A. G. Morozov, M. V. Nezlin, E. N. Snezhkin, and A. M. Fridman. *Laboratory simulation of the generation of the spiral structure of galaxies* (*theory and experiment*). The spiral arms of galaxies are primarily visible as formations with high luminosity, created by young bright stars. Radio observations show that virtually the entire gas is concentrated in the arms—the high gas density in the spirals is what enables the constant formation of stars there. In our galaxy, the gas mass is only 10% of the mass of the galactic disk, and the gravitational potential ψ in the spirals exceeds by approximately the same magnitude the background gravitational potential ψ_0. The gas component in the galaxy therefore plays an important role in the formation of the spiral structure.

In the gravitational conception of density waves, the gas is given an auxiliary role: it merely "responds" to the spiral gravitational perturbation of the density, arising initially in the stellar component.

In 1972 one of the authors (A. M. F.) advanced the hypothesis[1] that in the presence of velocity and density gradients, hydrodynamic instabilities whose main features exceed those of the gravitational instabilities (they develop at smaller wavelengths and over shorter periods of time, they are incomparably more difficult to stabilize, etc.) can develop in the gaseous galactic disk.

The observational discovery of a section with a sharp decrease in the rotational velocity of the gaseous galactic disk of a number of galaxies[2–4] (Fig. 1a) stimulated the development of the theory of stability of such disks.[5–8]

It was shown[5–8] for gaseous galactic disks[2–4] that for the reasons enumerated above the perturbed gravitational force can be neglected in the spiral density waves in comparison with the magnitude of the perturbed pressure force. In other words, the sole function of gravity is to maintain the equilibrium of the gaseous disk. This function is fulfilled by the stellar component, whose mass distribution is determined by the quantity $\partial\psi_0/\partial r$ and thereby fixes the observed velocity profile $V_0(r)$ in the gaseous disk (see Fig. 1), in accordance with the condition of equilibrium $V_0^2/r = \partial\psi_0/\partial r$ (the term with the pressure gradient, as a rule, is negligibly small).

Thus the "gravitational" terms are absent in the equations for the perturbations of the gaseous gravitating disk. As a result, we obtain the equations for the perturbations in rotating "shallow water" (the thickness of the disk is much smaller than its radius), taking into account the fact that the velocity of sound in the gas c_s is replaced by the characteris-

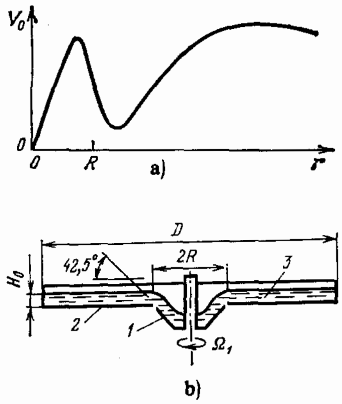

FIG. 1. a) The dependence of the linear rotational velocity of the gaseous disk V_0 on the radius r, observed in galaxies[2–4]; b) experimental arrangement. 1) Cone, rotating rapidly with angular velocity Ω_1; 2) slowly rotating (in particular, stationary) disk; for not too low rotational velocity, the disk 2 was replaced by a cone sloping at an angle of several degrees to the horizontal; 3) layer of shallow water.

tic velocity of waves in shallow water $c = \sqrt{gH_0}$ (g is the acceleration of gravity and H_0 is the depth of the liquid). Therefore, with a "galactic" profile of the rotation of shallow water (see Fig. 1a) we should see the "galactic" spirals (bulges on the perturbed surface of the liquid will correspond to increased gas density in the galactic disk) on the surface of the water.

To make a model check of the theory, the following experiment[9] was performed (Fig. 1b). A "discontinuity" of the velocity of width $\sim H_0$ was created in a thin layer of liquid with a depth of $H_0 = 2$, 3, and 4 mm, lying on the surface of a rapidly rotating cone 1 (the "nucleus," angular velocity Ω_1) and a disk 2 ("the periphery," angular velocity Ω_2) rotating slowly in the same direction (in particular, a stationary disk). The discontinuity occurred at a radius of $R = 4$ cm and the diameter of the disk was $D = 28$ cm. The experiments with the stationary periphery were performed for $\Omega_2 < 2\ \mathrm{s}^{-1}$, the ratio $\Omega_2/\Omega_1 = 0.1$ was close to the characteristic value for the galaxy studied. The largest value of Mach's number $\mathbf{Ma} = R\Omega_1/c$ in the experiment was equal to approximately 12. The working liquid was water, colored with a dye. In contrast photographs[12] the crest of the wave against the background of the white bottom appeared darker than the "trough" between the crests.

