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Nuclear kpc-sized Disks of Spiral Galaxies

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Abstract. The complex structure of nuclear disks of normal spiral galaxies is illustrated with the example of five galaxies, observed at the 6m telescope. The problem of gravitational stability of nuclear disks is briefly discussed.

1. Introduction

Circumnuclear regions within a radius of a few hundred parsecs are so diverse in their properties, that they may be called the most distinctive parts of galaxies. Usually these regions cannot be considered as a simple continuation of the main disks of parent galaxies, being decoupled by their structure, angular velocity, gas content, star formation rate, or metal abundance.

In this paper we will touch upon two topics: structure of nuclear disks, and the influence of their rotation on star formation.

2. Photometrical and kinematical structures of nuclear disks

Rapidly rotating central parts of the observed galaxies as a rule do not exceed 5-15″ by size, which makes their spectral study a rather difficult task. It appears that reliable data for their kinematic properties cannot be obtained from one-dimensional spectral cuts; actually two-dimensional velocity fields are necessary to distinguish between circular and non-circular motions of gas or stars.

To illustrate the structural and dynamical properties of the nuclear disks, we will discuss briefly the observational data for the inner regions of five normal spiral galaxies: NGC 972, 1084, 4100, 6181 and 7217. All spectral observations were carried out at the 6m telescope of the Special Astrophysical Observatory in Russia (SAO RAS) in 1993 -1997. A scanning Fabry-Perot interferometer (IFP) and Multi-Pupil Field Spectrograph (MPFS) developed in this observatory were used for obtaining the velocity field of the ionized gas in the H_α emission line. Although the observations were aimed mostly to study gas motions in a global galactic scale (program "Vortex" led by A. Fridman), five objects chosen here may give bright examples of different structures and kinematic peculiarities observed in the nuclear regions of non-AGN galaxies.

The main results of observations are illustrated in Table 1. As the Table shows, all galaxies have a circumnuclear structure, containing at least two kinematic subsystems: the inner one, which may be described as a minibar or

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dynamically decoupled disk, and the outer subsystem – a co-planar or moderately inclined gaseous disk, which contains spiral or ring structures.

The common feature of many galaxies is the turn of kinematic major axes in their circumnuclear region. There may be two probable interpretations of this effect – a bar-like perturbation of the velocity field, and the inclination of the nuclear disk with respect to the the main disk. To distinguish between these possibilities, photometric data were involved in addition to kinematic ones.

A general approach is quite simple. In the first case (the presence of a bar) one can expect some characteristic distortion of the velocity field the of gas. Both the models of gas dynamics in a barred potential and the observations of barred galaxies show that isovelocity contours in the vicinity of a bar tend to turn along the major bar axis, so the line of largest velocity gradient (kinematic major axis) turns towards the minor photometric bar axis. Hence, photometrically and dynamically obtained position angles (PAs) of the major axes change in a different way, turning in the opposite directions. In the second case, when the plane of the circular rotating nuclear disk is not coplanar to the main disk, the photometric axis always turns parallel to the dynamical one. Observations show that both cases occur in real galaxies.

Table 1. Kinematical structures and features of nuclear disks

NGC	Type	R($''$)	R(kpc)	Structure of nuclear region	Reference
972	Sb	6	0.6	minibar and pseudoring	Zasov & Sil'chenko (1996)
		20	1.8	star-forming ring + IR spiral (?)	Zasov & Moiseev (1998)
1084	Sc	6	0.6	radial motion of the ionized gas	Moiseev et al. in prep.
		20	1.8	dynamically revealed bar	
4100	Sbc	6	0.4	blue optical ring	Moiseev et al. in prep.
		11	0.9	inclined or polar star-forming disk	
6181	Sc	5	0.8	minibar	Sil'chenko et al. (1997)
		12	2.0	co-planar disk+expanding ring or strong vertical motion	
7217	Sb	2	0.15	polar disk and ring	Zasov & Sil'chenko 1997
		10	0.8	fine spiral arms in co-planar disk	

Some comments on the chosen galaxies:

NGC 972. This is an isolated galaxy of unusual optical structure with a dusty disk and negligible bulge. A wide dust lane, bordering the bright inner part of the galaxy in the south-west side, gives some hint of the weak inclined inner disk of interstellar matter which was confirmed by measuring the orientation of the line of nodes. The galaxy is rich of molecular gas, nevertheless it possesses rather moderate star formation which is concentrated in the small nucleus and in the ring of about 2 kpc radius. The latter is not visible in the images obtained at the 1m SAO telescope in VRI bands, but clearly noticeable in the H_α line and also in the map of the distribution of the Q-parameter , which is an absorption -independent combination of V,R and I magnitudes (Zasov & Moiseev 1998). The Q-parameter map also shows a small pseudoring with radius about 0.5 ± 1 kpc, which coincides with the H_α nuclear ring, found recently by Ravindranath & Prabnu (1998).

