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LETTER TO THE EDITOR

Star formation in outer rings of S0 galaxies

I. NGC 6534 and MCG 11-22-015

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ABSTRACT

Aims. Although S0 galaxies are usually thought to be "red and dead", they often demonstrate star formation that is organized in ring structures. We try to clarify the nature of this phenomenon and its difference from star formation in spiral galaxies. Two early-type galaxies with outer rings, NGC 6534 and MCG 11-22-015, were selected to be studied.
Methods. After inspecting the gas excitation in the rings using the Baldwin–Phillips–Terlevich method, we estimated the star formation rates (SFR) in the two outer rings of our galaxies using several SFR indicators derived from narrow-band photometry in the Hα emission line and archival GALEX ultraviolet images of the galaxies.
Results. The ionized gas is excited by young stars in the ring of NGC 6534 and partly by shocks in MCG 11-22-015. The oxygen abundances in the HII regions of the rings are close to solar. The derived SFRs allow us to qualitatively restore star formation histories (SFH) in the rings: in NGC 6534, the SFH has been flat during the last 100–200 Myr, and in MCG 11-22-015, the star formation has started only a few Myr ago. We suggest that the rings in NGC 6534 and MCG 11-22-015 have different natures: the former is a resonant ring supplied with gas perhaps through tidal effects, and the latter has been produced by a satellite accretion. Recent outer gas accretion is implied in both cases.

Key words. galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: structure

1. Introduction

Early-type galaxies possessing large-scale detached outer stellar rings were first noted by de Vaucouleurs (1959). Boris A. Vorontsov-Velyaminov, during his compilation of the Morphological Catalogue of Galaxies (MCG), had found galaxies with large-scale rings to be so numerous that he proposed to introduce a special branch into the Hubble fork to describe them (Vorontsov-Velyaminov 1960). Recent surveys reveal that outer stellar rings are to be found mostly in S0 galaxies: according to Comerón et al. (2014), up to 50% S0–S0/a galaxies have outer rings. A similar fraction of ring structures in early-type disk galaxies, 53 ± 5%, was noted by Laurikainen et al. (2011).

Rings are usually thought to be mostly of resonance nature: they represent the result of gas accumulation at Lindblad resonances of large-scale bars and of consequent star formation. However, not all galaxies with outer rings have large-scale bars, and not all S0s with outer rings demonstrate any gas presence and star formation in the rings. Our estimates based on the listing of the ARRAKIS catalog (Comerón et al. 2014) and on the GALEX imaging data reveal that about half of all outer rings in S0s have had star formation during the last 100–200 Myr (Kostiuk & Sil'chenko 2015). The problem of gas sources to feed star-forming rings in S0 galaxies is still unsolved; and nothing is known about the star formation histories of these spectacular structures. In this Letter we consider NGC 6534 and MCG 11-22-015, which are two early-type disk galaxies belonging to the red sequence with outer rings; their global properties are given in Table 1. The optical-band rings and first spectral results for these galaxies have previously been reported by one of us (Kostyuk 1975; Kostyuk et al. 1981). After the GALEX data releases, we have detected UV-rings there (Ilyina & Sil'chenko 2011) with radii corresponding to the optical rings. Now we present new spectral data as well as star formation rate (SFR) estimates obtained from the UV images and from our own Hα narrow-band imaging.

2. Observations and SFR calibrations

We exposed both galaxies with the SCORPIO reducer of the Russian 6 m telescope (Afanasiev & Moiseev 2005) operating in the imaging mode, through the narrow-band filter centered onto the redshifted Hα line (both galaxies have similar radial velocities) and in the neighboring continuum. A spectrophotometric standard, AGK+81d266, was also exposed on the same night through the FN674 filter. We also used the SCORPIO reducer to obtain spectra. We obtained green- and red-band medium-resolution spectra for NGC 6534 and only a red spectrum for MCG 11-22-015. The details of the observations are given in Table 2.

Table 1. Global parameters of the galaxies.

