by assuming a constant level of disc Lick indices over the whole galaxies. In all cases, the disc contributions are rather small and affect the bulge Lick indices only within  $0.15 \text{ \AA}$  for  $H\beta$ ,  $0.4 \text{ \AA}$  for  $Mgb$  and  $0.2 \text{ \AA}$  for  $\langle Fe \rangle \equiv (Fe5270 + Fe5335)/2$ . The halves of the effective radius values, mostly in the  $K_s$  band, and the corrected Lick indices  $H\beta$ ,  $Mgb$  and  $\langle Fe \rangle$  for the bulges are listed in Table 4. Seven galaxies of 15 have noticeable Balmer emission lines in their central spectra; the equivalent widths of the  $H\alpha$  emission lines, which are measured at  $R = 0.5r_e$  by applying Gaussian multicomponent fitting to the total line profiles taking into account also the wide stellar  $H\alpha$  absorption line, are listed in Table 4 too. Furthermore, before using the  $H\beta$  Lick index to determine the stellar population age and metallicities, we calculate the  $H\beta$  index corrections for the emission. The  $H\beta$  emission-line intensities are related to the  $H\alpha$  emission-line intensities by ionization models under the assumption of the excitation mechanisms.



**Figure 3.** Radial profiles of the Lick indices  $H\beta$ ,  $Mgb$ ,  $Fe5270$  and  $Fe5335$  as measured from the SCORPIO spectral data in (a) NGC 1032, (b) NGC 1184, (c) NGC 7332 and (d) NGC 2549 along their major axes. For comparison, the analogous profiles along the *minor* axes in the same galaxies published by Gorgas et al. (2007) and Proctor & Sansom (2002) are overplotted.

The largest correction corresponds to the gas excitation by young stars,  $\Delta H\beta \approx 0.4 \text{ EW}(H\alpha_{\text{emis}})$  (Burgess 1958); other mechanisms including effects of dust give steeper Balmer decrements. Our galaxies are of early type and do not reveal clear signs of current star formation. To calculate the  $H\beta$  corrections, we choose the empirical Balmer decrement found by Stasinska & Sodr  (2001) for a large

sample of disc galaxies which corresponds to the mixed gas excitation nature. The detailed description of the procedure can be found in Sil'chenko (2006). In any case, for the galaxies in our sample the largest possible correction is below  $0.4 \text{ \AA}$ .

To determine the stellar population properties, we compare our measured indices to the models of SSP by Thomas et al.

**Table 4.** Stellar population parameters of the bulges.

NGC/IC	$0.5r_e$ (arcsec)	EW(H $\alpha$ ) ( $\text{\AA}$ )	H $\beta$	Mgb	(Fe)	$T$ (Gyr)	[Z/H]	[Mg/Fe]
N502	1.5	–	1.78 $\pm 0.02$	4.41 $\pm 0.04$	2.88 $\pm 0.02$	$6 \pm 0.5$	+0.3	+0.20 $\pm 0.01$
N524	4.4	0.53	1.67 $\pm 0.02$	4.39 $\pm 0.01$	2.41 $\pm 0.04$	$11 \pm 1$	+0.0	+0.35 $\pm 0.02$
N1029	2	0.3 <sup>a</sup>	1.53 $\pm 0.09$	4.81 $\pm 0.07$	3.10 $\pm 0.11$	$10 \pm 2$	+0.4	+0.18 $\pm 0.05$
N1032	6	0.95	1.51 $\pm 0.09$	4.38 $\pm 0.07$	2.67 $\pm 0.07$	$8 \pm 2$	+0.2	+0.26 $\pm 0.04$
N1184	6	–	1.43 $\pm 0.04$	4.23 $\pm 0.04$	2.57 $\pm 0.03$	$15 \pm 2$	0.0	+0.25 $\pm 0.02$
N2549	6	–	2.32 $\pm 0.04$	3.71 $\pm 0.02$	2.89 $\pm 0.02$	$2 \pm 0.3$	+0.5	+0.13 $\pm 0.01$
N2732	4	0.38	2.09 $\pm 0.04$	3.75 $\pm 0.03$	2.58 $\pm 0.02$	$3 \pm 0.5$	+0.2	+0.22 $\pm 0.01$
N3166	2.7	–	2.16 $\pm 0.07$	3.26 $\pm 0.06$	2.64 $\pm 0.07$	$4 \pm 0.7$	+0.1	+0.08 $\pm 0.04$
N3414	3	0.61	1.23 $\pm 0.07$	4.56 $\pm 0.03$	2.75 $\pm 0.04$	$>12$	+0.0	+0.25 $\pm 0.02$
N4111	5	0.14(N)–0.97(S)	2.67 $\pm 0.04$	3.52 $\pm 0.03$	2.70 $\pm 0.02$	$<2$	$>+0.3$	+0.16 $\pm 0.01$
N4570	5.5	–	1.51 $\pm 0.09$	4.19 $\pm 0.04$	2.62 $\pm 0.04$	$14 \pm 2$	0.0	+0.23 $\pm 0.02$
N5308	5.5	–	1.49 $\pm 0.05$	4.32 $\pm 0.05$	2.48 $\pm 0.03$	$15 \pm 2$	–0.05	+0.30 $\pm 0.02$
N5353	6	–	1.63 $\pm 0.08$	5.05 $\pm 0.04$	2.98 $\pm 0.02$	$7 \pm 2$	+0.5	+0.28 $\pm 0.02$
N7332	4.5	0.22	2.28 $\pm 0.02$	3.22 $\pm 0.01$	2.45 $\pm 0.02$	$3 \pm 0.3$	+0.1	+0.16 $\pm 0.01$
I1541	2.5	–	2.14 $\pm 0.10$	4.09 $\pm 0.05$	2.50 $\pm 0.10$	$3.3 \pm 0.7$	+0.25	+0.31 $\pm 0.05$

<sup>a</sup>Measured by Jansen et al. (2000) in the central  $7 \times 3$  arcsec spectrum of NGC 1029.

(2003) for several values of the magnesium-to-iron abundance ratio. Fig. 4 presents the index–index diagnostic diagrams which allow us to break the age–metallicity degeneracy and to determine SSP-equivalent ages, metallicities and magnesium-to-iron abundance ratios for the stellar populations of the bulges which are also listed in Table 4. As one can see, the bulges have mostly  $[\text{Mg}/\text{Fe}] = +0.1$  to  $+0.3$  dex, and a range of SSP-equivalent ages from  $<2$  to 15 Gyr. The total metallicities are solar and higher.

