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Central regions of the polar-ring galaxies NGC 2685 and IC 1689*

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Abstract. Results of two-dimensional spectroscopy for central parts of polar-ring galaxies NGC 2685 and IC 1689 are presented. An orthogonality of star and gas rotations is detected. A strong break of absorption-line index Mgb between the nuclei and the inner bulges ("chemically decoupled nuclei") and perhaps an intermediate age of the stellar population in the nucleus of IC 1689 imply secondary star formation bursts in the centers of the polar-ring galaxies which are possibly related to accretion events having produced polar rings themselves.

Key words: galaxies: NGC 2685; IC 1689; nuclei; stellar content; kinematics and dynamics

1. Introduction

According to Whitmore et al. (1990), polar-ring galaxies are mostly S0 galaxies with luminous rings whose projected major axes are nearly orthogonal to the galactic main body major axes. This special class of galaxies seems to provide additional possibilities to reveal three-dimensional structure of early-type flattened galaxies; however even for a nearby prototype of the polar-ring galaxies – the famous NGC 2685 – there are different points of view on its real spatial configuration. On the one hand, the exponential photometric profile (Makarov et al. 1989, Whitmore et al. 1990) and the rapid rotation of stars around the projected minor axis (Schechter & Gunn 1978) provide evidence for an ordinary axisymmetric disk structure; on the other hand, attempts of gas-dynamical modeling of the two long-lived stable rings, one polar and one equatorial as seen in NGC 2685, favour a prolate tumbling model (Peletier & Christodoulou 1993). An analysis of the two-dimensional velocity field may help to distinguish between these alternatives, but until now only long-slit cross-sections along the major and minor axes have been obtained. By measuring an emission line [OII]λ3727, Ulrich (1975) had found that there was seen a line-of-sight velocity trend along the minor axis, and Schechter & Gunn (1978) had confirmed this finding, detecting however strong variations of stellar velocities along the major axis. Shane (1980) had suggested that circumnuclear gaseous condensation is related to neutral hydrogen of the polar ring which circularly rotates in the plane orthogonal to the plane of the galactic disk. Recently a similar long-slit study is made for another polar-ring galaxy, IC 1689 (Hagen-Thorn & Reshetnikov 1997); and again, the maximum velocity gradients are found for ionized gas along the minor axis and for stars along the major axis. Though this picture does not contradict a concept of S0 galaxies with accreted gas in the polar planes, a absence of full two-dimensional kinematical analysis and a marginal presence of stellar line-of-sight velocity variations along the minor axis in NGC 2685 (Schechter & Gunn 1978) leave a chance for prolate or triaxial models of polar-ring galaxies.

We had one more reason to undertake 2D spectroscopy of the central parts of NGC 2685 and IC 1689. During our search for chemically decoupled stellar nuclei in nearby spiral galaxies we have found that in central 400 pc of the isolated regular Sb galaxy NGC 2841 possessing a chemically decoupled nucleus its ionized gas rotates orthogonally to rotation of the stellar component (Sil'chenko et al. 1997). It looks like a kind of gaseous polar disk. This finding has encouraged us to search for chemically decoupled nuclei in "bona fide" polar-ring galaxies. So NGC 2685 and IC 1689 were included into our observational program.

2. Observations and data reduction

2D spectroscopy of the central parts of the polar-ring galaxies NGC 2685 and IC 1689 has been made by using the Multi-Pupil Field Spectrograph (MPFS, Afanasiev et al. 1990) of the 6m telescope of the Special Astrophysical Observatory (Nizhnij Arkhyz, Russia). The log of the observations is given in Table 1.

MPFS allows us to obtain simultaneously from 95 to 160 spectra from an extended area of the investigated galaxy. A set of enlargers projecting an object onto a rectangular array of microlenses provides a varying scale; we have used the 10 X

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* Based on observations collected with the 6m telescope of the Special Astrophysical Observatory (SAO) of the Russian Academy of Sciences (RAS) which is operated under the financial support of Science Department of Russia (registration number 01-43).