Galaxy	NGC 6534	MCG 11-22-015
R_{25}, arcsec (LEDA)	28	24
$R_{\rm ring}$ (outer edge), arcsec	19 × 13	20 × 18
$M_{\rm H}$ (NED)	–23.5	–23.7
$M_{\rm NUV}$, (our estimate)	–17.2	–16.1
$(u-r)_0$ (SDSS/DR9)	2.55	2.63
V_r (NED), km s^{-1}	8118	8064
Distance, Mpc (NED)	110	109
Scale, kpc per arcsec (NED)	0.518	0.514
PA$_{\rm phot}$ (LEDA)	16.5°	75°
PA$_{\rm ring}$ (our estimate)	21.7°	72.5°

To estimate the SFR over various temporal scales, we used the GALEX images in the near-UV (NUV) and far-UV (FUV) bands and our calibrated Hα images; the formulae for the SFR calculations have been taken from Hao et al. (2011) and from the review by Kennicutt & Evans (2012).

3. Structure of NGC 6534 and MCG 11-22-015

To study the large-scale structures of the galaxies, we used the imaging data from the SDSS/DR9. We made an isophotal analysis, and then we calculated azimuthally averaged surface brightness profiles by integrating the fluxes within elliptical annuli with running major axes and with a fixed ellipticity and major-axis orientation determined by the outermost isophote measurements. The results are shown in Figs. 1 and 2, together with the color maps $g-r$. Some differences in the whole structure and ring visibility in NGC 6534 and MCG 11-22-015 are evident. NGC 6534 is moderately inclined to our line of sight, as demonstrated by the elongated outer isophotes; the outer ring matches the ellipticity of the outermost isophotes, being evidently a round structure inside the exponential stellar disk. However, the inner isophotes, $R \leq 8''$, are very round; considering the quasi-exponential surface-brightness profile of the inner part of NGC 6534, we can suspect a pseudo-bulge containing an inner stellar ring that is slightly elongated orthogonally with respect to the outer isophotes and to the outer ring. MCG 11-22-015, in contrast, has rather round outer isophotes and two local ellipticity maxima at $R = 5''$ and at $R = 14''$. The latter radius corresponds roughly to the outer ring, so that when we assume that the galaxy is seen face-on, we must recognize the elliptical shape of its outer ring. The surface-brightness profiles show the prominent ring in NGC 6534 overposed onto the regular exponential disk ($\mu_{r,0} = 19.4$, $h = 9.8''$, or 5.1 kpc) and a Type-II disk, according to the Freeman (1970) classification, in MCG 11-22-015, with a scalelength of 4.″2, or 2.2 kpc. The elliptical ring in MCG 11-22-015 represents a boundary between the elongated lens and the outer exponential disk. Despite the structural differences, the rings in both galaxies are bluer than the underlying disks, in accordance with the fact that the rings were initially noted as UV-bright features (Ilyina & Sil'chenko 2011).

4. Corotating gas in NGC 6534

We obtained the spectrum in the green with a spectral resolution of 2 Å for NGC 6534 alone to determine the stellar and ionized-gas rotation curves and velocity dispersion. The velocities are shown in Fig. 3. The gas in NGC 6534 rotates strictly with the stellar component, and we can conclude that it is probably confined to the stellar-disk plane. The profile of the stellar velocity dispersion is typical for lenticular galaxies: it has a moderate maximum in the center, $\sigma_{*,0} = 140$ km s^{-1}, and a fast drop at $R > 10''$ that corresponds to the onset of disk domination in the total surface brightness.

When we exposed the green spectrum of NGC 6534 with the slit at PA = 16.5°, the southern nearby galaxy, half as luminous as NGC 6534 and also with S0 morphology, was serendipitously caught by the slit. Its radial velocity is not given in the NED database, therefore NGC 6534 is formally classified as an isolated galaxy. From the absorption-line spectrum of the satellite we have derived a systemic velocity of 2MASX J17560734+6415509, $V_r = 8124 \pm 20$ km s^{-1}. Since NGC 6534 has $V_r = 8118$ km s^{-1}, 2MASX J17560734+6415509 is a real and very close satellite of NGC 6534. It is slightly bluer than NGC 6534 according to the SDSS/DR9 data; but any signatures of ionized gas are absent from the spectrum. The projected distance between the galaxies is 75″, or only 39 kpc. If 2MASX J17560734+6415509 (or LEDA 2666218) has at any time been a gas-rich satellite, it might be a gas donor for NGC 6534.

