RESULTS OF SPECTRAL STUDY OF SEVERAL PECULIAR GALAXIES

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We present results of our investigation of several peculiar galaxies (IC 883, UGC 1198, UGC 4261) chosen from the catalog of the polar ring galaxies. This research was based on the detailed analysis of long slit and 3D spectral data obtained with the 6-m telescope (using the integral field and high resolution long-slit spectroscopy) for these objects. We revealed that all galaxies have the complex structure and kinematics of both gaseous and stellar components. As a result of observing the distribution of stellar age and metallicity in galaxies, we could assume their type and get an understanding the processes in these objects. We found that all objects under study do not belong to classical galaxies with polar rings, and they are going through different stages of the merging at present.

Keywords: galaxies; peculiar galaxies; interaction of galaxies — structure, kinematics, stellar population, metallicity, age

1. INTRODUCTION

The study of the processes of formation and evolution of galaxies is one of the most actively developing areas of modern astrophysics. Various types of interaction between galaxies (approach, merging, collision) occurring in the process of evolution lead to the occurrence of structural and kinematic features in galaxies (bars, warped disks, inner and outer rings/disks, multispin components, etc.). The first works on the study of peculiar galaxies with a multicomponent structure date back to the 80-90s of the last century. A program for the photometric and spectral study of polar ring galaxies (PRGs) included in the Whitmore catalog [1] was launched In Scientific Research Astronomical Institute of St. Petersburg University named after V.V. Sobolev. An analysis of the work carried out in subsequent

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years by various scientific groups, including our own, showed that, along with classical PRGs, there are a large number of peculiar galaxies with a multicomponent structure. To date, numerous surveys have been carried out using multicolor photometry and panoramic spectroscopy for hundreds of galaxies. However, the study of the photometric structure, kinematics, stellar composition, and star formation processes of individual objects makes it possible to reveal a more complex pattern of peculiarities. This article is part of our project for a detailed study of peculiar galaxies in which photometric signs of interaction are observed or a multicomponent kinematic structure is suspected.

2. OBSERVATIONS AND REDUCTION

The observations of IC 883, UGC 1198, and UGC 4261 were performed at the prime focus of the 6-m telescope at the Special Astrophysical Observatory of the Russian Academy of Sciences (SAO RAS) with the SCORPIO focal reducer [2] in the modes of "direct imaging", Fabry-Perot interferometer (FPI), and long-slit spectroscopy as well as with the Multi-Pupil Fiber Spectrograph (MPFS) (see the SAO RAS site[1)], [3]). The detector was an EEV 42-40 2048 × 2048-pixel CCD-array (the pixel size is 13.5 × 13.5 μm). A log of observations for galaxies under study is given in the Table 1.

For the galaxies's central regions, the spectroscopic observations in the green range were obtained with the MPFS, which allowed the velocity fields of both gaseous and stellar components to be constructed.

The large-scale velocity fields, velocity dispersion fields, and monochromatic images of the ionized gas were constructed from observations with the FPI, using gaussian fitting of the Hα and/or [NII]λ6584Å emission line profiles.

For all galaxies, long-slit spectra along their inner features or outer filaments were obtained with SCORPIO + long-slit mode in red and/or green spectral regions.

To analyze the velocity fields, we used the "tilted-ring" method ([4], [5]). It allows one to determine the positions of the dynamical center and the dynamical axis, to refine the galaxy's inclination to the plane of the sky, and to construct the rotation curve.

The ULySS[2)] software package was used to obtain information about the stellar population of galaxies. This package is based on simple stellar population (SSP) models constructed with a high spectral resolution [6]. The models were computed with an initial mass function from [7]. From the full range of metallic-

[1)] http://www.sao.ru/hq/lsfvo/devices/mpfs/mpfs_main.html
[2)] http://ulyss.univ-lyon1.fr

Table 1. Log of observations.