We have tried to find correlations between the parameters of the stellar populations of the bulges and the stellar velocity dispersions at  $R = 0.5r_e$ ; the results are presented in Table 6. In our small sample we have not found any correlation of the total metallicity with the stellar velocity dispersion measured by us *at the same radius*,  $0.5r_e$ ; marginal, just below  $2\sigma$  correlations however exist between the age and  $\sigma_*$ , and between  $[\text{Mg}/\text{Fe}]$  and  $\sigma_*$  (Fig. 5). Similar results were obtained by Howell for the sample of nearby field ellipticals (Howell 2005) and by us for the sample of the bulges of 80 nearby S0s (Sil’chenko 2008). For Fig. 5 we have calculated the regressions:  $[\text{Mg}/\text{Fe}] = (0.49 \pm 0.23)\log \sigma_* - (0.83 \pm 0.50)$ , in full agreement with the recent results of Annibali et al. (2010) for a sample of early-type galaxies (ellipticals+lenticulars) who give the slope of  $0.42 \pm 0.22$  and the zero-point of  $-0.74 \pm 0.46$ . However, our regression for the age,  $\log T(\text{yr}) = (1.69 \pm 0.75)\log \sigma_* - (6.2 \pm 1.6)$ , is much steeper than that by Annibali et al. (2010).

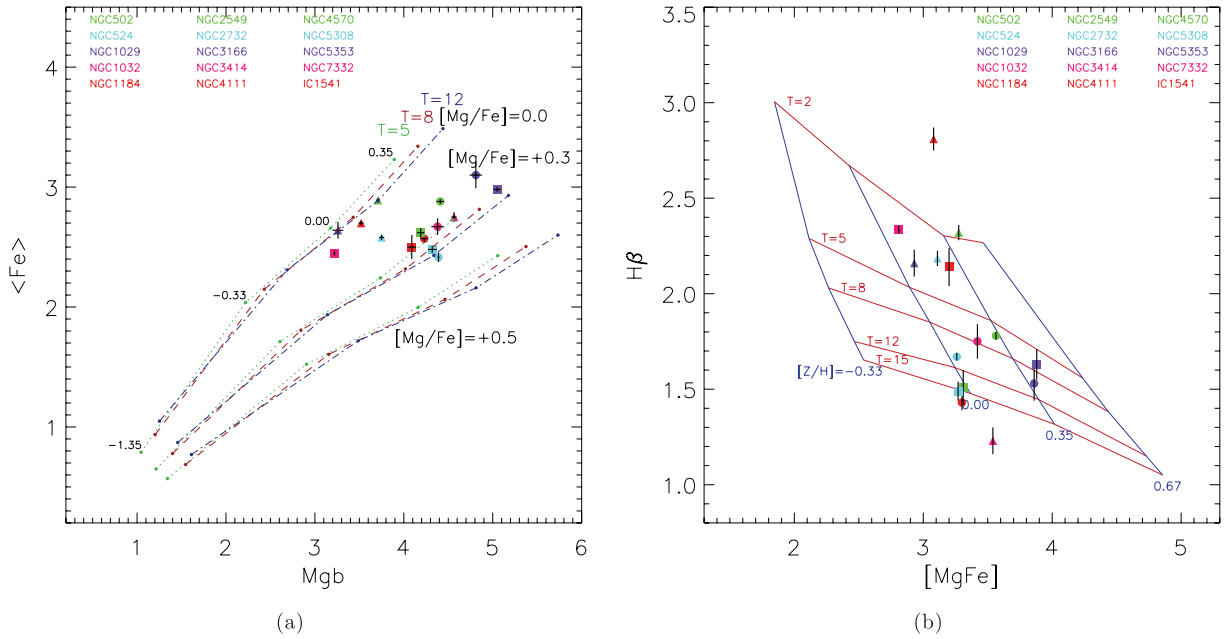
## 5.2 The discs

We tried to probe the outer parts of the discs where the bulge contributions are negligible and where there is no ionized gas so the

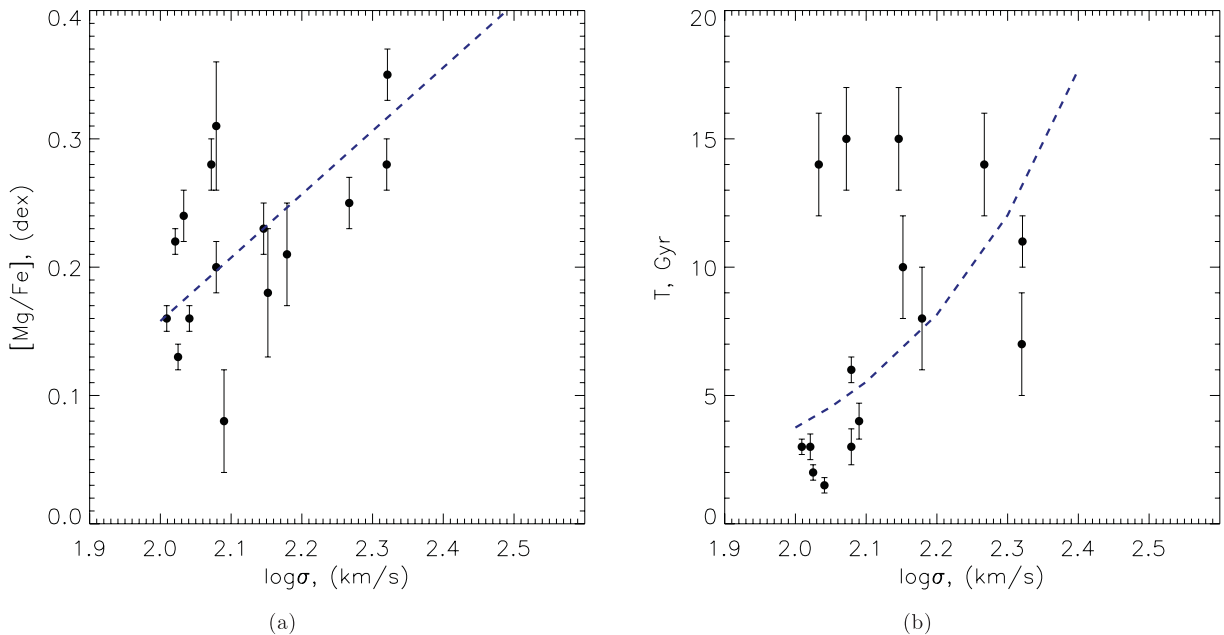
emission line H $\beta$  does not complicate the stellar age estimate. For NGC 502, we have summed two cross-sections at *different* position angles, after assuring that because of the symmetrical slit orientations with respect to the kinematical major axis they have identical stellar LOS velocity profiles and that the Lick index radial distributions do not have systematic shifts relative to each other. The only complicated case was NGC 3414 where we were restricted to the inner part of the antitruncated disc,  $R < 60$  arcsec, which is strongly polluted by the Balmer emissions. We tried to correct the Lick index H $\beta$  using our procedure (as described above), but perhaps some residual contamination remained. Finally, we averaged the Lick index measurements in the discs over rather extended radial intervals where the discs dominate photometrically and where the index profiles look rather flat. These intervals are indicated in the Table 5, as well as the mean Lick indices with their errors. As before, the errors are errors of the means calculated from 3–7 individual points.

