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New Structures in Galactic Disks: Predictions and Discoveries

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Abstract. Our main goal is to review: 1) some physical mechanisms which form the observed structures in galactic disks; 2) the discovery of new galactic structures predicted earlier. Specifically in the first part of the paper we discuss some questions associated with spiral structure. The second part is devoted to the prediction and discovery of giant vortices in gaseous disks of the grand design spiral galaxies using method of reconstruction of the full three-component velocity field from the observed line-of-sight velocity field. In the third part, we give some arguments in favour of existence of the slow bars in the grand design spiral galaxies.

1. Some Problems of Spiral Structure

1.1. Comparative Analysis of the Nature of Flocculent and Grand Design Spiral Galaxies

According to Elmegreen & Elmegreen classification (1982; 1987), the flocculent galaxies belong to the spiral type, although in Hα-line we do not see any regular structure (e.g. Fig. 1a).

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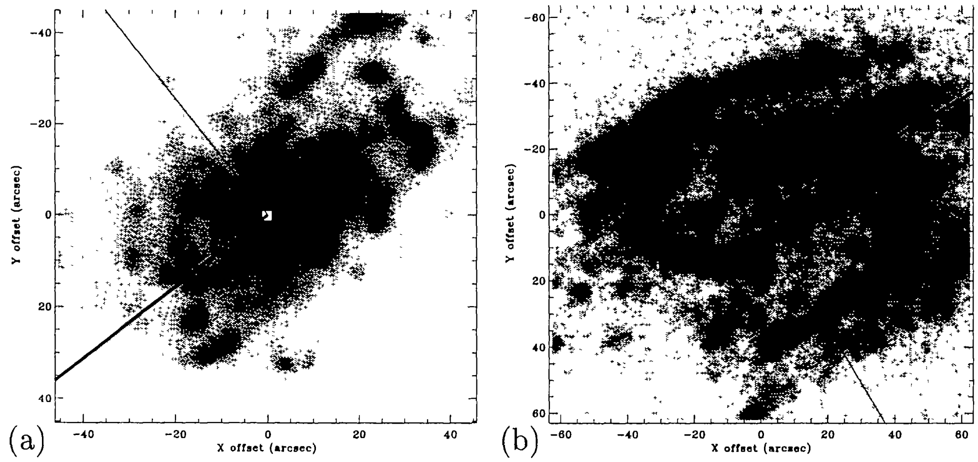


Figure 1. The monochromatic images of the flocculent galaxy NGC 4414 (a) and the grand design spiral galaxy NGC 157 (b) in the Hα emission line (6-m telescope SAO RAS). The gaseous disk of the former galaxy does not show any clear structure, while in the latter case a clear grand design spiral structure is seen.

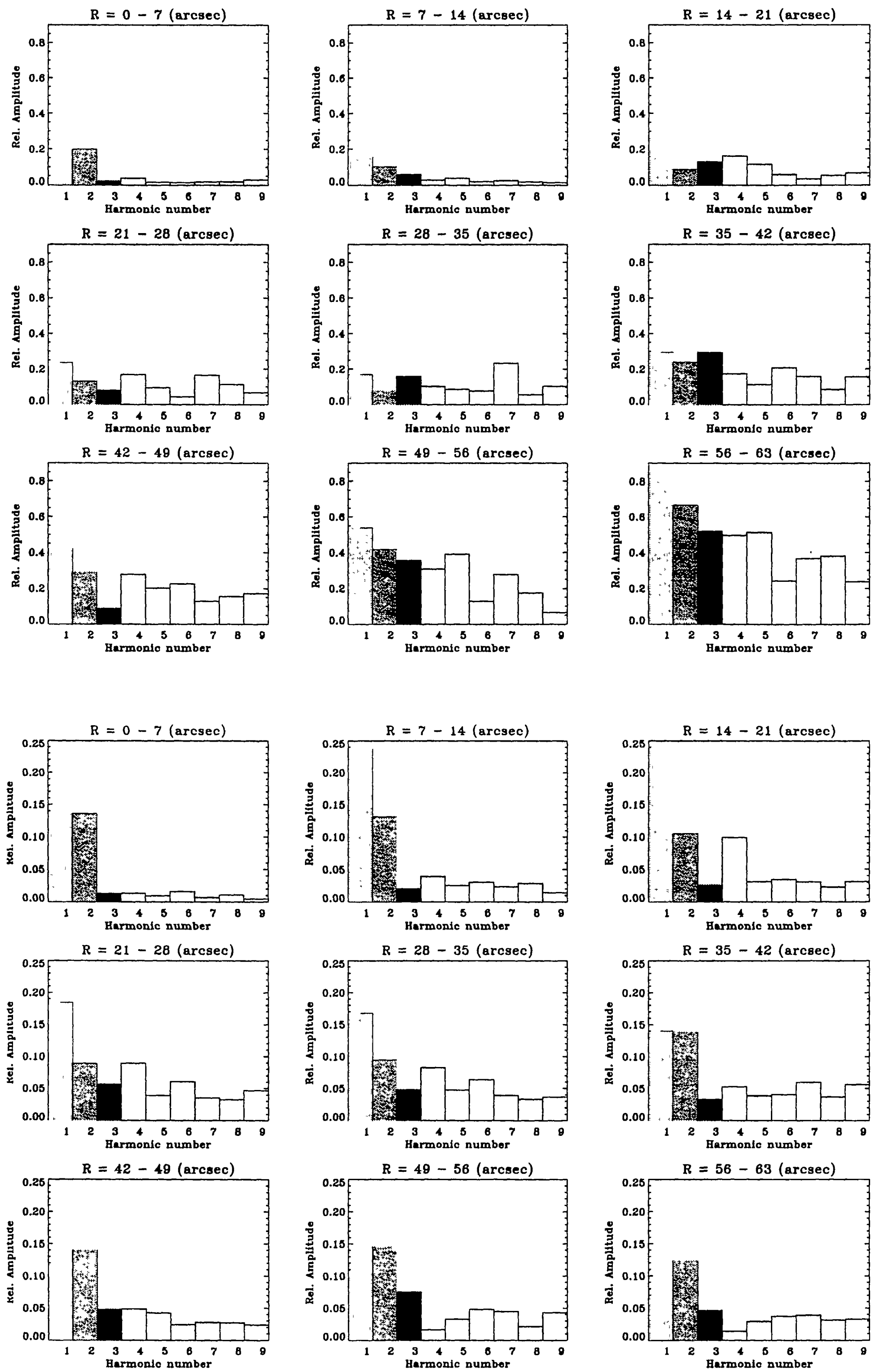
Starting from 1996, regular structures were found in the stellar disks of flocculent galaxies observed in the K'-band (2.1 μm) (Thornley & Mundy 1996, 1997a,b; Block, Elmegreen & Wainscoat 1996; Grøsbol & Pastis 1998; Elmegreen et al. 1999).