Spectroscopic observational material				
Object	Instrument	Field	Spectral range, Å	Spectral resolution, Å
IC 883	FPI	6′× 6′	Hα	2.5
			[NII]6584	2.5
	MPFS	16″× 16″	4428–5963	2.5
	Long slit	1″× 6′	5700–7400	5
			3900–5700	5
UGC 1198	Long slit	1″× 6′	3900–5700	5
			3100–7300	10
			4800–5570	2.2
UGC 4261	FPI	6′× 6′	Hα	2.5
	Long slit	1″× 6′	5700–7400	5
			3900–5700	5
			4800–5570	2.2
	MPFS	16″× 16″	4431–5966	2.5

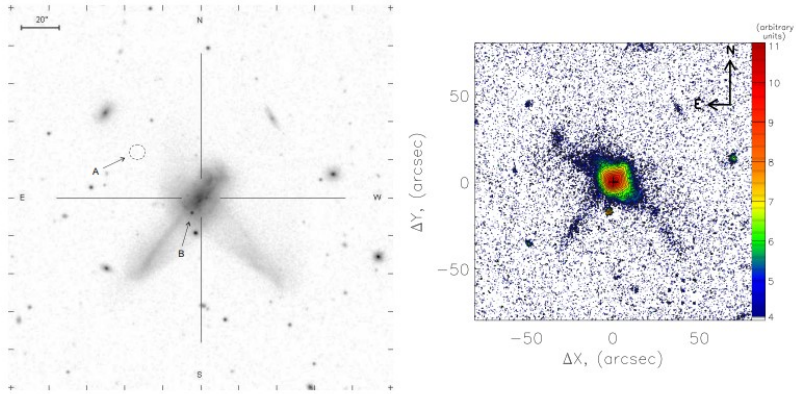

Fig. 1. Left: the gri image of IC 883 from the Sloan Digital Sky Survey (http://www.sdss.org/). Arrows indicate the "A" and "B" regions discussed in the paper. Right: an image of IC 883 in the Hα + [NII] emission lines with the subtracted continuum. 1″ corresponds to 0.5 kpc (H_0 = 72 km s^{-1} Mpc^{-1}).

ities and ages we picked the most suitable model with one stellar population to each long-slit spectrum. In the cross-correlation we used the spectrum obtained by convolving the model with the instrumental profile and took into account the kinematic parameters (the velocity and velocity dispersion). Since there is strong emission in the galaxies's spectra, the Balmer emission lines and [OIII] and [NII] lines were also included in the model spectrum.

To analyze the photometric structure of galaxies, photometric observations in the Johnson B and V bands and the Cousins R_c band as well as with a pair of medium-band filters were carried out with the SCORPIO + "direct imaging" mode. As a result, images of UGC 1198 in the B, V, R_c bands and IC 883 in the Hα + [NII] emission lines without any continuum were constructed.

3. RESULTS AND DISCUSSION

3.1. IC 883

The galaxy IC 883 (UGC 8387, ARP 193, VV 821, etc.) is an inclined peculiar disc galaxy with a long, almost linear southeastern tail and a faint diffuse southwestern tail (Fig. 1).At the distance of $\approx 8.5''$ from the galaxy center to the southeastern direction, one can see a compact brightening indicated by the letter "B" in Fig. 1. This feature presents in broadband optical and IR images too (see, for e.g., Fig. 1 from [8]) and coincides with the compact X-ray SE-source by the position [8].The high infrared luminosity of IC 883 and the existence of two tidal tails are explained by the recent merging of two disc galaxies (e.g., [9]). The optical spectra of the galaxy also pointed on the AGN activity, and it was classified as AGN + starburst composite in [10].

As a result of the analysis of the large amount of our material for IC 883, it was ascertained the following. (The detailed results of observations and their analysis have been published in [11]).

In general, the velocity field of the main body is typical for disc galaxies: the ionized gas and the stars rotate around the galaxy minor axis. The position difference of dynamic axes of the stellar and the gaseous disks was found. This indicates that the system is still in the perturbed state. The youngest stellar population (2–5 $\times$ 10^8 years) has the metallicity $+0.3 \pm 0.1$ dex and belongs to the circumnuclear region. The age and metallicity of the stellar disk at $r \geq 5''$ are 1 ± 0.1 Gyr and -0.4 ± 0.3 dex. Regions with signs of shock waves in a gas medium ([NII]/H_α > 1.5) are observed in the main body of IC 883 along the minor axis. At the same region the gas component shows large velocity dispersions up to 250 km/s. The processes of star formation are going on all over the disk especially in the central region of the galaxy ($r \leq 3''$) and in the tails.