Table 1. 2D spectroscopy of NGC 2685 and IC 1689

Date	Galaxy	Exposure	Configuration	Field	Spectral range	PA of long side	Seeing
22/23.10.93	NGC 2685	60 min	MPFS+IPCS 512 × 512	$12'' \times 14''$	Green	158°	1.5″
25/26.10.94	NGC 2685	90 min	MPFS+CCD 520 × 580	$14'' \times 22''$	Red	53.5°	1.5″
1/2.11.94	NGC 2685	60 min	MPFS+CCD 520 × 580	$14'' \times 16''$	Green	−55°	2.5″
9/10.10.96	IC 1689	90 min	MPFS+CCD 1040 × 1160	$11'' \times 21''$	Green	11°	1.6″
14/15.10.96	IC 1689	60 min	MPFS+CCD 520 × 580	$11'' \times 16''$	Red	43.5°	1.6″

enlarger with the scale of about 1.3″ per lens. The entire field of view is limited by the detector size; the detectors used and the fields of view obtained are listed in Table 1.

We have exposed the galaxies in two spectral ranges, named green and red. The green spectral range, 4700–5400 Å, contains a lot of stellar absorption lines including $H\beta$, MgIλ5175, FeI$\lambda 5270, 5335$ and others. It was used to study stellar rotation fields by a cross-correlation method. Bright components of the binary stars ADS 15470, STF 2788, and ES 560 have been taken as templates. A typical spectral resolution in this spectral range was 5–6 Å, a stellar velocity accuracy was about of 20 km/s. The green exposures were also used to study absorption-line strength radial profiles. For this purpose blank sky areas were exposed separately; sky-subtracted spectra were co-added in concentric rings centered onto the galactic nuclei to keep a constant level of signal-to-noise ratio along the radius. An accuracy of absorption-line equivalent widths is estimated as 0.3 Å for spectra registered with IPCS and 0.1 Å for spectra registered with CCD. Frames exposed in the red spectral range (6450–6750 Å) contain emission lines $H\alpha$ and [NII]λ6583 and are used to obtain velocity fields of the ionized gas. The spectral resolution is higher than in the green and reaches 2 Å for the observations of NGC 2685 in October 1994. An accuracy of gas velocities is better than 30 km/s. The data reduction – bias subtraction, flatfielding, cosmic ray hit removing, extraction of one-dimensional spectra, wavelength calibration, surface brightness and velocity mapping – have been done by using the software developed in the Special Astrophysical Observatory (Vlasyuk 1993).

3. Results

3.1. Gas and stellar kinematics

Fig. 1 presents stellar and gaseous velocity fields for the central part of NGC 2685, and Fig. 2 presents stellar and gaseous velocity fields for the central part of IC 1689. In both cases one can see that the stars rotate around the minor axes as it must be in disk galaxies, and the gas rotates around the major axes as if it is coupled with the more outer gas of polar rings.

In NGC 2685 the gas and star isovelocities are strictly orthogonal, and systemic velocities determined by the gaseous and stellar velocity fields are the same, namely, 860 km/s. In IC 1689 the picture is more complex. The stellar isovelocities are consistent with a circular rotation of stars in the plane of galactic disk. A systemic velocity determined by using this velocity field is 4470 km/s. An absence of systematic wavelength-scale shift is checked by measuring a night-sky emission line [OI]λ5577: a whole set of the night-sky line-of-sight velocity measurements shows a gauss-like distribution with a mean of –3 km/s and a dispersion of 17 km/s. Particularly, the measurement of [OI]λ5577 in the spectrum of the nucleus has given a value of –16 km/s. Since our estimate of the systemic velocity of the stellar component in IC 1689 differs strongly from that of Hagen-Thorn & Reshetnikov (1997), we have checked the result of cross-correlation by a direct gauss approximation of the magnesium absorption lines λ5170.0 (5167.3+5172.7) and λ5183.6 in the spectrum of the nucleus. Though a accuracy of such approximation is lower than that of cross-correlation, we have obtained $v_r(Mg)$ = 4486 km/s and 4471 km/s, consequently, in full agreement with the above mentioned systemic velocity derived from the cross-correlation. A systemic velocity determined by using the gas velocity field is higher by some 150 km/s – 4620 km/s. Gas isovelocities in the center of the galaxy are turned by some 45° with respect to both isophote axes, major and minor, and only at the radii more than 5″ we see an ionized gas rotating in a plane orthogonal to the plane of the galaxy: it is an inner polar ring seen also on ultraviolet (U) broad-band image (van Gorkom et al. 1987). A line-of-sight velocity difference between the ring and the nuclear gas is ±90 km/s, in agreement with the long-slit data of Hagen-Thorn & Reshetnikov (1997). Excitation mechanisms of emission-line spectra are quite different in the ring and in the nucleus: the ratio [NII]$\lambda 6583/H\alpha$ = 0.4 in the ring is consistent with a star-forming activity, and the nucleus lacking $H\alpha$ at all (only [NII]λ6583 is present) is a typical LINER. This result was firstly obtained by Hagen-Thorn & Reshetnikov (1997) too.

