TRACING REJUVENATION EVENTS IN NEARBY S0 GALAXIES

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ABSTRACT

With the aim of characterizing rejuvenation processes in early-type galaxies, we analyzed five barred S0 galaxies showing a prominent outer ring in ultraviolet (UV) imaging. We analyzed *Galaxy Evolution Explorer* far-UV (FUV) and near-UV (NUV), and optical data using stellar population models and estimated the age and the stellar mass of the entire galaxies and the UV-bright ring structures. Outer rings consist of young (≤ 200 Myr old) stellar populations, accounting for up to 70% of the FUV flux but containing only a few percent of the total stellar mass. Integrated photometry of the whole galaxies places four of these objects on the green valley, indicating a globally evolving nature. We suggest such galaxy evolution is likely driven by bar-induced instabilities, i.e., inner secular evolution, that conveys gas to the nucleus and the outer rings. At the same time, H I observations of NGC 1533 and NGC 2962 suggest external gas re-fueling can play a role in the rejuvenation processes of such galaxies.

Key words: galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: structure *Online-only material:* color figures

1. INTRODUCTION

A large spread in luminosity-weighted ages of early-type galaxies (ETGs hereafter), derived by modeling spectral linestrength indices, suggests that the nucleus may have been rejuvenated by recent, secondary star formation (SF) episodes (e.g., Annibali et al. 2007, and references therein). *Spitzer* nuclear spectra of ETGs support this view. Polycyclic aromatic hydrocarbon emission, characterizing both starburst and poststarburst phases, is detected in a large fraction of ETG nuclear spectra (e.g., Panuzzo et al. 2011, and references therein).

About 10%–30% of the ETGs imaged in the UV with *Galaxy Evolution Explorer* (*GALEX*) show signatures of such rejuvenation episodes, even after excluding classical UV-upturn candidates (e.g., Yi et al. 2005; Donas et al. 2007; Schawinski et al. 2007). Either accretion events or interactions seem to be at the origin of rejuvenation episodes. Rampazzo et al. (2007) and Marino et al. (2009) found evidence of young stellar populations in the nucleus of ETGs showing shell structures, signatures mainly produced by a small accretion event (see, e.g., Dupraz & Combes 1986; Ebrová et al. 2010, and references therein). Similar results have been obtained by Jeong et al. (2009).

Wide-field UV imaging from GALEX has enabled, for the first time, the detection of young stellar populations in extreme outskirts of galaxies. Thilker et al. (2010) discovered recent SF, likely fueled by an accretion episode, in the outermost portion of the S0 galaxy NGC 404, a local prototype. The FUV-bright sources are concentrated within an HI ring, signature of a merger event (del Río et al. 2004). Marino et al. (2009) found evidence of recent SF (<1 Gyr) in the polar-ring ETG MCG-05-07-01. Polar rings are sometimes generated by major merging events. The SF in the UV polar ring is also in this case associated with an HI ring. Recently, Bettoni et al. (2010) explored the case of another S0 galaxy, NGC 4262, where they found an H1 and a UV ring. The kinematics of the cold and warm gas associated with the UV ring is decoupled with that of the galaxy stellar population. The kinematical decoupling indicates that the origin of the outer ring is a past major interaction episode undergone

by NGC 4262 which is responsible for the onset of the SF in the UV-bright ring.

The presence of ring structures represents a normal phase in the secular evolution of S0 galaxies (Buta & Combes 1996). They are indeed found in about 20%–30% of S0 and spiral galaxies (see, e.g., Thilker et al. 2007; Aguerri et al. 2009). In most cases, rings are associated with nonaxisymmetric structures, such as bars, ovals, or triaxial bulges. Jeong et al. (2007) presented a *GALEX* study of NGC 2974. This misclassified S0 galaxy shows an arm-like structure in UV bands and possesses a bar as deduced from the perturbation of the stellar kinematics (Krajnović et al. 2005). Recently, Salim & Rich (2010) found star-forming rings, likely of different origin, in 15 out of a sample of 22 ETGs having extended UV emission.

If we exclude polar rings produced by minor/major accretion events and collisional rings, usually rare and recognizable from the off-centered nucleus, secular evolution is at the origin of rings in barred galaxies. Nuclear, outer, and inner rings correspond to the inner (ILR), outer (OLR) Lindblad's, and ultraharmonic dynamical resonances between the epicyclic oscillations in the stellar component and the rotation of the bar. The gas accumulates in these resonances and can induce SF. Bars, either spontaneously or externally triggered, can also drive the gas to the center of the galaxy, inducing nuclear SF (Combes 2008). The secular evolution driven by bar instabilities may then represent for a significant fraction of S0 galaxies a global rejuvenation mechanism whose effects extend from the galaxy nucleus to the galaxy outskirts.

