Committee 4
Treatment of Non-linear Systems in
Physics and Economics

DRAFT--Sept. 12, 1997
For Conference Distribution Only

LABORATORY MODELING ATMOSPHERIC, OCEANIC, ASTROPHYSICAL AND PLASMA VORTICAL STRUCTURES AND PREDICTION OF GIANT INTERARM VORTICES IN SPIRAL GALAXIES

by

Mikhail V. Nezlin
Leading Research Scientist
Institute of Nuclear Fusion
Kurchatov Institute
Moscow, RUSSIA

The Twenty-first International Conference on the Unity of the Sciences
Washington, D.C.   November 24-30, 1997

ORGINAL (EXTRA)

"Laboratory modeling atmospheric, oceanic, astrophysical and plasma vortical structures and prediction of giant interarm vortices in spiral galaxies".

M.V.Nezlin, A.Yu.Rylov, E.N.Snezhkin, K.B.Titishov, G.P.Chernikov

Russian Research Center "Kurchatov Institute", Kurchatov Square,1, 123182 Moscow, Russia.

E-mail: <nezlin@wowa.net.kiae.su> , <nezlin@qq.nfi.kiae.su>

ABSTRACT

An up-to-date review is given of the following fundamental results obtained in the rotating shallow water modeling of the natural vortical structures: (1) a new object of nonlinear physics - the Rossby soliton having quite unexpected properties - is discovered, (2) generation of Rossby vortices by the unstable zonal flows has been investigated, (3) a new soliton model of solitary vortices of the Jupiter Great Red Spot type has been elaborated, (4) the hydrodynamic conception of the galactic spiral structure generation has been substantiated, (5) on the basis of laboratory modeling, the existence of giant interarm vortices in real galaxies has been predicted (the prediction has been confirmed by direct astronomical observation - see the lecture by A.Fridman in this issue), (6) a conception is described, according to which all the above-mentioned structures are generated by the common centrifugal instability mechanism, (7) basing on the poits (1,2), the properties of drift solitary vortices in the magnetized plasma have been predicted with confidence.

CONTENTS

INTRODUCTION

This lecture bears a review nature. It is devoted to a description of the rotating shallow water experiments made by our team in the Institute of Nuclear Fusion of the RRC "Kurchatov Institute" on laboratory modeling largest and longest-lived vortical structures in nature. It consists of three parts which are closely physically linked with each other. The first part is devoted to the modeling atmospheric vortices of the type of the Great Red Spot of Jupiter (GRS), dominating on the giant planets, as well as the submarine oceanic "lenses". The second part concerns modeling the so called drift vortices widely spread in the magnetized plasma. The third part is devoted to the modeling hydrodynamic generation of spiral structure in galaxies.

I. PLANETARY VORTICES.

1a. OBJECTS FOR LABORATORY MODELING.

The sub'ect of this Section are the so called Rossby vortices. According to definition, they exist under the so called Rossby regime, namely, they are rotating around their local vertical axes more slowly than the planet itself rotates, and they drift along the parallels of a planet. A Rossby vortex may be considered as a packet of the Rossby waves. If the packet is linear, it suffers dispersion spread (i.e. dispersion decay) during some relatively short time, Tlin. However, the nonlinear packet may be not subjected to such a decay, if its dispersion spread is compensated by nonlinearity. Then it may survive for essentially longer time, i.e. it may be long-lived. In such a case, we call it soliton. For instance, a typical life time, Tlin, for a linear large-scale (planetary-size) Rossby wave packet in the terrestrial atmosphere is about two-four weeks (see, for instance, [1]). Therewith, there are no vortices in the terrestrial atmosphere, which survive essentially longer than one month. Hence, there are no long-lived vortices in the atmosphere of the Earth (in regard to the oceanic "lenses", see below). On the other hand, the long-lived vortices are widely presented in the atmospheres of giant planets: Jupiter, Saturn, Neptune. For instance, the famous anticyclonic vortex, the Great Red Spot of Jupiter (GRS), survives for more than three centuries, i.e. about 3-4 orders of magnitude longer than Tlin for a linear wave packet of the same size. Therefore, let us pay our attention to the typical atmosphere of a giant planet, namely, to Jupiter's one.

In Fig.1, a picture of zonal flows and the long-lived vortices in the Jovian atmosphere is shown [2]. The characteristic horizontal size, a, of the GRS exceeds the so called barotropic Rossby-Obukhov radius (Rr):

$$a > Rr = (gH)^{1/2}/ f \qquad (1)$$

where H is the e-folding thickness of the atmosphere, f is the Coriolis parameter: $f = 2\Omega\sin\phi$ where Ω is the angular velocity of the planet rotation, ϕ is the given latitude, g is the free-fall acceleration. The GRS own rotation period is one week, whereas Jupiter's rotation period is ten hours, so, the GRS exists in the Rossby regime. The effective thickness of the GRS, is unknown yet, hohever, there are grounds to believe that it is about the known e-folding thickness of the Jovian atmosphere:

$$H = kT/mg \qquad (2)$$

which is about 25 km. So, the GRS (as well as a number of other anticyclonic vortices dominating in the giant planet atmospheres) may be considered as a "shallow water structure". The latter approach [3] is supported even by F.Busse, who is the author of deep thermo-convection concept [4].

The system of Jupiter's zonal flows (Fig.1) turns out to be unstable with respect to generation of the large-scale, long-lived vortices. The instability seems to be arisen due to the fact that the known Rayleigh-Kuo instability criterion (see, for instance, [1]) is satisfied near the places of maximal flow velocity gradients.

The remarkable fact is that almost all the large long-lived vortices shown in Fig.1, are anticyclones (their own rotation in the planet frame is directed contrary to the planet rotation). The same qualitative situation takes place in Saturnian atmospheres (and the only big vortex in Neptunian atmosphere is also an anticyclone). The single exceptions from this rule are cyclonic "Barges" (Jupiter, 14 degrees North) and cyclonic "UV-Spot" (Saturn, 24 degrees North). So, very distinct cyclonic-anticyclonic asymmetry is observed in the atmospheres of giant planets.

One more manifestation of the asymmetry (Fig.1) is that all the zones with cyclonic flow vorticity (except for the "Barges" zone) are empty (cyclones are not observed in them), whereas all the zones with anticyclonic flow vorticity are filled with vortices of the anticyclonic polarity. In particular, there exists the so called "Little Red Spot" (which is about 2.5 times as small as GRS, i.e. it is nearly of the Earth size) situated symmetrically to the GRS with respect to the planet equator [2].

There exist other remarkable Rossby vortices, the so called oceanic "lenses". They are observed at a depth of a few hundred meters from the ocean surface, in the region of an interface between the water layers with different densities (see, for instance, [5]). They are rather widely-spread structures among the oceanic eddies. They also exist in the Rossby regime and have horizontal dimensions of the order of a few tens of kilometers, somewhat greater than the so called oceanic baroclinic Rossby radius. They drift along the planetary parallels with velocities close to the so called Rossby speed:

$$V_R = \beta Rr^2 \qquad , (3)$$

where $$\beta = df/dy \qquad , (4)$$

and y is the meridional coordinate. As a rule, the oceanic lenses are anticyclones (like vortices of the GRS-type dominating on the giant planets): they rotate contrary to the planet rotation. The lenses' life times reach a few years (see, for instance, [5]) and exceed the value of Tlin about 20 times or even more. So, they are the long-lived vortices, too.