A two-dimensional velocity field gives a unique opportunity to clarify a geometry of rotation and mass distribution. In the case of planar circular rotation a azimuthal dependence of central line-of-sight velocity gradients would be a pure cosine law with a maximum at the line of nodes (isophote major axis):

$$dv_r/dr = \omega \sin i \cos{(PA - PA_0)},$$

where ω is deprojected angular rotation velocity, i is an inclination of rotation plane, and PA_0 is an orientation of the line of nodes (isophote major axis). In the case of triaxial potential there must be a non-zero line-of-sight velocity gradient along the isophote minor axis.

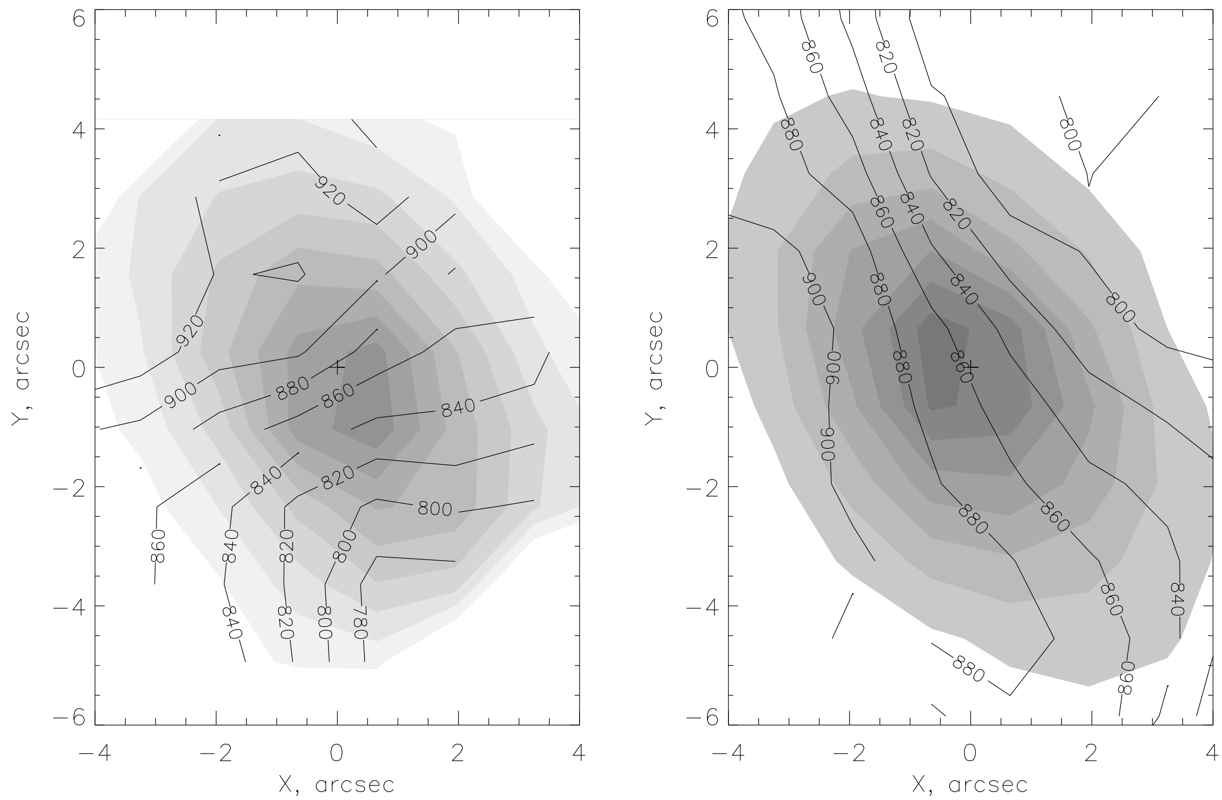

Fig. 1. The isovelocities of stars (left) and ionized gas (right) in the center of NGC 2685. The plus marks the photometric center of the galaxy. North is up, east is to the left. Gray-scaled continuum image is given to show an orientation of the galaxy isophotes.