Is the secular evolution induced by bars a viable global rejuvenation mechanism in ring S0 galaxies? Is wet accretion a necessary condition to ignite SF in ring S0s? In this paper, we analyze five S0s showing outer rings and/or arm-like structures prominent in the UV bands, selected from a larger sample of ETGs located in low-density environments. We describe the sample properties and the observations in Sections 2 and 3, respectively. We derive the UV and optical photometry in Section 4. We use synthetic stellar population models to derive ages and stellar masses for both the ring and the entire

galaxy in Section 5. In Section 6, we discuss the influence of the environment, the H_I distribution, the SF properties, and the color of S0s as a whole and of their ring structures on the color–magnitude diagram (CMD) in the context of galaxy evolution. Finally, we compare these S0s showing rejuvenation signatures with a larger sample of ETGs whose spectral energy distributions (SEDs) are consistent with mostly passive evolution.

2. THE SAMPLE PROPERTIES

We analyze five S0s, namely NGC 1533, NGC 2962, NGC 2974, NGC 4245, and NGC 5636, showing prominent outer rings (Figure 1) in UV wide-field imaging. The galaxies are part of a wider sample of ETGs, which we studied with a multiwavelength approach (Rampazzo et al. 2005; Annibali et al. 2006, 2007, 2010; Panuzzo et al. 2011; Marino et al. 2011b). The wider sample includes ETGs which are members of groups of different richness and show the presence of an interstellar medium component in at least one of the following bands: IRAS 100 µm, X-ray, radio, H1, and CO (Roberts et al. 1991). Most of them have a LINER nucleus as shown by Annibali et al. (2010) and Panuzzo et al. (2011) from analysis of optical and mid-infrared spectra, respectively. The UV-bright features of this sample warrant a different analysis which is the subject of this work. All our sample but NGC 2974 are classified as barred S0s. NGC 2974 has been erroneously classified as an elliptical in RC3 (de Vaucouleurs et al. 1991), although an exponential disk is evident both from the optical and UV luminosity profiles (see also Jeong et al. 2007, 2009; Marino et al. 2011b). In addition, Krajnović et al. (2005) found, with SAURON observations (de Zeeuw et al. 2002), the existence of non-axisymmetric perturbations consistent with the presence of an inner bar in NGC 2974. We conclude that all our systems are barred S0s with outer rings.

All our S0s are located in low-density environments since they are members of loose groups of galaxies. NGC 1533 is a member of the Dorado group. NGC 2962, NGC2974, NGC 5636, and its elliptical companion NGC 5638 belong to groups LGG 178, LGG 179, and LGG 386, respectively (Garcia 1993). NGC 4245 is located in the spiral-dominated group USGC-U478 (Ramella et al. 2002).

3. OBSERVATIONS

Imaging was obtained with *GALEX* (Martin et al. 2005; Morrissey et al. 2007) in two ultraviolet bands, FUV ($\lambda_{eff} = 1539$ Å, $\Delta\lambda = 1344-1786$ Å) and NUV ($\lambda_{eff} = 2316$ Å, $\Delta\lambda = 1771-2831$ Å), with a spatial resolution of 4.2 and 5.3 arcsec in FUV and NUV, respectively. The observations come partly from the *GALEX* public archive³ and partly from our Cycle 3 program (ID GI3-0087; PI: R. Rampazzo). The exposure times range from 1520 s (NGC 1533) to 2657 s (NGC 2974) corresponding to 3σ limiting mags of ~22.6/22.7 in FUV/NUV or deeper (Bianchi 2009). In addition to the UV data, we used optical Sloan Digital Sky Survey (SDSS) imaging in the *u* [2980–4130 Å], *g* [3630–5830 Å], *r* [5380–7230 Å], *i* [6430–8630 Å], and *z* [7730–11230 Å] bands, available for NGC 2962, NGC 4245, and NGC 5636.

Figure 1 shows the *GALEX* FUV/NUV, and SDSS color composite images, and the surface brightness profiles in FUV, NUV, and r bands. Inner bars are better visible in the optical

image (having three times higher resolution than UV imaging), while outer rings are clearly enhanced in FUV. NGC 2962 displays an inner ring more prominent in the optical image, and an outer ring, well defined in the *GALEX* imaging (see Figure 1). In all cases the outer structures are more sharply defined in FUV (which traces the youngest populations) than at optical wavelength where a mixture of populations is contributing. Resolution and depth differences between UV and optical images may partly contribute to the observed differences in galaxy morphology.