Here, on the base of the results of Fourier analysis of the brightness maps and line-of-sight velocity fields of flocculent and grand design galaxies, we try to clarify the nature of difference between these types of galaxies.

In Fig. 1 and below we compare the flocculent galaxy NGC 4414 with the galaxy NGC 157, which belongs to the highest type 12 of the grand design structures according to Elmegreen & Elmegreen (1987). But in general, there are no clear evidences of significant differences between flocculent and grand design spiral galaxies of Sa–Sc types, when we consider their photometric properties, star formation rate or gas content, due to large dispersion of their properties (Elmegreen & Elmegreen 1986; Romanishin 1985). However, two circumstances should be taken into account. First, there are practically no grand design galaxies among the types later than Sc (Elmegreen & Elmegreen 1986), whereas the late-type galaxies have the largest relative mass of H I with respect to the total mass (e.g., see Broeils & Rhee 1997). Second, the grand design galaxies have systematically lower radial gradient of the circular velocity curves in their outer disks with respect to the flocculent galaxies, that gives the evidence that, in the former type of galaxies, the ratio of the disk mass to the total mass is larger than that for the latter type (Biviano et al. 1991). It enables one to conclude that the grand design spiral structure tends to avoid the gas-rich galaxies with the lightest disk components with respect to the total mass.

The reason of the different visual appearance of gaseous disks of the flocculent and the grand design spiral galaxies is clearly seen from comparison of the Figs. 2a and 3a.

The figures show the Fourier spectra of deviation from the azimuthal symmetry in the different galactocentric rings for Hα brightness maps (6-m telescope



(a)

(b)

Figure 2. The Fourier spectra of the brightness maps of the gaseous (Hα) and stellar (R-band) disks of the flocculent galaxy NGC 4414.