5. Gas excitation and oxygen abundance in the rings

By inspecting the slit spectra of the galaxies, we identified radius ranges where the rings are betrayed by strong Balmer emissions; the spectra are shown in Fig. 4. We calculated the ratios of the strong emission lines to check the gas excitation. The excitation can be checked with log([NII]λ6583/Hα). In both cuts of the ring in NGC 6534 and at the southern side of MCG 11-22-015, these ratios are -0.40 ± 0.03, -0.37 ± 0.02, and -0.39 ± 0.20, correspondingly. In the ring of NGC 6534, for which we also have a green spectrum, log([OIII]λ5007/Hβ) is -0.12 ± 0.15 and 0.00 ± 0.09. According to Kewley et al. (2006), such emission-line ratios signify gas excitation by young stars in the southern parts of both rings and a possible composite excitation mechanism for the northern half of the NGC 6534 ring. At the northern side of the MCG 11-22-015, where the emission lines are weak, log([NII]λ6583/Hα) = -0.12 ± 0.12, which means that some shocks may be present here.

When the gas is excited by young stars, its oxygen abundance can be estimated using empirical calibrations of the strong-line ratios. For the ring regions where the gas is shown to be excited by young stars, we have probed two recognized calibrations: that by Pettini & Pagel (2004), through N2 for NGC 6534 and MCG 11-22-015, and that by Dopita et al. (2016), D16 with the [SII]λ6717,6731 lines as well, for NGC 6534. We obtained 12 + log(O/H) = 8.67 ± 0.02 from N2 and 12 + log(O/H) = 8.65 ± 0.10 from D16 for the southern tip of the ring in NGC 6534; for the star-forming site of the southern part of the ring in MCG 11-22-015, the indicator N2 gave 12 + log(O/H) = 8.68 ± 0.11. For the northern tip of the ring in NGC 6534, where the excitation may be composite, the Dopita et al. (2016) method gives 8.44 ± 0.06. However, the metallicity of the star-forming gas is in any case comparable with the solar value or slightly lower.

6. Hα emission morphology and star formation rates in the rings

By undertaking narrow-band photometry of the galaxies through the filters centered on the redshifted Hα line and on the nearby

Table 2. Log of the observations with the Russian 6m telescope BTA.

Date	Galaxy	Config/grism or filter	Exposure	PA (slit)	Spectral range	Seeing
Oct. 07, 2016	MCG 11-22-015	Slit/VPHG1800R	60 min	50°	6100–7100 Å	1″.5
Oct. 07, 2016	NGC 6534	Slit/VPHG1800R	60 min	20°	6100–7100 Å	1″.5
June 24, 2017	NGC 6534	Slit/VPHG2300G	60 min	16.5°	4800–5500 Å	3″.3
May 28, 2017	NGC 6534	Directimage/FN674	40 min	124°	6703–6763 Å	1″.5
May 29, 2017	NGC 6534	Directimage/SED608	17.5 min	124°	5976–6144 Å	1″.8
May 28, 2017	MCG 11-22-015	Directimage/FN674	30 min	124°	6703–6763 Å	1″.5
May 29, 2017	MCG 11-22-015	Directimage/SED608	15.5 min	124°	5976–6144 Å	1″.8
May 28, 2017	AGK+81d266	Directimage/FN674	1 min	–	6703–6763 Å	1″.5