Fig. 6 presents the diagnostic index–index diagrams where our measurements for the large-scale discs of the sample lenticular galaxies are compared to the SSP models by Thomas et al. (2003). One can see that the stellar discs of our lenticulars are mostly old,  $T_{\text{SSP}} = 8$  Gyr and older; only two galaxies, just those with young pseudo-bulges, NGC 4111 and NGC 7332, have also young large-scale stellar discs. The mean metallicities of stellar populations in the discs are mostly subsolar – only three youngest discs reach solar metallicity; in NGC 502, NGC 1029, NGC 3166 and NGC 3414 the mean disc stellar metallicities are very low,  $[\text{Z}/\text{H}] = -0.4$  to  $-0.7$ , as we can see from comparison of their location at the age-diagnostic diagram with some globular clusters of our Galaxy (the SSP models for such metal-poor systems are perhaps not particularly good).





**Figure 4.** Diagnostic index–index diagrams for the bulges at  $0.5r_e$  from the centre. Different galaxies are coded by different colours and different signs; in the legend the first column contains galaxies coded by circles, the second column the galaxies coded by triangles and the third column the galaxies coded by squares. (a) The  $\langle \text{Fe} \rangle$  versus  $\text{Mgb}$  diagram. The SSP models by Thomas, Maraston & Bender (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. (b) The age-diagnostic diagram for the stellar populations in the central parts of the galaxies under consideration; the  $H\beta$  index measurements are rectified from the emission contamination where it is, as described in the text. The stellar population models by Thomas et al. (2003) for  $[\text{Mg}/\text{Fe}] = +0.3$  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.



**Figure 5.** The correlations found by us for the bulges of S0 galaxies, those of the magnesium-to-iron ratio (a) and the age (b) versus the stellar velocity dispersion at the radius of  $0.5r_e$  (the half effective radii of the decomposed bulges); the blue dashed lines present the regressions (the formulae are in the text).

And the most striking feature of the large-scale discs in our lenticular galaxies is their high magnesium-to-iron abundance ratio: in every galaxy but NGC 1032 the  $[\text{Mg}/\text{Fe}]$  of the disc is  $+0.2$  to  $+0.5$ . If we compare these stellar population characteristics to those of stars of our Galaxy, they would resemble the thick disc of the Milky Way

(MW) (Fuhrmann 2008), with its age above 10 Gyr, subsolar stellar metallicities and  $\alpha$  elements overabundance.

Concerning the usually probed correlations, there is certainly no correlation between the metallicity or  $[\text{Mg}/\text{Fe}]$  ratio and the mass characteristics of the discs,  $V_{\text{rot}}^2 + \sigma_*^2$  (Table 6). For these particular

**Table 5.** Stellar population parameters of the discs.

NGC/IC	Scalelength ( $h$ in arcsec) (Band),	Radius range (arcsec)	H $\beta$	Mgb	(Fe)	$T$ , Gyr	[Z/H]	[Mg/Fe]
N502	10(V), 9.5( $r$ )	20–30	1.26 $\pm 0.08$	2.30 $\pm 0.21$	1.54 $\pm 0.15$	$> 12$	$< -0.5$	+0.20 $\pm 0.08$
N524	9(V)	25–65	1.56 $\pm 0.10$	3.66 $\pm 0.04$	2.23 $\pm 0.05$	$15 \pm 3$	$-0.2$	+0.30 $\pm 0.02$
N1029	9(K)	20–35	0.85 $\pm 0.08$	3.62 $\pm 0.06$	1.70 $\pm 0.09$	$> 12$	$< -0.4$	+0.46 $\pm 0.02$
N1032	29( $r$ )	40–60	1.87 $\pm 0.07$	3.28 $\pm 0.12$	2.48 $\pm 0.04$	$9 \pm 2$	$-0.1$	+0.12 $\pm 0.05$
N1184	27( $r$ )	40–60	1.88 $\pm 0.05$	3.74 $\pm 0.03$	2.50 $\pm 0.02$	$7 \pm 1$	0.0	+0.20 $\pm 0.01$
N2549	24( $r$ )	40–75	1.64 $\pm 0.13$	3.12 $\pm 0.05$	2.09 $\pm 0.07$	$15 \pm 4$	$-0.3$	+0.26 $\pm 0.05$
N2732	10(R)	25–45	1.91 $\pm 0.04$	3.52 $\pm 0.03$	2.17 $\pm 0.10$	$8 \pm 1$	$-0.1$	+0.29 $\pm 0.04$
N3166	49( $z$ ), 62( $r$ )	40–60 <sup>b</sup>	1.44 $\pm 0.15$	1.98 $\pm 0.08$	1.24 $\pm 0.26$	$> 12$	$< -0.5$	+0.26 $\pm 0.11$
N3414	17( $r$ )	25–60	1.12 $\pm 0.07$	3.09 $\pm 0.09$	1.82 $\pm 0.07$	$> 12$	$-0.4$	+0.33 $\pm 0.05$
N4111	28( $r$ )	40–70 <sup>a</sup>	2.68 $\pm 0.09$	2.82 $\pm 0.07$	2.20 $\pm 0.05$	$2 \pm 0.3$	0.0	+0.19 $\pm 0.04$
N4570	25( $r$ )	30–80	1.46 $\pm 0.04$	3.55 $\pm 0.04$	2.10 $\pm 0.03$	$15 \pm 1$	$-0.2$	+0.35 $\pm 0.02$
N5308	20( $r$ )	30–50	1.41 $\pm 0.02$	3.50 $\pm 0.04$	2.22 $\pm 0.02$	$15 \pm 1$	$-0.2$	+0.29 $\pm 0.02$
N5353	9( $r$ )	35–50 <sup>a</sup>	1.77 $\pm 0.23$	3.75 $\pm 0.09$	2.38 $\pm 0.12$	$10 \pm 5$	$-0.1$	+0.36 $\pm 0.07$
N7332	22( $r$ )	30–70	2.26 $\pm 0.04$	3.18 $\pm 0.04$	2.36 $\pm 0.04$	$3.5 \pm 0.3$	0.0	+0.18 $\pm 0.03$
I1541	7(V)	10–20	1.62 $\pm 0.15$	3.43 $\pm 0.14$	2.30 $\pm 0.24$	$15 \pm 5$	$-0.2$	+0.24 $\pm 0.14$

<sup>a</sup>Only the southern part of the disc is measured.<sup>b</sup>Only the eastern part of the disc is measured.