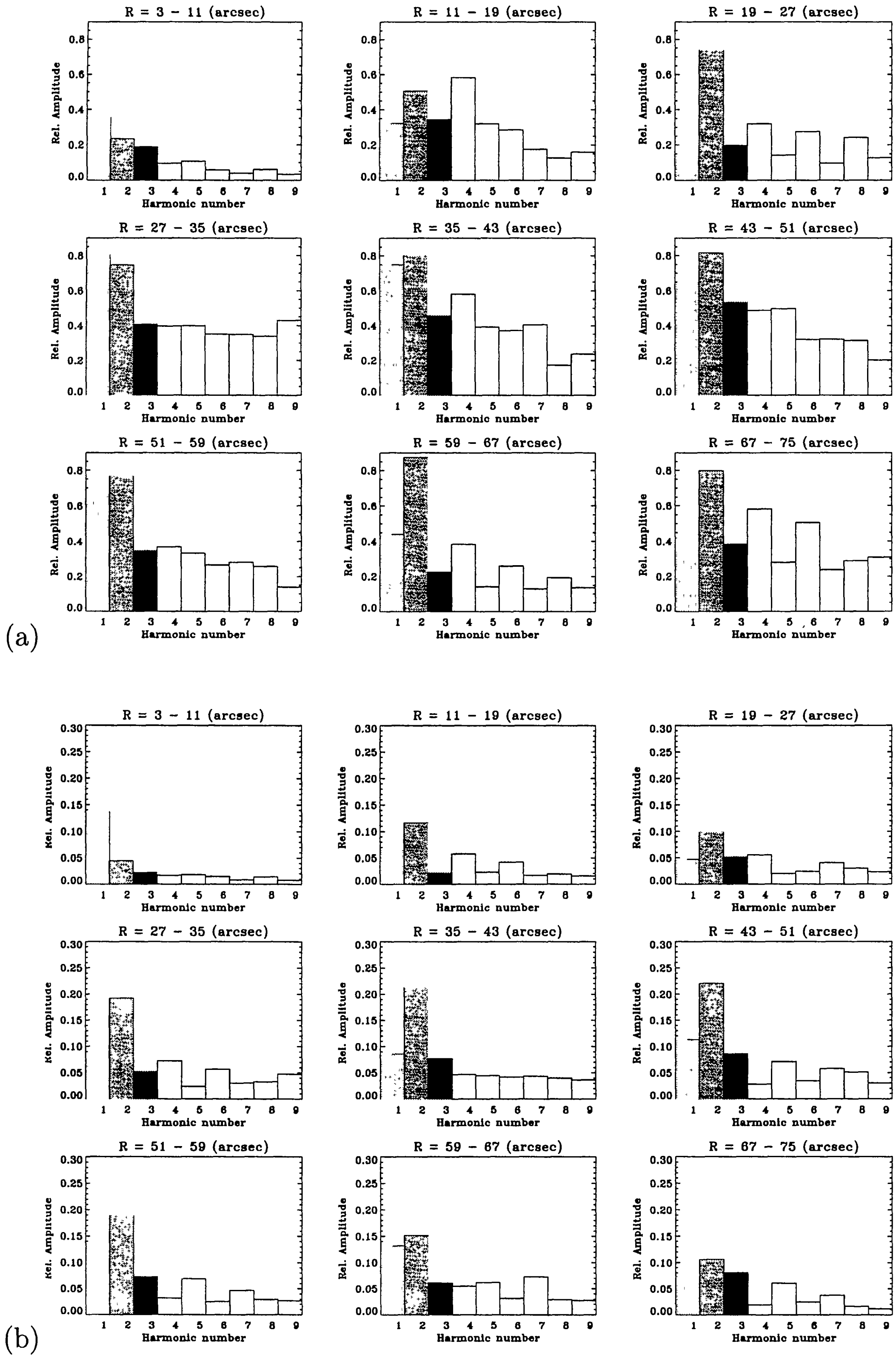


Figure 3. The Fourier spectra of the brightness maps of the gaseous (Hα) and stellar (R-band) disks of the grand design spiral galaxy NGC 157.

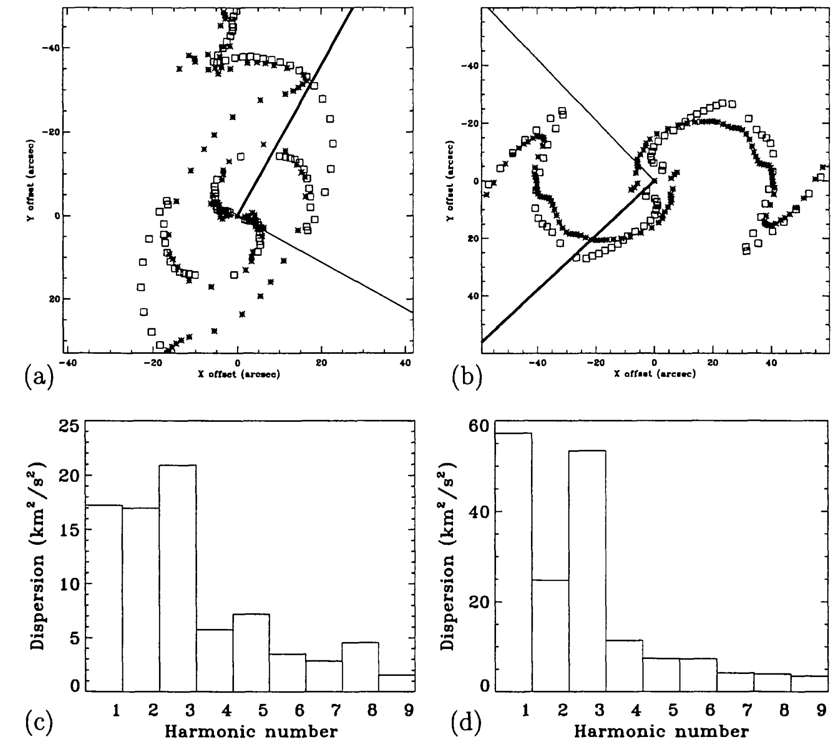


Figure 4. Some similarities between properties of the flocculent galaxy NGC 4414 (left column) and the grand design spiral galaxy NGC 157 (right column).