Table 2. Parameters of fitting the azimuthal dependencies of central line-of-sight velocity gradients for the stars and gas in NGC 2685 and IC 1689

	NGC 2685	IC 1689
$\omega_* \sin i$	26 km s^{-1} arcsec^{-1}	32 km s^{-1} arcsec^{-1}
$\omega_g \sin i$	41 km s^{-1} arcsec^{-1}	44.5 km s^{-1} arcsec^{-1}
$PA_{0,dyn,*}$	28°	322°
$PA_{0,dyn,g}$	130°	121°
$PA_{0,phot,inner}$	30°	164°
$PA_{0,phot,outer}$	32°	153°

Fig. 3 presents azimuthal dependencies of central line-of-sight velocity gradients for the ionized gas and stars in NGC 2685 and IC 1689, and Table 2 contains results of fitting these dependencies by cosine laws. (Photometric characteristics are taken from Peletier & Christodoulou, 1993, for NGC 2685 and from Reshetnikov et al., 1995, for IC 1689). They confirm the impressions given by Figs. 1 and 2.

The dependencies for NGC 2685 are quite perfect cosine ones; the dynamical major axis of the stars coincides with the photometric major axis while orientations of inner and outer isophotes are the same. All these facts provide evidence for a axisymmetric mass distribution and circular rotation of the main body of the galaxy. Thus, the nuclear ionized gas also rotates circularly, but in the plane which is orthogonal to the plane of the galactic disk. As it was noted earlier (e.g. Shane 1980), the nuclear ionized gas in this galaxy must be related to the neutral and molecular hydrogen of the polar ring. The only thing which is not clear is why the angular rotation velocities of the gas and stars differ in such a way: our estimate of the gas velocity dispersion inside $r \approx 3''$, 200 km/s, is higher than the published estimates of the stellar velocity dispersion, 60–114 km/s (Whitmore et al. 1990, Di Nella et al. 1995, McElroy 1995), so one might expect that nuclear gas rotates slower than stars; but we observe an opposite difference. After excluding non-circular motions and strongly different rotation plane inclinations (both stellar and gaseous subsystems seem to be seen edge-on), only different spatial resolution remains: as gas velocity gradients are measured closer to the center than those of stars, their higher values may signify that there is an unresolved drop of rotation velocity near $R \approx 3''$ (let us remind that the seeing was not too good during the CCD observations of NGC 2685 in the green spectral range – see Table 1). In other words, the nucleus of NGC 2685 may be dynamically decoupled.

The azimuthal dependencies for IC 1689 look less definitive. The dynamical major axis of stars is turned by 11° with respect to the line of nodes (outer isophote orientation), and a turn of photometric major axis between the innermost and the outermost regions is also 11°, but in opposite sense (Reshetnikov et al. 1995). These small discrepancies may be inside errors of