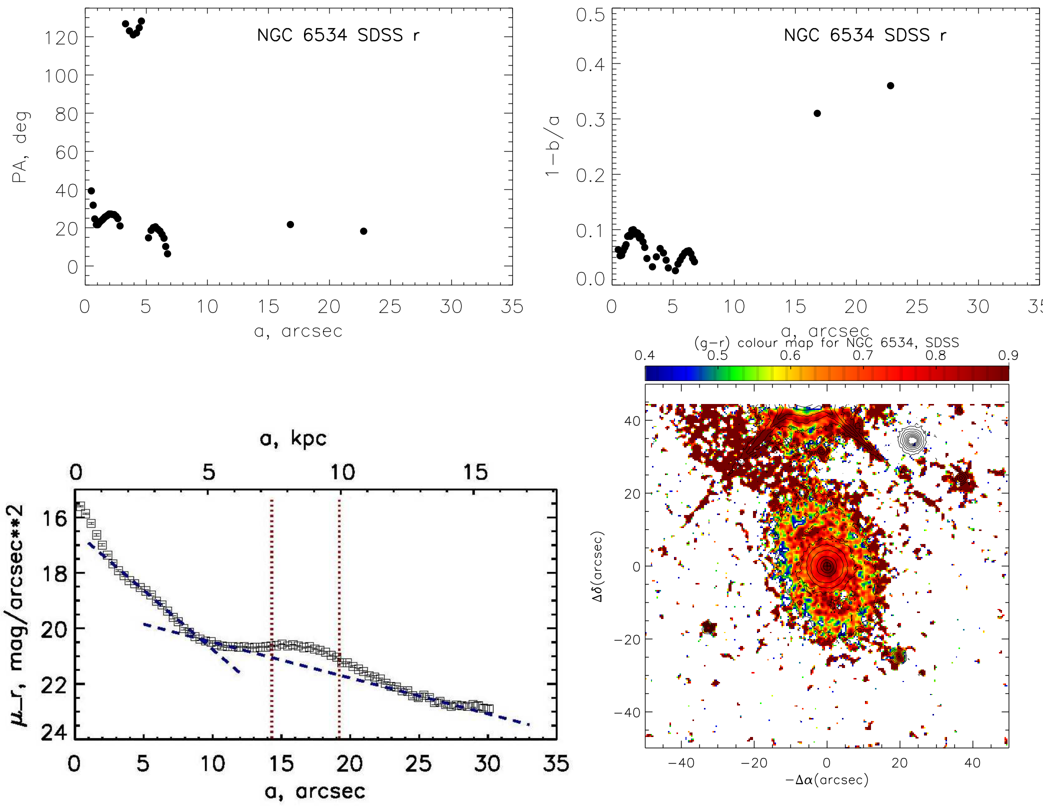

Fig. 1. SDSS photometry of NGC 6534: results of the isophote analysis (*upper row*), the azimuthally averaged surface brightness profile (*bottom left panel*), and the color map (*bottom right panel*). The fitted exponential laws are also shown. The red dotted verticals mark the borders of the Hα ring.

continuum, we tried to subtract the latter images from the former to derive net emission-line maps that are calibrated into energetic units with the image of the spectrophotometric standard observed on the same night. While subtracting, the off-emission images were normalized to reduce to zero the surrounding foreground stars that are implied to be pure-continuum sources. The resulting net Hα maps are shown in Fig. 5. The morphology of the emission-line image of NGC 6534 is somewhat unexpected: while in the broad bands the galaxy has an evident ring, quite detached from the main body of the galaxy, in the Hα emission we see patchy spiral arms starting from the ansae of the inner ring. The Hα morphology of MCG 11-22-015 is more traditional: it is a round, strongly inhomogeneous ring, with its southern half more bright in the emission line; it borders the inner lens, which is also filled by weak Hα emission.

