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A study of candidates to polar-ring galaxies by the methods of 2D spectroscopy

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We present new 2D-spectral data for some candidates to the polar-ring galaxies. The observations of these objects were carried out on the Russian 6-m telescope. The circumnuclear regions were observed with an MPFS integral-field spectrograph, the large-scale velocity fields of the ionized gas were constructed from observations with a Fabry-Perot scanning interferometer. We have constructed intensity maps and velocity fields for both ionizing gas and stars. The results of the study of the complex multicomponent structure of objects are presented.

Keywords: Galaxies; Polar-ring galaxies; Peculiar galaxies; Interacting galaxies: kinematics, structure

1 Introduction

In 2000 at the Astronomical Institute of the St. Petersburg State University a program on the investigation of polar-ring galaxies (PRGs) and related objects from the catalog of [1] by means of 2D spectroscopy was initiated. Towards this end the observations of candidates to PRGs using a multipupil fiber spectrograph (MPFS) ([2]) and a Fabry-Perot scanning interferometer (FPI) mounted within the multimode instrument SCORPIO ([3]) of the 6-m telescope of Special Astrophysical Observatory (Russia) were carried out. Many interesting and even unexpected results were obtained by our group during this program.

2 NGC 2685 (classical PRG [4])

The main body of NGC 2685 is probably a disk viewed almost edge-on, which is surrounded with luminous matter having a sharp outer boundary in the form of a ring in a plane approximately perpendicular to the main plane of the main body ("the polar ring"). All this structure is immersed in a faint outer envelope. The outer envelope and polar ring are clearly visible in the $\lambda 21$ cm line of neutral hydrogen [5]

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(see also [6]). The observations of Shane [5] at λ21 cm confirmed the existence of two mutually orthogonal kinematic systems, one related to the polar ring and the other system associated with the faint outer envelope.

To obtain the large-scale velocity field of the ionized gas of NGC 2685, we performed its observations with the FPI in the H_α emission line. The comparison of the H_α brightness distribution with the continuum-near-H_α brightness distribution shows that it is mainly the outer part of the disk (the ring) that emits in H_α, and the brightness distribution in this region is extremely nonuniform. There are also individual HII regions belonging to the outer envelope. The velocity field is consistent with the picture of a gas disk rotating in the polar (with respect of the galaxy's main body) plane. In the NE part, the disk is projected against the main body, while the disk is behind the main body in the SW-part.

An analysis of the velocity field using the "tilted ring" technique [7, 8] yielded a model for the disk's circular rotation in good agreement with the observations for a position angle of the dynamical axis $PA_d = 115^\circ$ and an inclination $i_d = 50^\circ$. For the position angle and inclination of the main body of the galaxy (assumed to be disk-shaped), $PA_g = 38^\circ$ and $i_g = 70^\circ$ [9], the angle between the galaxy's main plane and the plane of the disk will be 87°, so that the disk is actually a polar disk.

It seems to us that the head-on collision hypothesis [10] cannot explain the overall structure of the NGC 2685 system. Such a collision should have disturbed the galaxy's outer envelope, which is not the case [6]. On the other hand, if the disk was formed by accretion, a donor galaxy should be present in the polar-disk plane, which is also not observed. Thus, we believe that the formation of the disk was accretion-related, but that the donor galaxy was consumed by the primary galaxy after the polar disk had formed.

3 NGC 7468 (inner polar disk [11])

The direct images of this galaxy show an extended low surface brightness base and a bright nuclear region resolvable into several individual condensations. Lobes are observed along the major axis on the galaxy's southern and northern sides, which can suggest the existence of a ring; this was the reason why NGC 7468 was included in the catalog [1]. The southern protrusion transforms into a faint bar that ends with a brightening whose distance from the galaxy's center in the plane of the sky is ∼7 kpc.

We performed our spectral observations of the galaxy NGC 7468 with the MPFS and FPI. The large-scale velocity field for the emitting gas suggests the rotation of the galaxy's gaseous disk around its minor axis. However, a feature indicating the rotation of the gas around the galaxy's major axis is clearly seen in the central part of the velocity field. Thus, FPI data confirm the presence of two kinematic subsystems of gas in this galaxy.