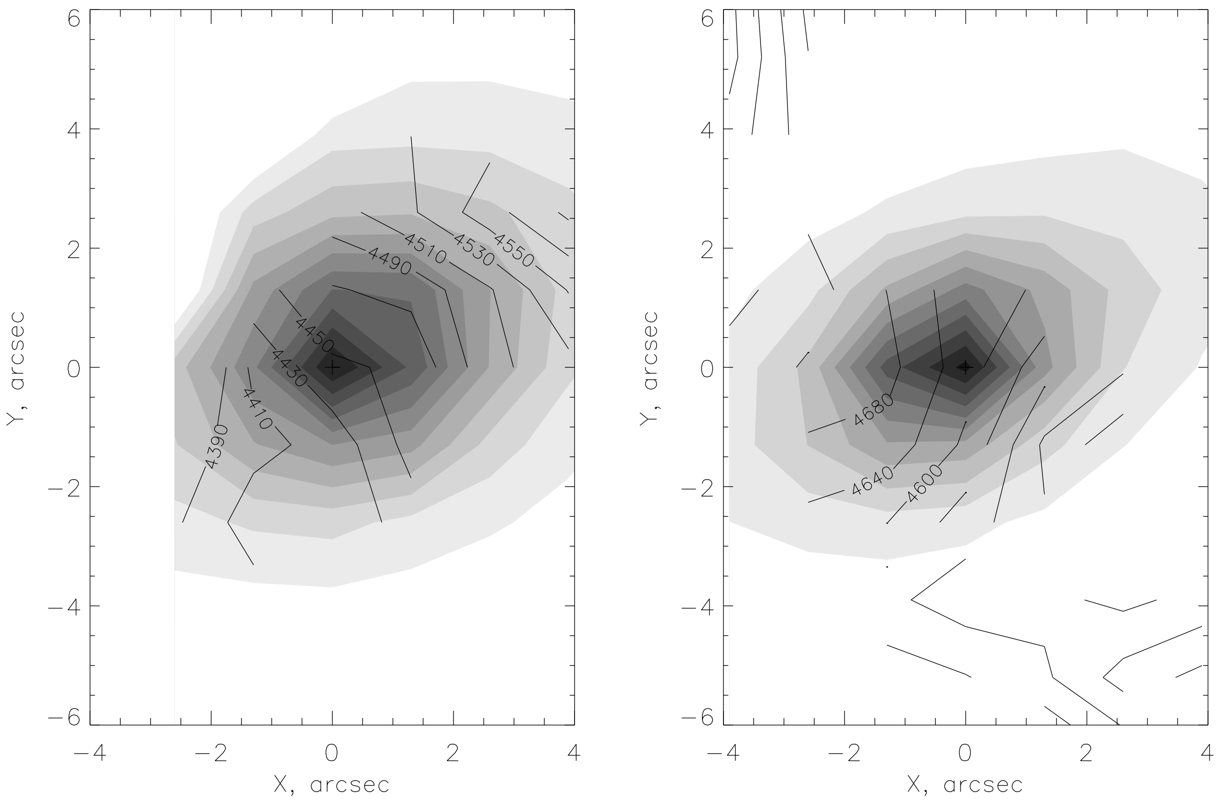

Fig. 2. The isovelocities of stars (left) and ionized gas (right) in the center of IC 1689. The plus marks the photometric center of the galaxy. The plots are turned by 44° the north being in the upper right corner, to show better a location of the polar ring. Gray-scaled continuum image is given to show an orientation of the galaxy isophotes.

measurements, but if they are real, it may be an evidence for a mild triaxiality of the galaxy.

3.2. Stellar contents of the nuclei

Fig. 4 presents radial profiles of absorption-line index Mgb in the central parts of NGC 2685 and IC 1689 (for a definition of the absorption-line indices – see Worthey et al. 1994). In both cases one can see a prominent magnesium-strength break between the nucleus and the surrounding bulge. If we treat this break as due only to metallicity variations, we can estimate a value of metallicity break by using single-age model calibrations of Worthey (1994). It reaches 0.7 dex for NGC 2685 and 0.5 dex for IC 1689.

For NGC 2685 we have plotted two independent measurement sets: in 1993 with IPCS as a detector and in 1994 with CCD. (The nuclear spectrum in 1993 had a low signal-to-noise ratio and is not plotted). In this particular case a accuracy of the Mgb index measurements has appeared to be good enough even with IPCS: the difference between two data sets does not exceed 0.1 Å anywhere except the points at $R = 2.6''$. The discrepancy at $R = 2.6''$ is naturally explained by the seeing difference (see Table 1): a seeing $FWHM$ of 2.5″ in 1994 affects the measurements at this radius. Though a radius range under consideration is rather small, we may suspect a presence of Mgb gradient in the bulge of NGC 2685. If we take the measurements in the radius range 2.5″–7″ – 4 points obtained in 1993 and 3 points obtained in 1994, – they are nicely fitted by a linear law:

$$Mgb = (3.19 \pm 0.08) - (0.136 \pm 0.017)R''.$$

Therefore even if we take a difference between the nuclear Mgb and the central bulge Mgb extrapolated by using this linear law, we would still obtain $\Delta Mgb = 1.15 \pm 0.18$ Å (Δ[m/H] = 0.51 ± 0.08). The metallicity gradient measured in the bulge, d[m/H]$/d\log r = -1.2$, is slightly higher than usual metallicity gradients in bulges of early-type disk galaxies which ranges from 0 to –1 (Balcells & Peletier 1994). It is interesting that Peletier & Christodoulou (1993) have noted that the nucleus of NGC 2685 is distinguished by its red colour, and in the bulge the $B - V$ gradient is absent.