So, the clear-cut cyclonic-anticyclonic asymmetry is a property of the mentioned planetary and oceanic vortices. A study of this property was one of the objectives for our laboratory modeling.

This problem seemed to be closely linked with a new version of the Rossby soliton concept, which appeared in 1979-1981 [6-8] and was essentially developed in [9]. According to that concept, the anticyclonic Rossby structures satisfying the condition (1) may be like solitons, i.e. they may be not subjected to dispersion spread because the latter is compensated by the nonlinearity.

An attempt of creating the Rossby soliton and a study of its properties was also one of the main objectives of our experiments.

(1b). LABORATORY INSTALLATIONS.

The necessity of satisfying condition (1) has predetermined the geometry of the experimental set-ups: they should be parabolically shaped, nearly similar to the shallow water free surface, which rotates rather fast; hence, the paraboloid curvature has to be rather large. That was the first essential difference of our set-ups from those ever used in other laboratories for modeling natural vortices. For instance, in the known experiments by P.Read and R.Hide [10] and J.Sommeria, S.Meyers and H.Swinney [11] a free surface of the rotating fluid was absent at all; in the experiments by F.Dolzhanskii [12] and Yu.Chernous'ko [13] the fluid rotation frequency was so small that the free surface effects did not play any essential role. Etc.

An essential distinction of our experiments from all other under consideration may be explained also in the following way. All the known experiments, except for ours (see, for instanc, [1]), were carried out under the conditions

$$a < Rr . \qquad (5)$$

This was determined by the fact of either very slow rotation (in [12,13]) or the presence of a solid lid on the fluid surface (in [11]). The inequality (5) meets the conditions in the Earth atmosphere, where Rr is about 3000 km. Unlike the works mentioned, our experiments meet the condition (1) which is typical for the Jovian GRS and like vortices and under which, according to theory [6-9], the monopolar (anticyclonic) Rossby solitary vortices are possible.

The second principal distinction of our experiments compared to the experiments of all other authors was determined by the method for intense vortex creation by means of unstable shear-flows. So, in the experiments [11] intense vortices could have only a cyclonic sign, and in the experiments [10], only an anticyclonic sign. As for our experiments, the generation conditions for cyclones and anticyclones were quite equal. The consequences of the differences mentioned will be discussed in the following parts of the paper.

(1c). FIRST STAGE OF THE EXPERIMENTS: ROSSBY SOLITARY VORTEX-A NEW OBJECT OF NONLINEAR PHYSICS.

Our first goal was creation of the Rossby soliton (solitary vortex) in its free motion. The first series of the experiments was carried out by means of the set-up shown in Fig.2, on the left [1]). Two paraboloids were used: the "little" one, 28 cm in diameter, and the "large" one, 72 cm in diameter; a "normal" rotation period at which H = const was equal 579 msec in the first case and 840 msec in the second one. Shallow water thickness, H (measured in the direction normal to the shallow water free surface), was varied from (3 - 5) mm in the small device to 7.5 cm in the large device. A description of methods for local vortex creation and the vortex diagnostics see in [1]).

A typical example of the structure under study is shown in Fig.3. It is a large-scale anticyclone (its size exceeds the Rossby radius, Rr) existing in the Rossby regime, drifting contrary to the vessel rotation with a velocity exceeding the Rossby speed (and so satisfying the known necessary soliton condition [1]). It survives longer than the linear Rossby wave packet of the same size, i.e. it is a long-lived structure. Its life time is precisely equal to the maximal life time for the Rossby vortices, determined by the molecular (table) viscosity [1].

The anticyclone collisions with like structures lead to their merger, two like structures never pierce each other as the KdV solitons do.

The necessary condition for the mentioned longevity of the structure under consideration has been discovered: the maximal linear velocity of its own rotation must exceed the velocity of its (westward) drift. This condition is shown to be necessary to avoid the structure "twisting" due to dependence of the drift velocity on the meridional coordinate. Therewith, the system of the structure stream lines includes the separatrix inside which there is the trapped fluid well transferred with the structure under study. It means that it is "a real vortex".

The effective fluid transfer by the vortex under consideration is demonstrated in Fig.4 where the anticyclonic vortex created at position 1 and colored at position 2 by a dye introduced from the above drifts westwards, together with the trapped fluid.

A cyclonic vortex having the same (or any other) parameters suffers dispersion decay and doesn't survive longer than the linear Rossby wave packet; unlike anticyclone, it is short-lived; this is an example of cyclonic-anticyclonic asymmetry manifestation.

The vortex characteristic size does not depend on its amplitude, being determined by the conditions (geometry) of the vortex creation only.

So, basing on the above-said we can conclude that the structure under study is a Rossby eddy having some properties similar to theoretical predictions for the wavy Rossby soliton [6-8]. However, from the viewpoint of the mentioned wavy version of the soliton theory, it is very "unusual", dualistic object because it has very clear-cut vortical properties unexpected from the viewpoint of the wavy theory. Those vortical properties appeared to be responsible for all the mentioned contradictions between theory [6-8] and the experiment. We call this dualistic object "solitary vortex". It is a new object of nonlinear physics discovered in the experiments described.

The experiments considered have stimulated development and improvement of the Rossby soliton theory [9] (see als [1] and the text below).

(1d). SECOND STAGE OF THE EXPERIMENTS: GENERATION OF THE ROSSBY VORTEX CHAINS BY MEANS OF UNSTABLE ZONAL FLOWS. CYCLONIC-ANTICYCLONIC ASYMMETRY IN LABORATORY.

Initially, the experiments were carried out with the set-up shown in Fig.2, on the right, but the most interesting results were obtained with the unit shown in Fig.5. In both cases, the local vortex source was absent and the counter-streaming shear-flows were produced by means of the rings rotated (in the paraboloid frame) contrary to each other and involved the adjacent shallow water layers. It should be stressed that the flows vorticity sign and, consequently, the polarity of vortices they generated (cyclones, anticyclones) could be easily regulated by switching rotation directions of the rings (positions 5 and 6 in Fig.2 and 4 and 5 in Fig.5). So, the conditions for cyclone and anticyclone generation were equal and that was of crucial importance for the results obtained.

The experiments have shown that the produced zonal flows were unstable and that manifestation of the instability was quite different, depending on the vorticity sign. We will consider first the case of anticyclonic vorticity.

In this case, the flows generate a vortex chain at any experiment geometry. The number of vortices in the chain is the less, the greater is the velocity shift ("shear") between the counter streaming flows (see below).

An example of vortex chain consisting of three solitary large-scale vortices carrying the trapped fluid and drifting contrary to the vessel rotation is shown in Fig.6.

