ON THE HYDRODYNAMICAL CONCEPTION OF THE SPIRAL STRUCTURE IN GALAXIES WITH A VELOCITY "KINK" ON THE ROTATION CURVE
(THEORY, LABORATORY EXPERIMENTS, NUMERICAL SIMULATION, OBSERVATIONS)

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ABSTRACT
The hydrodynamical conception of the spiral structure generation [1-8] in the galaxies with a "kink" on the rotation curve [9-14] is discussed. It treats the spirals as density waves in gas component of galactic disks. The main results of the fifteen-year study are presented. References are made to the papers of authors that prove a) the "gas" conception of the Galaxy spiral structure [15a], b) the identity of equations for rotating shallow water and galactic gas disk [15a,b], c) the method of laboratory modelling of galactic spirals induced by hydrodynamical mechanisms in shallow water experiments with the "Spiral" set up. The linear stability theory [4,15a] describes the mechanism of spiral arm formation and gives the parameters of the arms. Experiments agree with theory [5-7]. Besides, they show banana-like vortices between the arms near the generator [8]. Observational data on the galaxy NGC 1566 reveal a pronounced velocity kink [16] and may be explained in terms of the spiral-vortex gas conception [17]. The results of laboratory experiments and numerical simulations allow us to suggest certain hypothesis concerning observational evidences of the spiral-vortex structure.

In the last decades, the Lin-Shu theory gained wide acceptance [20,21]. Following Lindblad's ideas[23], it treated spiral arms as gravitational density waves in galactic disk stars. In his report in 1972 at the Alma-Ata conference "Dynamics of Galaxies and Star Clusters" Fridman[1] has suggested a different, hydrodynamical (HD) conception of the spiral structure formation: HD instabilities can develop in gas galactic disks at the presence of velocity and density gradients, and these instabilities may be stronger than gravitational instability, as they grow faster, at smaller wavelengths, with more difficult stabilisation, etc. The HD conception is aimed, first of all, at the galaxies with a kink on the rotation curve [9-14] (Fig. 1a). Spiral arms are then treated as density waves induced by HD shear instabilities in galactic disk gas. This emphasis on the importance of gas subsystems is in line with

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recent observations: the ratio of the radial velocity perturbations, $\tilde{V}_r$, in the spiral arm (near the sun) to the rotation velocity V_φ is so that $\tilde{v}_r^2/V_\varphi^2$ 0.14[18]; the ratio of the gas surface density σ_g (gas is known to follow the arms) to the total surface density σ_0 is $\sigma_g/\sigma_0 \lesssim 0.12$[19]. As both values are close and the first one gives the relative amplitude of the spiral potential, $\tilde{\psi}/\psi_0 \lesssim \tilde{v}_r^2/V_\varphi^2$, it evidently corresponds to gas perturbations.

A new step in studying physics of galactic spiral generation became possible due to shallow water experiments performed in 1981-1985 by Nezlin and his coworkers at the Plasma Physics Department of the Kurchatov Atomic Energy Institute. They demonstrated a physical analogy between two-dimensional hydrodynamics and shallow water dynamics[24], they lead to the soliton model of quasi-2D atmospheric vortices (like the Great Red spot of Jupiter) which were shown by laboratory experiments with thin rotating liquid layer to be generated due to unstable shear streams[28] (see also the review[29] and the papers referred to in it). These experiments have stimulated Fridman (1983) to suggest similar experiments for studying the hydrodynamical mechanism of galactic spiral structure generation since the same nonlinear equations described both galacitc gas disks and rotating shallow water[15]. The special set-up ("Spiral") was assembled for these experiments.

The principal element of the "Spiral" set-up was a vessel with rapidly rotating (angular velocity Ω_1) central part of its bottom and slowly rotating (Ω_2) periphery[5,6,8,27]. The bottom profile was chosen so that a liquid coming in rotation due to viscosity redistributed in a thin layer (in equilibrium) of nearly equal depth H_0.

