Nuclear kpc-sized disks of spiral galaxies

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

1. Introduction

Circumnuclear regions within a radius of a few hundred parsecs are so diverse by their properties, that they may be called the most unlike 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

Fast 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 the reliable data for their kinematic properties can’t 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 6m telescope of Special Astrophysical observatory in Russia (SAO RAS) in 1993 -1997. Scanning interferometer Fabry-Perot (IFP) and Multi-Pupil Field Spectrograph (MPFS) developed in this observatory were used for obtaining the velocity field of the ionized gas in the Hα emission line. Although the observations were aimed mostly to study gas motions in a global galactic scale (program "Vortex" led by Fridman A.), five objects chosen here may give bright examples of different structures and kinematic peculiarities, observed in nuclear regions of non-AGN galaxies.

The main results of observations are illustrated in Table 1.

As Table shows, all galaxies have a circumnuclear structure, containing at least two kinematic subsystems: the inner one, which may be described as minobar or 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 interpretation of this effect – bar-like perturbation of the velocity field, and the inclination of nuclear disk with respect to the the main disk. To distinguish between these possibilities photometrical 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 velocity field 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 photometrical 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)  |
| 1084 | Sc   | 6     | 0.6    | star-forming ring + IR spiral (?)  | Zasov & Moiseev (1998)     |
| 20   |      | 1.8   |        | radial motion of the ionized gas   | Moiseev et al. in prep.    |
| 4100 | Sbc  | 6     | 0.4    | blue optical ring                  | Moiseev et al. in prep.    |
| 6181 | Sc   | 5     | 0.8    | inclined or polar star-forming disk| Sii’chenko et al. (1997)   |
| 12   |      | 0.9   |        | minbar                            |                            |
| 7217 | Sb   | 2     | 0.15   | co-planar disk+expanding ring      | Zasov & Sil’chenko 1997    |
| 10   |      | 0.8   |        | fine spiral arms in co-planar disk |                            |

Some comments to the chosen galaxies:

**NGC 972.** This is the isolated galaxy of unusual optical structure with dusty disk and negligible bulge. 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 line-of nodes. The galaxy is rich of molecular gas, nevertheless it possesses a 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 telescope SAO in VRI bands, but clearly noticeable in $H_\alpha$ line and also in the map of distribution of Q-parameter , which is absorption-independent combination of V,R and I magnitudes (Zasov & Moiseev 1998). Q-parameter map also shows a small pseudoring with radius about 0.5 ± 1 kpc, which coincides with $H_\alpha$ nuclear ring, found recently by Ravindranath & Prabhu (1998).

IFP velocity field of the inner region of about 0.6 kpc radius reveals the turn of 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 authors) shows that the isophotes major axes turn in the opposite
direction. It gives evidence of minbar 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 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. 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 a less intense shifted components of H$_\alpha$ 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 1m telescope SAO in B,V,R,I bands. Image processing showed the turn of photometric major axis which has the opposite sign with respect to the turn of kinematic one. It agrees well with the presence of 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 Ursa Major cluster. Its fast 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 nuclear disk is closer to us. Blue color index and bright H$_\alpha$ 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 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 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, simmetrically 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 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 high luminous spherical component. Although this galaxy has two or
three optical rings, there is no bar at neither visible, nor near-infrared wave-
lengths. 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 circumnuclear region
this gradient amplitude sharply increases up to 250 km/s/kpc. The significant
turn of kinematic line-of nodes, is also noticeable. So, in this galaxy we have an
example of sharply kinematic 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 decreas-
ing 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 central 100-200
pc region of the galaxy.

3. Nuclear disk stability and star formation

A 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 the surface density $\sigma_{\text{gas}}(R)$ is gravitationally stable if
radial velocity dispersion of gas $C_{\text{gas}}$ is high enough for the Toomre $Q$-parameter
($Q \sim C_{\text{gas}} \cdot \kappa(R) / \sigma_{\text{gas}}(R)$, 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 ‘flat’ rotation curve, but keeps close to 1 if the angular
velocity $\Omega \approx \text{const}$ (Polyachenko et.al. 1997). It follows then, that in the case
of rigid-body rotation, which usually takes place in a circumnuclear regions,
a higher value of the gas surface density $\sigma_{\text{gas}}$ 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 $\sigma_{\text{gas}}$ exceeds $10^3 M_\odot/\text{pc}^2$, 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 $C_{\text{gas}}$, corresponding to
$Q_c \approx 1$, remain rather low. The estimates of marginal values of $C_{\text{gas}}$ (from the
data taken in the literature) for about two tens of galaxies which have molecular
nuclear disks, shows, that for most of them $C_{\text{gas}} \leq 15 \text{km/s}$ 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 is especially true for

\footnote{Small polar nuclear disks in normal spiral galaxies probably are not so seldom: for example,
their presence was claimed in NGC 2685 (Sil’chenko et al. 1998), NGC 253 (Ananthramaiah
& Goss 1996) and some other galaxies.}
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 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 of 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 photometrical observations 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 spiral pattern is the hydrodynamical instability in the 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 mechanism of compression of gaseous medium there.

Acknowledgments. Authors are grateful to Afanasiev V., Boulesteix J., Burenkov A., Dodonov S., Sil’chenko O. and Vlasyuk V. for the obtaining the observational data. This work was supported by grant RFBR 98-02-17102.

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