Quite different results were obtained at cyclonic vorticity of the flows. First, at the same experiment geometry as that in Fig.6, intense cyclones were not generated. A typical picture is shown in Fig.7. It turned out that in order to obtain a cyclonic vortex chain it's necessary to approach the flows to each other as near as possible. In particular, if the distance between the flows equal to 1 mm, a chain of intense cyclones is generated - Fig.8.

A striking difference between the results of the cyclone and anticyclone creation can be easily explained, if one takes into account the results of the preceding chapter. Since anticyclones are long-lived, a rather low level of "pumping" them by the shear-flows is sufficient for sustaining their large amplitude. At the same time, cyclones are short-lived, and they may be successfully generated and sustained only by extremely strong "pumping" and therefore, require for their generation an extremely high shear flow velocity gradient. It is our understanding of cyclonic-anticyclonic asymmetry of the large-scale, long-lived Rossby vortices in laboratory.

As for the cyclonic-anticyclonic asymmetry in the giant planet atmospheres, the results described in this chapter seem to explain this remarkable phenomenon. Namely, the zonal velocity gradient in the GRS region is rather small: it is about 200 m/s over 13000 km; on the other hand, the gradient in the region of "Barges" (Fig.1) is about 120 m/s over the distance of only 1300 km. So, the transition from the generation conditions of laboratory anticyclones (Figs.6,10, see below) to those for cyclones (Figs.7b, 8b) seems to be similar to the transition from the generation conditions for GRS-like vortices to those for "Barges" (Fig.1). This is our understanding of cyclonic-anticyclonic asymmetry of the large-scale vortices in the Jovian atmosphere. (Further details see in [1] and Refs. there).

(1e) : UNIQUE SOLITARY ROSSBY VORTEX AS A LABORATORY MODEL FOR THE GREAT RED SPOT OF JUPITER AND LIKE VORTICES

In Fig.9 the number of anticyclonic vortices across the system perimeter, generated by the unstable counterstreaming flows, is plotted as a function of the shear-flow velocity shift. Naturally, this nonlinear phenomenon exposes hysteresis.

According to Fig.9, at a sufficiently large velocity shear, an unique vortex, single over the whole system perimeter, is generated - Fig.10. It survives for an unlimited time. Its own vorticity exceeds that of the surrounding flow, similar to the analogous property of the GRS. This self-organizing structure is considered by us to be a laboratory analogue of natural vortices of the Jovian GRS type. So, the observational fact that the GRS is an unique vortex over the latitude circle is no more a physical problem.

Note that the same properties of the vortices under study were demonstrated by the thorough numerical simulations (see Refs.cited in [1]).

(II). MODELING OF THE EARTH POLAR VORTEX (THE "OZONE HOLE" PROBLEM)

Laboratory modeling stability of the large-scale intense barotropic atmospheric polar Rossby vortices has been carried out. Vortices having closed stream-lines were created by the method of sources of mass (for anticyclones) and sinks of mass (for cyclones). The vortex dimensions were greater or approximately equal to the Rossby-Obukhov radius. The experiments were carried out on a parabolic vessal, 72 cm in diameter and 36 cm height, which was rotated with a period of 0.85 sec. Water having a free surface was used as a working liquid. The thickness of the water layer was regulated within the limits from 0.75 cm to 7.5 cm. After switching the source on for a short time (and then switching it off), a free motion of the vortices (without external perturbations) was studied. The experiments have shown that the vortices did not move from the paraboloid pole (where they were created) and decayed in time quietly. Dependence of the e-folding time (T) for the maximal linear rotation velocity of a vortex on the thickness (Ho) of the water layer has had the following peculiarities: (1) when Ho decreases from 7.5 cm to zero, the value of T decreases smoothly from 45 sec to To = 18 sec (for anticyclones) and from 38 sec to To = 12 sec for cyclones; (2) when Ho approaches zero, the value of T does not approach zero (as it takes place in the absence of the liquid free surface), but remains a rather large (T = To). These regularities are well explained by the theory of viscous Rossby vortex damping, with due account for the free surface. The damping time is equal to the Ekman time multiplied by the factor equal to (unity plus the vortex radius squared over the Rossby-Obukhov radius squared); in other words, the damping time exceeds the Ekman time by the value of To. Cyclones survive on the pole approximately 1.25 times less compared to anticyclones. This fact is in an accordance with the expression for the viscous damping time which is proportional to the water thickness, H (the latter is less with cyclones), and inversely proportional to the square root of the sum of the Coriolis parameter and the frequency of the vortex own rotation (the latter is positive with cyclones and negative with anticyclones). Cyclones on the pole survive longer than on the "beta-plane" (since in the latter case, they are shifted along a meridian and therefore lose energy - see below and [15]). The investigation described relates to the intense vortices bearing trapped liquid. Being formed, the vortices do not let the media particles neither in nor out. Such polar vortices, in the absence of external perturbations, do not show any signs of instability. The results obtained are of great importance, in particular, in the context of "ozone hole" problem. The next task of the work will be a study of the polar vortex behavior in the presence of external perturbations like waves or the planetary zonal flows.

(III). SELF-ORGANIZATION MECHANISM AND A NEW TYPE OF CYCLONIC-ANTICYCLONIC ASYMMETRY OF THE ROSSBY AND PLASMA DRIFT VORTICES .

Solitary structures described in preceding Sections manifest some properties similar to those of the first, classical, soliton in the history of science, which was discovered by Scott Russel in 1833 on non-rotating shallow water and thoroughly described by Korteveg and de-Vries (KdV) in 1995. Firstly, they are observed if their size exceeds some minimal scale (in the case considered, the radius Rr). Secondly, in case of constant shallow water thickness, they are elevations (anticyclones), but not depressions of the shallow water free surface. Thirdly, the so called generalized Charney-Obukhov equation describing the objects under consideration [6-8] contains a nonlinearity of the KdV type and, if the vortex is cylindrically symmetrical, the mentioned nonlinearity is the only one in the vortex equation (since the second nonlinearity presented by the Jacobian equals zero in that case). Therefore, the first assumption [1] was that the objects under study are solitons of the KdV type. However, there remained a fundamental question concerning the mechanism of interaction of dispersion and nonlinearity, which provided formation of the Rossby vortices having the properties mentioned. It was the following: in the soliton of the Russel-Korteveg-de Vries (KdV) type, dispersive spreading inherent in a wave packet is balanced by the nonlinear steepening. And vice versa, the unlimited nonlinear steepening (and overturning) of the packet is prevented by dispersion. This equilibrium, in particular, manifests in that there exists quite a definite relationship between the packet width and its amplitude: the larger is the amplitude (the stronger nonlinearity), the less is the width (the stronger dispersion). The similar theoretical relationship does exist also in the case of solitary (purely wave) structure [6-8] which was accepted to be named Rossby soliton (or drift plasma soliton).