We shall compare the results of the linear theory of stability of a gaseous galactic disk (or rotating shallow water with a "discontinuity" of the angular rotational velocity: $\Omega = \Omega_1$ for $r < R$ and $\Omega = \Omega_2$ for $r > R$) with the experimental results.

A qualitative comparison shows that the experiment confirms the following results of the theory:

1. In the case $\mathbf{Ma} < 1$ the stability develops both for $\Omega_2 < \Omega_1$ and $\Omega_2 > \Omega_1$, and we identify it as a Kelvin-Helmholtz instability.[10,11]

2. In the case $\mathbf{Ma} > 1$ the instability develops only for $\Omega_2 < \Omega_1$, and we call it a centrifugal instability.[1),9]

3. The centrifugal instability generates spiral surface density waves, rotating in the same direction as the nucleus (Fig. 2).[2),9]

4. The generated spirals are backward spirals: their ends are oriented opposite to the direction of rotation (Fig. 2).[9]

5. The angular velocity of the spiral pattern Ω_p is less than the angular velocity of the nucleus Ω_1 (Fig. 3).[9]

6. The dependence of the angular velocity of the spiral pattern Ω_p on the angular velocity of the nucleus Ω_1 is linear (Fig. 3a).[9]

7. As the Mach number $\mathbf{Ma}$ increases, the number of arms in the generated spiral structure decreases (Figs. 2 and 3).[9]

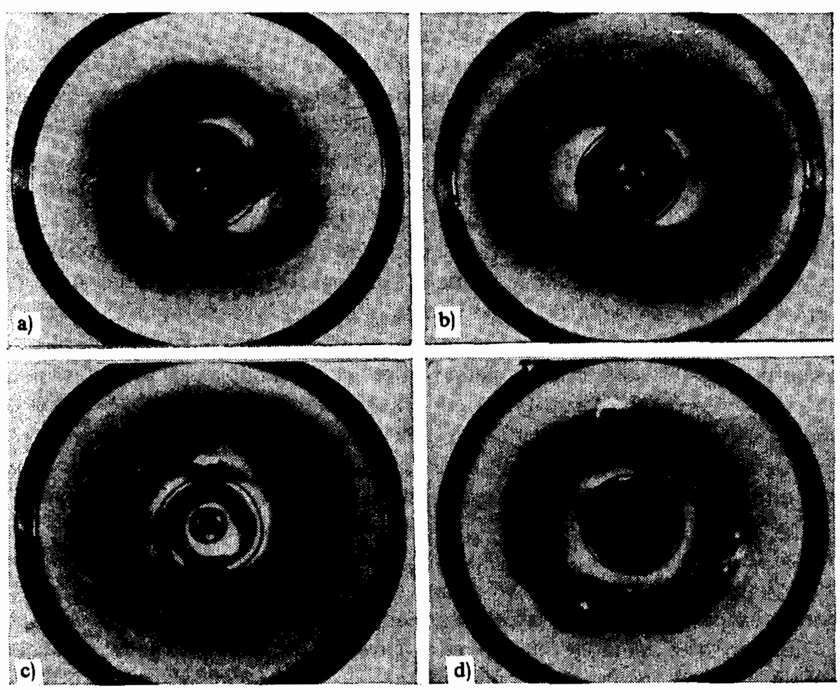

FIG. 2. Typical examples of spiral surface density waves. The modes $m = 3,2,1$, and 0. The last case corresponds to the frequently observed ring galaxies.