4. PHOTOMETRY AND SURFACE BRIGHTNESS PROFILES

We used FUV and NUV *GALEX* background-subtracted intensity images to compute integrated photometry of the galaxies. The FUV and NUV magnitudes (AB system) within elliptical apertures are given in Table 1 for each galaxy. Errors on UV magnitudes were estimated by propagating the Poisson statistical error on source and background counts. Background counts were estimated from the sky background image and high-resolution relative response map provided by the *GALEX* pipeline in the same apertures used to compute the galaxy luminosity. In addition to the statistical error, we added an uncertainty to account for the systematic uncertainties in the zero-point calibration of 0.05 and 0.03 mag in FUV and NUV, respectively (Morrissey et al. 2007).

Columns 2 and 4 in Table 1 provide for each galaxy the adopted distance and the major axis of the optical μ_{25} isophote (de Vaucouleurs et al. 1991), respectively. R_{TOT} (Column 5) is where the NUV surface brightness is 3σ above the background, a/b (Column 6) and P.A. (Column 7) in Table 1 are the length of the major axis, the major axis/minor axis, and the position angle. Total FUV and NUV magnitudes in Table 1 (Columns 8 and 9) were computed in elliptical apertures within R_{TOT} .

After registering the SDSS images (corrected frames with the soft bias of 1000 counts subtracted) to the corresponding *GALEX* NUV images, SDSS magnitudes⁴ were computed within the same apertures used in the UV (Columns 10–14 of Table 1).

Figure 1 (right panels) shows background-subtracted, foreground-extinction-corrected UV surface brightness profiles obtained using the ELLIPSE fitting routine in the STSDAS package of IRAF (Jedrzejewski 1987). The extinction correction for the foreground component was performed using the E(B - V)values taken from NED and reported in Table 1 (Column 3) assuming Milky Way dust with $R_v = 3.1$ (Cardelli et al. 1989). The $A_{\lambda}/E(B-V)$ may vary significantly at UV wavelengths (see Table 2 of Bianchi 2011). However, in all our sample galaxies E(B - V) is very small and the correction adopted does not influence the results. Rings produce a hump in the UV-flux profile and are bluer than the body of their respective galaxy. The luminosity of the ring structures was measured integrating the surface photometry between the inner (R1) and outer (R2) radii reported in Table 1 (Column 5) and indicated in Figure 1 (right panels) with vertical blue dashed lines. R1 and R2 were chosen from the FUV profiles where rings are prominent and well defined. The same R1 and R2 have then been used in the NUV and optical bands where rings are much weaker. In order to evaluate the ring luminosity we subtracted the galaxy contribution. The underlying galaxy profile was estimated (blue solid line in

³ http://galex.stsci.edu.

⁴ We converted SDSS counts to magnitudes following the recipe provided in http://www.sdss.org/df7/algorithms/fluxcal.html#counts2mag.

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Figure 1. Composite FUV (blue) and NUV (yellow) *GALEX* images of all targets and optical SDSS-g/r/i (blue/green/red) images of NGC 2962, NGC 4245, and NGC 5636. Luminosity profiles along the semimajor axis are shown in FUV (blue filled dots), NUV (red empty points), and SDSS-r bands (magenta squares). The vertical lines indicate the ring inner and outer radii (blue), optical D_{25} (green), and NUV-defined R_{TOT} (red: see the text). For comparison we also plot the luminosity profile of the elliptical galaxy NGC 5638 (Marino et al. 2011b), which does not show outer rings.