Romero-Cañizales with co-authors in [12] revealed great nuclear star formation activity SFR = 157 $M_\odot$ / year with SN = 1.1 per year and detected a number of radio sources in the nuclear region and consistent with AGN and SNs. Based on the X-ray and VLBA data, there were discovered the core-jet structure in the radius about 1 kpc and the jet have subluminal proper motion [13]. Based on the VLT observation, Herrero-Illana with co-authors in [14] proved the SFR for the IC 883, estimated the contribution of AGN energy to the all luminosity of this object and found that it is not more than 5%.

We have found that forbidden lines are very intensive and the H_α line is in absorption in the center of the compact "B" region. Furthermore, it has been ascertained the kinematic decoupling of this area — its counter-rotation with respect to the main body with a velocity range ∼120 km/s. We determined its age and metallicity (4 – 8 Gyr and –1.7 - –1. dex), as well as a lower mass estimation of this region within a radius of $1''.5$ (8.4×10^8 $M_\odot$). Our analysis of kinematics, age, metallicity, and mass of the "B" region indicates that it is neither globular cluster nor HII region of the galaxy main body, but represents a separate system and can be a dwarf Im galaxy or a remnant of spiral companion galaxy destroyed during the merging.

The velocities in the southeastern tail do not correspond to the circular rotation around the minor axis of the galaxy, therefore this structure can be either a remnant of a destroyed satellite or a fragment of the unwound bent spiral arm. The second variant seems to us the most likely. The similarity of the chemical composition of the galaxy main body and the southeastern tail as well as simulations of similar structures [15] evidence in favor of this assumption.

On the continuation of the northeastern protrusion the weak region "A" radiating in emission lines (Fig. 1) but invisible in broadband images of IC 883 was detected.

The observed peculiar structure of the object under study was, probably, formed as a result of the merger of two galaxies. The morphology and kinematics of the tidal tails and main body of the galaxy, concentration of the gas to the center point out on the middle/late stage of the merging. Based on our results one can say that the "A" region, SW-tail, and NE- and SW-protrusions apparently form a system of the ionized gas which has a complex knotty appearance and a large spread of line-of-sight velocities and moves approximately along the minor axis of the galaxy. Perhaps, this gas was pulled off from a companion galaxy. The resulting cumulative distribution of velocities in this structure does not allow to say that there is a formed polar ring in the galaxy; thus, at present IC 883 does not belong to the class of galaxies with polar rings. The "B" region is perhaps a dwarf Im galaxy or a remnant of spiral companion galaxy destroyed during the merging. The gas of the cloud "A" and SW-tail can be ionized by an

active nucleus.

3.2. UGC 1198

UGC 1198 is a small galaxy which shows a slight enhancement along the minor axis in the inner region, especially toward the north [1], and two linear structures elongated approximately along the main body of the galaxy (Fig. 2). A slight dust lane is present on the east side. A bright spot (indicated by the