Parameters of the set-up satisfied the main conditions of similarity to real galactic gas disks. 1) Rotating liquid layer had a free surface and was thin enough to suit the shallow water approximation $(gH_0)^{1/2}$(g-gravitational acceleration) being equivalent to the sound speed in gas. 2) There was a "kink" ("discontinuity") between the central part ("nucleus") and the periphery (the radius of discontinuity is R, its initial width $\sim H_0$). 3) The "Mach number" at the kink, $M=(\Omega_1-\Omega_2)R/(gH_0)^{1/2}$, was ranged within 0.5 - 12. 4) $\frac{\Omega_2}{\Omega_1} \leq 0.2$. 5) In a series of experiments ($\Omega_2/\Omega_1=0.2$) the set-up radius D/2 was much more than the Rossby radius $r_R=(gH_0)^{1/2}/2\Omega_2$, r_R being equivalent to gas cloud epicyclic radius. The bottom was white, the liquid was a colored water (solution of $NiSO_4$), so the wave "crests" on the free surface seemed darker than the "troughs". Water motions were traced by white floating test particles.

The main experimental results are the following [5,5,8,27]. 1. HD instability develops in differentially rotating shallow water and leads to the formation of spiral surface density waves - "crests" - going out of the kink (the generator region) in both sides. If M>>1, the instability occurs only for $\Omega_2<\Omega_1$. We call it centrifugal in contrast to the Kelvin-Helmholtz instability that occurs at $M<2\sqrt{2}$ both for $\Omega_2<\Omega_1$ and $\Omega_2>\Omega_1$ (see also [24]). 2. The spiral pattern is stable, with no shade of breaking into separate smaller structures even for the wavelengths along the crest $L\gtrsim 10 r_R$[27]. 3. The arms rotate always slower than the nucleus.

4. The nucleus and the periphery rotating in one direction, the HD shear instability induces trailing spiral waves with the same direction of rotation (Figs. 2,3).
The results 1-4 confirm theoretical predictions[4,15a].
5. Ωp increases with Ω_1 (fig. 4) and for modes with the number of arms $m=1$, follows the theoretical linear dependence. For m=2,3 Ωp measured differs from the predicted values by not more than 40%.
6. The arm number m decreases with the Mach number Ma increasing (Fig. 4, H_0=const). Mode transitions 6→5, 5→4, 4→3, 3→2 (under experimental conditions of Fig. 4) are observed at Ma=3.3, 3.7, 4.0, and 4.4, while the theoretical values numerically computed for the "smoothed" cylindrical tangential velocity kink are Ma=2.5, 2.7, 3.3, and 5.2. Such a good agreement is fairly surprising since real mode transitions are considerably nonlinear, with small growth rate difference[7]. These mode transitions get the following interpretation [7,8]. When the m-mode instability develops, it dissolves the velocity kink, and the system reaches its stability boundary (for this mode). At larger Ma the kink becomes still more smoothed, favouring now the (m=1)-mode only. The same is qualitatively observed in modelling the planetary vortices of the kind of the Great Red Spot of Jupiter[28]. This suggests a possible universality of the mechanisms producing the two natural formations [8,27,29].

The experiments performed allow us to make some predictions concerning several specific features of real galactic spirals.
1. Nucleus velocity Ω_1 (or any other free parameter) gradually changing, the mode transition begins in the kink region and the nes mode runs outwards. We see therefore an arm "branching" during the transition, so the arms fork outwards if the nucleus accelerates (Fig. 5). It feeds an idea that the arm branching and non-stationarity of galaxy may also be related[5].
2. Experiments show and theory explains the banana-like anticyclonic vortices (with density minima inside) between the spiral waves strung on the kink line (fig. 6a,b). The trapped vortex particles flow into the arms and keep moving with considerable radial velocity at corotation. This states in a new fashion a question on the motion of galactic matter relative to the disk in this region. Spiral arms are continued inside the corotation circle narrowing when approaching the latter from both inner and outer sides (Fig. 6a). This agrees with data on the galaxy NGC 1566[17] (Fig. 6c). We see the arms crossing the corotation region, which cannot be explained in terms of the gravitational conception of the spiral structure[25].
3. Experiments with opposite rotation of the nucleus and the periphery reveal the leading spirals, rotating with their tips ahead, against the nucleus rotation. As leading arms were observed in some galaxies only in close pairs[26], it may suggest[8,27] that the leading spiral can be formed in that component of a close galaxy pair whose spin is opposite to the orbital momentum of its neighbor. Then the tidal "crest" - the peripherical density wave - runs against the rotation of the galaxy central part.
4. Numerical simulations of the spiral structure in galactic gas disks and rotating shallow water[7] also show the formation of the spiralvortex

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structure and, besides, the evolution of the azimuthally averaged surface density. The latter means: a) a pronounced clustering towards the disk center, b) a denser middle part of the periphery (the "molecular ring"), c) a gap between these concentrations in the kink region (Fig. 7). We arrive at the hypothesis that these features of gas density distribution observed in a number of galaxies, the smoothed kinks on the rotation curves, and the considerable radial motions of gas are to a substantial degree the result of the existence of the spiral-vortex structure, induced by the shear instability, that govern the evolution of the gas disk. As a rule, instabilities work to remove their reason. It leads to smoothing the observed velocity kink and density gradient.