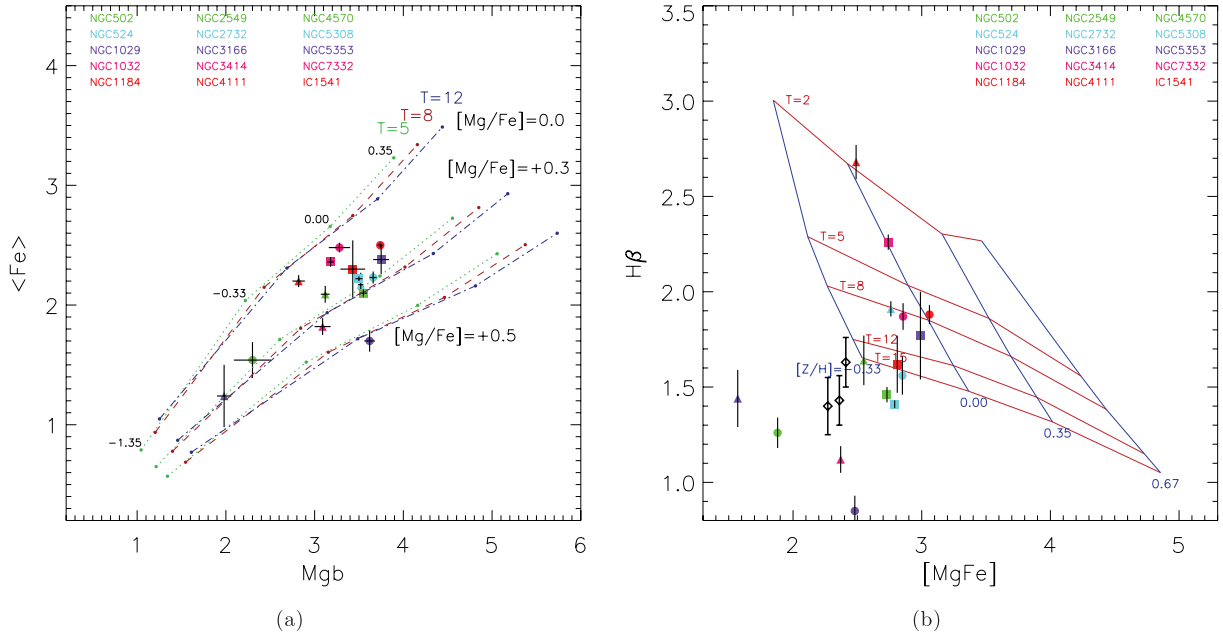
correlations, we have analysed only edge-on galaxies, so here the stellar velocity dispersions measured along the LOS are close to the tangential components of the stellar chaotic motions.

Another set of possible correlations may exist between the properties of the disc stellar populations and the environment density. To quantify the environment density, we took the numbers of galaxies in the groups to which the sample galaxies belong. To make the estimates as homogeneous as possible, we used the recent group catalogue by Makarov & Karachentsev (2011) for most galaxies; only NGC 1029 which is absent in the catalogue by Makarov & Karachentsev (2011) is attributed according to the catalogue of isolated triplets by Karachentseva, Karachentsev & Shcherbanovskiy (1979), and for IC 1541, which is too far from us to be involved into the catalogue by Makarov & Karachentsev (2011), we have used the estimates from the work by Mahdavi & Geller (2004). Fig. 7 presents the plots of the disc ages and magnesium-to-iron ratios versus the environment density. For the age, the correlation is surely absent. We can only conclude from the right-hand plot of Fig. 7 that in sparse environments the disc age estimates cover the full range of possible values; in other words, the S0 galaxies in sparse environments sometimes rejuvenate their discs after  $z < 1$ .

Several galaxies have rather extended Lick index profiles, and we are able to estimate stellar population parameters gradients *within the discs* (Fig. 8). Again we see a difference between the galaxies in dense environments having old discs and the galaxies in sparse environments having intermediate-age discs. In NGC 5308

and NGC 4570 the discs are homogeneously old at all radii, and the metallicity gradient between  $R = 2.5$  kpc and  $R \approx 6$  kpc (if we assume that NGC 4570 is at the distance of the Virgo cluster) does not exceed  $-0.04$  dex kpc<sup>-1</sup> that is quite typical also for early-type spiral galaxies (Zaritsky, Kennicutt & Huchra 1994). The isolated galaxy NGC 1184 shows negligible gradients both in age and abundances. In NGC 7332, the member of a non-interacting triplet, and in NGC 1032, isolated, the mean stellar age *falls* along the radius, from 5 to 2.5 Gyr in the former and from 10 to 8 Gyr in the latter. Consequently, the metallicity gradient is positive in NGC 7332 and zero in NGC 1032: the prolonged star formation in the outer discs have increased there the mean stellar metallicity. NGC 2549, the loose-group central galaxy, demonstrates quite a different behaviour: its SSP-equivalent stellar age rises significantly between  $R = 40$  ( $\sim 3$  kpc) and 70 arcsec ( $\sim 5$  kpc), from  $6.5 \pm 0.5$  to  $\geq 12$  Gyr, while the metallicity decreases moderately, by 0.15 dex, so the metallicity gradient can be estimated as  $-0.08$  dex kpc<sup>-1</sup>. Here we must keep in mind that NGC 2549 has a wide surface-brightness excess – probably, a star-forming-ring relic – at the radius of  $R = 25$ –40 arcsec (Seifert & Scorza 1996).

In NGC 524 which has an antitruncated large-scale stellar disc (Ilyina & Sil'chenko 2012) with the high surface brightness inner part, we are able to estimate separately the parameters of the stellar populations in the inner,  $r = 10$ –25 arcsec, and in the outer,  $r = 25$ –65 arcsec, stellar discs. We found  $H\beta = 1.62$  and  $[Mg/Fe] = 2.85$  for the inner disc, so the parameters of the stellar populations are  $T = 13 \pm 2$  Gyr and  $[Z/H] = -0.1$ . We can state that the inner disc looks



**Figure 6.** Diagnostic index–index diagrams for the large-scale stellar discs averaged over their full extension. The different galaxies are coded by different colours and different signs; in the legend the first column contains galaxies coded by circles, the second column the galaxies coded by triangles and the third column the galaxies coded by squares. (a) The  $\langle \text{Fe} \rangle$  versus Mgb diagram. The SSP 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. (b) The age-diagnostic diagram for the stellar populations in the large-scale discs of the galaxies under consideration. The stellar population models by Thomas et al. (2003) for  $[\text{Mg}/\text{Fe}] = +0.3$  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  $[\text{Fe}/\text{H}] = -0.4$  to  $-0.7$ , are also plotted by black diamonds for comparison; their indices are taken from Beasley et al. (2004).