However, the situation has become more complicated, when in the model experiments described in ([1]), there was discovered that the typical size of the structures under consideration turned out to be independent of the amplitude, which evidenced a more complicated dynamics of the structure formation compared to the simple compensation of dispersion by the nonlinearity of the KdV-type .

A new understanding of the dynamics mentioned [14] has appeared in the course of our discussions with J.Nycander and G.Sutyrin, the authors of [9]. Shortly speaking, we have in mind a different type of the solitary structure self-organization at which, besides the Rossby wave dispersion and the "scalar" nonlinearity (of the KdV-type), at least one more nonlinearity, namely, the "vector" one (presented by the Jacobian in the vortex equations), is involved into the process. In particular, if, at a given structure size, its structure amplitude is too large, i.e. the scalar nonlinearity exceeds the Rossby wave dispersion, then the insufficient dispersive compensation of the scalar nonlinearity is provided by the vector nonlinearity which prevents the structure from the unlimited steepening. In this case, the vector nonlinearity "works" against the scalar one. In another case, when, at a given structure size, its amplitude turns out to be too small, so that the wave dispersion exceeds the scalar nonlinearity, the vector nonlinearity "helps" the scalar one, i.e. it works against the wave dispersion. Certainly, the very vortex is slightly axially asymmetrical (otherwise, the vector nonlinearity vanishes).

It must be noted that the term "self-organization" is used here mainly in the context with an elucidation which factors (dispersion and nonlinearities of different kind) condition formation of the solitary (stable, long-lived) Rossby structures. Although, the experimental fact (see below) that the size of solitary vortices turns out to be more or less close to the Rossby-Obukhov radius, independently of the size of the vortex local source, reminds formation of an attractor.

A recent continuation of the experiments described above has led us to a discovery of "anomalous" cyclonic-anticyclonic asymmetry. The point is the following. At constant shallow water thickness (the case described above), the asymmetry is "normal", i.e. the solitary vortices may only be as anticyclones, not cyclones. Such a type of the asymmetry manifests, in particular, in that the big, long-lived vortices dominating in the giant planet atmospheres are, as a rule, anticyclones. Unlike that, the new type of the asymmetry manifests in that the large-scale solitary vortices may only be as cyclones, not anticyclones. This phenomenon is observed in the presence of a rather strong gradient in the rotating shallow water thickness, directed parallel to the gradient in the Coriolis parameter. This very type of the asymmetry exists with drift vortices in the magnetized plasma [14-16]. The latter is not surprising because there is a remarkable fact: the generalized Charney-Obukhov equation for the Rossby nonlinear waves (vortices) and the generalized Hasegawa-Mima equation for nonlinear drift waves (vortices) are similar like two drops of water (see [16]).

The evidence of existence of the new type of cyclonic-anticyclonic asymmetry was observed in the following way. The point is that the linear waves (vortices) of the type considered have the limiting propagation speed: the so called Rossby speed (Vr) in geophysical fluid dynamics and the drift speed (V*) in a plasma. The existence condition for a soliton is that its propagation velocity has to lie beyond the range of the linear wave velocities (otherwise, it will be in the Cerenkov resonance with linear waves and will lose its energy due to radiation, that is, it will not be long-lived and, consequently, will not be soliton-like). It means that the soliton velocity (Vd) must exceed the limiting linear wave speed: in case of the Rossby structures,

$$Vd > Vr \qquad (6)$$

where

$$Vr = g d/dy(H/f) \quad ; \qquad (7)$$

in case of plasma drift structures,

$$Vd > V* \quad . \qquad (8)$$

(Note that in case when the shallow water thickness Ho is not constant, the soliton condition (6,7) has some "nuances" connected with meridional motion of the Rossby vortices (see [15])).

And, as shown in the experiments considered [14-16], in case of constant shallow water thickness, the condition (6) may only be satisfied for anticyclones, whereas in case of the above gradient in shallow water thickness and, analogously, in case of the magnetized plasma where the (negative) radial gradients in plasma density and electron temperature are parallel to ich other, the conditions (6-8) may only be satisfied for cyclones. Therewith, a cyclonic solitary structure can only propagate to the "east", whereas its anticyclonic counterpart can only propagate to the west, i.e. in the usual direction of the planetary Rossby wave propagation.

In the experiments mentioned [14,15], the rather paradoxical (on the first glance) effects were observed.

Namely, it is well known that at Ho = const, the drift velocity of a cyclone (which is a depression of the shallow water surface) is the less, the greater is its amplitude (i.e.the deeper is the the well on the water). However, in the presence of a sufficiently large negative radial gradient in the shallow water thickness, in accordance with the solitonic condition (6-7), everything occurs in the contrary way: namely, the deeper is the cyclonic well, the faster it propagates to the east. The similar effect has been observed for a solitary anticyclone. Namely, whereas at Ho = const an anticyclone drifts to the west the faster, the larger is its elevation, in the presence of a sufficiently large negative shallow water thickness, the anticyclone drifts to the east the slower, the larger is its elevation (!). In more detail, see [14,15].

(1d). SECOND STAGE OF THE EXPERIMENTS: GENERATION OF THE ROSSBY VORTEX CHAINS BY MEANS OF UNSTABLE ZONAL FLOWS. CYCLONIC-ANTICYCLONIC ASYMMETRY IN LABORATORY.

Initially, the experiments were carried out with the set-up shown in Fig.2, on the right, but the most interesting results were obtained with the unit shown in Fig.5. In both cases, the local vortex source was absent and the counter-streaming shear-flows were produced by means of the rings rotated (in the paraboloid frame) contrary to each other and involved the adjacent shallow water layers. It should be stressed that the flow vorticity sign and, consequently, the polarity of vortices they generated (cyclones, anticyclones) could be easily regulated by switching rotation directions of the rings (positions 5 and 6 in Fig.2 and 4 and 5 in Fig.5). So, the conditions for cyclone and anticyclone generation were equal and that was of crucial importance for the results obtained.

The experiments have shown that the produced zonal flows were unstable and that manifestation of the instability was quite different, depending on the vorticity sign. We will consider first the case of anticyclonic vorticity.

In this case, the flows generate a vortex chain at any experiment geometry. The number of vortices in the chain is the less the greater is the velocity shift ("shear") between the counter streaming flows (see below).

An example of vortex chain consisting of three solitary large-scale vortices carrying the trapped fluid and drifting contrary to the vessel rotation is shown in Fig.6.

Quite different results were obtained at cyclonic vorticity of the flows. First, at the same experiment geometry as that in Fig.6, intense cyclones were not generated. A typical picture is shown in Fig.7. It turned out that in order to obtain cyclonic vortex chain it's necessary to approach the flows as near as possible. In particular, at the distance between the flows equal to 1 mm, a chain of intense cyclones is generated - Fig.8.

A striking difference between the results of the cyclone and anticyclone creation can be easily explained, if one takes into account the results of the preceding chapter. Since anticyclones are long-lived, a rather low level of "pumping" them by the shear-flows is sufficient for sustaining their large amplitude. At the same time, cyclones are short-lived, and they may be successfully generated and sustained only by extremely strong "pumping" and therefore, require for their generation an extremely high shear flow velocity gradient. It is our understanding of cyclonic-anticyclonic asymmetry of the large-scale, long-lived Rossby vortices in laboratory.