The observed velocity field is best described by the model of circular rotation at an inclination of the galactic disk $i_{\rm disk} \sim 45^\circ$ and that of the inner disk/ring, $i_{\rm ring} \sim 60^\circ$. Here, two values of the angle between the galactic disk and the plane of the inner disk are possible: $\Delta i \sim 50^\circ$ and $\Delta i \sim 86^\circ$. In the first case, the orbits of the gas are unstable, and, therefore, noncircular motions must be observed in the velocity

field. However, such motions have not been found, so the second value (86°) of the angle between the galactic disk and the plane of the inner disk should be taken.

We suggested two ways of the observed structures formation: 1) the central collision of NGC 7468 with a gas-rich dwarf galaxy and their subsequent merging seem to be responsible for the formation of the inner polar disk, and the features along major axis are either tidal structures or weakly developed spiral arms; 2) the galaxy has the triaxial Stackel potential ([12]), the outer brightness excess may belong to the polar ring formed after the interaction with the companion observed in HI map (at distance 45.5 kpc).

4 NGC 7465 (inner polar disk [the paper is accepted for publication in Astronomy Letters (vol. 38, No 5, 2012)])

NGC 7465, a member of the compact group of peculiar galaxies NGC 7465/64/63, was included by Whitmore et al. to catalog of PRGs ([1]) because of a very faint outer ring at a position angle of about 45°, offset slightly southeast of the center of the galaxy.

We have carried out the observations of the group NGC 7465/64/63 using the scanning FPI. In the central region of NGC 7465 the difference between the distributions of stellar component and of ionized gas radiating in the line H_α is discovered (Fig. 1a). A chain of radiating in line H_α knots located to the SE from the center of NGC 7465 falls on spiral arms of the galaxy and goes to NGC 7464. Our analysis of the large-scale line-of-sight velocity field of NGC 7465 (Fig. 1b) by the tilted-ring method showed that the positions of the photometric and dynamical centers coincide and the system heliocentric velocity equals 1963 km s^{-1}. We also obtained that in the central region ($r \leq 5$–$7''$) parameters of the model of ionized gas motion are: the position angle of the dynamical axis $PA_{dyn} \sim 50°$ and the inclination to the plane of the sky $i_{dyn} \sim 50°$; in more external parts the turning of the dynamical axis occurs and PA_{dyn} possesses the value ∼120° and $i_{dyn} \sim 60°$ (Fig. 1c). All these features allowed us to suggest the presence of the inner polar disk in NGC 7465 which was probably formed as a result of the close encounter with NGC 7464.

5 NGC 660 (warped polar ring [the paper is preparing to press])

NGC 660, known for a long time as a peculiar galaxy containing two inclined dust lanes, was also included in catalog of PRGs [1]. The existence of two different kinematic systems was established from radio HI ([13]) and CO ([14]) observations, and the galaxy was classified as a kinematically confirmed PRG ([15]).

We have carried out observations of NGC 660 using FPI in the line H_α. On the basis of the analysis of the velocity field of ionized gas, the rotation curves for the host galaxy and the ring were obtained. The rotation curve of the host galaxy may be fitted by bulge ($r_e = 0.8$ kpc), disk ($h = 2.8$ kpc) and halo ($\rho_0 = 0.01$ $M_\odot$ pc^{-3}, $r_c = 6.5$ kpc). The fitting of rotation curves in the plane of the host galaxy disk and in the plane of the polar ring by the spherical isothermal halo with the same parameters did not turn out well, so this fact indicates the presence of the nonspherical potential.