**Table 6.** Correlations between stellar population properties and mass characteristics of galaxy components.

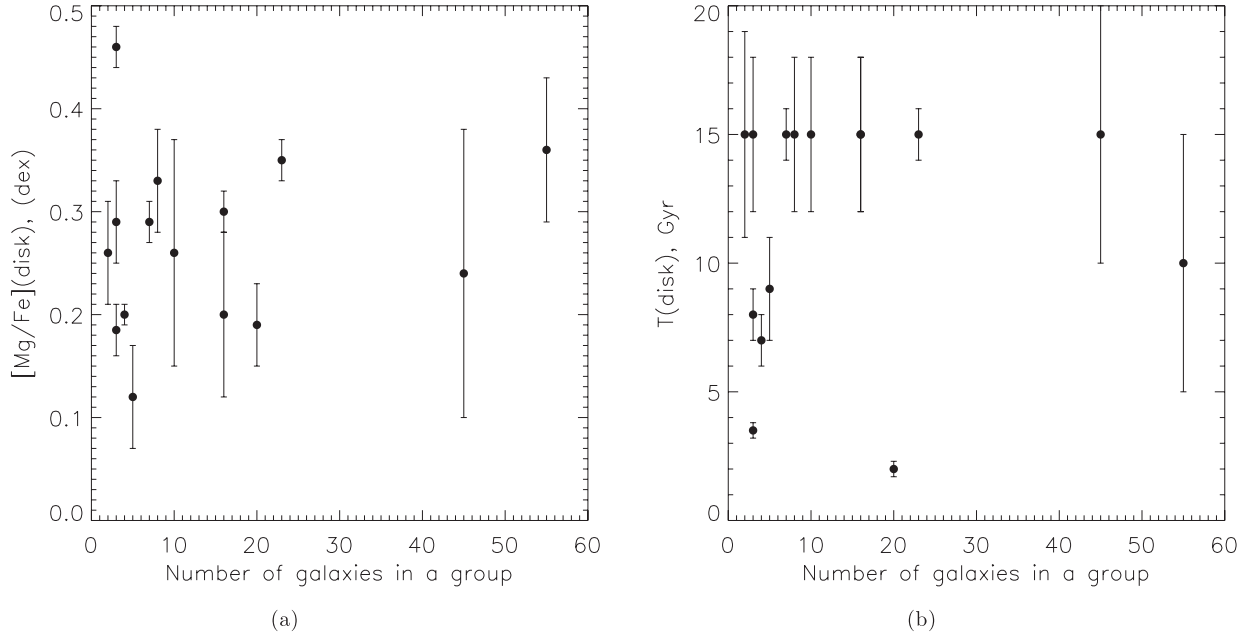
	Spearman's correlation coefficient	Probability of no correlation
Bulges, at $r = 0.5r_{\text{eff}}$ , 15 galaxies		
$T$ versus $\log \sigma_*$	0.500	0.058
$[\text{Z}/\text{H}]$ versus $\log \sigma_*$	−0.069	0.808
$[\text{Mg}/\text{Fe}]$ versus $\log \sigma_*$	0.462	0.083
Discs, only edge-on, 11 galaxies		
$T$ versus $\log(v_{\text{rot}}^2 + \sigma_*^2)$	0.380	0.248
$[\text{Z}/\text{H}]$ versus $\log(v_{\text{rot}}^2 + \sigma_*^2)$	−0.234	0.489
$[\text{Mg}/\text{Fe}]$ versus $\log(v_{\text{rot}}^2 + \sigma_*^2)$	0.251	0.456

slightly younger and slightly more metal rich than the outer one, though the difference is within the accuracy of our measurements.

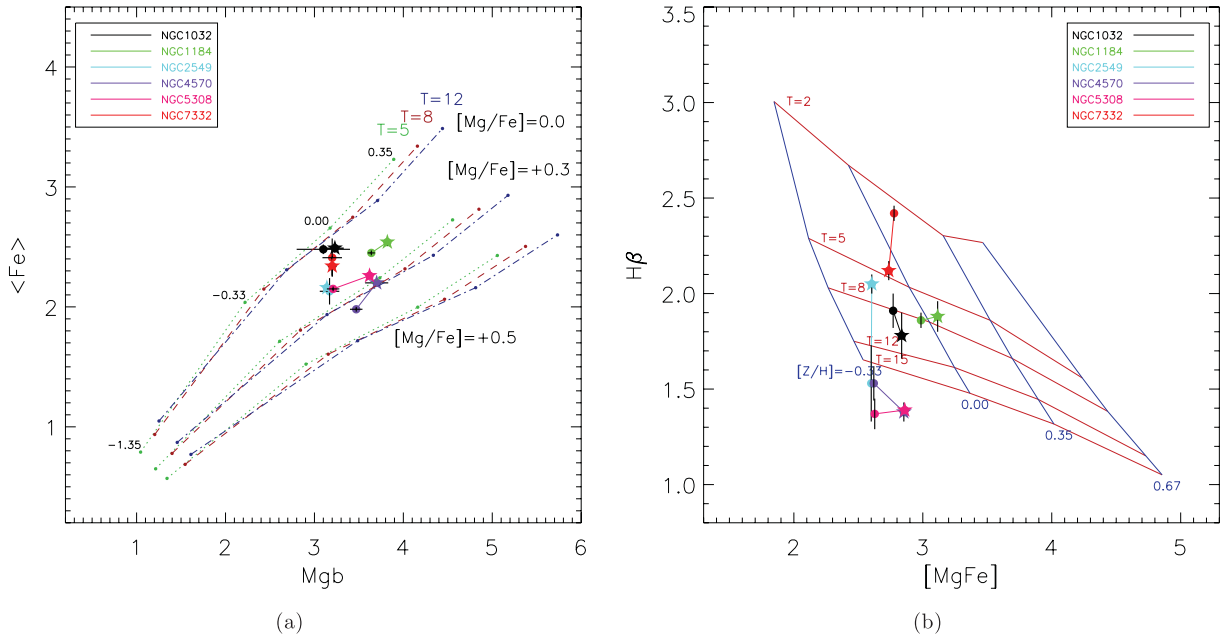
## 6 DISCUSSION

The old ages and strong magnesium overabundances of the large-scale stellar discs measured by us in this work for the sample of S0s contradict the commonly accepted paradigm described in Section 1 – that S0 galaxies have born ‘en mass’ from spiral progenitors by quenching star formation in their discs when having fallen into dense environments around  $z = 0.4$  (4 Gyr ago). In meantime, the SSP-equivalent age of 8 Gyr which is found for the discs of the field galaxies NGC 1032, NGC 1184 and NGC 2732 may reflect the constant-rate star formation with quenching abruptly 5 Gyr ago; the SSP-equivalent age of 12 Gyr corresponds to the constant-rate star formation with quenching 10 Gyr ago (Allanson et al. 2009; Smith