As for the cyclonic-anticyclonic asymmetry in the giant planet atmospheres, the results described in this chapter seem to explain this remarkable phenomenon. Namely, the zonal velocity gradient in the GRS region is rather small: it is about 200 m/s over 13000 km; on the other hand, the gradient in the region of "Barges" (Fig.1) is about 120 m/s over the distance of only 1300 km. So, the transition from the generation conditions of laboratory anticyclones (Figs.6,10, see below) to those for cyclones (Figs.7b, 8b) seems to be similar to the transition from the generation conditions for GRS-like vortices to those for "Barges" (Fig.1). This is our understanding of cyclonic-anticyclonic asymmetry of the large-scale vortices in the Jovian atmosphere. (Further details see in [1] and Refs. there).

(1e) : UNIQUE SOLITARY ROSSBY VORTEX AS A LABORATORY MODEL FOR THE GREAT RED SPOT OF JUPITER AND LIKE VORTICES

In Fig.9 the number of anticyclonic vortices across the system perimeter, generated by the unstable counterstreaming flows, is plotted as a function of the shear-flow velocity shift. Naturally, this nonlinear phenomenon exposes hysteresis.

According to Fig.9, at a sufficiently large velocity shear, an unique vortex, single over the whole system perimeter, is generated - Fig.10. It survives for an unlimited time. Its own vorticity exceeds that of the surrounding flow, similar to the analogous property of the GRS. This self-organizing structure is considered by us to be a laboratory analogue of natural vortices of the Jovian GRS type. So, the observational fact that the GRS is an unique vortex over the latitude circle is no more a physical problem.

Note that the same properties of the vortices under study were demonstrated by the thorough numerical simulations (see Refs.cited in [1]).

(II). MODELING OF THE EARTH POLAR VORTEX (THE "OZONE HOLE" PROBLEM)

Laboratory modeling stability of the large-scale intense barotropic atmospheric polar Rossby vortices has been carried out. Vortices having closed stream-lines were created by the method of sources of mass (for anticyclones) and sinks of mass (for cyclones). The vortex dimensions were greater or approximately equal to the Rossby-Obukhov radius. The experiments were carried out on a parabolic vessal, 72 cm in diameter and 36 cm height, which was rotated with a period of 0.85 sec. Water having a free surface was used as a working liquid. The thickness of the water layer was regulated within the limits from 0.75 cm to 7.5 cm. After switching the source on for a short time (and then switching it off), a free motion of the vortices (without external perturbations) was studied. The experiments have shown that the vortices did not move from the paraboloid pole (where they were created) and decayed in time quietly. Dependence of the e-folding time (T) for the maximal linear rotation velocity of a vortex on the thickness (Ho) of the water layer has had the following peculiarities: (1) when Ho decreases from 7.5 cm to zero, the value of T decreases smoothly from 45 sec to To = 18 sec (for anticyclones) and from 38 sec to To = 12 sec for cyclones; (2) when Ho approaches zero, the value of T does not approach zero (as it takes place in the absence of the liquid free surface), but remains a rather large (T = To). These regularities are well explained by the theory of viscous Rossby vortex damping, with due account for the free surface. The damping time is equal to the Ekman time multiplied by the factor equal to (unity plus the vortex radius squared over the Rossby-Obukhov radius squared); in other words, the damping time exceeds the Ekman time by the value of To. Cyclones survive on the pole approximately 1.25 times less compared to anticyclones. This fact is in an accordance with the expression for the viscous damping time which is proportional to the water thickness, H (the latter is less with cyclones), and inversely proportional to the square root of the sum of the Coriolis parameter and the frequency of the vortex own rotation (the latter is positive with cyclones and negative with anticyclones). Cyclones on the pole survive longer than on the "beta-plane" (since in the latter case, they are shifted along a meridian and therefore lose energy - see below and [15]). The investigation described relates to the intense vortices bearing trapped liquid. Being formed, the vortices do not let the media particles neither in nor out. Such polar vortices, in the absence of external perturbations, do not show any signs of instability. The results obtained are of great importance, in particular, in the context of "ozone hole" problem. The next task of the work will be a study of the polar vortex behavior in the presence of external perturbations like waves or the planetary zonal flows.

(III). SELF-ORGANIZATION MECHANISM AND A NEW TYPE OF CYCLONIC-ANTICYCLONIC ASYMMETRY OF THE ROSSBY AND PLASMA DRIFT VORTICES .

Solitary structures described in preceding Sections manifest some properties similar to those of the first, classical, soliton in the history of science, which was discovered by Scott Russel in 1833 on non-rotating shallow water and thoroughly described by Korteveg and de-Vries (KdV) in 1995. Firstly, they are observed if their size exceeds some minimal scale (in the case considered, the radius Rr). Secondly, in case of constant shallow water thickness, they are elevations (anticyclones), but not depressions of the shallow water free surface. Thirdly, the so called generalized Charney-Obukhov equation describing the objects under consideration contains a nonlinarity of the KdV type and, if the vortex is cylindrically symmetrical, the mentioned nonlinearity is the only one in the vortex equation (since the second nonlinearity presented by the Jacobian equals zero in that case). Therefore, the first assumption [1] was that the objects under study are solitons of the KdV type. However, there remained a fundamental question concerning the mechanism of interaction of dispersion and nonlinearity, which provided formation of the Rossby vortices having the properties mentioned. It was the following: in the soliton of the type of Russel-Korteveg-de Vries (KdV), dispersive spreading inherent in a wave packet is balanced by the nonlinear steepening. And vice versa, unlimited nonlinear steepening (and overturning) of the packet is prevented by dispersion. This equilibrium, in particular, manifests in that there exists quite a definite relationship between the packet width and its amplitude: the larger is the amplitude (stronger nonlinearity) the less is the width (stronger dispersion). The similar theoretical relationship exists also in the case of solitary (purely wave) structure which was recently accepted to be named Rossby soliton (or drift plasma soliton).

However, the situation has become more complicated, when in the model experiments ([1]), there was discovered that the typical size of the structures under consideration turned out to be independent of the amplitude, which evidenced a more complicated dynamics of the structure formation compared to the simple compensation of dispersion by the nonlinearity of the KdV-type .

A new understanding of the dynamics mentioned has appeared in the course of our discussions with J.Nycander and G.Sutyrin, the authors of [8]. Shortly speaking (in details, see [14]), we have in mind a different type of the solitary structure self-organization at which, besides the Rossby wave dispersion and the "scalar" nonlinearity (of the KdV type), at least one more nonlinearity, namely, the "vector" one (presented by the Jacobian in the vortex equations), is involved into the process. In particular, if, at a given structure size, the structure amplitude is too large, i.e. the scalar nonlinearity exceeds dispersion, then the insufficient dispersive compensation of the scalar nonlinearity is provided by the vector nonlinearity which prevents the structure from the unlimited steepening. In this case, the vector nonlinearity "works" against the scalar one. In another case, when, at a given structure size, the structure amplitude turns out to be too small, so that the wave dispersion exceeds the scalar nonlinearity, the vector nonlinearity "helps" the scalar one, i.e. it works against dispersion. Certainly, the very vortex is slightly axially asymmetrical (otherwise, the vector nonlinearity vanishes).