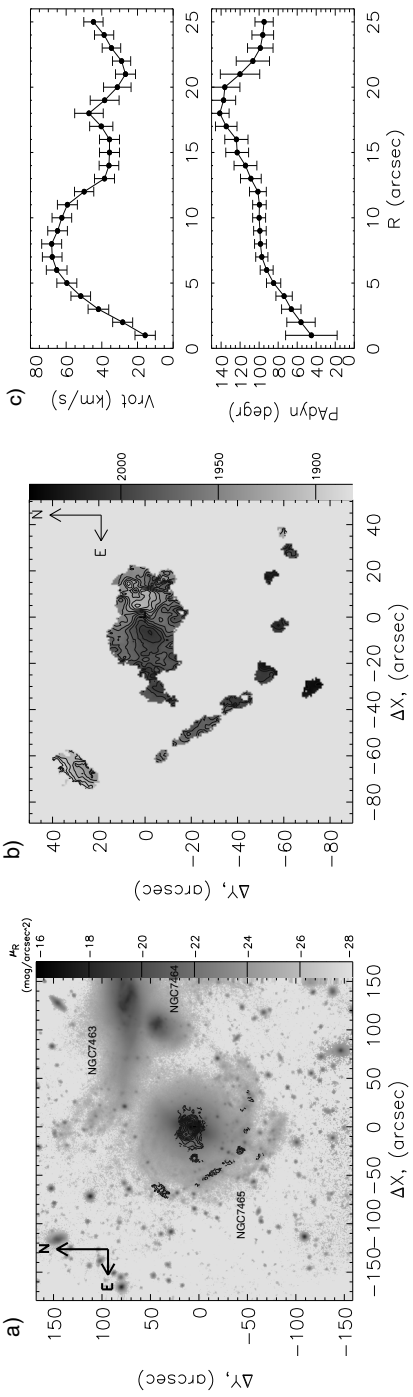


Figure 1 NGC 7465: a – deep R-image with H_α isophotes overlapped; b – the velocity field in the line H_α; c – the observed rotation curve for the gaseous component and the change in the location of the dynamic axis with radius.

In addition, the model of the warped polar ring was constructed that gave following results: the angle between the plane of the inner ring and of the outer ring is ∼30°; the mass of the rings varies from 6.8×10^8 $M_\odot$ to 1.2×10^{10} $M_\odot$ (the ring is quite heavy to stabilize by self-gravity). At present some attempts of numerical simulations of this object are in progress.

6 UGC 5600 (polar warped ring [16, 17])

The galaxy UGC 5600, the member of isolated pair of galaxies VV 330, is known as the most likely candidate for PRGs ([1]). Our spectral observations of UGC 5600 were performed with the FPI and MPFS.

The continuum and H_α brightness distributions for UGC 5600 are different, particularly in the central region. The distribution of the lines of equal velocity (isovels) in the large-scale line-of-sight velocity field obtained in H_α with FPI shows regular deviations from the normal pattern of rotation of a flat galactic disk. A kinematic subsystem rotating around the galaxy's major axis is clearly identified in the region of the inner ring. The velocity field of the stellar component obtained using MPFS data clearly points to rotation around the galaxy's minor axis.

Analysis of our spectral data has shown the following. (1) The main body is a stellar disk with a diameter of ∼6 kpc, $PA_{dyn} \sim 182°$, and $i_{dyn} \sim 50°$. (2) The inner gas ring rotating in a plane close to the polar plane of the stellar disk has $PA_{dyn} \sim 260°$ and $i_{dyn} \sim 60°$. (3) The outer gas disk or ring of low surface brightness is traceable at distances approximately from 4 to 8 kpc from the galactic center. For this component, $PA_{dyn} \sim 303°$ and $i_{dyn} \sim 30°$. Thus, the outer gas disk rotates in a plane that is appreciably inclined (either by 70° to by 40°) to the plane of the galaxy's main body.

We suggested that a warped polar ring is present in UGC 5600. One of the formation mechanisms for such rings is the mass accretion from a gas-rich galaxy onto a neighboring galaxy. A warped polar ring or disk is formed around the latter as a result of mass transfer [18]. The second component of the pair, UGC 5609, may be considered as the donor galaxy. We assumed that the entire gas in UGC 5600 constitutes a single system and that the turn of the dynamical axis from the central regions to the periphery is related to the warp of the gas disk. In this case, the observed features of the velocity field can be the result of projection effects. To test this hypothesis, we constructed a model of a warped ring. We assumed that PA_{dyn} and i_{dyn} changed linearly from the inner edge of the ring to its outer edge. The model velocity field was constructed at the following parameters: $PA_{dyn} = 240°$ and $i_{dyn} = 45°$ for the inner boundary; $PA_{dyn} = 300°$ and $i_{dyn} = 30°$ for the outer boundary. The angle between the normals to the surface at the inner and outer boundaries is ∼10°. The residual velocity map showed that the model velocity field describes satisfactorily the observed one.