The Sample Photometry													
Name	Dist. (Mpc)	$\frac{E(B-V)^{a}}{(mag)}$	D ₂₅ ('')	<i>R</i> _{TOT} (") R1–R2 (")	a/b ^b	P.A. ^c (deg)	FUV (AB mag)	NUV (AB mag)	u (AB mag)	g (AB mag)	r (AB mag)	<i>i</i> (AB mag)	z (AB mag)
NGC 1533 NGC 1533 ^d	13.4	0.015	97.2	108 39–80	1.2	149	$\begin{array}{c} 16.90 \pm 0.09 \\ 18.38 \pm 0.11 \end{array}$	$\begin{array}{c} 16.04 \pm 0.05 \\ 18.27 \pm 0.10 \end{array}$					
NGC 2962 NGC 2962 ^d	30.6	0.058	68.4	98 41–98	1.4	1	$\begin{array}{c} 17.78 \pm 0.15 \\ 18.15 \pm 0.27 \end{array}$	$\begin{array}{c} 17.09 \pm 0.10 \\ 17.98 \pm 0.31 \end{array}$	14.19 ± 0.11	12.32 ± 0.02	11.49 ± 0.02	11.17 ± 0.02	10.53 ± 0.04
NGC 2974 NGC 2974 ^d	28.5	0.054	104.4	131 35–72	1.4	44	$\begin{array}{c} 17.78 \pm 0.09 \\ 19.07 \pm 0.15 \end{array}$	$\begin{array}{c} 16.2 \pm 0.05 \\ 18.86 \pm 0.09 \end{array}$					
NGC 4245 NGC 4245 ^d	11.4	0.021	76.8	100 20–55	1.2	146	$\begin{array}{c} 16.95 \pm 0.07 \\ 18.15 \pm 0.14 \end{array}$	$\begin{array}{c} 15.84 \pm 0.04 \\ 17.80 \pm 0.09 \end{array}$	13.49 ± 0.06	11.88 ± 0.02	11.10 ± 0.02	10.65 ± 0.02	10.42 ± 0.03
NGC 5636 NGC 5636 ^d	22.2	0.033	28.8	60 10–42	1.3	40	17.86 ± 0.14 18.41 ± 0.07	16.84 ± 0.06 18.01 ± 0.11	15.14 ± 0.13	13.66 ± 0.03	12.98 ± 0.03	12.65 ± 0.034	12.56 ± 0.09

Table 1

Notes. All magnitudes are in the AB system and are uncorrected for Galactic extinction.

^a From NED.

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^b $a (= R_{\text{TOT}})$ and b are the semimajor and semiminor axes from NUV light profiles. Total magnitudes in Columns 8–14 are calculated within the ellipse defined by these axes.

^c From HyperLeda.

^d Ring luminosity between R1 and R2, defined from the FUV images (Figure 1).



Figure 2. $5' \times 5'$ *GALEX* FUV background-subtracted images of the sample with the optical D_{25} ellipse (green solid line) superimposed. Red dashed lines indicate the R_{TOT} ellipse, defined from NUV light profiles (see the text). For NGC 2962 and NGC 5636, the optical diameter does not include the extent of the entire FUV emission.

(A color version of this figure is available in the online journal.)

Figure 1) by fitting a spline to the luminosity profile excluding the ring portion. Approximately 25%, 71%, 30%, 33%, and 60% of the total FUV luminosity of NGC 1533, NGC 2972, NGC 2974, NGC 4245, and NGC 5636 comes from the rings. In the optical bands, rings are not prominent (at the SDSS depth and S/N) and only upper limits were obtained.

Figure 2 shows FUV background-subtracted images with, superimposed, the optical D_{25} and the NUV-defined R_{TOT} ellipses obtained as described above. The UV aperture R_{TOT} is in all cases larger than the optical one. UV ellipticity and orientation differ from the optical values, suggesting that UV young stellar populations in outer rings are rather different from those in the central part of the respective galaxies. For NGC 2962 and NGC 5636, the optical D_{25} ellipse does not include the extent of the entire galaxy in FUV (Figure 2).

5. AGES AND STELLAR MASSES OF THE GALAXY POPULATIONS

We characterize the epoch and strength of the rejuvenation episodes in the S0 sample by estimating ages and stellar masses of the entire galaxies and their outer rings. We compared the observed SEDs with a grid of synthetic stellar population models computed by Marino et al. (2010) with the GRASIL code (Silva et al. 1998), which takes into account the effects of the agedependent extinction with young stars being more affected by dust. We used our grid for two different SF histories (SFHs): one typical of elliptical galaxies, characterized by a short (1 Gyr) intense period of SF followed by pure passive stellar evolution, and one typical of spirals with a more prolonged SF. SFH parameters are given in Table 5 of Marino et al. (2010). The model grid was computed assuming a Salpeter initial mass function (IMF) with a mass range between 0.15 and $120 M_{\odot}$ for ellipticals and between 0.1 and 100 M_{\odot} for spirals following Silva et al. (1998). Our GRASIL model grid was computed for ages from a few Myr to 13 Gyr (Marino et al. 2010; see in particular their Figure 10). The best-fit model obtained by χ^2 fitting of the observed SED (FUV to SDSS-z band), and interpolating within the grid, yields the age of the composite population and the foreground extinction. The stellar mass is derived by scaling the best-fit model to the observed SEDs, using the distances in Table 1 and taking extinction into account.