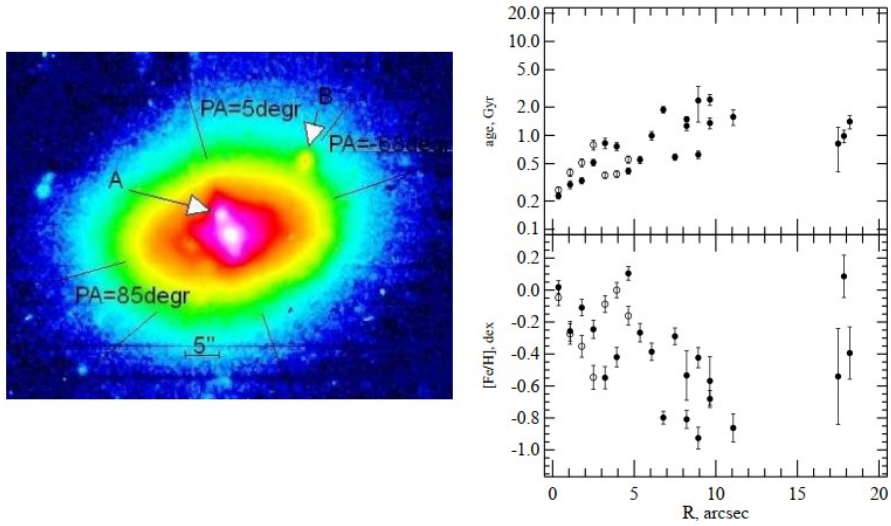

Fig. 2. Left: The image of UGC 1198 in B-band taken from: http://www.astro.spbu.ru/PolarRing/prg.html. The positions of the slit during our observations are shown. Arrows indicate the "A" and "B" objects discussed in the paper. North is up and east is to the left. 1″ corresponds to 0.9 kpc, H_0 = 72 km/s/Mpc. Right: Dependences of age (top) and metallicity (bottom) of the stellar population of UGC 1198 on distance along PA = –68° .

letter "A" in Fig. 2) is observed at 5″ to the north approximately along the minor axis. A faint elliptical object (the letter "B" in Fig. 2) is located 17″ NW of the galaxy center. The observed morphology and the $B - V$ color index distribution of UGC 1198 suggest that the slight enhancement along the minor axis can be an almost edge-on warped disk or ring [16].

As a result of the analysis of our material obtained for UGC 1198, it was ascertained the following. (The detailed results of observations and their analysis have been published in [17]).

Based on our study, we can conclude that UGC 1198 is a dwarf elliptical galaxy (dE) with evidence of interaction. This is suggested by the relative com-

pactness of the object (R $\approx$ 3.5 kpc at a level of $\mu_B = 26.0$ mag/$\Box''$) and its basic photometric and kinematic characteristics.

Our study of the kinematics of UGC 1198 showed that we observe at least two systems. One of them is associated with the stellar system of UGC 1198 itself with weak rotation (40 km/s) around the minor axis of the galaxy. The second system is associated with the gaseous disk/ring rotating with a velocity of $\sim$110 km/s at an angle of 72° to the equatorial plane of the galaxy. The dynamical centers of both systems coincide within the error limits.

The gaseous polar disk/ring could be formed during the merging of a dwarf elliptical galaxy characterized by a small amount of gas with a galaxy of approximately the same or lower mass containing the gas. The fact that almost all of the gas is concentrated within the central kiloparsec suggests the accretion of gas onto the dynamical center of the system as the companion is disrupted. This process led to strong star formation at the center and in the regions of dynamical contraction in the accreting matter itself. The brightening "A" which is distinguished photometrically and spectroscopically at a distance of $5''$ to the north of the galactic center and has a size of $\sim$300 pc can be such a region. The colors of this region ($B - V$ and $V - R_c$ are $0^m.32$ and $0^m.85$, respectively) point to active star formation in it. The difference between the line-of-sight velocities of region "A" and those of the gaseous disk/ring at this distance (by about 20 km/s) is most likely related to the intrinsic noncircular motions.

At the galactic center there is good agreement between the metallicities of the gas and young stars (the metallicity is, on average, –0.3 dex, the age is 2×10^8 yr; Fig. 2). The stars with an age of 2×10^9 yr make a major contribution (90%) to the luminosity at r $> 5''$. The merging of galaxies that gave rise to UGC 1198 can be assumed to have occurred less than one billion years ago.

3.3. UGC 4261

The galaxy UGC 4261 was included by [1] into the catalog of PRGs into the group of possible candidates for such objects under the number C-21 due to its peculiar morphology (Fig. 3). The extended structure crossing the irregular body of this object looks like an open ring. Spectral observations confirmed the existence of two kinematic almost orthogonal subsystems [18]. In their photometric study of UGC 4261, Reshetnikov with co-authors [19] suggested that the galaxy was formed as a result of the destruction of a less massive, gas-rich companion near the spiral galaxy.

The galaxy UGC 4261 turned out to be a more complex system than previously thought, which has been found out thanks to recent spectral and photometric data. As a result of the analysis of our new material for UGC 4261, it

was ascertained the following. The detailed results of our observations and their analysis are being prepared for publication.