To calculate SFR by using three independent indicators, namely, UV fluxes from the GALEX images as well as our estimates of the fluxes in the Hα emission line, we overposed the same elliptical apertures on all three images of every galaxy. To determine the borders of the apertures, we used the Hα images because they have the highest contrast. The apertures are shown in Fig. 6. We measured the fluxes inside the elliptical annuli, just between the inner and outer ellipses of Fig. 6 for the three (NUV, FUV, and Hα) bands for NGC 6534 and only for the deep NUV/MIS image and the Hα image of MCG 11-22-015. The latter galaxy is weak in the UV, and its shallow FUV/AIS image does not contain any signal in the ring above 3σ of the sky level. Then we applied the calibrations of the SFR from Kennicutt & Evans (2012) and corrected the UV-based estimates of the SFR for the intrinsic dust as described

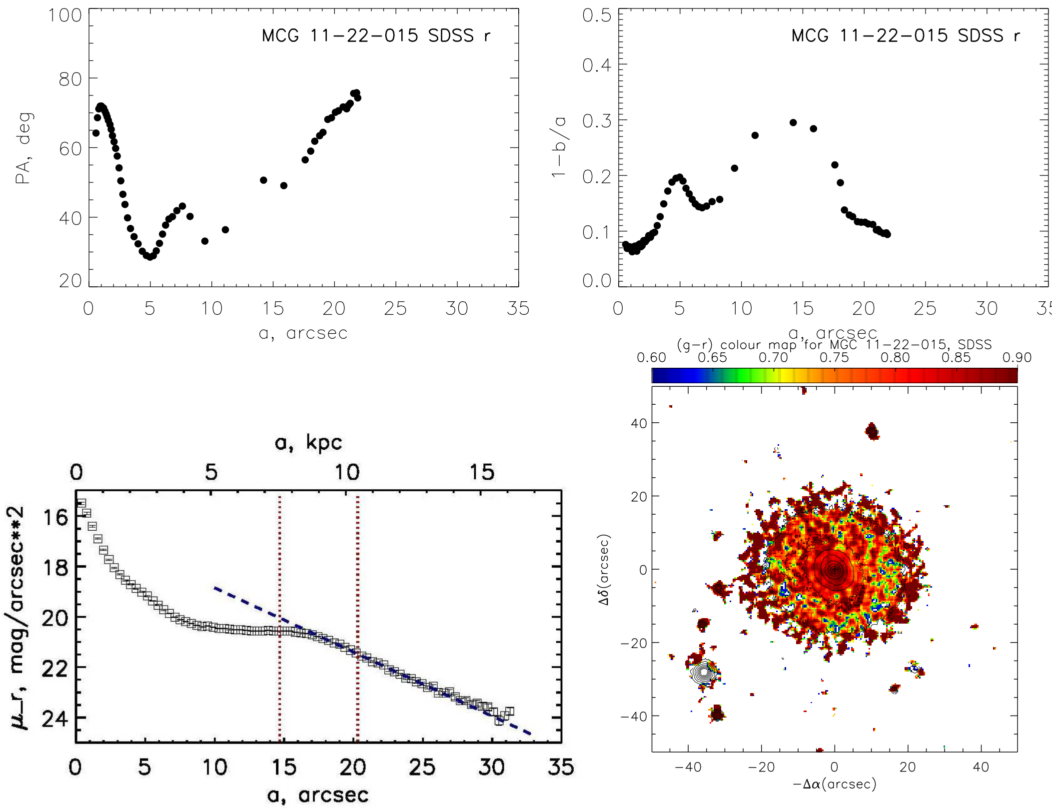

Fig. 2. SDSS photometry of MCG 11-22-015: results of the isophote analysis (*upper row*), the azimuthally averaged surface brightness profile (*bottom left panel*), and the color map (*bottom right panel*). The fitted exponential law, which is valid over a two-scalelength extension, is also shown. The red dotted verticals mark the borders of the Hα ring.

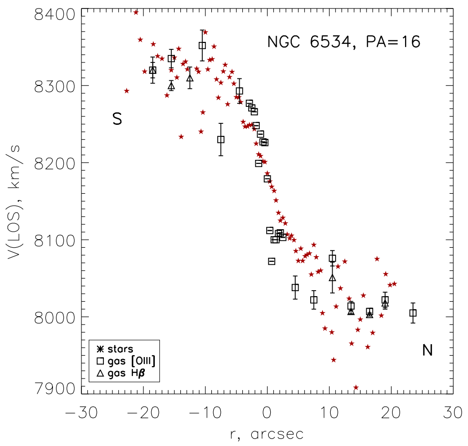

Fig. 3. Line-of-sight velocity profiles for the stars and ionized gas in NGC 6534 taken along its major axis.

in Kostiuk & Sil'chenko (2018) using the WISE imaging in 22 μm.