In Figure 3, we plot the SEDs within R_{TOT} (full dots) of NGC 2962, NGC 4245, NGC 5636, the three sample galaxies for which UV and optical measures are available, and of the elliptical NGC 5638, from Marino et al. (2011b), which does not show UV-bright ring features. The solid line represents the best-fit model obtained adopting an elliptical SFH and assuming the foreground extinction given in Table 1 in addition to the internal extinction accounted for by GRASIL (left panels). Right panels show the best fit obtained considering an additional E(B - V) component as a free parameter in the fitting. By imposing a maximum value of foreground E(B-V) as given in Table 1, the best-fit model matches well the optical SED of all S0s but an observed FUV excess indicates an additional young stellar component. Reproducing both the FUV excess and the optical colors with simply passive SFH and additional reddening (right panels) requires unrealistically high values of the resulting E(B-V) and can be ruled out. Such FUV excess is not seen in NGC 5638. The formal "best-fit" age of NGC 5638 of 12.6 Gyr agrees with the independent estimate of 9.1 ± 2.3 Gyr obtained by Annibali et al. (2007) from Lick indices in the nuclear region.

Lacking optical data for NGC 1533 and NGC 2974, we used only FUV and NUV measures to estimate the age using the same GRASIL grids. In this case, ages are largely uncertain since the contribution of the young component cannot be separated from the passively evolving population.

For estimating ages and stellar masses of outer ring structures we are compelled to use only FUV and NUV measures since only upper limits can be derived from the SDSS images. Ring FUV and NUV magnitudes were compared both with GRASIL and single-burst stellar population (SSP; e.g., Bianchi 2011) models. Comparing the FUV-NUV color with SSP, elliptical and spiral SFH model color yields markedly different ring ages (Column 4 in Table 2). We derive very young ages (≤ 200 Myr) adopting an SSP SFH and ages of ~ 1 Gyr with an elliptical SFH. The ages derived assuming spiral SFH appear older than those of the entire galaxy, ruling out the assumption of continuous SF for the ring population. The most plausible SFH for the population of the outer UV-emitting rings appears to be SSP-like. An exponentially decaying SFH would give similar results to the SSP models in, e.g., Efremova et al. (2011). The very different ages obtained when assuming different SFHs and the comparison of observed FUV-NUV colors with model colors in Figure 4 underscore the importance of obtaining



Figure 3. FUV to near-infrared SEDs (dots), measured within R_{TOT} given in Table 1, with overplotted best-fit models (lines) obtained assuming an elliptical SFH and either the foreground extinction given in Table 1 (left panels, showing an FUV excess in the data) or leaving E(B - V) as a free parameter (right panels). Ages are in Myr. In the bottom left panel we plot the SED and the best-fit model of the elliptical NGC 5638.

significant measurements of the outer ring structures at longer wavelengths, which we will pursue with deep optical imaging.

The stellar mass of the outer rings is about 1%-4%, <1%, 1%, and 5%-8% of the total stellar mass of NGC 1533, NGC 2962, NGC 2974, NGC 4245, and NGC 5636, respectively. The estimate of stellar mass is affected by uncertainties in the photometry, extinction, distance, and derived ages. The errors provided take into account only the photometric error, but not the larger indetermination which may result from the assumption of a given SFH.

In Column 6 of Table 2, we also report the stellar mass surface density (averaged over the photometry aperture).

6. DISCUSSION

6.1. The Environment

Possible signatures of either recent accretion events or of ongoing interactions are reported in the literature for three of our S0s. DeGraaff et al. (2007) describes NGC 1533 as a late stage of transition from a barred spiral to a barred S0 galaxy.

Grossi et al. (2009) and Werk et al. (2010) found HI tails in NGC 2962 and NGC 1533, respectively (see Section 6.2). Tal et al. (2009) report the presence of a shell system surrounding NGC 2974.

In order to evaluate an interaction probability the perturbation parameter f has been computed. This parameter, defined in Varela et al. (2004) as

$$f = \log(F_{\text{ext}}/F_{\text{int}}) = 3\log(R/D_p) + 0.4 \times (m_G - m_p),$$

is the logarithmic ratio between inner (F_{int}) and tidal forces (F_{ext}) acting upon the galaxy by a possible perturber (where *R* is the size of the galaxy, D_p is the projected distance between the galaxy and the perturber, and m_G and m_p are the apparent magnitudes of the primary and perturber galaxies, respectively). Varela et al. (2004) show that "unperturbed" galaxies (which they call "isolated") have $f \leq -4.5$.