In IC 1689 we detect an enhancement of the magnesium-line strength in both the nucleus and at a radius of 5.″5, where the polar ring crosses the major axis.

Fig. 5 may help us to check if the magnesium-strength breaks in NGC 2685 and IC 1689 are due only to the metallicity differences. It presents a ($H\beta$, Mgb) diagram which provides age-metallicity disentangling. Since $H\alpha$ emission is quite absent inside $R \leq 4''$ in both galaxies, we are sure that $H\beta$ absorption line is not contaminated by an emission in the nuclei and in the innermost bulge regions, and the age diagnostics is

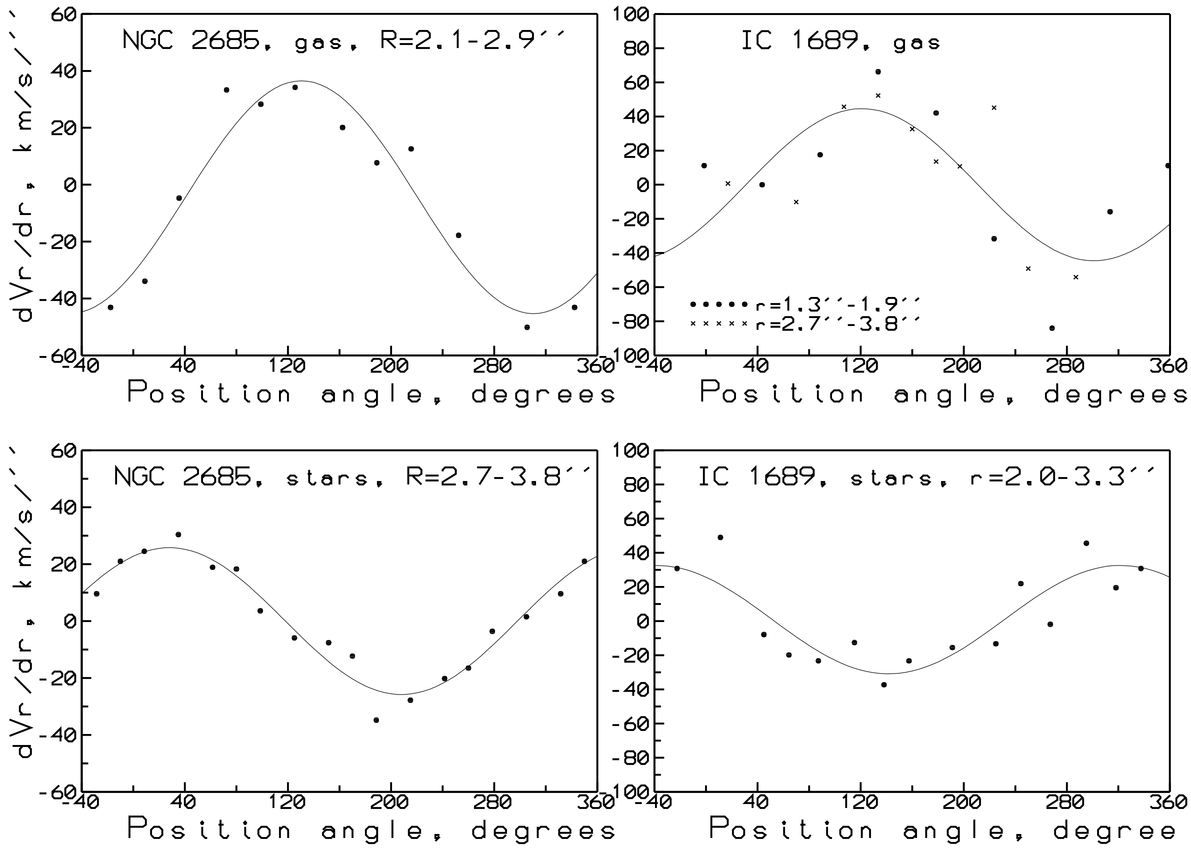

Fig. 3. The azimuthal dependencies of central line-of-sight velocity gradients for the stars and ionized gas in NGC 2685 and IC 1689. The solid lines present cosine laws fitted by the least-square method