et al. 2009), or at  $z \sim 2$ . If the star formation before quenching was not constant but e-folding, the quenching must have happened even earlier given the SSP-equivalent ages for the S0 discs found by us (Allanson et al. 2009; Smith et al. 2009). IC 1541, NGC 502, 524, 3414, 5308 (rich group members) and NGC 4570 (Virgo cluster member) have their SSP-equivalent stellar ages of the large-scale discs older than 12 Gyr, so they quenched their star formation at  $z > 2$ . It seems that the sudden appearance of (red, bulge-dominated) S0 galaxies in clusters and groups at  $z = 0.4$ , or 4 Gyr ago, is not related to their morphological shaping. Within these dense environments the lenticulars, shaped earlier and accreted during the massive halo assembly at  $z < 1$ , might experience some brief rejuvenation of their inner parts (bulges) forcing them to look bluer at  $z = 0.4$ – $0.7$  than later (and earlier). This idea was proposed by Burstein et al. (2005) who did not find the required large difference between typical luminosities of S0s and spirals that was expected in the scenario of



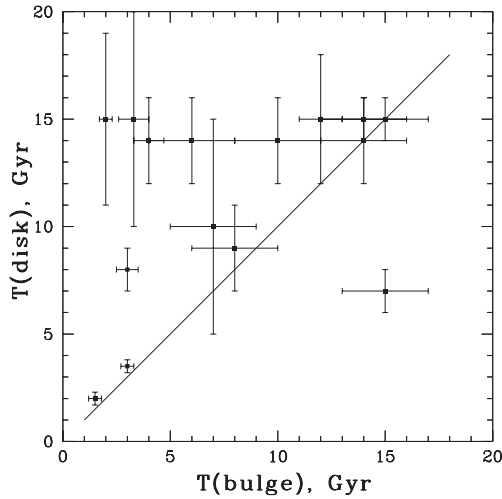
**Figure 7.** The correlations found by us for the disc stellar population properties of the sample S0 galaxies and their environment density (the number of galaxies in the groups to which the sample S0s belong).



**Figure 8.** Diagnostic index–index diagrams for discs as a function of the distance from the galaxy centres. (a) – The  $\langle Fe \rangle$  versus Mgb diagram. The large signs connected by lines are our galaxies’ discs with the innermost measurements marked by stars and the outermost measurements marked by filled circles. The SSP 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. (b) – The age-diagnostic diagram for the stellar populations in the discs of the galaxies under consideration. The large signs connected by lines are our galaxies’ discs with the innermost measurements marked by stars and the outermost measurements marked by filled circles. 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.

S0s fading from spirals. At  $z > 0.7$  the same galaxies/bulges look exactly as red as at  $z = 0$  (Koo et al. 2005a,b). In the frame of this hypothesis, the numerous results on early-type galaxies number increase in clusters and groups when moving from  $z = 0.8$  towards  $z = 0$  (e.g. Simard et al. 2009) can be easily understood. Early

morphological types are often classified quantitatively by the high bulge-to-total (B/T) ratio or by the high Sérsic index when applied to a galaxy as a whole. So the natural secular bulge build-up of disc galaxies within dense environments under gravitational and hydrodynamical influences should provide just a visibility of the



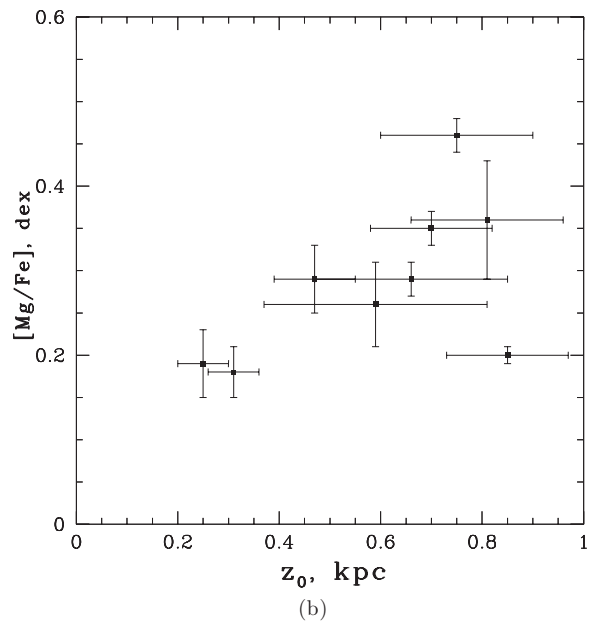
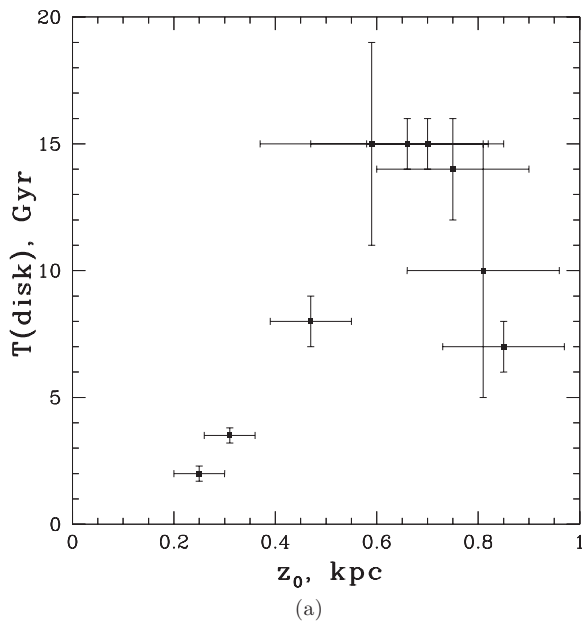
**Figure 9.** The comparison of the obtained SSP-equivalent ages of the discs and bulges in our sample S0s. The equality straight line is plotted for the reference.

early-type galaxies number increase with time. In reality, the main morphological attribute of S0 galaxies – large-scale old stellar discs – is already in place at  $z = 0.8$ –1, though the whole population of S0s at  $z = 1$  may possess on average smaller bulges than the present S0 population. Curious dependencies found by Dressler (1980), namely, the bulge *size* increasing with the environment density demonstrated both by S0s and spirals (and the steeper increase is demonstrated just by spirals!), are quite in line with this idea.