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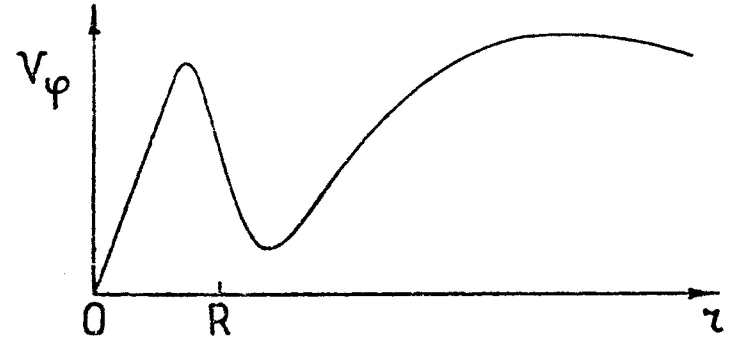
a



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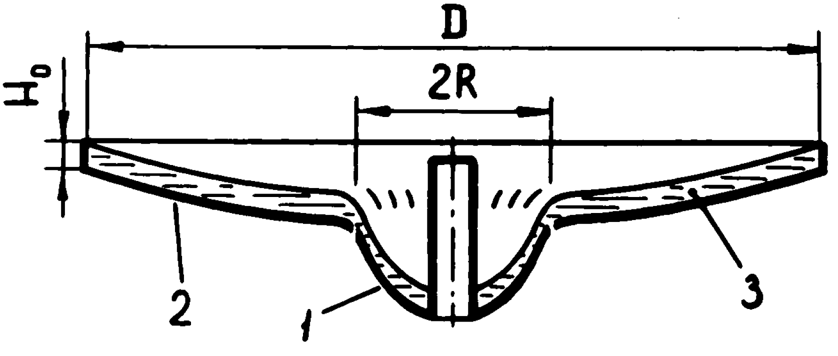

Fig. 1a.: - typical galactic gas disk rotation curve with a velocity "kink",
b.: - the set-up "Spiral": "nucleus" (1), "periphery" (2), shallow water layer (3); first modification - D=28cm,R=4cm, second modification - D=60cm, R=8cm.