SAO RAS) of the flocculent galaxy NGC 4414 (Fig. 2a) and the grand design spiral galaxy NGC 157 (Fig. 3a). In the first case (NGC 4414) we can not detect predomination of any definite harmonic in the total disk area. In the case of NGC 157, predomination of the second harmonic takes place everywhere except the region 11″-19″, where the 4:1 resonance is located[1]. In several rings, generation of the higher even harmonics is obvious.

In contrast with the case of the gaseous disks, Fourier analysis of the R-band brightness maps Figs. 2b and 3b (Hubble Space Telescope and Jacobus Kapteyn Telescope archives) reveals clear predomination of the second harmonic in the stellar disks of both galaxies[2]. This fact explains different visual appearance of the gaseous and stellar disks in the flocculent galaxies, whereas close correlation exists between spiral structures in the stellar and the gaseous disks of the grand design spiral galaxies.

[1]Relatively high amplitude of the first harmonic in NGC 157 represents non-equal brightness of the two spiral arms due to asymmetry of the brightest star formation regions. If we mask the star formation regions, the amplitude of the first harmonic would be reduced by half.

[2]The strong first harmonic in the region $r < 40''$ in the case of NGC 4414 and in the region $r < 10''$ in the case of NGC 157 is caused by extinction of the bright spherical component by the disk and does not correspond to any disk structure, see also Fig. 4 in Fridman & Khoruzhii (2000).

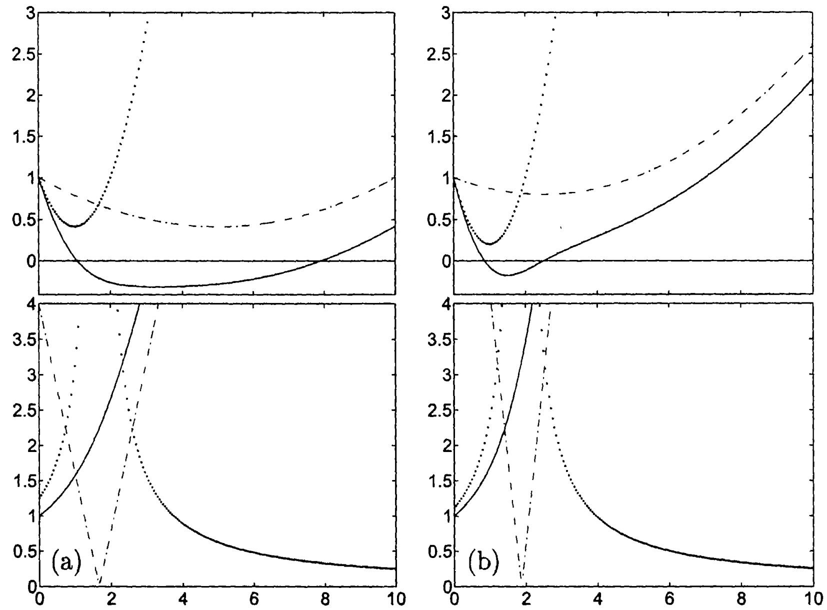


Figure 5. Some spectral characteristics of eigen perturbations in: the gaseous disk alone (dashed line), the stellar disk alone (dotted line) and the system of these disks (solid line) as a function of dimensionless radial wave vector ($k_r/[\pi G\sigma_*/c_*^2]$). Upper panels: Dimensionless squared eigen frequency (ω^2/κ^2). Lower panels: Ratio of dimensionless amplitudes of density perturbations ($[\tilde{\sigma}_g/\sigma_g]/[\tilde{\sigma}_*/\sigma_*]$). (a) A flocculent galaxy; (b) a grand design spiral galaxy.

More detailed analysis shows that the gaseous disk of the flocculent galaxy is not decoupled, but is dynamically connected with the stellar one. Moreover, in some respects, close similarity exists between the flocculent and the grand design spiral galaxies. Particularly, almost perfect coincidence of the phases of the second Fourier harmonics of the brightness of the gaseous (squares) and stellar (asterisks) disks exists in both cases[3] (Figs. 5a and 5b). Also in both cases, the spectra of the line-of-sight velocity of the gaseous disks after subtraction of the rotation velocity demonstrate domination of the first three Fourier harmonics (Figs. 5c and 5d). This fact is the evidence of domination of the second harmonic in the residual velocity fields of both galaxies (Lyakhovich et al. 1997; Fridman et al. 1997, 1998, 2001a). Thus both in the grand design spiral and the flocculent galaxies, the observed behaviour of the stellar and the gaseous disks is caused by the same dynamical mechanism.

