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# CURRENT STAR FORMATION IN THE OUTER RINGS AMONG EARLY-TYPE DISK GALAXIES

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**Abstract.** We use ARRAKIS, the atlas of stellar rings in galaxies (Comerón et al. 2014), based on data of the S4G survey, to compile a list of early-type, S0-Sb, disk galaxies with outer stellar ring-like features ('pure' rings, R, or pseudorings, R$'$). We searched for current star formation signatures within these features through the NUV-maps of the galaxies provided by the ultraviolet space telescope GALEX. We found that current star formation, with the mean age of the young stellar population of less than 200 Myr, is present in about a half of all 'pure' rings; and within the pseudorings it is observed almost in all cases.

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

## 1. INTRODUCTION

Large-scale ring structures, both outer and inner ones, can be met in more than half of all galactic disks (for the statistics, see ARRAKIS, 'Atlas of Resonance Rings As Known In the S4G', Comerón et al. 2014). The rings described in the ARRAKIS are purely stellar ones because at the wavelength of 4 $\mu$m we see mostly old stellar populations. On the contrary, in the near ultraviolet (NUV) we can see mostly stars younger than a few hundred million years, and it is in this wavelength domain that the morphology of nearby galaxies can be studied using the public data from the GALEX space telescope (Gil de Paz et al. 2007). Comerón (2014) inspected the sample of inner rings from the ARRAKIS catalogue using the far ultraviolet (FUV) maps from GALEX and narrow-band H$\alpha$ photometry. His analysis reveals that among early-type disk galaxies, S0-Sab, only 21% ($\pm$3%) of the inner rings are not seen in the FUV and so do not harbor current star formation. Consequently, the dissipation time of the inner rings, if computed in terms of the resonance hypothesis of their origin, exceeds 200 Myr, which corresponds to about one orbital period in the central part of the galaxies. We perform a similar analysis, but apply it to the outer rings in early-type disks galaxies in order to search for recent star formation there.

## 2. THE SAMPLE

We (Kostiuk & Sil'chenko 2015) used the ARRAKIS catalogue of stellar ring-like structures (Comerón et al. 2014) to compile a list of 118 galaxies with outer ring-like structures ('pure' rings, R, and pseudorings, R′) to study UV morphologies of the outer rings in early-type disk galaxies. The ARRAKIS catalogue is based on the 3.6 $\mu$m and 4.5 $\mu$m data of the S4G survey (S4G≡ The Spitzer Survey of Stellar Structure in Galaxies, Sheth et al. 2010) which covers a nearby galaxy sample limited by the following constraints: distance $D < 40$ Mpc, galactic latitude $\mid b \mid > 30^\circ$, integrated magnitude $m_{B,\,\mathrm{corr}} < 15.5$, and angular diameter $D_{25} > 1'$. To reliably determine the parameters of ring-like structures, an additional constraint onto outer isophote ellipticity (and hence onto disk inclination to avoid strictly edge-on orientations) is needed; we apply the condition of $1 - b/a < 0.5$ just as it was done in the ARRAKIS, to derive the statistical characteristics of the rings. For our study we use only outer rings that are close to the optical boundaries of galactic disks, and only in disk galaxies of early morphological types, S0–Sb, where the ring structures are indeed frequent.

## 3. STARFORMING RINGS

We inspected our sample by using the public archive of GALEX space mission images (intensity maps from `http://galex.stsci.edu/GR6/`); we explored the images taken in the NUV band 1770–2730Å, which are dominated by the light of B-type stars. Because of their mass, the lifetime of these stars does not exceed 200 Myr, and this is therefore the dating of recent star formation in the stellar rings. We estimate the mean NUV signal in the outer rings and for background surrounding the galaxies. If the mean NUV signal in a ring exceeds twice that of the background, we mark the corresponding galaxy as having UV-radiation in its outer ring-like structure (the notations are R+ and R′+). Ninety-four galaxies in our list are of SB or SAB type, and hence possess bars; however, the presence of a bar has no effect on the presence or absence of star formation in the outer ring. Eighty-four galaxies of our list demonstrate current star formation in their outer rings. The fraction of rings and pseudorings varies in galaxies according to their morphological types: pseudorings are not found in S0 galaxies, while 'pure' outer rings are a typical feature of S0s (60%, according to Comerón et al. 2014); in early spirals, Sab–Sb, pseudorings are much more commonly found than 'pure' rings. Fig. 1 shows our results – the frequency of current star formation in the outer rings and pseudorings among the galaxies of different morphological types. The fraction of both 'pure' rings and pseudorings with current star formation increases when we pass from S0 to Sb through S0/a–Sa. However, even in S0s, where the fraction of star-forming outer rings is minimal, it can be as high as 56%. Practically all spirals, Sab–Sb, have a UV-signal in the outer ring-like features. We specify three subclasses of UV morphology of the outer rings — unclosed, clumpy, and outer rings in a filled disk, — and among those the clumpy rings are the most frequent; moreover, they are two times brighter in UV than the other subclasses.