a

b

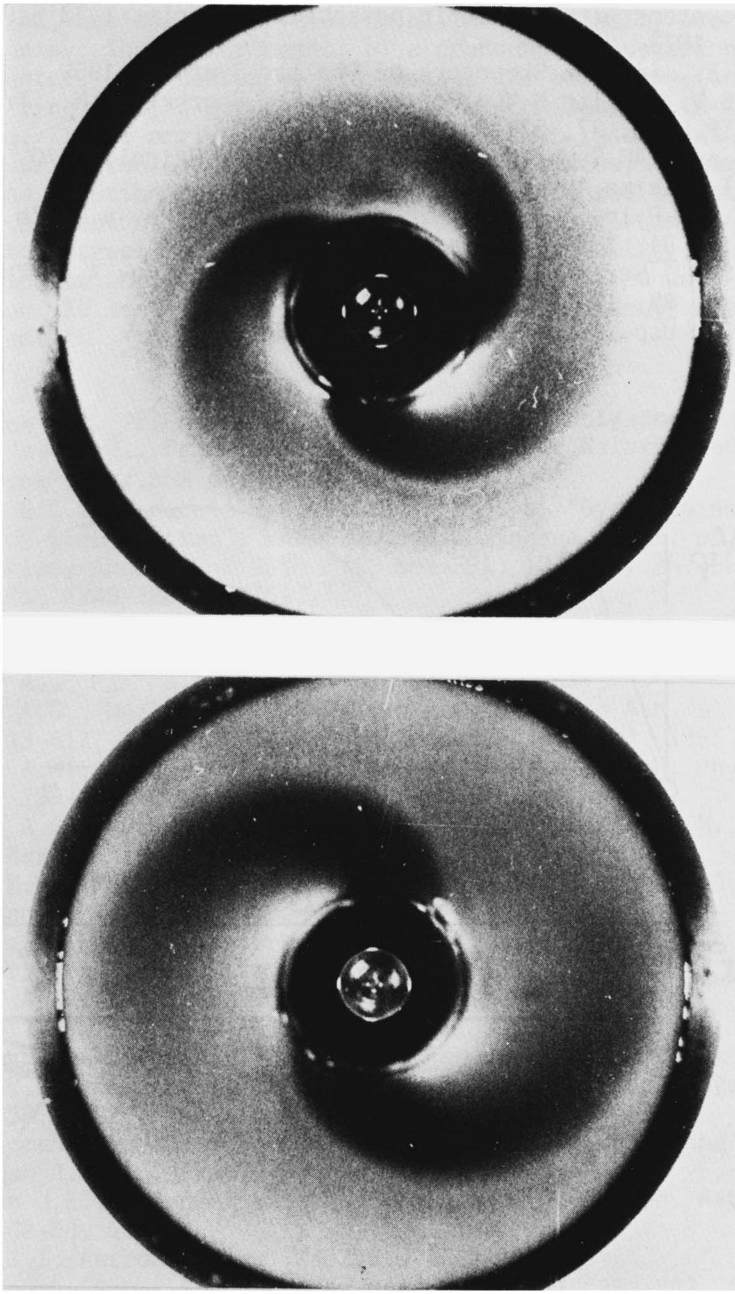

Fig. 2.: Shallow water surface density waves in the 1st set-up: m=3,2, 1,0 (fig. 2a-d); nucleus rotation is clockwise, $\Omega_2=0$.

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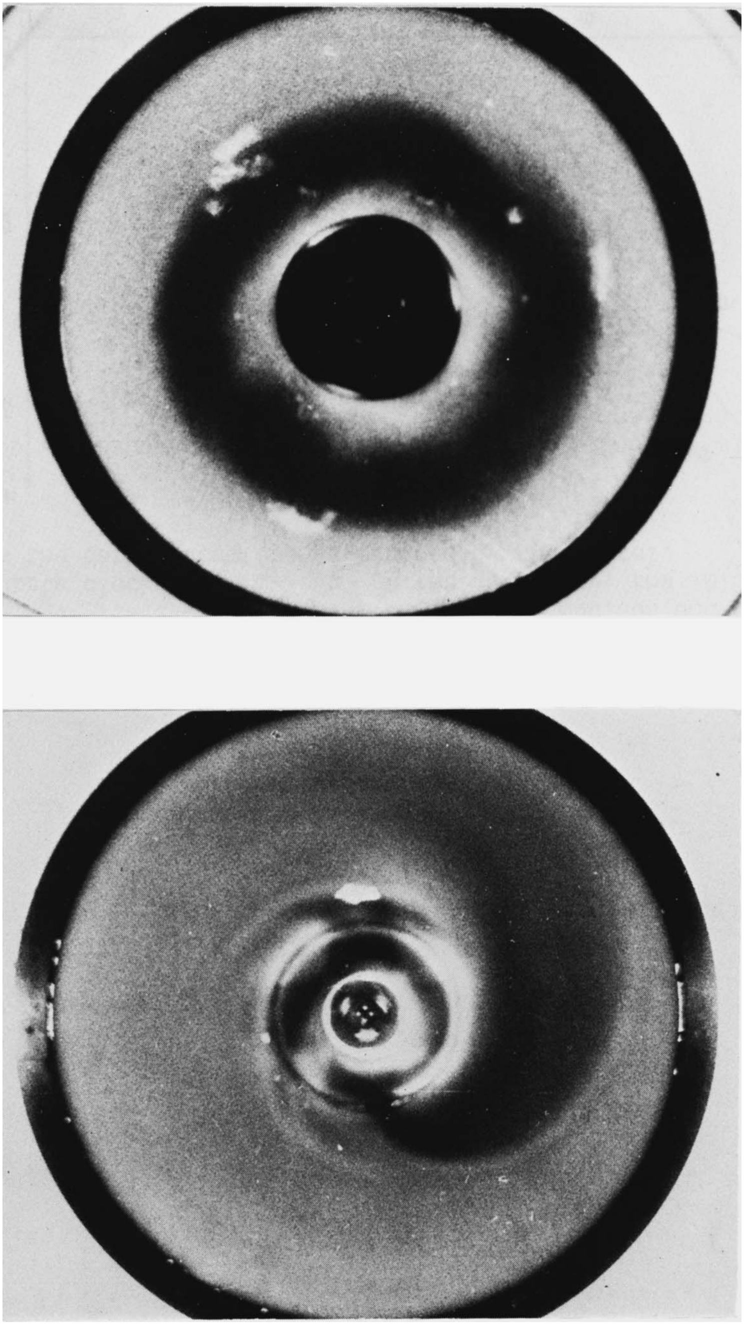