valid. But the outer points – two in NGC 2685 and three in IC 1689 – must be excluded from the consideration due to a noticeable emission contamination of their $H\beta$. After examining Fig. 5 we conclude that stellar population in the nucleus of NGC 2685 is rather old, of 10 billion years or older, and a age gradient along the radius is undetectable. Meanwhile the decoupled nucleus in IC 1689 may be as young as of 5 billion years, and the innermost bulge may be much older. Unfortunately, for this galaxy we have only one point in the inner bulge which $H\beta$ absorption line is not contaminated by an emission, so for $R \geq 4''$ we can estimate only upper limits of the stellar population ages, and the result on age difference between the nucleus and the inner bulge is marginal. But we must keep in mind that if the nucleus is much younger than the bulge, the metallicity difference corresponding to the same ΔMgb is higher. In the case under consideration it reaches 0.7 dex instead 0.5 dex reported above.

4. Discussion

Can we choose now between oblate axisymmetric main body and tumbling prolate one in the case of NGC 2685? Yes; as there is no stellar velocity gradient along the minor axis, we can definitely state that it is not a tumbling prolate ellipsoid. The velocity field of stars agrees well with a picture of an ordinary edge-on disk. The cosine-like azimuthal dependence of the central line-of-sight velocity gradient for the gaseous component (Fig. 3) with the maximum at the photometric minor axis can be obtained in two configurations: circular rotation in the plane of the polar ring or pure radial motions in the plane of the galactic disk. Our spectral resolution for the red spectra of NGC 2685, ~ 2 Å, allows to estimate a velocity dispersion of the nuclear ionized gas; it appears to be near 200 km/s – much higher than that of stars in the center of NGC 2685. The estimates of the stellar velocity dispersion range from 60 km/s to 114 km/s (Whitmore et al. 1990, Di Nella et al. 1995, McElroy 1995). So, the high velocity dispersion of the gas keeps a possibility of radial motion dominance over the rotation. However several other reasons force us to prefer a hypothesis of circular rotation in the plane of polar ring: neutral hydrogen in the polar ring demonstrates the same sense and amplitude of velocity variations (Shane 1980), and the molecular gas does so (Watson et al. 1994, Δv_r = $\pm$120 km/s), so it seems improbable to suggest an existence of supersonically expanding or compressing gaseous disk with a radius of 5 kpc taking into account its regular appearance.

It is a case of IC 1689 where a hypothesis of a prolate tumbling potential may justify: we observe a small velocity gradient along the minor axis for the stars, and an overall shape of the polar ring is roundish as if it has a central orthogonal "spindle"

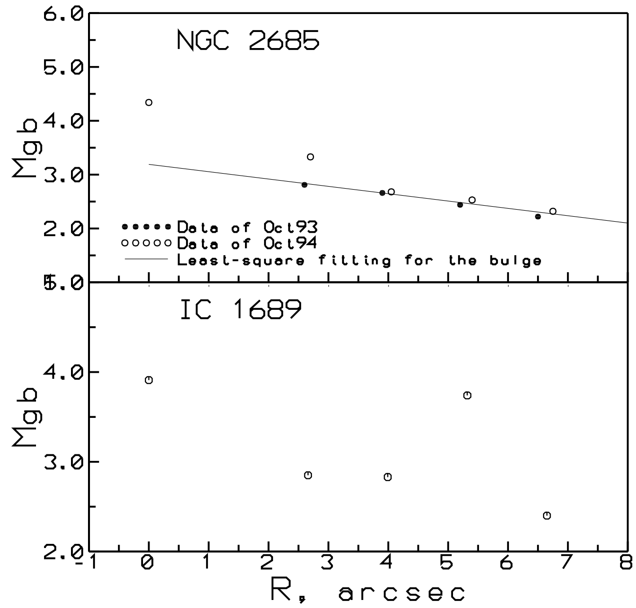

Fig. 4. Azimuthally-averaged magnesium-line strength profiles for NGC 2685 (two sets of measurements) and for IC 1689

