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OUTER RINGS IN EARLY-TYPE DISK GALAXIES: STAR FORMATION RATE

I. P. Kostiuk[1] and O. K. Sil'chenko[2]

[1] *Special Astrophysical Observatory of the Russian Academy of Sciences, Nizhnij Arkhyz 369167, Russia; kostiuk@sao.ru*

[2] *Sternberg Astronomical Institute, M. V. Lomonosov Moscow State University, University av. 13, Moscow 119991, Russia; olga@sai.msu.su*

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Abstract. The total ring star formation rates and their surface densities are determined for 34 early-type disk galaxies with outer stellar rings which were detected in the UV with the GALEX space telescope. The total level of the integrated star formation rate in the outer rings appears to be low – less than 0.1 $M_{\odot}\,\mathrm{yr}^{-1}$, with typical surface densities from 10^{-4} to 10^{-3} $M_{\odot}\,\mathrm{yr}^{-1}\,\mathrm{kpc}^{-2}$.

Key words: galaxies: evolution – galaxies: structure – ultraviolet: galaxies

1. INTRODUCTION

Outer stellar rings are found in more than half of all early-type disk galaxies. For the statistics, one can consult ARRAKIS, 'Atlas of Resonance Rings As Known In the S^4G' (Comerón et al. 2014), compiled by inspecting the 3.6 μm and 4.5 μm band images from the large nearby galaxy survey undertaken by the Spitzer infrared space telescope. This 'Spitzer Survey of Stellar Structure in Galaxies' (S^4G) presents an analysis of the near-infrared images of more than 2350 nearby galaxies (Sheth et al. 2010). The rings included in the ARRAKIS are purely stellar ones because at 4 μm we see mostly old stellar populations. On the contrary, in the ultraviolet one can only see stars younger than a few hundred million years: with typical ages, according to Kennicutt & Evans (2012), less than 100 Myr seen in the far-ultraviolet (FUV) band ($\lambda = 1344 - 1786$ Å) and less than 200 Myr when seen in the near-ultraviolet (NUV) band ($\lambda = 1771 - 2831$ Å). And it is just in these photometric bands that a lot of star-forming rings have been discovered in S0 galaxies by the GALEX space telescope (Gil de Paz et al. 2007). Comerón (2013) has inspected a sample of the inner rings from the ARRAKIS catalog using the FUV maps from the GALEX survey and Hα narrow-band photometry. His analysis reveals that only 50% ($\pm$3%) of the inner rings in S0 galaxies are not seen in the FUV-band, and hence do not harbor current star formation; but starting from the S0/a and later types the vast majority of the inner rings are star-forming ones. We (Kostiuk & Sil'chenko 2015a) performed a similar study of *outer* stellar rings using the ARRAKIS sample of early-type disk galaxies. And again, like in the case of inner rings, half of all outer stellar rings in S0s appeared to be star forming. In spiral galaxies where most of outer ring-like structures have the form of 'pseudo-rings' (unclosed), GALEX signal is detected in almost all the cases, implying ongoing star formation.