7 UGC 5119 (stellar polar ring [19])

Since the peculiar galaxy UGC 5119 has almost square outer isophotes (Fig. 2a), it was included in the catalog [1]. We carried out the observations of UGC 5119 using the MPFS and the long-slit spectrograph. The analysis of the velocity field (Fig. 2b) by the tilted-ring method and the examination of velocity dispersion map (Fig. 2c) with its isolines elongated along the galaxy's minor axis suggested the presence of a rapidly rotating disk. Because of the limited field of view of MPFS ($16''\times 16''$), the long-slit spectroscopy with the slit position along the ring major axis was carried out. We constructed a radial velocity curve for stars which showed the following feature: the velocity gradient increases sharply in its outer parts ($r \leq -8''$ and $r \geq 10''$) and reaches $\sim$36 km s^{-1} kpc^{-1}. This can be explained by the existence of a second kinematic subsystem (possibly a "polar" ring rotating around the galaxy's major axis).

We have calculated the Lick indices of H_β, Mgb, Fe 5270, and Fe 5335 absorption lines and compared them with evolutionary synthesis models. Differences in [Mg/Fe] ratios, metallicities, and ages of the stars were found: the young stellar population with the solar [Mg/Fe] ratio and high metallicity dominates in the circumnuclear region ($r \leq 1$ kpc), while the old stellar population with a low metal abundance dominates in the ring.

Based on the entire set of spectral and photometric data, we conclude that UGC 5119 is a medium-luminosity elliptical galaxy with a rapidly rotating disk at $r \leq 3.2$ kpc and a stellar, possibly, polar ring. As was noted above, the latter does not belong to typical polar rings, which are rich in gas and young stars. The capture and absorption of a dwarf elliptical galaxy was probably responsible for the stellar ring formation. This scenario was considered by [20], who showed that the destruction of the companion resulted in a rapid separation of its stellar and gaseous remnants. The stars form a shell and the gas can form a compact disk while settling to the center of the main galaxy. The results of numerical simulations presented in this paper show that at certain inclinations, the stellar shell can look like a "polar" ring.

8 NGC 2748 (stellar polar ring [21])

Another galaxy which seemed to have stellar polar ring is NGC 2748. The main structural peculiarity of NGC 2748 is the presence of faint diffuse extensions along the galaxy's main axis that suspected to be "polar ring".

We have carried out observations of NGC 2748 in emission lines H_α and [NII] λ6584Å using FPI. We have found that along the minor axis the gas radiation in emission lines extends to smaller distances than the continuum radiation. As a whole the velocity field of gas looks like typical one for the disk galaxies inclined by a large angle to the line of sight, except for some peculiarity in the central region.

From our long-slit spectra in the green range along the major (PA = 42°) and minor (PA = 132°) axes of the galaxy, line-of-sight velocity curves of stars were constructed. In the central region ($r \leq 20''$) along the minor axis the velocity of the stellar component does not vary; but in the outer parts of the curve the velocity gradient about 6 km s^{-1} kpc^{-1} is observed.