We found that over the NGC 6534 ring, the star formation proceeded with a roughly constant rate during the last 200 Myr: the SFRs from the NUV, FUV (GALEX/AIS), and Hα fluxes are 0.13, 0.12, and 0.18 $M_{\odot}$ yr^{-1}, respectively, with an individual accuracy of the estimates of 0.03 $M_{\odot}$ yr^{-1}.

The situation is more complex in MCG 11-22-015. The NUV flux measured in the deep MIS-image gives an SFR = 0.07 ± 0.01 $M_{\odot}$ yr^{-1}, while the Hα flux gives an SFR = 0.26 ± 0.01 $M_{\odot}$ yr^{-1} with the standard calibration. In this situation we recall the caveat from Calzetti (2013) that the standard UV-SFR calibration is valid only for star formation proceeding over long timescales, $\geq$100 Myr. If the star formation timescale is shorter, we must increase the SFR estimate; for example, for star formation occuring during only the last 2 Myr, we must multiply the standard calibration by a factor of 3.45 (Calzetti 2013). By multiplying our UV-based SFR of 0.07 $M_{\odot}$ yr^{-1} by 3.45, we obtain 0.24 $M_{\odot}$ yr^{-1}. The latter estimate leads to consistency with the SFR from the Hα. For MCG 11-22-015 we may therefore suggest that its star formation in the ring is quite recent, no older than a few Myr.

7. Conclusions

We have studied the outer star-forming rings in two lenticular galaxies, NGC 6534 and MCG 11-22-015: spectral data as well as narrow-band and UV images were analyzed. The ionized gas in the rings is mostly excited by young stars and demonstrates nearly solar metallicity, rejecting the possibility of an origin in cosmological filaments. Although NGC 6534 is classified as an isolated galaxy in the NED, we have detected a very close companion, PGC 2666218, at some 40 kpc from it in projection. MCG 11-22-015 has previously been known as a member of an X-ray bright group (Henry et al. 1995). Both facts mean that there is no problem with the outer gas sources feeding star formation; it may be tidal harassment of the neighbor by NGC 6534 and a minor merger for MCG 11-22-015. The star formation histories in the rings are different: the SFR has been constant at least for the last 200 Myr in NGC 6534, in accordance with the possible resonance nature of its ring, and it started recently in MCG 11-22-015, betraying a fresh gas-rich satellite cannibalism. The quasi-solar or only slightly subsolar metallicity

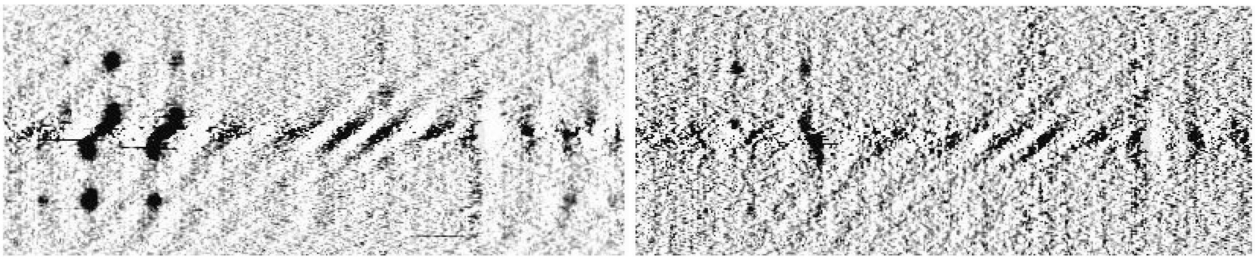

Fig. 4. Continuum-subtracted spectra near the Hα emission line for NGC 6534 (*left panel*) and for MCG 11-22-015 (*right panel*).