Fig. 9 presents the comparison of the SSP-equivalent ages between the discs and the bulges in the sample S0s. We see that while the discs are mostly old, the bulges occupy uniformly the whole range of ages between 2 and 15 Gyr, and the discs are almost always older than the bulges. The only exception is NGC 1184, rather isolated galaxy, which has the old bulge and the disc of intermediate age. We can also mention an analogous case of NGC 3115 –

the quite isolated S0 galaxy which has the 12 Gyr old bulge and the 6 Gyr old disc (Norris et al. 2006). The relation between the bulge and disc ages similar to our Fig. 9 has been obtained by Prochaska Chamberlain et al. (2011) with their sample of 59 S0s. They constructed a distribution of  $\Delta T(\text{disc-bulge})$  which looked like a Gaussian peaked at zero with a long tail to positive values. Also, 24 per cent of their sample galaxies have revealed the outer discs older than 10 Gyr. In principle, almost all the mechanisms proposed up to date to transform a spiral galaxy into S0 are able to produce star formation bursts just in the centres of the galaxies. Hydrodynamical mechanisms acting through stripping cold gas from the outer discs by hot-gas ram pressure leave intact the inner gas of the galaxies infalling into a cluster or a massive group and even compress it provoking star formation bursts (Quilis et al. 2000; Kronberger et al. 2008). Recent simulations by Bekki & Couch (2011) of a spiral transforming into S0 by tidal distortions inside a galaxy group show again multiple starbursts in the bulge area during the transformation. But to upbuild a disc, or to burn secondary star formation over an extended disc-dominated area, a galaxy needs obviously to settle within sparse environments where smooth cold-gas accretion is possible. This idea has an observational support: for example, blue-cloud E/S0s which demonstrate star formation over the whole galaxy body at the present epoch are located in sparse environments (Kannappan, Guie & Baker 2009).

As we have noted above, the stellar population chemistry in the discs of lenticular galaxies of our sample appear to lack any correlation with the mass (characterized by  $\sigma^2 + v_{\text{rot}}^2$ ) or with the luminosity of the discs. However, some hints to correlations have been found, and these are correlations with the thickness of the discs. In Fig. 10 we confront the ages and the magnesium-to-iron ratios of the stellar populations in the discs of nine edge-on S0s versus the scale heights of the discs found by Mosenkov et al. (2010) through the surface photometry analysis. The correlation between  $[\text{Mg}/\text{Fe}]$  and  $z_0$  is suggestive, with the Spearman correlation coefficient of 0.6 (less than 10 per cent – probability of no dependence). The correlation between the age and the disc thickness is formally insignificant, with the Spearman correlation coefficient of about 0.35, due to the



**Figure 10.** Correlations between the scale heights of the stellar discs derived from the surface photometry of the edge-on S0 galaxies and their stellar age (a) and magnesium-to-iron ratio (b).



thick disc of NGC 1184 which has an intermediate age, but nevertheless all the *old* discs of our sample galaxies are *thick* discs, while the only two young discs, those of NGC 4111 and NGC 7332, are certainly *thin* discs. The disc of NGC 2732, with its SSP-equivalent age of 8 Gyr and the scale height of 0.5 kpc, is halfway between thin and thick discs. The range of the scale heights is from 0.3 kpc (in the discs with the ages of 2–3 Gyr and  $[\text{Mg}/\text{Fe}] \leq +0.2$ ) to 0.6–0.9 kpc (mostly in the discs with the ages  $\geq 10$  Gyr and  $[\text{Mg}/\text{Fe}] \geq +0.3$ ). Let us compare it to our Galaxy discs’ scale heights: 0.3 kpc for the thin stellar disc and about 1 kpc for the thick stellar disc (Cabrera-Lavers, Garzón & Hammersley 2005).

Many arguments evidence for S0s and spiral galaxies being relatives – the most recent arguments in favour of the parallel morphological sequences of Ss and S0s can be found, e.g. in Kormendy & Bender (2012) and Cappellari et al. (2011). But after taking into account our present results, it looks like S0s are progenitors of spirals, opposite to what was thought before. Indeed, if we compare stars of the thick disc of our own Galaxy with the thick stellar discs of S0s studied here we will see full resemblance: the ages  $> 10$  Gyr,  $[\text{Mg}/\text{Fe}] > +0.2$ , the total metallicity, which is closer to  $[\text{Mg}/\text{H}]$  due to Mg coupling with oxygen, both being  $\alpha$  elements, than to  $[\text{Fe}/\text{H}]$ ,  $[\text{Z}/\text{H}]$  is between 0.0 and  $-0.7$  (Bernkopf & Fuhrmann 2006; Schuster et al. 2006). In other spiral galaxies thick stellar discs are also much older than the embedded thin discs (Yoachim & Dalcanton 2008). So if now one provides fresh cold gas accretion into the discs of our S0s, after several Gyr of star formation we would get typical spiral galaxies, with the thick old stellar discs and thin younger stellar discs. The idea by Fuhrmann (Fuhrmann 2011) that primary large-scale components of all galaxies must be thick stellar discs plays here nicely.

Indeed, observations reveal that star formation in disc galaxies at  $z \sim 2$  proceeds in clumps with the sizes of about 1–1.5 kpc embedded into large-scale discs which are gravitationally bound, and the scale heights of these discs correspond to the clump sizes so the gaseous discs at  $z \sim 2$  are thick (Bournaud et al. 2008). Hence, the stellar discs forming from this gas in these galaxies should also be thick. The smoothed particle hydrodynamics simulations of the secular evolution for such a configuration promise very effective (and so brief) star formation (Bournaud, Elmegreen & Elmegreen 2007); observations of star-forming galaxies at  $z > 2$  confirm the short time-scales of their star formation (Genzel et al. 2008), so after ceasing star formation the emerged passively evolving stellar structures would possess magnesium-overabundant stellar population. The first observations of the massive, disc-dominated, passive (no star formation) galaxy population at  $z > 2$  have already appeared in the literature (Bruce et al. 2012).

Initial simulations of the evolution of massive clumpy turbulent star-forming discs implied strong radial inflow of the clumps into the galactic centres, and so it seemed to be a way to form bulges of the future early-type disc galaxies: the resulting model bulges looked similar to the ‘classical’ bulges, with large Sérsic indices and slow rotation (Elmegreen, Bournaud & Elmegreen 2008). However, later inclusion of the star formation feedback into the simulations has resulted in stopping strong gas radial inflows due to shorter lifetimes of the clumps, and instead of the bulges, thick stellar discs emerge now from these simulations (Genel et al. 2012; Hopkins et al. 2012). Bournaud, Elmegreen & Martig (2009) conclude directly that intense star formation in high-redshift clumpy discs may produce the present thick discs of spiral galaxies.