2. THE SAMPLE AND ITS ANALYSIS

The parent sample included 118 early-type disk galaxies, of S0–Sb type, possessing closed regular outer stellar rings (57 galaxies) or unclosed 'pseudo-rings' (61 galaxies), which we drew from the ARRAKIS (Comerón et al. 2014). Within this sample, we found 34 regular rings by revealing UV signal based on GALEX space telescope UV imaging data (Kostiuk & Silchenko 2015a,b). These include six S0 galaxies, nine S0/a galaxies, and 19 early-type spirals, with the morphological classification provided by the S^4G team (Buta et al. 2015). In our further analysis we used the open-source SAOImage Display program (DS9, Joye & Mandel 2003) to derive the integrated FUV and NUV fluxes of the rings by using GALEX images with the sky background subtracted (*-intbgsub.fits). We retrieved the FUV and NUV images of the galaxies from The Mikulski Archive for Space Telescopes (MAST)[1]. We adopted the parameters of the rings – center coordinates, inner and outer radii, ellipticities and position angles of the major axes – from the ARRAKIS catalog. We then superposed ring-shaped masks onto the GALEX FUV and NUV images. The Galactic foreground stars were identified by comparing the GALEX and ARRAKIS images and then eliminated; their mean contribution to the integrated fluxes was about 6%. After integrating the FUV and NUV fluxes measured in GALEX counts per second over the ring-shaped masks, we estimated the FUV and NUV magnitudes of the rings, $m_{\rm AB}$, and corresponding fluxes by using the formulae from the GALEX tutorial at the website of the project[2]. We corrected our estimates for the foreground extinction by applying the formulae $A_{NUV} = 8.0E(B-V)$ and $A_{FUV} = 7.9E(B-V)$, derived from the well-recognized extinction law by Cardelli et al. (1989) assuming $R_V = 3.1E(B-V)$; we adopted the $E(B-V)$ color excesses from the NASA/IPAC IRSA[3], where they are computed in accordance with Schlegel et al. (1998). We applied no corrections to account for possible internal dust absorption in the rings: as a zero approximation, we suggest that early-type galaxies are gas-poor and hence with small amount of dust. The star formation rates (SFR) which can be derived from the FUV- and NUV-fluxes refer to the number of stars younger than 100 Myr and 200 Myr, correspondingly. We followed Kennicutt (1989) and Schiminovich et al. (2010), but adopted the Salpeter initial stellar mass function with $0.1\,M_\odot$ and $100\,M_\odot$ cutoff, to calibrate the FUV and NUV luminosities into the SFR measured in solar masses per year. We used their calibrations adopting the galaxy distances from the NED to calculate the star formation rates in the outer rings of our galaxies.

The GALEX ultraviolet space telescope carried out an all-sky survey with rather short signal integration times: individual exposures of the GALEX fields were about 100 sec. These images are marked by 'AIS' label. However, many galaxies were observed within some particular projects and have deeper acquisitions: those observed in the medium-deep surveys ('MIS') were exposed during 1000–1500 seconds, and a few galaxies observed in the NGS, GI, and LeoRingS

[1] http://archive.stsci.edu/

[2] http://galex.stsci.edu/GR6/

[3] http://irsa.ipac.caltech.edu/applications/DUST/

Table 1. Mean errors of magnitudes and star formation rate estimates.

Survey	N	NUV			FUV		
		$\sigma(m_{AB})$	$\sigma(\lg \mathrm{SFR})$	$\sigma(\lg \Sigma_{\mathrm{SFR}})$	$\sigma(m_{AB})$	$\sigma(\lg \mathrm{SFR})$	$\sigma(\lg \Sigma_{\mathrm{SFR}})$
		mag	dex	dex	mag	dex	dex
AIS	15	0.05	0.07	0.02	0.15	0.10	0.04
deep	25	0.01	0.07	0.02	0.03	0.09	0.03
all	34	0.02	0.07	0.02	0.07	0.10	0.04