To compute f we consider as possible perturbers the galaxies taken from HyperLeda that have M_B brighter than -12 mag, D_{25} corresponding to more than 2 kpc, $\Delta V \leq 500$ km s⁻¹,

 Table 2

 Ages and Stellar Masses of the Ring Structures and of the Entire Galaxies

Name	Region	SFH Assumed		Age (yr)	$\begin{array}{c} \text{Mass}_{\star} \\ (10^6 \ M_{\odot}) \end{array}$	$\frac{\text{Mass}_{\star}/\text{Area}}{(10^6 \ M_{\odot})/\text{kpc}^2}$	$M_{\rm H{\scriptscriptstyle I}}$ (Area) (10 ⁶ M_{\odot}) (kpc ²)
NGC 1533	Ring	SSP	а	$0.7^{+0.6}_{-0.4} \times 10^8$	$0.9^{+1.1}_{-0.6}$	0.02	
	-	Е	а	$10.0^{+0.2}_{-4.0} \times 10^8$	$6.4^{+1.3}_{-8.9}$	0.1	
		Sp	а	$2.6^{+0.5}_{-0.5} \times 10^9$	$46.6^{+83.9}_{-31.4}$	0.9	
	$\leq R_{\text{TOT}}$	Е	а	$11.0^{+0.3}_{-0.1} \times 10^8$	$175^{+46.1}_{-37.9}$		3700 (?)
NGC 2962	Ring	SSP	а	$0.9^{+0.7}_{-0.5} \times 10^8$	$0.4^{+0.5}_{-0.3}$	0.001	
		Е	а	$10.1^{+0.1}_{-2.6} \times 10^8$	$2.2^{+0.4}_{-4.4}$	0.01	
		Sp	а	$2.7^{+0.4}_{-0.4} \times 10^9$	$20.3^{+26.3}_{-12.6}$	0.05	
	$\leq R_{\rm TOT}$	Е	b	$13:\times 10^9 (E(B-V) = 0.07)$	690:		287 (~1700)
			b	$1.1 \times 10^9 (E(B - V) = 0.67)$	347:		
NGC 2974	Ring	SSP	а	$1.1^{+0.9}_{-0.7} \times 10^8$	$0.2^{+0.4}_{-0.2}$	0.002	
		Е	а	$10.1^{+0.2}_{-2.6} \times 10^8$	$1.1^{+0.3}_{-2.0}$	0.01	
		Sp	а	$2.8^{+0.4}_{-0.5} imes 10^9$	$12.6^{+16.7}_{-9.0}$	0.1	
	$\leq R_{\rm TOT}$	Е	а	$12.6^{+0.3}_{-0.2} \times 10^{8}$	$152^{+31.5}_{-26.2}$		1150 (~700)
NGC 4245	Ring	SSP	а	$1.8^{+0.6}_{-0.8} \times 10^8$	$6.1^{+5.1}_{-3.6}$	0.3	
		Е	а	$10.3^{+0.2}_{-0.2} \times 10^{8}$	$16.3^{+3.8}_{-3.0}$	0.8	
		Sp	а	$3.7^{NA}_{-0.8} \times 10^9$	$356.3^{NA}_{-204.4}$	18.4	
	$\leq R_{\text{TOT}}$	Е	b	$2.2:\times 10^9 (E(B-V)=0.03)$	1844:		23 (?)
			b	$1.1 \times 10^9 \ (E(B - V) = 0.52)$	2929:		
NGC 5636	Ring	SSP	а	$2.0^{+0.5}_{-0.6} \times 10^8$	$1.8^{+0.8}_{-0.9}$	0.04	
		Е	а	$10.3^{+0.2}_{-0.1} \times 10^{8}$	$3.9^{+0.7}_{-0.6}$	0.1	
		Sp	а	$4.0^{NA}_{-0.8} \times 10^9$	$97.9^{NA}_{-39.0}$	2.2	
	$\leq R_{\text{TOT}}$	Е	b	$1.4: \times 10^9 (E(B-V) = 0.04)$	57:		150 (?)
			b	$1.0 \times 10^9 (E(B - V) = 0.39^{\text{a}})$	99:		
NGC5638	Total	Е	b	$12.6 \times 10^9 (E(B - V) = 0)$	1076:		

Notes.

^a From FUV and NUV only.

