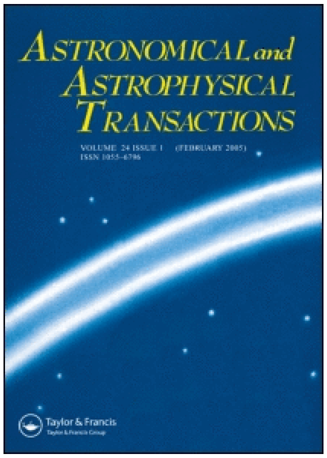

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STRUCTURE AND STAR FORMATION IN CIRCUMNUCLEAR REGIONS OF SPIRAL GALAXIES

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Photometric and kinematic properties of inner regions of spiral galaxies are considered. It is shown that the fast rotation of nuclear gaseous disks makes them gravitationally stable or marginally unstable. Star formation there may continue even in the absence of large-scale gravitational instability.

KEY WORDS Nuclei of galaxies, star formation

1 INTRODUCTION

Inner parts of spiral galaxies within about 1 kpc from their nuclei in many cases appear to be peculiar regions, by their dynamical and photometrical properties, even if we restrict our attention to normal galaxies which do not possess strong nuclear activity. Here I note three main peculiarities of these regions, well illustrating the complexity of evolutionary processes there.

First, circumnuclear regions often reveal rather complex – regular or irregular – photometric structure which may be connected or – sometimes – not connected with the general structure of the main disk. It includes spiral arms (examples: M 100, NGC 4314), short nuclear bars or nuclear rings of a resonance nature (see Buta and Crocker 1993) or bright 'hot spots', which seems to be sites of active star formation. Most of these features are related to large-scale bars in SB-galaxies, although in many cases the presence of a bar is not evident from optical observations.

Second, in many galaxies (especially of early types Sa-Sbc), including our own Galaxy, the central regions accumulate interstellar gas into a dense molecular disk of about 1 kpc size. These central 'islands' (or sometimes rings or bar-like features) of molecular gas are more a rule than an exception for massive spiral galaxies. In many cases the dense circumnuclear gas produces strongly enhanced star formation which gives the phenomenon of a starburst nucleus.

Note that the presence of a large-scale bar is proved to be an efficient (but not the only) mechanism for driving the interstellar medium into the nuclear region, to feed starburst or mild star formation within a few hundred parsecs from the centre, and – under favourable conditions such as the formation of a nuclear bar – to turn on the activity of the nucleus (see for example Friedli and Benz, 1993; Telesco *et al.*, 1993; Schlosman *et al.*, 1989).

Third, as optical and CO observations have shown, in many normal galaxies their nuclear gaseous disks are distinguished by rapid rotation of gas and stars, being often dynamically decoupled from the rest of the galaxy (Afanasiev *et al.*, 1989; Zasov and Sil'chenko, 1996; Rubin *et al.*, 1997; Sofue, 1997 and references therein).

A detailed comparison of spectra of nuclear H II regions with the H II regions of main disks which was carried out by Ho *et al.* (1997), showed that they are similar in many respects: their luminosities, masses of ionized gas and internal colour excesses are within the same ranges. However some properties are systematically different: as a rule, H II nuclei emit stronger low-ionization forbidden lines compared to disk H II regions; they also have lower equivalent widths of Balmer emission lines, which gives evidence of bright background light of the stellar population. Nuclear emission regions also have an unusually low filling factor of around 10^{-5} (Ho *et al.*, 1997). It is worth mentioning also that the Hubble Space Telescope observations revealed the presence of unusually bright and compact young (globular?) stellar clusters in the regions of active circumnuclear star formation (see, for example, Barth *et al.*, 1995). All these peculiarities show that the conditions of star formation there may differ from what we observe in spiral arms of galaxies.

In this paper I review briefly some results of investigations of nuclear regions of spiral galaxies, related to their structure and star formation.

2 ROTATION OF INNER DISKS

For a typical distance to galaxies considered here $D = 10$–20 Mpc a nuclear disk with diameter of about 1 kpc is seen at an angle $10''$–$20''$. It is very difficult to get the velocity field or velocity curve so close to the centre. Nevertheless even the 'classical' one-dimensional long slit observations gave strict evidences of fast rotation of nuclear regions of 0.5–1 kpc radius in many galaxies (Afanasiev *et al.*, 1989; Rubin *et al.*, 1997). For the most reliable estimates of velocity gradients it is necessary to use several spectral cuts passing through a nucleus or to involve a two-dimensional velocity field. Evidently without using two-dimensional data it is impossible to verify the rotational nature of the gas velocities. As an example it is worth mentioning that from 17 galaxies where Rubin *et al.* (1997) found dynamically detached nuclei, only for half of them did circular rotation of circumnuclear gas fit the data.