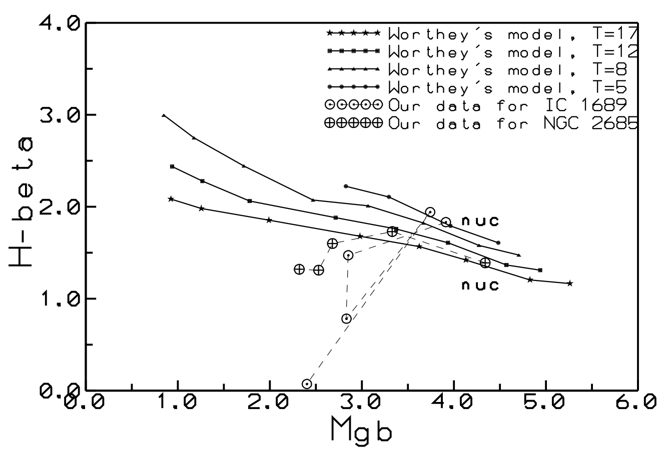

Fig. 5. The diagram ($H\beta, Mgb$) for age-metallicity disentangling in the nuclei and bulges of NGC 2685 and IC 1689. The measurements are made at the positions shown in Fig. 4; the nuclear positions are identified. The models are taken from Worthey (1994), the ages are given in the legend in billion years. Two outer points for NGC 2685 and three outer points for IC 1689 are shifted down by a weak $H\beta$ emission

directed almost towards us. There are also rather strong evidences for radial gas motions towards the nucleus: the emission surface brightness distribution has a shape of bar elongated in $PA \approx 80^\circ$ while a dynamical major axis of the gas demonstrates an orientation intermediate between that of the gaseous bar and continuum isophotes; such a turn together with a ratio of ω_{gas} to ω_* close to $\sqrt{2}$ implies a superposition of tangential and radial motions of roughly equal amplitudes. A difference of systemic velocities determined by using the velocity fields of gas and stars can also be explained in the frame of strong radial motion hypothesis: we observe mostly the southern half of the nuclear gaseous disk which, according to Reshetnikov et al. (1995), is seen fore the main body of the galaxy and which has positive velocity excess (motions towards the nucleus), so the average (systemic velocity) must be overestimated. For the gas distributed in the polar plane a projection of radial velocity component onto the line of sight is zero at $PA \approx 70^\circ - 80^\circ$ and $250^\circ - 260^\circ$; and indeed a marginal deviation of points down from the cosine curve is seen at these PAs in Fig. 3. That means that if we calculate a gas systemic velocity by averaging only v_r values at $PA \approx 70^\circ - 80^\circ$ and $250^\circ - 260^\circ$, we would obtain a value much closer to the systemic velocity for stars.

Another interesting perspective is opened by discovering a possible age difference between the decoupled nucleus and the surrounding bulge in IC 1689. An origin of chemically decoupled nuclei may be related to some gas accretion event (Sil'chenko et al. 1997); if it is the same event that produced also a appearance of the polar ring, there must be age similarity between the nuclei and the polar rings. Some qualitative effect may be traced in the case of NGC 2685 and IC 1689: the colour $B - V$ of the ring in NGC 2685 (0.7, Peletier & Christodoulou 1993) is redder than that in IC 1689 (0.3, Reshetnikov et al. 1995), and the mean age of the stellar population in the nucleus of NGC 2685 is significantly larger than that of IC 1689 (see Fig. 5). But a quantitative agreement is absent: Peletier & Christodoulou estimate the age of the ring in NGC 2685 as 2–5 billion years, we give a age of the nucleus equal to 10 billion years or more. The situation in IC 1689 gives a hint for solving this problem: the age of the stellar population in the nucleus is 5 billion years (Fig. 5), but the emission spectrum in the middle of the ring provides evidences for intense present star formation, so the epoch of the star formation in the ring may be long enough. It is not predicted by any models, and if this finding is confirmed views on polar ring formation would be changed.

5. Conclusions

Two-dimensional velocity fields of stars and ionized gas in central parts of polar-ring galaxies NGC 2685 and IC 1689 are investigated with the Multi-Pupil Field Spectrograph of the 6m telescope. Rotation axes of stars and ionized gas have appeared to be roughly orthogonal in both cases. But if NGC 2685 seems to be surely an edge-on disk galaxy with the polar gaseous disk penetrating into the center, the other polar-ring galaxy, IC 1689, demonstrates a set of velocity-field properties which allow to suspect a presence of tumbling triaxial structure. In both galaxies chemically decoupled stellar nuclei are found; in IC 1689 the decoupled nucleus may also be much younger than the innermost bulge. This finding confirms the hypothesis of an origin of decoupled nuclei in secondary star formation bursts provoked by accretion of a significant gas mass.

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