^b From SED fits (FUV to near-infrared). The two values of age and mass are the results of the best-fit models obtained (1) using the foreground extinction values from Table 1 and (2) treating E(B - V) as a free parameter (see Section 5). Results with an additional E(B - V) are unrealistic as discussed in Section 5 and are shown "ab absurdo," supporting the view that UV light traces a distinct, younger population superimposed on a passively evolving stellar population in these objects.

with the primary and projected angular separation $\leq 5^{\circ}$. Within the above conditions our barred S0s have $-6.4(\text{NGC }2974) \leq$ $f \leq -0.74(\text{NGC }5636)$. At face value, f indicates in all cases but NGC 2974 that our UV-ringed S0s currently inhabit sparsely populated environments. In such environments strong interaction episodes can take place, since the velocity dispersion of the galaxies is comparable to the galaxy stellar velocity dispersion. HI tidal tails and shells, often revealed in ETGs located in low-density environments, are signatures of recent dynamical perturbations (Reduzzi et al. 1996; Rampazzo et al. 2006, 2007, and references therein).

6.2. Star Formation and H I Distribution

FUV and H_I flux distributions usually correlate in starforming regions (e.g., Neff et al. 2005; Thilker et al. 2005; Xu et al. 2005). H_I masses, computed from the flux⁵ with the relation $M_{\rm H_{I}} = 2.36 \times 10^5 d^2 S_{\rm H_{I}}$, where *d* is the distance in Mpc and $S_{\rm H_{I}}$ is the integrated flux in Jy km s⁻¹, are reported in Column 7 of Table 2 together with the respective area when available. In NGC 1533, Ryan-Weber et al. (2003) report H_I arcs around the galaxy, spanning from 2' and 11'.7 from the optical center of the galaxy, i.e., outside of the FUV ring, with a mass of $7 \times 10^9 M_{\odot}$, and conclude that the H_I is most likely the remnant of a tidally destroyed galaxy.

Burstein et al. (1987) found that most of the gas may be in a ring approximately coincident with the outer disk of NGC 2962. They measure a flux of 1.3 ± 0.2 Jy km s⁻¹ within a radius less than 2/6 that is comparable to R_{TOT} . Adopting this H I flux, the $M_{\text{H}1}$ over stellar mass ratio is between ~0.4 (assuming E(B - V) = 0.07 mag) and ~0.8 (assuming E(B - V) =0.67 mag). The H I flux associated with NGC 2962 as measured by Grossi et al. (2009; 4.22 ± 0.12 Jy km s⁻¹) and Wardle & Knapp (1986; 5.3 ± 2.5 Jy km s⁻¹) is significantly greater than the value measured by Burstein et al. (1987). Grossi et al. (2009) found that the H I emission of NGC 2962 appears to be connected to that of the galaxy SDSSJ094056.3+050240.5 located at a projected distance of ~8' from NGC 2962.

Kim et al. (1988) measured an H I flux associated with NGC 2974, equal to the value we adopt, in an area of $\sim 4' \times 2'.4$, about 20% larger than the optical extent of the galaxy and with a distribution aligned with the optical isophotes. From the NED database, NGC 4245 is the most H I deficient in the sample with an H I flux of 0.77 \pm 0.14 Jy km s⁻¹.

In sum, H_I emission has been detected in all our S0 galaxies with UV-bright rings, and in one case (NGC 1533) in its nearby environment. Oosterloo et al. (2010) found that H_I is detected,

⁵ Taken from NED.



Figure 4. FUV–NUV model color vs. age for SSP (green dot-dashed lines) and spiral (blue solid/dotted lines for inclination $i = 0^{\circ}/90^{\circ}$) and elliptical (red dashed lines) SFHs. Thin lines are models with internal extinction but no foreground extinction; thick lines are for models reddened with an additional foreground extinction of E(B - V) = 0.5 mag. Measured colors of the rings (horizontal solid lines) and of the entire galaxies (horizontal dashed lines) are also shown. Age labels are in Myr (diamonds).

(A color version of this figure is available in the online journal.)

with a detection limit of a few times $10^6 M_{\odot}$, in $\sim 2/3$ of the field ETGs while < 10% of Virgo members have H I detections. Basically all fast rotating galaxies, like typical S0s, have an H I disk. The H I detection in our S0s, members of groups, is not an exception. Furthermore, Oosterloo et al. (2010) note that field S0s are "rejuvenated" with respect to their cluster counterparts. This is also the case of our barred ring S0s: secular evolution, accretion of fresh gas, or both, taking place in low-density environments, may feed secondary SF events.