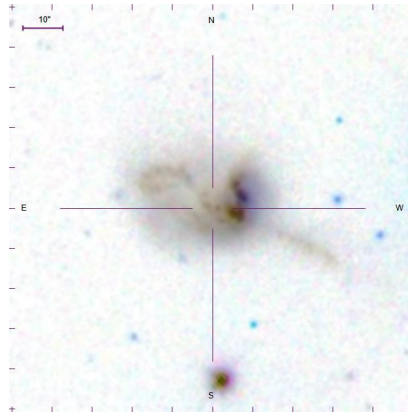

Fig. 3. The $griz$ image of UGC 4261 from the Sloan Digital Sky Survey (http://www.sdss.org/).

We have discovered that the main body of the object consists of two nuclei of the interacting galaxies. They have different kinematics, age and metallicity. The both nuclei have almost the same size of about 4 kpc according to the photometrical data, but the northern one has steeper stellar velocity gradient along it major axis (ΔV = 200 km/s, 21 km/s/kpc) and R_{max} of the line-of-sight velocity curve is about 5 kpc (it means that the northern nuclear has diameter about 10 kpc). The stellar velocity dispersion σ is about 90 km/s. The obtained ages of stars are $5 \pm 0.2 \times 10^7$ years with the solar metallicity and $8 \pm 1.5 \times 10^9$ yrs with [Fe/H] $\approx -1.5 \pm 0.05$ dex. The stellar component of the southern nucleus has very slow rotation velocity component along major and minor axes: $\Delta V = 20$ km/s and $\sigma = 80$ km/s. There, too, two stellar populations with age of $4 \pm 0.5 \times 10^7$ and $10 \pm 2 \times 10^9$ years and with solar metallicity and [Fe/H] $\approx$ –2.2 $\pm$ 0.07 dex, respectively, were found.

There were revealed many stars around the nuclei which have age of not more than 1 Gyr and kinematics close to the shells.

The gaseous component demonstrate complex kinematics which doesn't coincides with the stellar component one anywhere except for the region of the loop. There are bright gaseous bridges between the nuclei and, perhaps, several loops. Due to their line-of-sight location, these components produce a complex velocity field. We just estimated the distance to the galaxy about 98 Mpc (H_0 = 65 km/s/Mpc) and the mass of $1.5 \times 10^{10} M_\odot$ at $R_{max} = 28''$ (13 kpc). Although the shock excitation of gas was not detected in the galaxy, the FeI emission lines (λ4958, 5015, 5035, 5070Å) were detected in the region of the

northern nucleus. UGC 4261 was inspected to the existence of AGN by many authors [20] – [22]. They refer the galaxy to starburst galaxies and its SFR rate is 0.6–0.8 $M_{\odot}$/yr. Also we obtained the gas metallicity which is 12+log[O/H] $\sim$ 8.7 (sub-solar).

According to results of our investigation (the length of the tidal structures (larger than 10 kpc), type of the old stellar population and metallicity of the gas), UGC 4261 is on the early stage of merging of two spiral galaxies with close masses. Perhaps, they made one-two turnover around each other.

Possibly, the amount of matter in the northern core region is not yet enough for the active core to enter to the active phase, but the presence of emission lines of neutral iron indicate a high temperature in this region. Maybe, this system will become a galaxy with an active core after some time.

4. CONCLUSIONS

Based on the results presented in this paper, all three objects in the Polar Ring Galaxies catalog are interacting systems and each of them is at a different stage in the merging process. UGC 1198 is a dE galaxy. It has already formed the polar ring from the gas of a dIrr companion galaxy. In spite of the large gas mass $M_{HI} = 0.13 \times 10^9\ M_{\odot}$, there is no evidence of the AGN. IC 883 is a spiral Sc galaxy. It is at the earlier stage of merging of two spiral galaxies than UGC 1198. There are a lot of gas concentrated in the central part of the galaxy. The nucleus of IC 883 is an AGN + starburst composite. UGC 4261 is the youngest merging system of Sc/Sd galaxies. The gas mass is also significant ($M_{HI} = 8 \times 10^9 M_{\odot}$). But the gas is not so strongly concentrated towards the center yet, and the merging galaxies are far enough to each other. There are no sign of AGN by the radio, IR and X-ray observations but the FeI emission lines demonstrate high temperature in the region of the northern nucleus. Perhaps, it can be observed the starburst with AGN in future.

5. ACKNOWLEDGMENTS

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