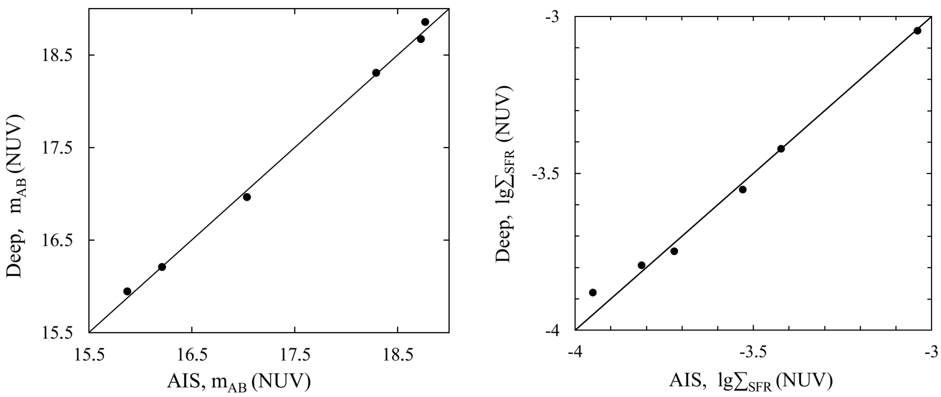

Fig. 1. Comparison of NUV magnitudes m_{AB} (*left*) and the NUV-defined SFR surface densities in $M_\odot\,\mathrm{yr}^{-1}\,\mathrm{kpc}^{-2}$ (*right*) inferred from the data of AIS and deeper GALEX surveys for six galaxies observed twice. The solid straight line is the equality line.

programs had even deeper integration times, with the exposures as long as 11 000 seconds. We bothered whether the data from different surveys could yield inhomogeneous SFR estimates. In any case, the accuracy of magnitudes (listed in Table 1) differed considerably from survey to survey. In this table we give the typical errors of our measured NUV- and FUV-magnitudes of the rings, as well as the typical errors of the star formation rates and surface densities of the star formation rate, Σ_{SFR}, in logarithmic units.

As one can see from the statistics in Table 1 (the second column), six galaxies of the sample were observed by the GALEX both within the framework of the all-sky survey (AIS) and in deeper surveys; we can compare the SFR estimates obtained from the AIS data with those obtained from deeper exposures. The comparison is presented in Fig. 1. The left-hand panel compares the ring-integrated NUV magnitudes m_{AB} corrected for the foreground stars and Galactic extinction, and the right-hand panel compares the NUV-defined SFR surface densities measured in $M_\odot\,\mathrm{yr}^{-1}\,\mathrm{kpc}^{-2}$ and corrected for the foreground stars, Galactic extinction, and inclination of galactic disks (we adopted the galactic disk inclinations from the S^4G data[4]). The measurements are well concentrated around the equality lines with a scatter of 0.05 mag and 0.03 dex for NUV-magnitudes and logarithmic SFR surface densities, respectively.

[4] http://irsa.ipac.caltech.edu/data/SPITZER/S4G/

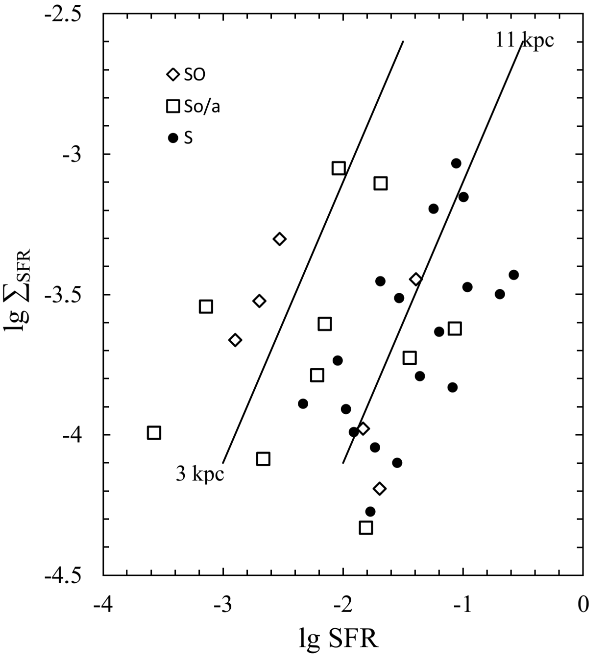

Fig. 2. SFR surface density in $M_{\odot}\,\mathrm{yr}^{-1}\,\mathrm{kpc}^{-2}$ vs. integrated ring SFR, in $M_{\odot}\,\mathrm{yr}^{-1}$.