Fig. 2 (continued)

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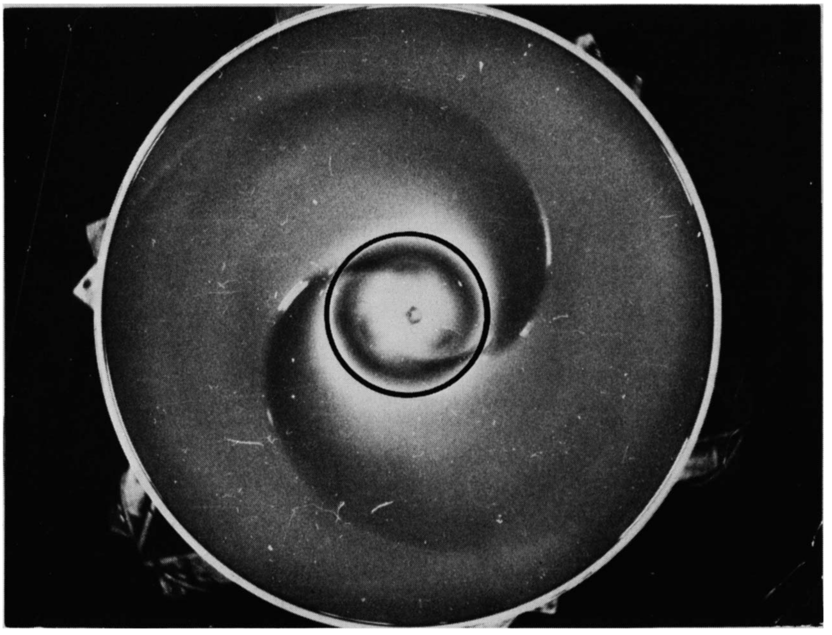

Fig. 3.: Shallow water surface density waves in the 2d set-up: m=2, H_0=3.5mm, Ω_1=13s^{-1}, Ω_2=2.6s^{-1}, Ω_p=6s^{-1}; nucleus and periphery rotate clockwise; r_R=3.5cm at the periphery; the velocity kink is the dark circumference crossed by the spiral.

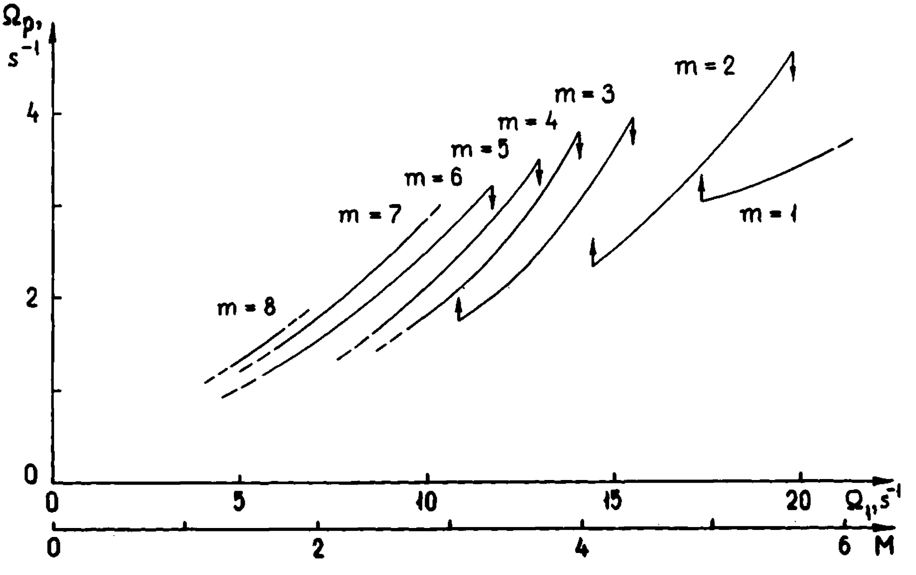

Fig. 4.: Spiral pattern angular velocity Ω_p as a function of the Mach number M (H_0=2mm).