## 4. DISCUSSION

As noted by Sil'chenko et al. (2014), the nature of outer rings in disk galaxies is controversial and is not yet understood. There are two popular scenarios of the outer ring origin: the resonance and impact mechanisms. In the former scenario

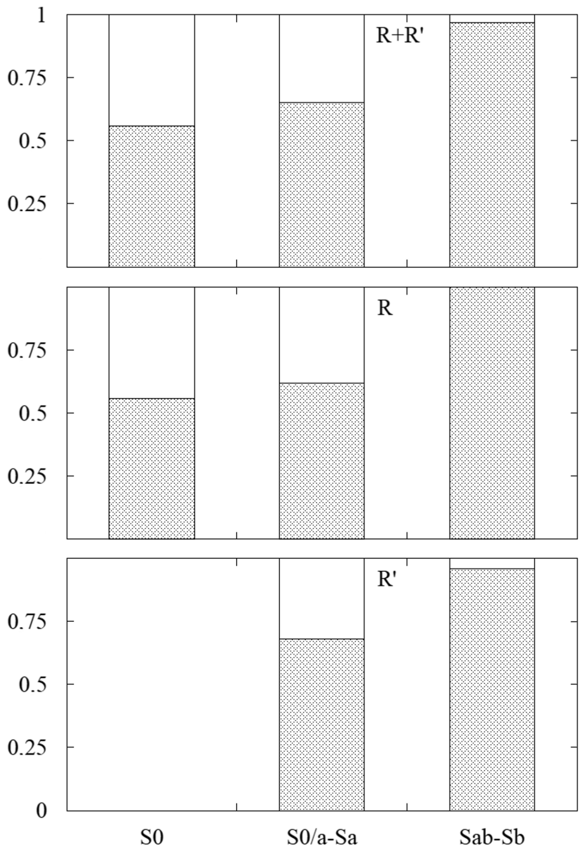


**Fig. 1.** The fraction of galaxies with UV-radiation in an outer ring (*shaded*) among the galaxies with outer stellar rings ($4\,\mu$m) for different morphological types: all the ring-like features, R+R$'$ (the upper panel); only 'pure' rings, R (the middle panel), and pseudorings, R$'$ (the bottom panel). For each type the total number of galaxies is normalized to unity.

(Schommer & Sullivan 1976; Athanassoula et al. 1982; Buta & Combes 1996), the formation of the ring is related to the presence of a bar – non-axisymmetric density perturbation in the center of the galaxy. The bar rotates as a rigid body, at an angular velocity that is constant along the radius, and so it marks dynamically distinct radial zones where the differential rotation of gas occurs in resonance with the bar. Near these resonances the orbits of gas clouds crowd, the gas condenses, and necessary conditions for the onset of star formation occur. After star formation proceeds, stellar rings emerge. Interestingly, in the frame of this mechanism the first structures that form by gas cloud crowding are pseudorings, with 'pure' rings emerging later (Schwarz 1981; Byrd et al. 1994); and according to our observational statistics, ongoing star formation can be found more often in pseudorings than in 'pure' rings, which is consistent with the theoretical results above. Also, a theory of 'manifolds' was proposed (Romero-Gómez et al. 2007), which stated the existence of persistent gas cloud orbits around stability points within a triaxial (bar) potential. The impact scenario – the second most popular formation mechanism for rings in galactic disks – developed by Freeman & de Vaucouleurs (1974), Theys & Spiegel (1976), Few & Madore (1986), Athanassoula et al. (1997), implies the fall of a satellite from highly inclined orbit onto the galactic disk near the center. Such impact triggers a circular gas density wave running outward through the disk. As a result of gas compression, at some radius, again, star formation may ignite, and a stellar ring may form. In the case of a pure stellar disk, the impact can generate transient stellar density enhancement, which looks like an outward-moving ring (Wu & Jiang 2012). A third possibility for an outer in-plane ring to form is by the accretion of cold gas from outside as a result of tidal interaction or from a cosmological filament; it was mentioned by Buta & Combes (1996) and by Byrd et al. (1994), but was not discussed exhaustively yet.

Meantime Pogge & Eskridge (1993), who searched for star formation in HI-rich S0 galaxies, noted that, first, star formation in S0s was always organized in ring-like structures, and second, the occurrence of star formation (it was found in a half of gas-rich S0s) did not depend on the amount of gas. A hypothesis was then formulated that star formation in gas-rich S0s had to be driven not by intrinsic gravitational instability, but by some kinematical effect. Indeed, surface density of HI in outer disks of early-type galaxies was often below the Kennicutt (1989) threshold, and, e.g., Noordermeer et al. (2005) noted that star formation in the outer ring of NGC 7217 could not proceed because gas had to be stable. However, observations reveal star formation sites in this low-density gas. Some external triggering, like outer cold gas supply and shock compression due to accretion, seems to be rather necessary.

It is known that the distribution of cold gas in gas-containing early-type galaxies can be even more extended than in spirals – regular HI disks in S0s may reach up to 200 kpc in diameter (Oosterloo et al. 2007). The statistics by Afanas'ev & Kostyuk (1988) based on surface photometry showed that galaxies with outer rings possess more extended stellar disks than galaxies without rings. We believe that it is due to disk growth inside-out through the stimulated star formation in the outer cold-gas rings accreted from outside.

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