It must be noted that the term "self-organization" is used here mainly in the context with an elucidation which factors (dispersion and nonlinearities of different kind) condition formation of the solitary (stable, long-lived) Rossby structures. Although, the experimental fact (see below) that the size of solitary vortices turns out to be close to the Rossby-Obukhov radius, independently of the size of the vortex local source, reminds formation of an attractor [15].

A recent continuation of the experiments described above has led us to a discovery of "anomalous" cyclonic-anticyclonic asymmetry [14, 15]. The situation is the following. At constant shallow water thickness (the case described above), the asymmetry is "normal", i.e. the solitary vortices may only be anticyclones, not cyclones. Such a type of the asymmetry manifests, in particular, in that the big, long-lived vortices dominating in the giant planet atmospheres are, as a rule, anticyclones. Unlike that, the new type of the asymmetry manifests in that the large-scale solitary vortices may only be as cyclones, not anticyclones. This phenomenon is observed in the presence of a rather strong gradient in the rotating shallow water thickness, directed parallel to the gradient in the Coriolis parameter. This very type of the asymmetry exists with drift vortices in the magnetized plasma [14-16]. The latter is not surprising because there is a remarkable fact: the generalized Charney-Obukhov equation for the Rossby nonlinear waves (vortices) and the generalized Hasegawa-Mima equation for nonlinear drift waves (vortices) are similar like two drops of water (!) [16].

The new type of cyclonic-anticyclonic asymmetry was observed in the following way. The point is that the linear waves (vortices) of the type considered have the limiting propagation speed: the so called Rossby speed (Vr) in geophysical fluid dynamics and the drift speed (Vdr) in plasma. The existence condition for a soliton is that its propagation velocity has to lie beyond the range of the linear wave velocities (otherwise, it will be in the Cerenkov resonance with linear waves and will loose its energy due to radiation, that is, it will not be long-lived and, consequently, will not be soliton-like). It means that the soliton velocity (Vd) must exceed the limiting linear wave speed: in case of the Rossby structures,

$$Vd > Vr \quad , \qquad (6)$$

where

$$Vr = gd/dy(H/f) \quad ; \quad (7).$$

in case of drift structures,

$$Vd > V* \quad . \quad (8)$$

(Note that in case when the shallow water thickness Ho is not constant, the soliton condition (6,7) has some "nuances" connected with meridional motion of the Rossby vortices (see [15])).

And, as shown in the experiments considered [14,15], in case of constant shallow water thickness, the condition (6) may be satisfied only for anticyclones, whereas in case of the above gradient in shallow water thickness and, analogously, in case of the magnetized plasma where the (negative) radial gradients in plasma density and electron temperature are parallel to ich other, the conditions (6-8) may be satisfied only for cyclones. Therewith, a cyclonic solitary structure can propagate only to the "east", whereas its anticyclonic counterpart can propagate only to the west, i.e. in the usual direction of the planetary Rossby wave propagation.

In the experiments mentioned, rather paradoxical (on the first glance) effects were observed.

Namely, it is well known that at Ho = const, the drift velocity of a cyclone (which is a depression of the shallow water surface) is the less the greater is its amplitude (i.e.the deeper is the well). However, in the presence of sufficiently large negative radial gradient in the shallow water thickness, in accordance with the theoretical solitonic condition, everything occurs in the contrary way: namely, the deeper is the cyclonic depression of the shallow water free surface, the faster it propagates to the east. The similar effect is predicted for a solitary anticyclone. Namely, whereas at Ho = const an anticyclone drifts to the west the faster, the larger is the shallow water elevation, in the presence of sufficiently large negative shallow water thickness gradient, the anticyclone drifts to the east the slower, the larger is its elevation (!). For more detailed description of the effects mentioned, see [14,15], as well as another experiment [17] in which the rotating parabolic free surface layer of shallow water was also used, but the statement of the experiment was quite different from [14, 15].

(IV). MODELING OF THE GENERATION OF SPIRAL STRUCTURE AND PREDICTION OF GIANT ANTICYCLONES IN GALAXIES

(4a). INTRODUCTION

The experiments described in this Section represent a part of our general program on rotating shallow water modeling of planetary, galactic, and plasma vortical structures in the laboratory. This modeling is based on the analogous dynamics of a compressible 2-D gas and incompressible shallow water having a free surface. The modeling was realized in accordance with A.Fridman's concept [18] of spiral structure generation by theunstable shear-flow between the central and peripheral parts of agalactic gaseous disk (see the Fridman lecture in this issue).

(4b). PREREQUISITES FOR THE LABORATORY EXPERIMENTS AND THE SETUPS

Prerequisites for the laboratory experiments were the following. (i). The state of a spiral galaxy isquasi-stationary, i.e., strong gravitation is counterbalanced by the centrifugal force due to the galaxy's rotation. (ii). According to the recent astronomical observations, in most galaxies there exists a narrow region between the dense galaxy bulge and the less dense periphery, where the rotation velocity fal off rapidly (see, for instance, [1] and Refs. cited there). This velocity jump produces an unstable shear flow in the gaseous galaxy disk, which is considered to be acause of hydrodynamical creation of spiralstructure in the galaxy. (iii) Geometrically, the spiral arms in a gaseousgalaxy disk are "shallow-water" systems because their thickness is verysmall compared to their transverse dimensions.

These structures may be simulated in the laboratory, since there exists a deep physicalanalogy between the dynamics of a 2-D compressible gas and shallow water with a free surface. In this analogy [19],the perturbation of ashallow-water free surface plays the role of a perturbation in the realgas density, the quantity Vg equal to the square root of (gH) is an analog of thesound speed, c, and the value U/Vg (where U is the shallow-water velocity) is an analog of the Mach number; the latter is of the order of 5-10 in real galaxies. So,in the laboratory modeling experiments it is necessary to ensure a rotating shallow water shear-flow with the appropriate velocity jump and Mach number. (iv). There are some requirements concerning another hydrodynamical numbers: for instance, the Reynolds number, Re, must be much more than unity (for more detail see [1]).

(4c). GENERATION OF SPIRAL WAVES AND THE HYDRODYNAMICAL CONCEPT OF GALAXY ARM FORMATION

In accordance with the above, the typical experimental setup (Fig.11) consisted of two parts. The central part ("the core") is a parabolic vessel, 2R=16 cm in diameter, "the periphery" is a paraboloid about 60 cm in diameter. Both parts are shaped so that the working shallow water brought into steady rotation by the bottom is spread over the vessel in a thin layer of approximately constant thickness, H (usually about 2-3 mm). These two paraboloids rotate with different angular velocities (internal one, $\Omega1$, outer one, $\Omega2$; usually $\Omega1/\Omega2 = 5$), so that a velocity jump is formed in the shallow water layer between the "core" and the "periphery"; the maximal value of $\Omega1$ is 42 1/s, the maximal value of $\Omega2$ is 3.6 1/s, and the maximal value of the Mach number $M = R(\Omega1-\Omega2)/ Vg$ is about 20. One can see that the above-mentioned adequacy criteria for the spiral structure modeling were fulfilled. For details concerning the structures under study, and diagnostics used in the experiments see [1] and Refs.cited there.