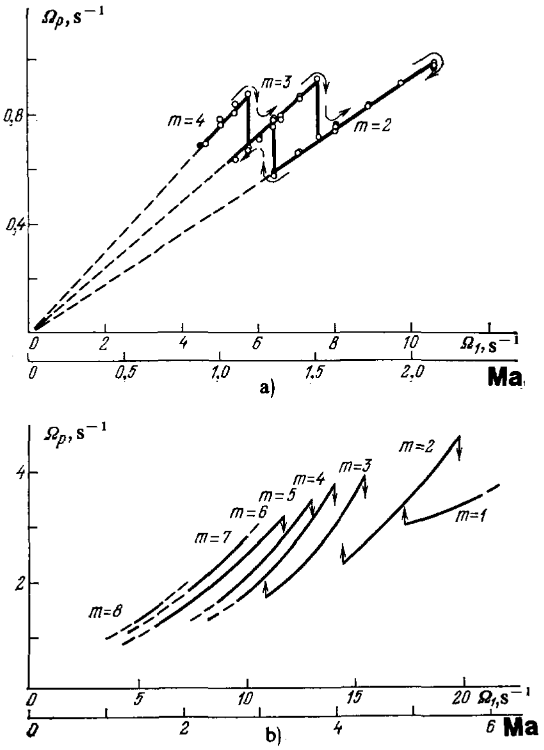

FIG. 3. Dependence of the angular rotational velocity of the spiral pattern Ω_p on the angular rotational velocity of the nucleus Ω_1 ($\Omega_2 = 0$) with a constant depth of the liquid $H_0 = 4$ mm (a) and 2 mm (b). The Mach numbers **Ma** are also plotted along the abscissa axis. The arrows indicate the sequence of modes accompanying a change in Ω_1.

A quantitative comparison of the experimental results and the theory leads to the following conclusions.

8. The theory predicts the Mach numbers at which the increment of the centrifugal instability of mode m begins to exceed the increment of mode $m + 1$ as **Ma** increases. In the experiment, a restructuring of the modes also occurs as **Ma** increases. Transitions between the modes 6⟶5, 5⟶4, 4⟶3, and 3⟶2 under the experimental conditions (Fig. 3b) is observed at **Ma** = 3.3, 3.7, 4.0, and 4.4, and the corresponding theoretical values are equal to **Ma** = 2.5, 2.7, 3.3., and 5.2.[9] It is evident that the experimentally determined **Ma** numbers differ from the theoretically computed values by not more than 30%.

9. The linear theory gives the ratio $\Omega_p/\Omega_1 = 1/2$ (for $\Omega_2 \ll \Omega_1$). The experimentally observed ratio Ω_p/Ω_1 is two to five times smaller than the theoretical value; in addition, this difference increases as m decreases. The indicated disagreement between the experiment and the linear theory[5–8] could be due to the nonlinearity of the processes studied. One of the indications of this nonlinearity is the jump-like and hysteretic nature of the transitions between modes with different values of m (see Fig. 3).[9] The second factor of nonlinearity consists of the fact that at the base of the spirals the observed perturbations have the nature of vortices (which are generated due to the studied centrifugal instability at the discontinuity of the rotational velocity).[9] The amplitude of these vortices is so large that their boundaries are impenetrable to the particles of liquid. During their motion, these vortices, which are reminiscent of Rossby vortices, studied experimentally in Refs. 12 and 13, excite "ship" type waves, which in this case have the form of large spirals in shallow water. The velocity of rotation of the spirals around the center of the system coincides with the velocity of the vortices, so that (in the light of the results of Refs. 12 and 13) it is not surprising that it is lower than the values predicted by the linear theory.

It is important to note that the theory being discussed is in good qualitative agreement with the data obtained from astronomical observations. In galaxies, where, as in the experiments described, the processes studied undoubtedly are strongly nonlinear, the angular rotational velocity of the spiral pattern is less than the theoretical value of Ω_p. It is interesting that the quantitative disagreement here is close to the disagreement between the given linear theory and the model experiment under study.[9]

We can thus state that the theoretically predicted new instability of rotating shallow water with a tangential discontinuity of the velocity, in particular, exceeding the characteristic velocity of waves, has been observed experimentally. The instability develops if the radial gradient of the angular velocity is negative at the discontinuity. It is apparently responsible for the formation of the spiral structure of galaxies with an analogous profile of the rotational velocity.[2–4] It is interesting to note that under different experimental conditions the instabilities studied here are apparently the reason for the generation of the Rossby autosoliton, which models the Great Red Spot on Jupiter.[14]

In conclusion, we indicate the following experimental fact: in the nonstationary state, for example, in the presence of a gradually changing rate of rotation of the nucleus, the restructuring of the modes occurs first near the nucleus and then the new mode forming at the discontinuity gradually propagates toward the outer part of the periphery. In this case, during the transient process a "two-level" structure of the spiral pattern is observed: the arms "branch" (for example, they bifurcate) outwards, when the nucleus accelerates and inwards when the nucleus decelerates. This fact suggests the hypothesis that the two-level galaxies of the two types indicated above, observed by astronomers, are also in a strongly nonstationary state.

[1)]Only this stage (**Ma** > 1, $\Omega_2 < \Omega_1$) is discussed below, since it is characteristic for the galaxy studied.

[2)]The experiments on obtaining the mode $m = 0$ were performed with the participation of A. S. Trubnikov.

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