So now we are proposing the following new scenario of disc galaxy evolution. All disc galaxies were S0s immediately after their birth at  $z > 2$ . Later, at  $z < 1$ , some of them were provided with

cold gas accretion sources to form thin stellar discs – those might become spirals – and some of them failed to find such sources – these remained lenticulars. Inside large cluster-size and group-size dark haloes, there are little chances to find external sources of cold gas accretion, due to surrounding hot intergalactic gas – so in nearby clusters the dominant disc-galaxy population is lenticulars. Or perhaps, the tidal effects – harassment resulting in starvation – are more effective in stripping the outer cold gas reservoirs of the disc galaxies preventing late building of thin discs; this hypothesis is more in line with the smooth dependence of the S0 (and S) fraction on the local environment density over a full range of the latter parameter, from field to clusters (Postman & Geller 1984; Cappellari et al. 2011). Our scenario implies that the discs of spiral galaxies must be on average more massive (and so more luminous, say, in the  $K$  band) than the discs of S0s; indeed, we see such a difference in fig. 11 of Laurikainen et al. (2010), where at fixed bulge luminosity, the discs of spirals are more luminous than the discs of S0s. Moreover, the bulges of early-type spirals are also on average slightly more luminous (in the  $K$  band) than the bulges of S0s (Graham & Worley 2008); so we think that the bulge growth during thin disc formation is probably unavoidable. In general, our scenario explains a long-standing problem with the S0s being fainter than E and Sa galaxies between which they are positioned at Hubble’s ‘tuning fork’ (van den Bergh 2009). Also, it explains why the Tully–Fisher relation of S0 galaxies goes in parallel to the Tully–Fisher relation for spirals, but with the 0.5 mag shift in the  $K_s$  band towards fainter luminosities at the fixed rotation velocity (Williams, Bureau & Cappellari 2010): this shift is too small for the star formation truncation 4–5 Gyr ago, but, as the authors conclude, ‘could therefore be explained by a systematic difference between the total mass distributions of S0s and spirals, in the sense that S0s need to be smaller . . . than spirals’.

The open question remains what can be these sources of cold-gas prolonged accretion – they may be cosmologically motivated filaments (Dekel & Birnboim 2006) or rich systems of irregular-type dwarf satellites which have been merging with the host galaxy one after another. To support the latter possibility, we would like to bring forward the recent curious finding by Karachentseva, Karachentsev & Melnyk (2011): by considering a sample of isolated host galaxies, they have found that the pairs ‘S0+satellite’ have on average twice higher velocity dispersion (LOS velocity differences) than the pairs ‘S+satellite’. A close inspection of their figures reveals an absence of the ‘S0+satellite’ pairs with the velocity differences of less than  $50 \text{ km s}^{-1}$ . It might mean that the satellites of the present S0s have much less chances to merge with their host galaxies than the satellites of spirals. Perhaps, among a primordial population of isolated S0s covering a full range of satellite velocity dispersions the host galaxies with the lower satellite velocity dispersions have become spirals, and only the host galaxies with the high satellite velocity dispersions preventing their numerous minor mergers remain still S0s.

## 7 CONCLUSIONS

We have studied the stellar population properties along the radius up to several scalelengths of the discs in 15 S0 galaxies spread over a range of luminosities (though all are more luminous than  $M_B = -18$  and  $M_K = -22$ ) and settling in different environments.

For the large-scale stellar discs of the galaxies, we have found metallicities from the solar one down to  $[\text{Z}/\text{H}] = -0.4$  to  $-0.7$ , elevated magnesium-to-iron ratios,  $[\text{Mg}/\text{Fe}] \geq +0.2$ , and mostly old ages. Nine of 15 galaxies have large-scale discs older than

10 Gyr, which includes all the galaxies from the sample which reside in dense environments. The isolated and some loose-group galaxies have intermediate-age (7–8 Gyr) stellar discs, and only two galaxies, NGC 4111 and NGC 7332, demonstrate the SSP-equivalent ages of their discs of 2–3 Gyr. Just these two young discs have appeared to be thin, and the other, old, discs have scale heights typical for thick stellar discs.

We conclude that S0 galaxies are the primordial type of disc galaxies largely shaped by  $z \sim 1.5$ –2, especially those found in clusters today. Some rejuvenation of the discs, but mostly of the bulges, is possible later for some, but not all, lenticular galaxies. The bulges are almost always coeval or are younger than the discs. Spiral galaxies may form from lenticulars at  $z \leq 1$  by accreting external cold gas into their discs; in dense environments cold gas deficiency exists so the most primordial lenticulars in dense environments remain S0s up to now being the dominant galaxy population in the galaxy clusters at  $z = 0$ .

Despite apparent homogeneity of the S0 morphological type ('smooth red disc+bulge systems...'), the glance 'in depth' reveals very large scatter of main structural and evolutionary properties even among lenticular galaxies of the same luminosity: S0s may be disc- or bulge-dominated galaxies (van den Bergh 1976; Komremdy & Bender 2012), with exponential or de Vaucouleurs-like surface brightness profiles of the bulges, and all the intermediate values of the Sérsic parameter  $n$  can be met too (Laurikainen et al. 2010); the stellar population of the bulges spans the full range of ages – Morelli et al. (2008) and also this paper. This diversity provokes a suggestion that S0 galaxies may be formed through different evolutionary channels, and many theoretical suggestions provide a variety of possible physical mechanisms of S0 shaping (see Section 1). However, the properties of stellar populations, especially in the outer parts of S0 galaxies less suffering from secular evolution (influencing mainly the central parts of galaxies), can restrict strongly the possible scenario of S0 galaxy formation. Namely, the old ages and high magnesium-to-iron ratios of the large-scale stellar discs of S0s exclude evidently their (trans-)formation from spirals at intermediate redshifts,  $z < 0.5$ . We have now in hand some hints on the ages larger than 10 Gyr in many large-scale discs of S0 galaxies, especially those populating dense environments: our sample studied in this paper reveals a majority of old discs, but it is very small and spread over various environment types, and also the recent results by Roediger et al. (2011) for the Virgo 53 S0s give the mean age of their (inner and) outer parts of  $10.2 \pm 0.7$  Gyr. If the tendency for the outer discs of S0s to be old is confirmed, all the scenarios which suggest spiral galaxy transformation into S0s in clusters and rich groups at intermediate redshifts would be disproved. What then remains? Only turbulent unstable star-forming thick gaseous discs at  $z > 1.5$  (Bournaud et al. 2009) which might leave thick quiescent stellar discs after a brief effective star-forming epoch, and perhaps also gas-rich major mergers, if they occur at  $z > 2$  in future cluster environments (Bois et al. 2011), and subsequent evolution with episodic rejuvenation according to our scenario proposed above. However, to make more certain conclusions, further investigations of the stellar population properties in the outer parts of lenticular galaxies are quite necessary.

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