The simplest model explaining the observational facts described above is demonstrated in Figs. 5a and 5b.

Here k_r is the radial component of the eigen vector, σ_i and c_i are the surface density and the velocity dispersion, index 'g' marks parameters of the gaseous disk, index '$*$' – parameters of the stellar disk, perturbations are marked by tilda, κ is the epicyclic frequency. In the case (a) we used the following parameters: $Q_*^2 = (\kappa c_*/\pi G\sigma_*)^2 = 1.7$, $\sigma_g/\sigma_* = 0.2$, $c_g/c_* = 0.2$, which give $Q_g^2 = 1.7$. In

[3]The coincidence is broken only in the narrow region from 25″ to 35″ (Figs. 5a), the analysis of this fact will be performed elsewhere.

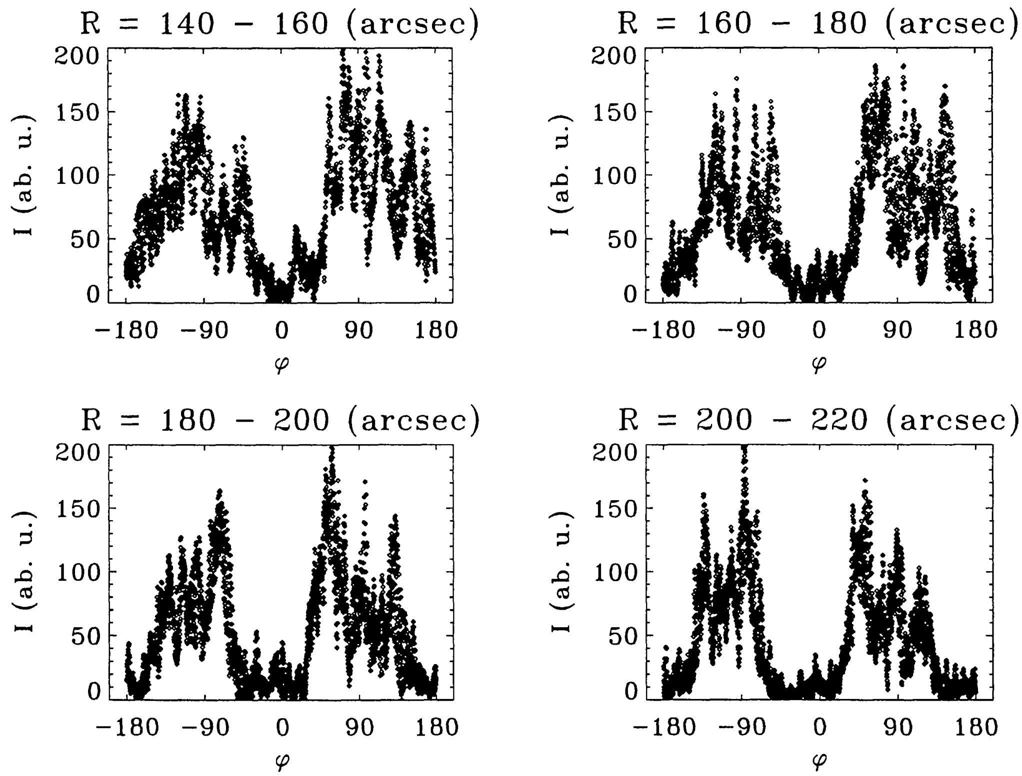


Figure 6. Azimuthal cuts of the 21-cm surface brightness of grand design spiral galaxy NGC 1365 (kindly provided by P. O. Lindblad) at different radii.

the case (b): $Q_*^2 = 1.25$, $\sigma_g/\sigma_* = 0.1$, $c_g/c_* = 0.2$, which give $Q_g^2 = 5$. These parameters are chosen as an example only to demonstrate the idea, and do not correspond to any particular galaxy. Note however that they are in agreement with the properties mentioned in the beginning of this section: the flocculent galaxies have higher ratio of masses of the gaseous to the stellar disks and lower ratio of the disk component to the total mass than the grand design galaxies.

In a flocculent galaxy (Fig. 5a), both the stellar disk in the absence of the gaseous disk, and the gaseous disk in the absence of the stellar disk are marginally stable. As a result of the gravitational interaction between disks, the instability takes place in a wide range of azimuthal wave numbers (Fig. 5a, upper panel). However, because of the higher velocity dispersion of the stellar disk, an appreciable relative amplitude of the surface density perturbations occurs only for the lowest wave numbers (Fig. 5a, lower panel). Nevertheless, the potential mainly is controlled by the stellar disk perturbations. As a result, the velocity field is highly organized like the density perturbations in the stellar disk. In a grand design spiral galaxy, gaseous disk (alone) is much more stable — the instability takes place in a narrow region of wave numbers only (Fig. 5b).