6.3. The UV-Optical CMD

In Figure 5, we plot the UV-optical CMD of the ring structures, the galaxy central part (empty circles), and the entire galaxies (filled circles) for both our sample and a comparison sample of 13 ETGs without outer rings from Marino et al. (2011b). We also overplot the Yi et al. (2005) fit to the "red sequence" in ETGs (solid line). We recall that for the ring structures only an upper limit to the optical flux was obtained. The ETGs in Marino et al. (2011b) have a large spread in the luminosity-weighted ages as estimated by Annibali et al. (2007) from line strength indices. The youngest ETG is NGC 3489, with an estimated age of 1.7 ± 0.1 Gyr for the nuclear population, while the oldest is NGC 5363, with an age of 12 ± 2.3 Gyr. Such ETGs lie in the red sequence irrespective of the luminosityweighted age of their nucleus. Annibali et al. (2007) do not provide a luminosity-weighted age for the nucleus of NGC 2962. The (NUV-r) color of the central portion of this S0 is redder than the total galaxy color although it includes the ring structure. The (NUV-r) central and total colors of NGC 4245 and NGC 5636 progressively detach from the red sequence and place the galaxies in the so-called green valley, where evolving galaxies



Figure 5. M_r vs. (NUV–r) measurements of the ring structures (triangles), the central galaxy portion ($\leq R_1$; empty circles), and the total galaxy (within R_{TOT} ; filled circles) for NGC 2962 (red), NGC 5636 (green), and NGC 4245 (blue), respectively. Black circles are the measurements within the optical D_{25} of 13 ETGs with no evidence of ring structures from Marino et al. (2011b). We also overplot the Yi et al. (2005) fit to the red galaxy sequence (solid line). NGC 2962 is in the red sequence while ring colors lie on the blue sequence. NGC 4245 and NGC 5636 lie in the green valley (e.g., Salim et al. 2007).

(A color version of this figure is available in the online journal.)

are located (Salim et al. 2007). Ring structures (triangles in Figure 5) lie in the blue sequence locus.

The locations of the rings and the entire galaxies appear well separated also in the (FUV–NUV) versus (NUV–*r*) plane (see Marino et al. 2011a, their Figure 3).

7. SUMMARY AND CONCLUSIONS

We derived the properties of the stellar populations in outer ring structures and in the main galaxy in a sample of barred S0 galaxies from model analysis of UV and optical photometry. We find evidence of recent SF in the rings whose stellar populations are younger than the mean galaxy population. The stellar masses of the outer rings are only a few percent of the galaxy total stellar mass while the luminosity accounts for up to 70% of the total FUV flux.

The UV, star-forming rings in NGC 4245, NGC 5636, and NGC 1533 are located at the end of the bar structure. The optical and UV images, shown in Figure 1, suggest that NGC 2962 has two rings: one at the end of the bar and one more external, prominent in the UV *GALEX* images, showing arm-like structures. The ring and the outer features detected in NGC 2974 are reminiscent of NGC 2962, which is seen more face-on.

All S0s in our sample show evidence of a bar in optical imaging. UV-bright outer rings are likely related to the bar perturbation. At the same time, there are several indications that NGC 1533, NGC 2962, and NGC 2974 may have been re-fueled with fresh gas by either nearby gas-rich companions (NGC 1553 and NGC 2962) or by a minor merger event, considering the presence of shells (NGC 2974). Recently, Serra & Oosterloo (2010) have shown that a large fraction of ETGs have continued their assembly over the past few Gyr in the presence of a mass of cold gas of the order of 10% of the galaxy stellar mass: a material that is now observable as H I and young stars. Their study includes both NGC 2974 (to which they associate a central luminosity-weighted age of $3.0^{+1.0}_{-0.6}$ Gyr) and NGC 5638 ($8.1^{+0.8}_{-1.2}$ Gyr).

We suggest that rings in our barred S0 sample are an effect of the secular (inner) evolution following the formation of a bar likely aided by fresh gas accreted from gas-rich perturbers. The tumbling bar drives gas inward and the gas accumulates at the Lindblads resonances (Buta & Combes 1996) where SF may take place. In all S0s but NGC 4245, HI is still detected outside the galaxy rings. Rebuilding the secular evolution scenario of the S0 NGC 4570, van den Bosch & Emsellem (1998) concluded that the mass of the outer rings does not require a large gas supply and may even be consistent with these structures having formed from mass loss by the older population of stars. This could also apply to NGC 4245, which is HI poor (Garcia-Barreto et al. 1994).

Kannappan et al. (2009) identify a population of morphologically defined E/S0 galaxies lying on the locus of late-type galaxies in color-stellar-mass space-the blue sequence-at the present epoch. In addition, they noticed that "bars, rings, and dust are evident in both red and blue sequences of E/S0s." The color and the masses computed for our barred S0s with UV-bright rings locate them in the so-called green valley (Salim et al. 2007). We are likely catching them in the evolving path following their rejuvenation produced by the interplay between secular and externally driven evolution (in-flight re-fueling, small wet accretion), evolving back to the E/S0 red sequence.

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