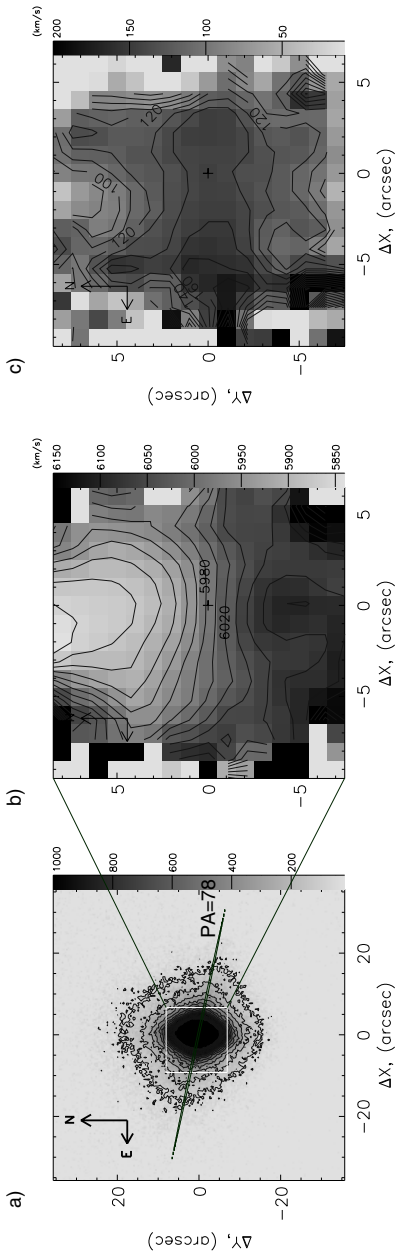


Figure 2 UGC 5119. (a) V-band brightness distribution of the galaxy, the straight line indicates the location of the spectrograph slit and the square is the MPFS field; (b) the stellar velocity field, the step between the isovels is 20 km s^{-1}; (c) the velocity dispersion distribution.

To explain the formation of observed for NGC 2748 peculiarities we can suggest a scenario of the minor merging (the capture of a dwarf disk galaxy) similar to the scenario suggested for UGC 5119.

9 UGC 4892 (the pair of interacting galaxies [22])

The galaxy UGC 4892 has a complex and unusual structure. Its brightness distribution exhibits a feature at a position angle of 198° from the nucleus with the second condensation lying at its base. Assuming this feature to be attributable to the existence of a kinematic system orthogonal to the principal plane of the galaxy, Whitmore et al. included UGC 4892 in their catalog of PRGs [1].

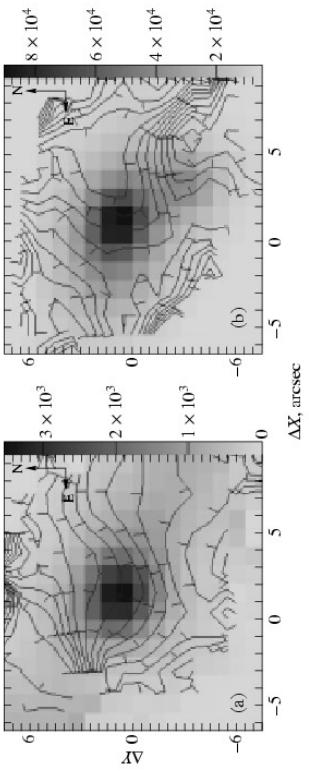


Figure 3 UGC 4892. The velocity fields determined from (a) the H_α line and (b) absorption lines superimposed on the brightness distribution in H_α (a) and in the continuum near λ6100Å(b). Isovels are drawn at steps of (a) 30 and (b) 20 km s^{-1}. The velocities at point (0,0) are (a) 7830 and (b) 7710 km s^{-1}. The coordinates of the nucleus of the main galaxy are $\Delta X = 1.5$ and $\Delta Y = 1.5$.

Our spectral observations of UGC 4892 were carried out with the MPFS. We have found the significant difference between isovel patterns for the gas and stellar

components and the difference between the H_α and continuum brightness distributions (Fig. 3). The gas velocity field is relatively regular and suggests the rotation of the gas masses around an axis close to the major axis of the galaxy. The isovels for the stellar component that twist at an almost right angle at a distance of about $3''$ to the SW of the center point to the existence of two almost perpendicular kinematic systems.

On the basis of photometrical analysis of the images of this object we have assumed, as was done by [23], that the SW condensation is the nucleus of a galaxy (a companion galaxy) interacting with a galaxy elongated in the east–west direction (the main galaxy). The observational facts can probably be explained if these galaxies are assumed to actually constitute a physical pair, with the companion galaxy moving in a highly elongated elliptical orbit whose pericenter lies to the NE of the nucleus of the main galaxy. In this case, irrespective of whether the companion galaxy is closer to (i.e., recedes from the pericenter) or farther from the observer, this galaxy will exhibit a negative radial velocity relative to the main galaxy. The large extent of the gaseous structure should be explained by the fact that the companion galaxy has already made more than one turn around the main galaxy.