In conclusion, let us make two remarks. First: the dispersion curves in Fig. 5 correspond to the local dispersion relation, while for more accurate analysis, calculations should be done for the global eigen modes (for references see Bertin & Lin 1995; Bertin 2000). Second: we use the conditions of the gravitational instability of the radial perturbations. However, theoretical analysis, as well as the observations (see e.g. Fig. 1b), show that the real unstable perturbations have comparable values of k_r and k_φ, and the condition of instability is modified only quantitatively. Hence, the qualitative difference of spectral characteristics, demonstrated in Fig. 5 does not change after more accurate calculations.

1.2. Internal Oscillatory Structure in Grand Design Spiral Arms

Mikhailovskii, Petviashvili & Fridman (1977, 1979) have shown that the nonlinear wave dynamics of galactic disks on the boundary of the gravitational instability is described by the nonlinear Schrödinger equation. From the equation it follows that spiral arms are envelope solitons. In Fig. 6 one can see a two-scale structure of the surface density perturbations in the gaseous disk of NGC 1365. The large scale modulation corresponds to the two spiral arms, each of which has a structure of an envelope soliton with many intraarm peaks. In principle, the same observational appearance could have a result of the secondary gravitational instability, which generates shorter secondary waves in the medium compressed by the primary instability.

2. Prediction and Discovery of Giant Vortices in Gaseous Disks of Grand Design Spiral Galaxies

In the left side in Figs. 7–9 we have drawn schematically some earlier predicted structures in the velocity fields of the grand design spiral galaxies (Nezlin et al. 1986; Baev, Makov & Fridman 1987; Lyakhovich, Fridman & Khoruzhii 1996; Fridman et al. 2001a). Unperturbed velocities are marked by solid arrows, perturbed velocities – by dashed arrows, maxima of the surface density by solid lines with $\tilde{\sigma}_{max}$, minima – by solid lines with $\tilde{\sigma}_{min}$, zeros – by solid lines with $0(\tilde{\sigma})$. In the right side in Figs. 7–9 one can see the correspondent structures discovered in the velocity fields of the real galaxies (Fridman et al. 1997, 1999, 2001a,b).

Fig. 7 shows that with respect to the field of residual velocities in gaseous galactic disks, the theory predicts symmetrical location (at the corotation radius) of equal-size cyclones and anticyclones. The anticyclones lie between spiral arms, whereas the cyclones – at the arms (left panel). The vortices are clearly seen in the 2D residual velocity field of the gaseous disk in the grand design spiral galaxy NGC 157 (right panel). Overlaid squares show locations of the maxima of the second Fourier harmonic of the K-band brightness map of the galaxy.

Fig. 8 shows the velocity field in the disk plane in the reference frame rotating with the spiral arms under the condition that the radial gradient of the perturbed azimuthal velocity is less than that of the rotation velocity in this reference frame ($\left|\partial\tilde{V}_\varphi/\partial r\right| < |d(V_{rot} - \Omega_{ph} r)/dr|$). The theory predicts presence of two anticyclones situated near the corotation circle between the spiral arms (left panel). Such kind of structures were discovered in the gaseous disk of NGC 157 where the condition mentioned above is fulfilled (right panel).

Fig. 9 demonstrates that under the opposite condition ($|\partial\tilde{V}_\varphi/\partial r| > |d(V_{rot} - \Omega_{ph} r)/dr|$) besides two anticyclones between spiral arms, the theory predicts existence of two pairs of cyclones with centers inside and outside both the corotation circle and the spirals (left panel). The vortex structure of this type was