The series of experiments presented here is, a logical sequel to the preceding experiments by our team (see above), where differentially rotating shallow water was considered as a model of an atmosphere or an ocean. The experiments carried out with the configuration shown in Fig.11 yield the following results which we summarize here (see [1,20] and Refs. cited there).

(1). Differential shallow-water rotation with a velocity jump is unstable both for low Mach numbers, $M < 1$, and for high Mach numbers: $1 < M < 12$.

(2). The developing instability gives rise to spiral waves of surface density, which cross the discontinuity circle (the region of generator) and stretch across the core and the periphery. In the stationary regimes the waves form a symmetrical pattern of m arms which are elevations of the liquid surface (m-mode).
The pattern rotates steadily in the same direction as the core and the periphery so that the spiral tails are directed contrary to the rotation ("trailing spirals"). Note that all solitary spiral galaxies (having no satellites) have trailing arms.

(3). The angular velocity of the pattern rotation, Ωp, lies between $\Omega1$ and $\Omega2$ (Figs.12,13). The only exception is a degenerate mode, m=0, existing in the relaxational regime: as it develops, the liquid withdraws itself from the velocity shear region, and the instability ceases; after the wave reflected from the outer wall returns, the instability is regenerated again, and so on ad infinitum. (4). In the regimes with fast-rotating periphery (Fig.

4), the visible spiral arm lengths along their ridges are greater, by at least an order of magnitude, than the Rossby-Obukhov radius at $\Omega = \Omega2$, the counterpart of the characteristic epicyclic radius in galaxies. The arms show no tendency to decay into smaller-scale structures. Recall that in real galaxies of the type we are trying to simulate, the arm lengths are also much greater than Rr. Indeed, the arm length is of order of 10 kpc, whereas Rr is of the order of some tenths of a kpc.

(5). The number of spirals along the system perimeter decreases with an increasing velocity shift across the jump, i.e., with an increase in M (see Fig.14.). It is necessary to stress that the regularity presented in Fig.14 is qualitatively the same as that in Fig. 9 relating to the experiment geometry (Figs. 2, 5) for modeling the atmospheric vortices. It should be also noted that the regularity mentioned turns out to be a rather general and has been observed in a number of different experiments (see, for instance, Refs. cited in [20]). The given regularity may be interpreted from the viewpoint of maximum in the instability growth rate at constant viscous damping ([20]).

(6). The experiments have revealed, for the first time, the banana-like anticyclonic vortices between the spiral arms in the shear region, drifting together with the spiral arms around the vessel axis, so that a joint spiral-vortex structure is formed (Fig.15).

(7). The test particles captured by vortices move in the azimuthal direction between the spirals and in the radial direction inside the spirals, where their velocities are close to $c = V_g$. Their azimuthal velocities are somewhat higher. The longitudinal axes of the vortices run close to the "velocity discontinuity" circle.

(8). The liquid layer thickness is smallest at the vortex centers. This means that the resulting centripetal particle acceleration at the ends of the anticyclonic vortex counterbalances the sum of the Coriolis force and the pressure gradient force. Therefore, taking property (7) into account, one can conclude that the width of the banana vortices is of order of the Rossby-Obukhov radius defined by the expression (1).

(9). In the presence of such structures, there appears an essential broadening in the initial flow velocity jump which has been the primary cause of the instability [20].

(10). The instability creating spiral-vortex structures described here may be identified as the centrifugal instability of a differentially rotating liquid, when its inner part is rotating faster than its outer part (see [1,20] and Refs. cited there).

(11). In the non-stationary regime, when the core rotation frequency increases smoothly, spiral mode rearrangement takes place, spiral structures are asymmetric, and spiral-arm branching outwards may be observed at a definite stage of this transient process. For instance, with an increase in the core rotation speed, the number of spiral arms is reduced near the core first, and then at the periphery, and the spirals come to be outward branched. These facts allow one to predict that the asymmetric and branching galaxies observed by astronomers are in a non-stationary state.

The totality of experimental evidence discussed above, that is, the very existence of an instability in a differentially rotating system, the formation of spiral structures, their trailing shapes, rotation of the spiral pattern in the same direction as the core at a velocity intermediate between those of the core and periphery, qualitative insensitivity of the instability pattern to the peripheral angular velocity, the observed switch-over sequence between modes with different numbers of spiral arms when the value of the velocity jump in the flow system is changed, the existence of the instability at any value of the Mach number--all these facts are in a good agreement with the linear theory [18,21], where a hydrodynamical mechanism is used to describe generation of spiral structure in galaxies whose rotation curves contain a velocity jump.

There is also a qualitative agreement between the principal results of our experiments described here and the results of the numerical calculations stimulated by these experiments. Such calculations were carried out [22, 23], in particular, for the conditions of the shallow-water experiments of our team.

It should be pointed out that spiral structures with different numbers of arms are found in real galaxies, similarly to the laboratory observations described above. In particular, natural structures corresponding to the mode m=0 are known as the "ring-galaxies".

Sometimes it is argued that our experimental configurations are greatly different from the natural objects to be simulated, because they have a solid bottom which causes external (the Rayleigh) friction of the spiral structures created, whereas there is no bottom in real galaxies (!). Our answer to this argument consists in the following. First, according to the experiments described, all the effects observed remain qualitatively the same when the viscosity of the working fluid is increased by an order of magnitude. Second, contrary to the argument about the absence of an external friction in galaxies, our hypothesis is that the external friction does exist in galaxies too. It is the friction between the gaseous structures and the stars. Recall that, according to the hydrodynamical concept we discuss here, the spiral structures are formed in the gaseous subsystem of the galactic disk. If, for instance, all the stars were located in the central plane of the galaxy, the friction of the spiral gaseous structures against the stars would be an obvious analog of the external (Rayleigh) friction between the atmospheric (say, terrestrial) vortices and the underlying surface. Clearly, the fact that the stars are actually distributed over the galaxy disk height does not affect the qualitative picture. We believe that according to the Rayleigh law the specific volume force, f, of the gas friction against the stars in a galactic disk may be represented in the same form as the friction of the terrestrial atmosphere against the Earth's surface [20]. The same friction law is also assumed when analyzing the dissipation of large-scale zonal flows in the upper Jovian atmosphere. The underlying surface is then assumed to be the surface of the thick adiabatic gaseous layer located below the upper layer of clouds which bears the large-scale vortices like the Jovian Great Red Spot (see [3,24]). Thus the friction of the rotating shallow water against the bottom of the vessel used for the laboratory modeling of the mechanism which generates the spiral structures in galaxies is not an interference, but a necessary condition for such a simulation to be adequate.