10 UGC 4385 (the pair of interacting galaxies [21])

The appearance of the galaxy UGC 4385 in optical range is similar to PRG one. Its main body surrounded by faint luminous envelope is elongated approximately along the N–S direction. Nearly orthogonal to the main body (PA $\sim 107^\circ$) a patchy structure (possibly, a ring or a disc) is observed, its major axis size is comparable to galaxy major axis's. Image of the UGC 4385 on the K_s band (2MASS) differs from the optical one. There are two bright spots on it, one of them coincides with the maximum brightness in the optical range and the second one is located at a distance of $\sim 7''$ to the N from it. The radiation on the K_s band is provided by the old stellar population which is usually grouped in the galaxy symmetrically around the dynamical center, thus we suspected that the bright spots observed in this filter might be the nuclei of the colliding galaxies.

The galaxy UGC 4385 was observed using FPI by our group. The large-scale velocity field in the H_α line confirms the complicate character of the ionized gas motion. The most regular structure of the velocity field resembling the rotation of the inclined disk is in the region of the polar ring, but the dynamical center is shifted to the north according to the photometric center of brightness and is close to the location of the northern spot in the K_s band. We analyzed the velocity field of this subsystem using the tilted ring method. We obtained that the model of the circular rotation of the ring with the nonzero radial velocity component has the best accordance with the observational data. The expansion velocity is close to zero in the central part, it starts to rise linearly from $r = 10''$ with the distance and becomes equal 40 km s^{-1} at $r = 35''$ from the center. The regions on the north and south of the main galaxy were not included for the model construction. The gas of the regions of the main galaxy mentioned above rotates around the minor axis of the galaxy.

Relying on the all data we conclude that in the case of UGC 4385 we observe two galaxies on the stage of the face-on collision. The main galaxy is probably a spiral

galaxy of late type inclined by the large angle to the plane of sky and elongated along the N–S direction. The structure elongated on the W–E direction (polar disk/ring) is the second galaxy, and it partly shields the main galaxy from center to the south, but in the north we see the main galaxy. The galaxies are interacting, they are "spitting" each other. As a result, one galaxy has the features of the "collision ring galaxy" (the famous example is the "Cartwheel galaxy") and another has a distorted shape, warped outermost parts, higher nucleus activity.

11 NGC 6286 (superwind galaxy [24])

Whitmore et al. [1] included NGC 6286, one of the pair of interacting galaxies, in the catalog of polar-ring galaxies as a possible candidate (C-51), because a diffuse structure (semi-ring) located to the SE of the main body of the galaxy is clearly seen in the reproduction in the atlas by [25].

FPI observations were carried out by us with filters centered on H_α and [NII] λ6583Å lines. The [NII] emission-line and continuum intensity distributions for NGC 6286 are different. In both cases, disk components crossed by the dust lane are traceable. The outer continuum isophotes are lenticular in shape, while two extended regions that are symmetric relative to the point shifted from the photometric center by about 5″–7″ to the NE in the continuum are observed in the emission lines. Remarkably, with the exception of a few separate knots, there is no gas emission inside the cones with an opening angle of about 60° the vertices of which are located at the above point. On both sides of the plane of the galactic disk, the intensity of the [NII] line rapidly increases compared to H_α.

The shape of isovels near the gaseous disk is indicative of its rotation around an axis perpendicular to the galactic plane. However, this axis does not pass through the photometric center in the continuum, but is shifted by 5″–7″ to the NE of it. Its position roughly coincides with the vertices of the cones in the emission-line images. The shape of the isovels in emission-line regions outside the galactic disk is of considerable interest. The velocities are approximately constant along the straight lines that are parallel to the generatrices of the cones. In general, the velocity field of NGC 6285 is characteristic of an inclined gaseous disk with solid-body rotation in its central part.

Based on the entire set of observational data, we have concluded that the peculiarities of NGC 6286 are attributable to the presence of a superwind that outflows from its central region. The starburst in the central region of the galaxy that gave rise to the superwind was probably triggered by a close encounter of the two galaxies.

Summary

Detailed analysis of the data obtained by means of 2D spectroscopy allowed us to conclude that investigated objects have a complicated multicomponent structure. Among them we have been able to distinguish galaxies with classical polar rings, with circumnuclear polar disks, galaxies with warped gaseous disks and rings and even with stellar polar rings. Some of the objects studied turned out not to refer to PRG at all.

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