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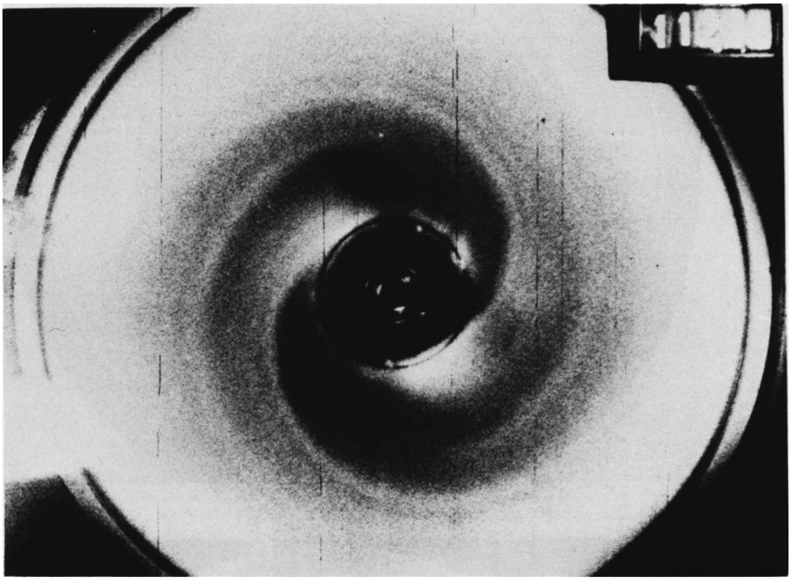

Fig. 5.: Arm branching in the mode transition 4 2 caused by acceleration of the nucleus rotation.

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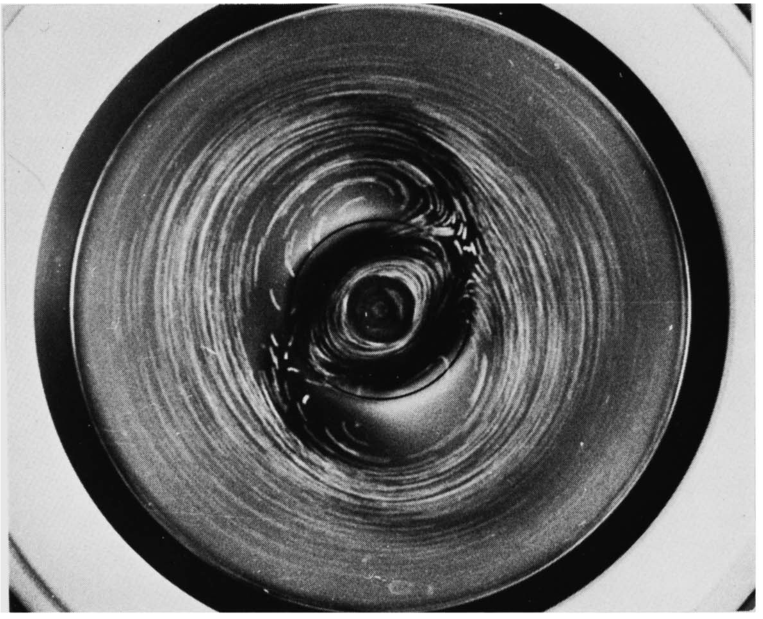
a