3. STAR FORMATION RATE IN RINGS

Figure 2 compares the SFR surface densities (the means of the FUV and NUV estimates) with integrated SFRs for the rings distinguishing the galaxies of different morphological types: S0, S0/a, and spirals. One can see that while SFR surface densities are comparable in the rings of S0s and spirals, $\lg\Sigma_{\mathrm{SFR}}$ in the range –4 to –3, the integrated SFRs are higher by an order of magnitude in the outer rings of spiral galaxies: $\langle\lg\mathrm{SFR}\rangle = -2.5$ in S0s versus $\langle\lg\mathrm{SFR}\rangle = -1.5$ in spirals. To explain such a behavior, we overplotted the contour lines of equal ring outer radii. It becomes clear that the rings of spiral galaxies are tightly concentrated around the locus corresponding to $R_{\mathrm{out}} = 11.5$ kpc, while some lenticular galaxies have rings of smaller radius, with the $\langle R_{\mathrm{out}}\rangle = 2.6 \pm 0.4$ kpc. Fig. 3 (the upper panel) shows the histogram of the distribution of ring outer radii, which confirms that spiral galaxies have, on the average, larger ring radii. In our sample, however, spiral galaxies appear to have more extended large-scale stellar disks than the sample of lenticular galaxies if we adopt the photometric boundaries as given in $\mathrm{S^4G}$ (the bottom panel of Fig. 3). Interestingly, in almost all galaxies, except for five objects, the ring center is offset on the average by 0.5 ± 0.1 kpc with respect to the galactic nucleus in the NUV maps.

In Figs. 4 and 5 we show the diagrams similar to those presented by Gil de Paz et al. (2007). The solid lines delimit the locus of spiral galaxies. Outer rings in spiral galaxies are bluer than those in S0 galaxies and are also more luminous in the UV-bands – just as revealed by integrated UV characteristics measured for nearby galaxies of different types by Gil de Paz et al. (2007). We also see a clear trend within every morphological type: more luminous (in the UV) rings are bluer. This trend is more prominent among spiral galaxies. The $FUV - NUV$ colors of S0s

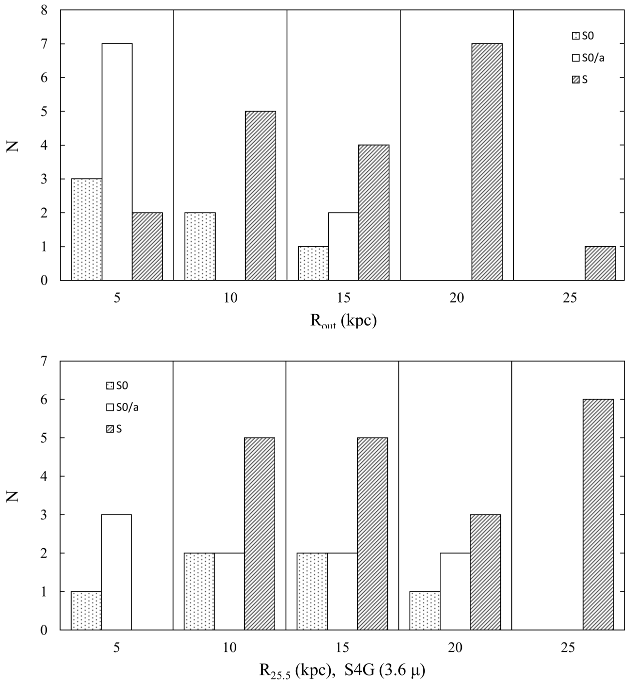

Fig. 3. Distributions of the ring outer radii (*top panel*) and of the stellar disk radii in the NIR-band (*bottom panel*). The horizontal axis is binned into five intervals, 2.5–7.5 kpc, 7.5–12.5 kpc, 12.5–17.5 kpc, 17.5–22.5 kpc, and 22.5–27.5 kpc. Within each radius interval, we build histograms of the distributions of morphological types of galaxies.