One of the methods of seeking small fast rotating dynamically decoupled nuclei is to measure the line-of-sight velocity gradient dV_r/dR at the centre of a galaxy along the different positional angles **PA**. This approach appears to be highly efficient.

Observations of more than a dozen normal spiral galaxies obtained with Fabry–Perot and multipupil spectrograph observations at the 6-metre telescope of SAO RAS (Laboratory of Spectroscopy and Photometry of Extragalactic Objects) have shown that such nuclei may be revealed down to 1–3 arc seconds from the centre (some examples are given in Zasov and Sil'chenko, 1996). Typical nuclear velocity gradients are found to be a few hundred km/s. They may be even higher if we take into account that the angular sizes of nuclei are comparable to the seeing during the observations. Note however that in the case of rigid-body rotation the finite angular resolution does not distort the slope of the rotation curve (Fridman *et al.*, 1994). This method allows us not only to determine the velocity gradient in the nucleus, but also to find the position of the dynamical axis (line-of-nodes) and hence to reveal its agreement or disagreement with the major axes of galaxies. Happily in most cases the divergence of these axes at $R \approx$ several hundred parsecs is not too large, which gives evidence of approximately circular rotation of the gas (although bright exceptions were also found, e.g. NGC 895, NGC 972, NGC 7217). In principle, the turn of the dynamical axis may be caused both by a non-asymmetrical bar-like potential and by the inclination of the nuclear disk to the plane of the main disk. To reveal its nature it is necessary to use kinematic and photometric data together. In particular, a good criterion of the inclined nuclear disk is the similarity of radial variations of position angles of the dynamical major axis (line of nodes) and the photometrically determined major axis of the isophotes.

It is curious that unlike nuclear rings, dynamically revealed inner bars (mini-bars) do not strictly relate to large-scale optically visible bars: the former were found not only in SB-galaxies, but also in SA-galaxies where the presence of a large-scale bar is not evident (NGC 895, NGC 972, NGC 4100, NGC 7217). It gives evidence that such small features as nuclear bars may be of non resonance nature. Instead they may appear due to the instability of extended orbits of stars in slowly rotating stellar components (see Polyachenko and Polyachenko, 1994).

Radio observations of CO-rich nuclei also confirm the fast rotation of gas within the inner several hundreds of parsecs with velocity gradients similar to those observed in the optically selected galaxies (velocity of rotation 200–250 km/s reaches within R = 100–200 pc (Sofue, 1997)), so optical and radio samples of nuclear regions are non-distinguishable by their gas kinematics.

3 NUCLEAR DISK STABILITY AND STAR FORMATION

As pointed in the Introduction, nuclear star formation takes place in galaxies of all types. However the intensity of this process differs by several orders of magnitude – from weak emission nuclei to bursting star formation nuclei and further up to ultraluminous far-infrared galaxies which have both extremely high luminosity in the far infrared (10^{11}–$10^{12} L_{\odot}$) and abnormally large surface density of circumnuclear molecular gas (10^3–$10^4 M_{\odot}/\mathrm{pc}^2$) (see, for example Sanders *et al.*, 1991). Concerning H II nuclei of normal spiral galaxies, their properties are in general similar to properties of giant H II regions in the main disks, with the exception of higher concentration n_e and very low filling factor $\approx 10^{-5}$ (Ho *et al.*, 1997). The latter peculiarity may just be a consequence of a large number density of gas which makes the sizes of H II regions abnormally small. Indeed, for a given excitation parameter of a single ionizing star the volume filled by ionized gas is proportional to n_e^{-2}, so it must be much lower than in the main disk, and hence compact H II regions may occupy just a small volume fraction of the circumnuclear star-forming disk. One can expect that high resolution observations, if they were available, would show the presence of thousands of small-sized H II regions connected to O-stars, immersed in the dense non-homogeneous gaseous medium of the nuclear disk.

The other peculiarity of molecular clouds of circumnuclear disks is high gas pressure caused by the high number density of the gas (both molecular and H II). A good example was given by the investigations of the nucleus of the spiral galaxy NGC 1808 (Aalto *et al.*, 1994): the analysis of radio emission in different molecular lines led the authors to the conclusion that $P/k \approx 10^8$ cm^{-3} K, which is three to four orders of magnitude higher than in the disk of the Galaxy. The high pressure may be a factor which significantly enhances star formation efficiency which is observed in gas-rich nuclei.