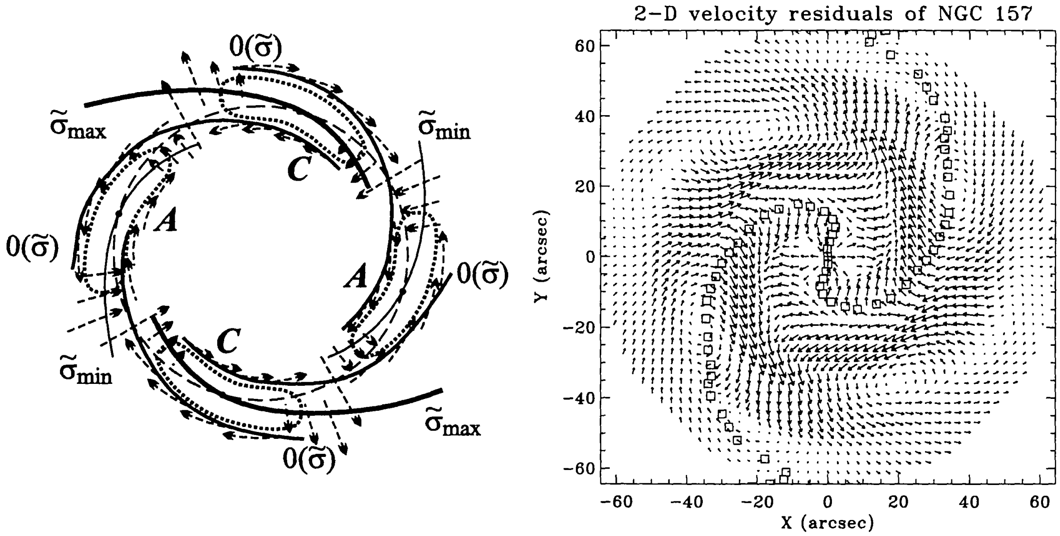


Figure 7. The predicted (left panel) and discovered (right panel, NGC 157) field of residual velocities in gaseous galactic disks. The anticyclones lie bewteen spiral arms, whereas the cyclones at the arms.

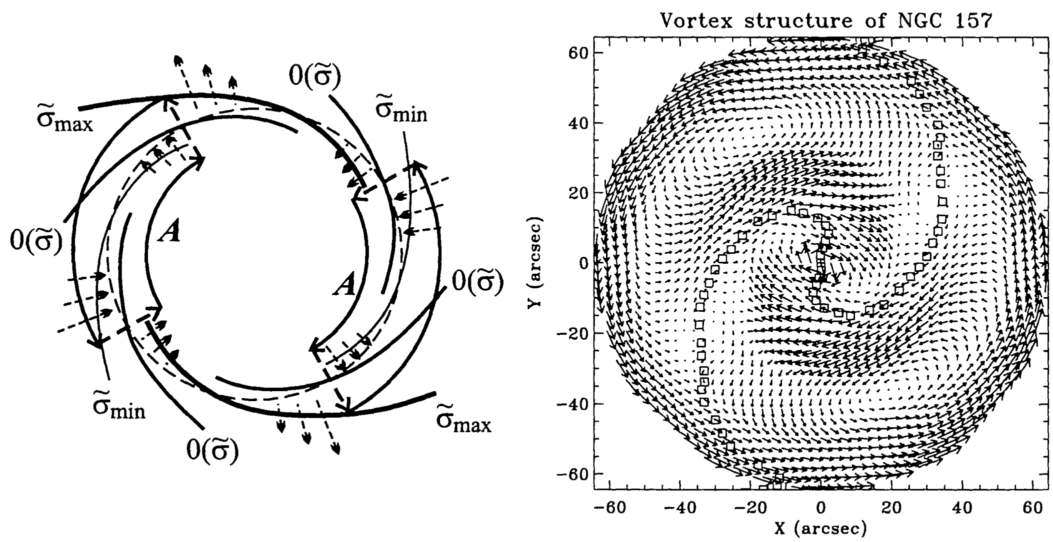
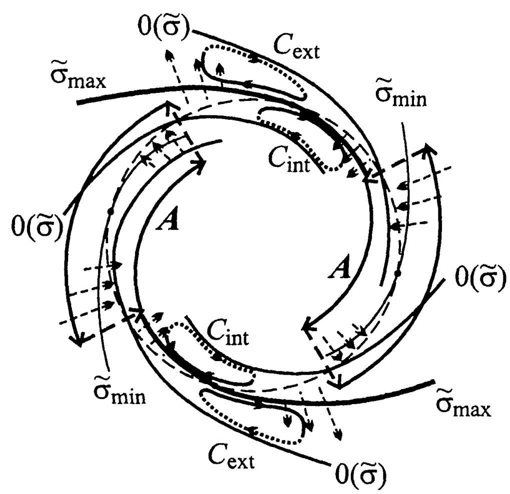


Figure 8. The predicted (left panel) and discovered (right panel, NGC 157) velocity field in the disk plane in the reference frame rotating with the spiral arms in the galaxies with relatively weak density wave. Two giant anticyck-lones lie near the corotation circle between the spiral arms.

revealed in the grand design galaxy NGC 3631 (right panel). Overlaid asterisks show locations of the maxima of the second Fourier harmonic of the R-band brightness map of the galaxy. The thin circle marks position of the corotation. Solid lines demonstrate vortex separatrices or nearly closed streamlines in the absence of a separatrix.