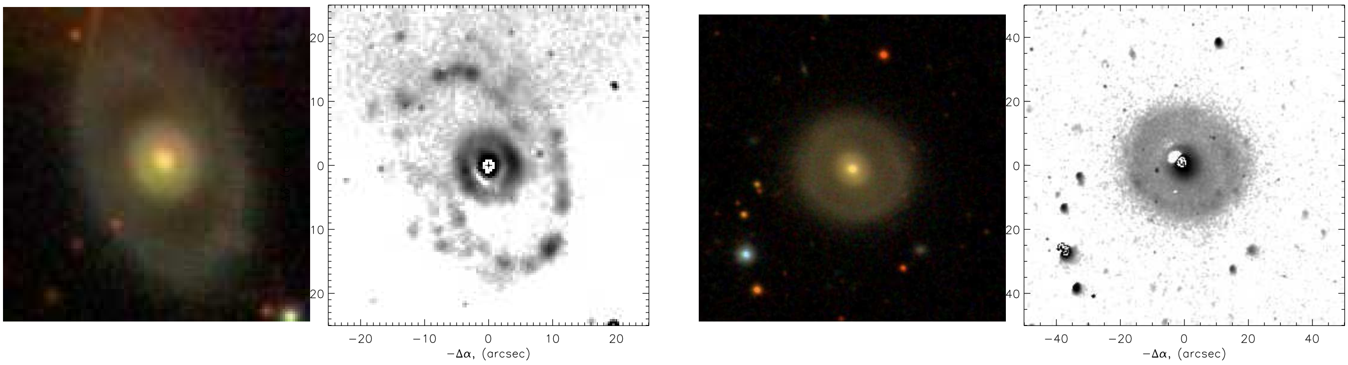

Fig. 5. Comparison of the broad-band SDSS images (*left plot in every pair*) and the narrow-band Hα images (*right plot in every pair*). NGC 6534 is to the *left* and MCG 11-22-015 is to the *right*.

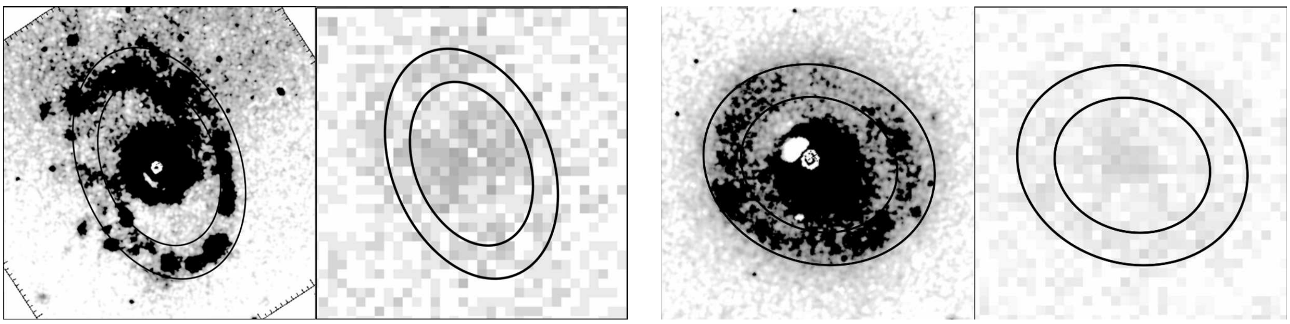

Fig. 6. Elliptical-annulus apertures used to integrate the fluxes for SFR derivations overposed on the Hα and the NUV images (*left and right plots in every pair*). The size of the fields shown is 50″; NGC 6534 is to the *left* and MCG 11-22-015 is to the *right*.

of the gas in the outer star-forming rings of S0 galaxies has previously been found by us more than once, including the cases of obvious minor mergers; see, for example, NGC 4513 with its counter-rotating gas (Ilyina et al. 2014). We may need some specific effective chemical evolution mechanisms to explain this phenomenon.

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