It is worth mentioning that the fast rotation of the inner parts of galaxies, especially of dynamically decoupled nuclei, is a factor which, on the contrary, tends to reduce their star formation activity (even in the case of rigid body rotation) due to the conservation of angular momentum of the collapsing regions of the gaseous disks, preventing them from being gravitationally unstable.

For a flat disk large-scale gravitational instability is absent if the radial velocity dispersion C_{gas} exceeds the critical value:

$$C_{\mathrm{gas}} = \frac{Q\pi G\sigma_{\mathrm{gas}}}{\kappa(R)}.$$

Here σ_{gas} is the surface density, and $\kappa(R)$ is the epicyclic frequency (for rigid-body rotation $\Omega = \text{const}$, $\kappa = 2\Omega$). The stability parameter is $Q = 1$ for purely radial perturbations (Tbomre's criterion). In galactic disks, where the dispersion velocity of the gas is about 10 km/s, the parameter Q is 1.5–2 (Kennicutt, 1989; Zasov and Bizyaev, 1994). This agrees with the non-WKB analysis of stability which shows that the threshold for instability reaches $Q \approx 1.7$ for a flat rotation curve but keeps close to 1 for $\Omega \approx \text{const}$ (Polyachenko *et al.*, 1997). Hence, as follows from the equation, in the region of rigid-body rotation, which usually takes place in a circumnuclear region, a lower value of C_{cr}, is necessary for the disk to be stable due to lower Q and the higher ratio κ/Ω.

Note that the strict threes-dimensional criterion of gravitational stability is not yet obtained, so all the usually adopted conditions for the instability may be considered in the best case as only approximate ones (see the discussion in the book of Gor'kavy and Fridman, 1994).

Now I return to the question: Are circumnuclear disks of observed galaxies gravitationally stable? The answer would be definitely 'yes', if their gas surface densities were not too high – say, not too much higher than the density at larger distances from the centre in the main disk, where the angular rotation of the gas is

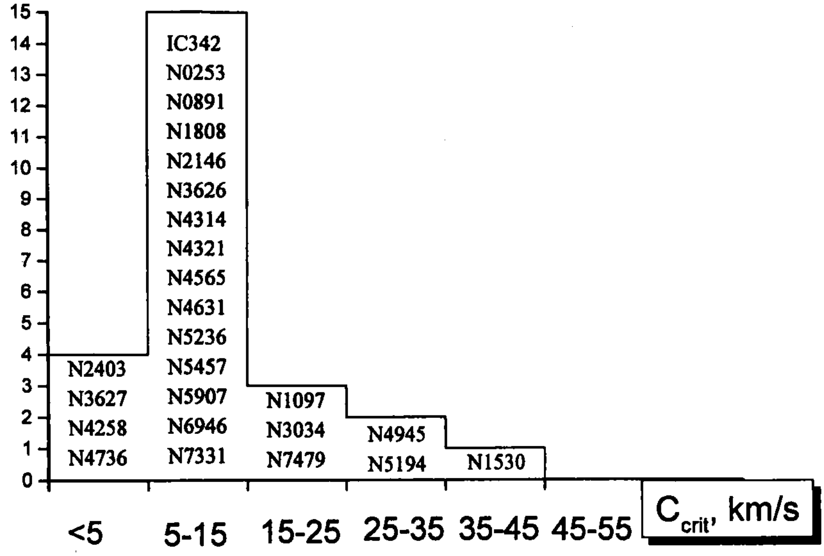

Figure 1 Histogram of the distribution of critical velocity dispersions C_{cr} (Toomre's criterion) of gas clouds for the nuclear regions of galaxies with dense molecular disks.

lower. But what about those galaxies (including our own) where radio observations in molecular lines show the presence of dense gaseous nuclear disks? For them σ_{gas} often exceeds $10^3 M_\odot/\mathrm{pc}^2$, which makes their selfgravity rather significant, so a large angular velocity is necessary to stabilize the disk.

To illustrate the situation, Figure 1 shows a histogram of the distribution of C_{cr} (Toomre's criterion) for the inner regions of galaxies where both the rotation curve and the CO intensity map or σ_{gas} are available from the literature. Surface gas density values correspond to the standard conversion factor 3×10^{20} K cm^{-2}. Note that due to the restricted angular resolution Ω may be underestimated which allows us to consider C_{cr} as an upper limit.