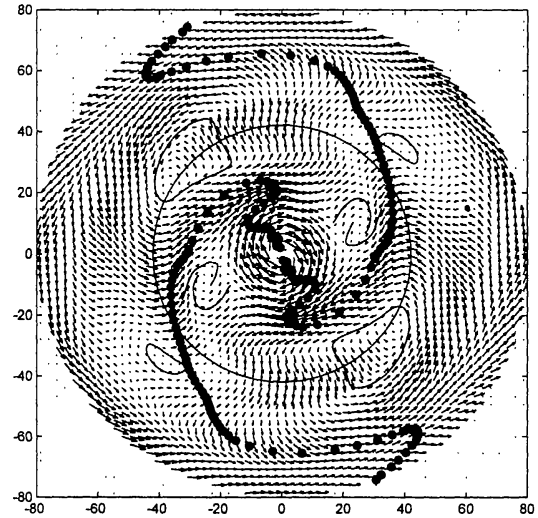


Figure 9. The predicted (left panel) and discovered (right panel, NGC 3631) velocity field in the disk plane in the reference frame rotating with the spiral arms in the galaxies with strong density wave. Besides two anticyclones between spiral arms, the vortex structure includes two pairs of cyclones with centers inside and outside both the corotation circle and the spirals.

3. Arguments in Favour of Existence of the Slow Bar in NGC 157

Fourier analysis of the photometric data on the central part of NGC 157 reveals that all brightness maps represent superposition of several subsystems with different brightness in different bands (Fridman & Khoruzhii 2000). Spiral structures in the disc are more prominent in the visual band whereas the bar is more luminous in the NIR. Different curves of maxima of the second harmonic of the disc brightness in the different bands with rather high angular resolution coincide very closely (Fig. 10a). These curves have a form of two-armed trailing spiral which in the vicinity of ILR transforms into the leading spiral. The latter is linked with the ends of the bar forming an integral structure. The leading spiral being short in radial extension is very tightly wound, and makes a half of revolution between the outer spiral and the bar. Our analysis of main resonances in the disc of the NGC 157 shows that the bar touches with its ends the IILR and the trailing spiral starts close to the OILR (Fridman & Khoruzhii 2000). The short leading spiral is located between them being a natural extension of the bar, on one side, and the trailing spiral, on the other side.

The similar form of the perturbed density of the galactic disk as a response to the gravitational potential of a bar in the vicinity of the split ILR (in 2D approximation: Polyachenko 1994; Yuan & Kuo 1997; Shlosman 1999; in 3D approximation: Fridman & Khoruzhii 2000) argues in favour of the solid unity of the observed bar-spiral structure (Fig. 10b). From this it follows that the bar in NGC 157 is the slow bar.

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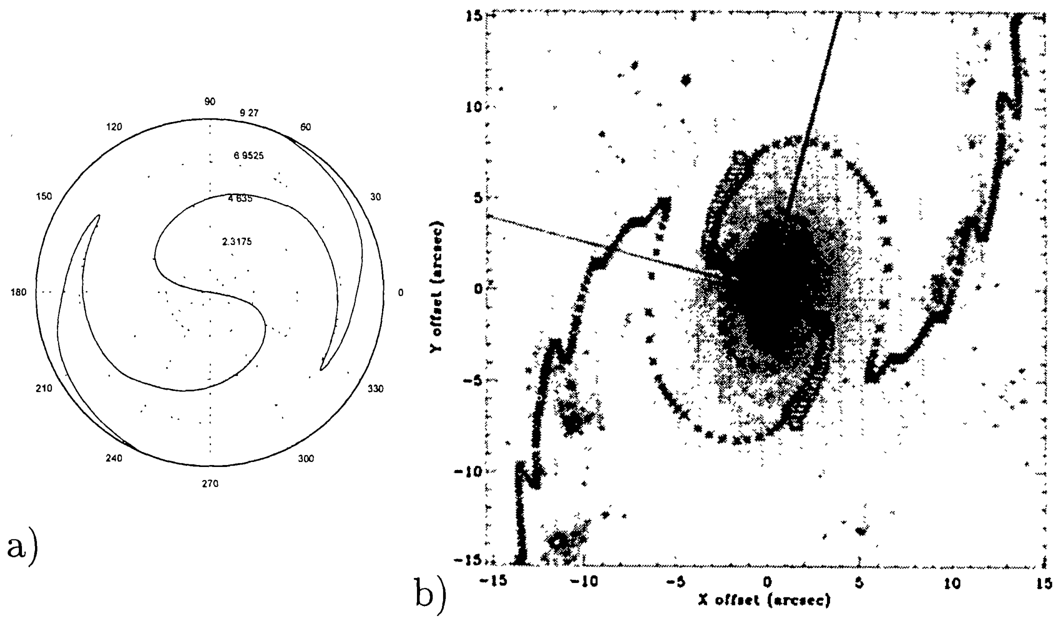

Figure 10. Schematic view of the predicted form of response of the galactic disk to the gravitational potential of the slow bar (a) and positions of maxima of the second Fourier harmonics of the wide optical brightness map (*) and the H-band brightness map overlaid on the grey-scale optical image of the central part of NGC 157 (b). The galaxy rotation in both figures is directed clockwise. It means that we see the leading spirals starting from the bar ends and making a half of revolution between the bar and the outer grand design trailing spirals. Qualitative coincidence of bar-spiral structures in the both figures is evident.

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