The IFP velocity field of the inner region of about 0.6 kpc radius reveals the turn of the kinematical axis at about 30° relative to the orientation of the outer line of nodes found earlier from the observations with MPFS (Zasov &

Sil'chenko 1996). The K-band image (which was obtained in UKIRT and kindly given by Stuard Ryder to the authors) shows that the isophotes major axes turn in the opposite direction. It gives evidence of a minibar inside the nuclear ring. In between the central disk and the ring the rotation of gas is circular. The irregular structure of this region, seen in K-band, resembles a widely opened spiral. So there are two kinematic subsystems, coexisting in the inner part of this galaxy.

NGC 1084. This is a late-type galaxy with a well defined spiral structure. The velocity field analysis of the very inner bright region within 6″ (0.6 Kpc) from the centre demonstrates a fast circular rotation of gas in the plane of the main disk, in addition to less intense shifted components of H_α and [NII] line profiles, revealing non-circular (probably radial) motions. The most unusual peculiarity of gas kinematics which was found from IFP observations is the long (about 1.5 kpc size) shock front, crossing the inner part of the galaxy, where the line-of-sight velocity changes at 80-100 km/s within several arcsec perpendicular to the front line. Direct images of NGC 1084 were obtained at the SAO 1m telescope in B,V,R,I bands. Image processing showed the turn of the photometric major axis has the opposite sign with respect to the turn of the kinematic one. It agrees well with the presence of a bar-like perturbation with radius about 2 kpc. Why the presence of a any optical feature in this region is not seen in the image of this galaxy is a puzzle. It seems that the contrast of the bar potential is rather weak.

NGC 4100. This is non-barred galaxy in the Ursa Major cluster. Its rapidly rotating nucleus was found by Afanasiev et al.(1992). Analysis of the velocity field showed that in the inner 11″, or about 0.8 kpc, where a very large velocity radial gradient is present, a kinematical axis turns by 20° with respect to the outer disk. Ellipticity of the isophotes is maximal at the central 6″. The photometric axis in R,I bands turns parallel to the kinematical one, which indicates the existence of the inclined inner disk in the central 0.8-0.9 kpc. In the frame of circular gas motions the dynamically determined inclination of the main disk and the nuclear region differ by 22 ° in such a way that the nuclear disk looks more opened for the observer. There are two possible solutions for the inclination angle between the planes of two disks: 25° or 87°, depending on what side of the nuclear disk is closer to us. The blue color index and bright H_α emission gives evidence of intense SF in the nuclear disk.

NGC 6181. In addition to IFP observations, the images of this SAB(rs)c galaxy obtained at the 1m telescope were used (see Sil'chenko et al. 1997). In the very centre of this galaxy, at radius of about 0.6-0.8 kpc, both kinematic and photometric major axes turn in the opposite directions, which enables us to conclude that a small nuclear bar exists in this galaxy.

The central part of the residual velocity field, obtained by the subtraction of the observed and the expected circular velocity fields, reveals two ring-like arcs at radius 1.8 kpc, symmetrically positioned near the minor axis, where deviations from the circular rotation locally exceed 50 km/s. It is not clear what may cause such strong radial motions (or z-motions) of gas – these regions do not reveal themselves in the brightness distribution. There is also no hint of the related shock wave or the enhanced line emission. A plausible explanation is that we observe here an unusually large amplitude of oscillation of gas velocities associated with the density waves, which penetrate deep into the inner part of the disk.

NGC 7217. Contrary to the galaxies discussed above, this galaxy possesses a highly luminous spherical component. Although this galaxy has two or three optical rings, there is no bar at either visible, or near-infrared wavelengths. Observations with IFP and MPFS show that the azimuthal variation of the line-of-sight velocity gradient follows a nearly sinusoidal curve, which indicates that the gas moves along circular orbits. In the circumnuclrear region this gradient amplitude sharply increases up to 250 km/s/kpc. The significant turn of the kinematic line of nodes is also noticeable. So, in this galaxy we have an example of a sharply kinematically distinct nucleus.