Observational estimates of the velocity dispersion of molecular clouds in dense central gaseous disks of galaxies are very scarce and unfortunately not too reliable. I will adopt 10 km/s as a lower limit of C_{gas}. In fact, for gas-rich nuclei it is of this order of magnitude or higher: direct measurements lead to values $C_{gas} \approx$ 12–50 km/s (see Wright *et al.*, 1993 for IC 342; Sofue *et al.*, 1989 for NGC 4631; Ishizuki *et al.*,, 1990 for NGC 6946; Garcia-Burillo, 1992 for NGC 891).

Hence the general conclusion which follows from the histogram in Figure 1 is that a significant number of the galaxies considered here possess nuclear disks which are on the threshold of gravitational stability or definitely stable.

The probem of revisiting the conversion factor which is used for the transition from the intensity I_{co} to σ_{gas} and the lowering of molecular mass estimates for nuclear molecular gas is well known (see Arimoto *et al.*, 1993 and references therein). Here I note that in the nuclear part of the nearby actively starforming galaxy M 82

Figure 2 Photometric structure of the inner region of NGC 7217 (HST archive data) after subtracting the axially symmetrical background component (the bulge). The subtraction was done inside the circle with radius 16″ (1.3 kpc). The position angle of the vertical axis is −73°, and east is up (see Zasov, Sil'chenko, 1997).

observations in different molecular lines (^{12}CO, ^{12}CO) confirm that the conversion factor is lower with respect to that usually adopted (Wild *et al.*, 1992). Evidently if we take it into account, it will strengthen the conclusion about the gravitational stability of the majority of observed nuclear disks.

It is worth noting that the gravitational instability of a disk is not the only mechanism which may lead to star formation, so the latter may take place even in the case of a gravitationally stable disk. A good illustration is the nuclear region of NGC 7217. The intensity of H_α in this gas-poor galaxy monotonically rises towards the centre. In spite of the low gas density, star-forming regions not only exist in the nuclear disk, but, as the analysis of HST observations show, apparently have a surprisingly well-ordered spiral-like structure (see Figure 2 taken from Zasov and Sil'chenko, 1997). This spiral pattern is not visible in the original images of this galaxy because its details are swamped by the emission of the substantially brighter stellar bulge which has unusually high luminosity in this galaxy. The nature of this structure is not evident. Even if the nuclear disk of NGC 7217 were marginally unstable (independently of whether it has a gaseous or stellar nature), the wavelength of perturbations corresponding to the maximum of the instability increment would not correspond to the observed scale of wave-like features. For the observed velocity gradient $\approx$ 200 km/(s kpc) the expected wavelength of perturbations is equal to several hundreds of parsecs, whereas the observed structure presents a sort of 'rippled surface' with a significantly smaller scale (the characteristic radial distance between neighboring arcs is about 1″ , or less than 0.1 kpc). Therefore, the observed pattern cannot be caused by gravitational oscillations in either a stellar or gaseous disk.

A possible alternative to the gravitational formation of a spiral pattern is the action of hydrodynamical instability in the gaseous disk that does not require a high surface density to come into action. One of the conditions to be fulfilled for such an instability to occur is the presence of a local maximum in the rotation curve, followed by a region of rapidly decreasing angular velocity (see the discussion by Fridman (1990, 1994)). Observations showed that in NGC 7217 such region may really exist at the outer boundary of the dynamically distinct nucleus, where the velocity gradient falls sharply down outwards (Zasov and Sil'chenko, 1997).

Note that the inner spiral structure may frequently occur in the nuclear disks, although it is usually difficult to extract it from the photometrical observations due to the bright bulge background and the restricted angular resolution. As an example, a similar small-scale inner spiral-like structure was found by HST observations in the central part of NGC 6951 (Barth *et al.*, 1995).

4 CONCLUSIONS

(1) Inner (nuclear) regions of spiral galaxies within several arc seconds from the centre often possess nuclear bars and/or inclined disks which may be revealed not only from photometric or gas distribution data, but also from the analysis of the inner gas kinematics. Nuclear gaseous disks are usually distinguished by their high angular velocity.

(2) In most cases the inner molecular disks ≤ 1 kpc size appear to be gravitationally stable or marginally unstable. If, as may be proposed, the conversion factor used for the inner disks is overestimated, then this conclusion is strengthened.

(3) Star formation and some regular wave-like structure may develop in nuclear disks even if they are gravitationally stable. Hence there is (are) some non-gravitational mechanism(s) which regulate(s) the process of star formation there.

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