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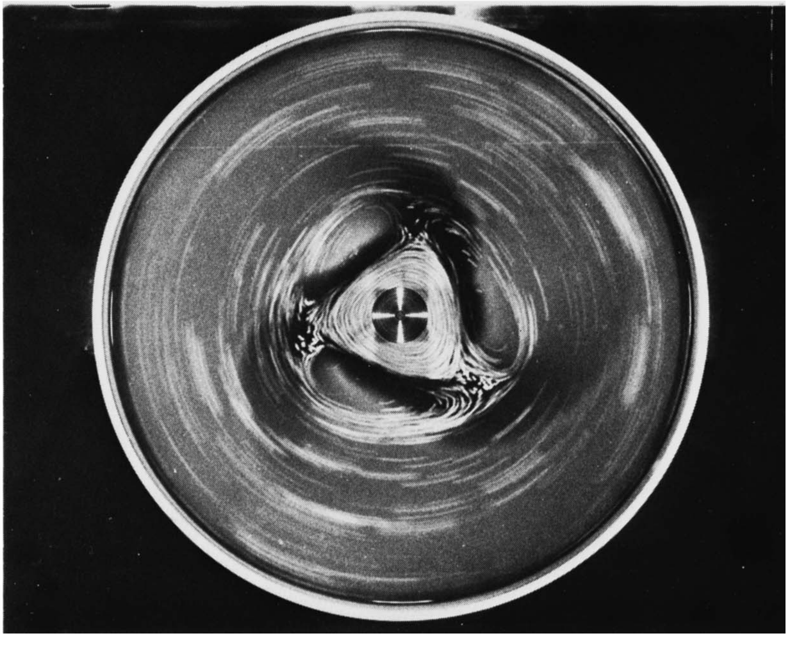

Fig. 6: a,b - spiral-vortex structures (m=2,3) with density minima in banana-like vortices; the camera is rest in spiral pattern frame.

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c

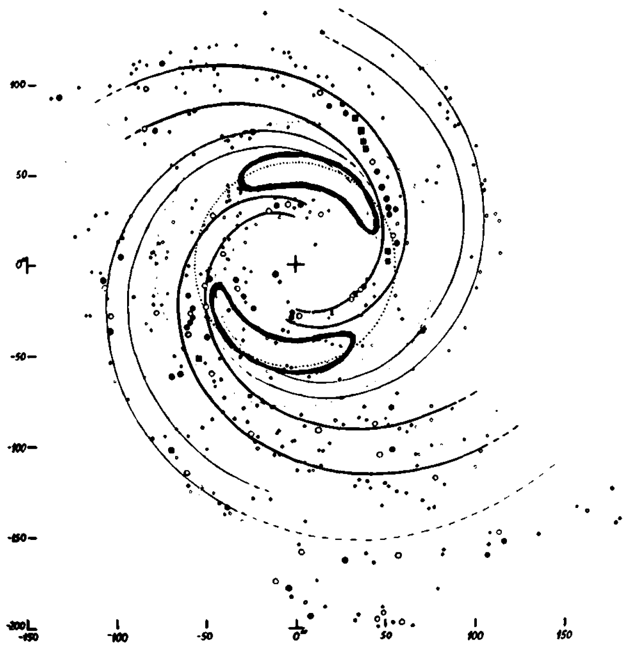

Fig. 6: c - the observed distribution of HII regions and spiral arms in NGC 1566, deprojected to face-on orientation. Two symmetrically superimposed "bananas" mark regions "free" from the HII regions. We see the general resemblance to the experimentally observed pattern (Fig. 3).

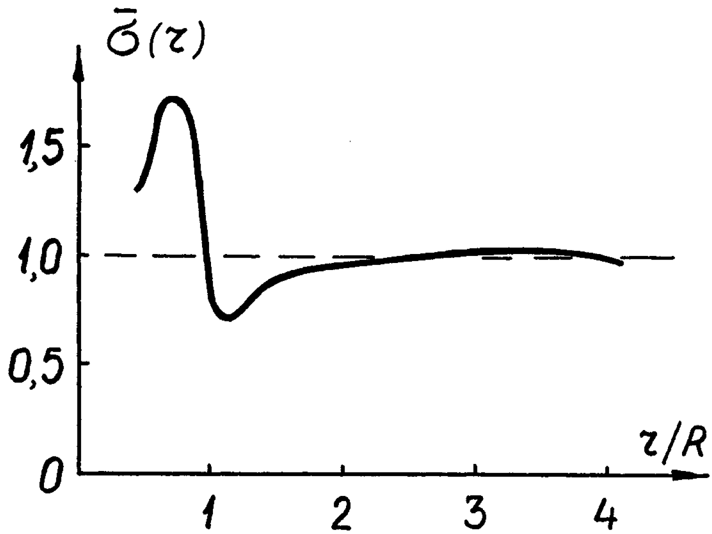

Fig. 7.: Azimuthally averaged surface density of galactic gas disks versus the distance from the center as a result of the spiral structure formation.

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