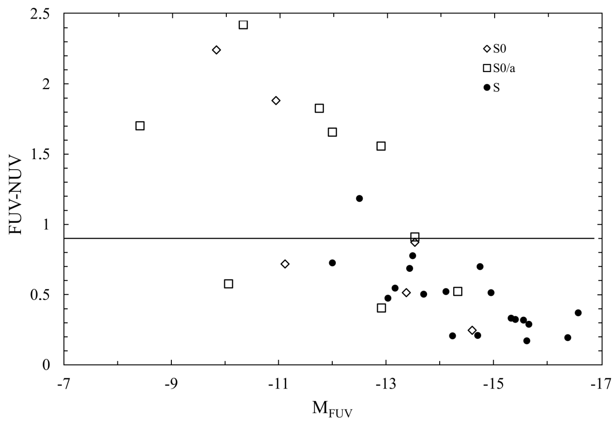

Fig. 4. The UV color $FUV - NUV$ vs. FUV absolute magnitude of the rings. The horizontal solid line corresponds to the border between spiral and lenticular galaxies according to Gil de Paz et al. (2007).

and S0/a galaxies are indistinguishable. The mean colors are: $\langle FUV - NUV \rangle = 0.8 \pm 0.1$ for the whole sample, $\langle FUV - NUV \rangle = 1.1 \pm 0.2$ for S0s and S0/a's, and $\langle FUV - NUV \rangle = 0.5 \pm 0.1$ for spirals.

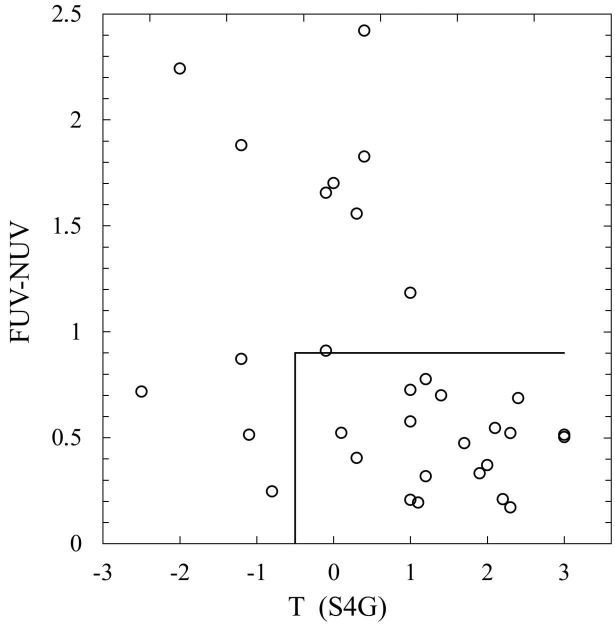

Fig. 5. The UV colors $FUV - NUV$ for the outer rings of the galaxies of different morphological types. The right bottom box contains the *integrated* characteristics of spiral galaxies according to Gil de Paz et al. (2007).

4. CONCLUSIONS

We used the UV-imaging data of the GALEX space telescope to measure the integrated star formation rates (SFR) and the star formation rate surface densities ($\Sigma_{\rm SFR}$) in the outer stellar rings for a sample of early-type galaxies covering the morphological types from –3 (S0) to +3 (Sb). We found the outer rings to have homogeneously low SFR surface densities, $\lg \Sigma_{\rm SFR}$ in the range –4 to –3, where $\Sigma_{\rm SFR}$ is in $M_\odot$ per yr per kpc^2, and such a low level of the rings' $\Sigma_{\rm SFR}$ is independent on the galaxy morphological type. However, in our sample the rings (and disks) of spiral galaxies are on the average larger than those in lenticular galaxies, and as a result the integrated star formation rates in the outer rings of the spiral galaxies are, on the average, by one order of magnitude higher than the integrated star formation rates in the S0s. The $FUV - NUV$ colors of the rings of the spiral galaxies are bluer than those of the S0 rings, and agree with the integrated UV colors of spiral galaxies according to the Gil de Paz et al. (2007) estimates.

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