Our data show a rapid decrease in the photometric PA of the major axis toward the center of the galaxy, beginning from about 4″. However, the HST measurements, taken from the NASA/ESA archive data, show that this decreasing actually occurs closer to the center – at a distance of about 1″ in such a way that the central isophotes become nearly perpendicular to the outer ones. They also increase their ellipticity toward the centre. The kinematic axis orientation is in satisfactory agreement with the photometric estimates. Therefore, the most likely explanation for the rotation of the photometric and dynamical axes is the presence of a small, strongly inclined, (probably polar) disk in the central 100-200 pc region of the galaxy. [1]

3. Nuclear disk stability and star formation

Fast rotation of nuclear disks of galaxies is a factor which tends to reduce the star formation activity due to angular momentum of collapsing gas regions, which prevents gaseous disks from being gravitationally unstable.

A flat gaseous disk of surface density $\sigma_{gas}(R)$ is gravitationally stable if the radial velocity dispersion of gas C_{gas} is high enough for the Toomre Q-parameter ($Q \sim C_{gas} \cdot \kappa(R)/\sigma_{gas}(R)$, where $\kappa(R)$ is the epicyclic frequency) to be larger than some critical value Q_c, so that $Q_c = 1$ for pure radial perturbations (Toomre criterion). In disks of spiral galaxies $Q_c = 1.5 - 2$ (Kennicutt 1989, Zasov & Bizyaev 1994). Non-WKB analysis of stability shows that the threshold for instability $Q_c \approx 1.7$ for a 'flat' rotation curve, but keeps close to 1 if the angular velocity $\Omega \approx$ const (Polyachenko et.al. 1997). It follows then, that in the case of rigid-body rotation, which usually takes place in circumnuclear regions, a higher value of the gas surface density σ_{gas} is necessary for the disk to be unstable – due to lower Q_c and higher $\kappa(R)$.

Indeed, many spiral galaxies possess dense molecular circumnuclear disks of about one kpc size, for which σ_{gas} exceeds $10^3\, M_{\odot}/pc^2$, so a large angular velocity is necessary to stabilize the disk. However, as a rule, values of $\kappa(R)$ for them are also very high, and, as a result, the velocity dispersions C_{gas}, corresponding to $Q_c \approx 1$, remain rather low. The estimates of marginal values of C_{gas} (from the data taken from the literature) for about twenty galaxies which

[1] Small polar nuclear disks in normal spiral galaxies probably are not so rare: for example, their presence was claimed in NGC 2685 (Sil'chenko et al. 1998), NGC 253 (Ananthramaiah & Goss 1996) and some other galaxies.

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have molecular nuclear disks shows that for most of them $C_{gas} \leq 15$km/s, which does not exceed the observed velocity dispersion of gas (Zasov 1999). This result gives evidence that in many cases nuclear molecular disks are on the threshold of gravitational stability or definitely stable. The latter is especially true for nuclear regions of galaxies poor of gas, such as NGC 7217. Nevertheless some star formation takes place even there. In NGC 7217 not only the growth of the intensity of H_α towards the centre is observed, but also, as the analysis of HST observations showed, a surprisingly well-ordered spiral-like structure exists within the inner $10''$ (Zasov & Sil'chenko 1997).

Even if the inner disk of NGC 7217 is marginally stable, the wavelength of growing gravitational perturbations is expected to be about several hundreds of parsecs there, whereas the observed structure presents a sort of "rippled surface" with a significantly smaller scale. It confirms that the observed pattern cannot be caused by gravitational oscillations.

Note that the small-scale spiral pattern may frequently occur in the nuclear disks, although it is usually difficult to extract it from the photometric observations with restricted angular resolution. As an example, a complex circumnuclear spiral-like structure was found in NGC 6951 (Barth et al. 1995) and NGC 488 (Sil'chenko 1999).

A possible alternative mechanism of formation of the spiral pattern is the hydrodynamical instability in gaseous disks which does not require a high surface density to develop (see the discussion by Fridman (1994)). So the presence of star formation in rapidly rotating disks may give evidence of the importance of non-gravitational mechanisms for compression of the gaseous medium there.

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