(4d). PREDICTION OF THE EXISTENCE OF INTERARM ANTICYCLONIC VORTICES IN SPIRAL GALAXIES

The experimental data presented above (see, for example, Fig. 15) have allowed us to predict [25] that giant anticyclonic vortices having dimensions of the order of the Rossby-Obukhov radius, Rr, and physically similar to those observed in the experiments described, should exist in real galaxies, in the region of the velocity jump. The recent study by an international team of astronomers, based on the laboratory experiments described (see [26] and the lecture by A.Fridman in this issue), may be considered as the direct evidence for the existence of the galactic vortices under discussion. The study [26] was specially intended to verify the prediction under consideration. Using the 6-meter reflector at the Special Astronomical Observatory, the field of velocities and the distribution of ionized hydrogen were investigated for the dual-arm galaxy Mrk 1040, which has a jump in its rotation curve. The authors of the mentioned paper believe that the areas predicted on the basis of laboratory simulations, that is, areas of anticyclonic matter motion and low hydrogen density, have been identified unambiguously between the spiral arms and that the radial dimensions of those areas are nearly equal to the Rossby-Obukhov radius, in accordance with the above-mentioned prediction.

It should be noted that the gravitational (not hydrodynamical) concept [27] also assumes the existence the closed trajectories of particles in spiral galaxies. However, this concept has been made within the framework of the single-particle approximation, whereas the concept considered has been based on collective motion of the medium under study.

(4e). CONCLUSION

Thus, the totality of the regularities presented in this paper allows one to believe that there is a common physical mechanism generating large scale (giant) vortices in planetary atmospheres and spiral structures in galaxies. More detailed study shows that this mechanism is likely connected with the centrifugal instability of rotating flows having a velocity shear ([1, 20, 28]).

In conclusion, one has definite grounds for believing that the rotating shaalow water modeling of astrophysical structures seems to be rather fruitful and adequate (see [1,20].

ACKNOWLEDGEMENTS.

This work was supported by the Russian Foundation of Basic Research (RFBR, grant 96-05-64061) and by the INTAS-RFBR grant 95-0988.

REFERENCES

1,a. M.V.Nezlin and E.N.Snezhkin : "Rossby Vortices, Spiral Structures, Solitons", Springer-Verlag, Heidelberg, Berlin, New York, 1993. 223 pp.

1,b. M.V. Nezlin: "Rossby Solitary Vortices, on Giant Planets and in the Laboratory". Chaos 4 (2),.187-202 (1994).

2. Reta Beebe: "Characteristic Zonal Winds and Long-Lived Vortices in the Atmospheres of the Outer Planets". Chaos 4 (2), 113-122 (1994).

3. T.E.Dowling, A.P.Ingersoll: "Jupiter's Great Red Spot as a Shallow Water System". J.Atmos.Sci. 46, 3256-3278 (1989).

4 . F.H.Busse: (a) "Convection Driven Zonal Flows and Vortices in the Major Planets". Ibidem, 123-134; (b) "Convection-Driven Zonal Flows in the Major Planets". PAGEOF 121, 375-390 (1983).

5 (a). J.C.McWilliams : "Sub-Mesoscale, Coherent Vortices in the Ocean", Rev.Geophys. 23, 165-182 (1985).

(b). L.A.Armi, D.Hebert, N.Oakey, J.Price, P.L.Richardson, T.Rossby, B.Ruddick: The History and Decay of a Mediterranean Salt Lens", Nature 333,649-651(1988).

6 (a). G.R.Flierl: "Planetary Solitary Waves", POLYMODE News 62, 7-14 (1979).

(b). J.G.Charney and G.R.Flierl:" Oceanic Analogues of Large Scale Atmospheric Motions", in "Evolution of Physical Oceanography", ed.by B.A.Warrev and C.Wunsch, Chap.18, 504-548, MIT Press, Cambridge, Massachusetts, 1981.

7. E.N.Mikhailova and N.B.Shapiro: " A Two-Dimensional Model of the Evolution of Synoptic Perturbations in the Ocean", Izv. Atmos. Ocean Phys. 16, 587-597 (1980).

8. V.I.Petviashvili: "Red Spot of Jupiter and Drift Soliton in a Plasma", JETP Letters 32, 619-622 (1980).

9. J.Nycander, G.Sutyrin: "Steadily Translating Anticyclones on the Beta Plane". Dyn.Atmos.Oceans, 16, 473-498 (1992).

10. P.L.Read and R.Hide: "An Isolated Baroclinic Eddy as a Laboratory Analogue of the Great Red Spot of Jupiter", Nature 308, 45-48 (1984).

11. J.Sommeria, S.D.Meyers and H.L.Swinney:" Laboratory Simulation of Jupiter's Great Red Spot". Nature 331, 689-693 (1988).

12. F.V.Dolzhanskii: "On the Generation of Vortical Perturbations upon the Background of Two-Dimensional Shear-Flow Excited in the Coriolis Force Field by the Sources and Sinks of Mass". Izv. Atmos. Ocean Phys. 17, 413-423 (1981).

13. Yu.L.Chernous'ko: "Experimental Study of Two-Dimensional Flows with a Horizontal Velocity Shear in the Rotating System". Izv. Atmos. Ocean Phys. 16, 285-289 (1980).

14. M.V.Nezlin, G.P.Chernikov, A.Yu.Rylov, K.B.Titishov : "Self-Organization of the Large-Scale Planetary and Plasma Drift Vortices". "Chaos", 6(3), 309-327 (1996)

15. M.V.Nezlin, G.P.Chernikov, A.Yu.Rylov, K.B.Titishov: "Anomalous Cyclonic-Anticyclonic Asymmetry of the Solitary Rossby Vortices in the Presence of a Gradient in the Rotating Shallow Water Layer Depth in the Paraboloid, 1997, Izv. Atmos. Ocean. Phys., 33 (3), 1997. (In press).

16. M.V.Nezlin , G.P.Chernikov: "Analogy Between Drift Vortices in Plasma and Geophysical Hydrodynamics". Plasma Phys. Reports. 21.(11), 922-944 (1995).

17. B.Stenum, T.S.Laursen, J.J.Rasmussen, E.N.Snezhkin: "Drift Velocities of Forced Monopoles in Rotating Shallow Water". Annales Geophysicae. 14, Suppl.II, Part II, P. C676 (1996).

18. A.M.Fridman: "Formation of Spiral Structure in Galaxies". Sov.Phys.Uspekhi 21, 536 (1978).

19. L.D.Landau, E.M.Lifshits: "Hydrodynamics". (1987).

20. M.B.Nezlin: "Modeling of the Generation of Spiral Structure by Laboratory Experiments in Rotating Shallow Water and Prediction of Interarm Anticyclones in Galaxies" - in "Physics of the Gaseous and Stellar Disks of the Galaxy", Ed. by I.R.King, ASP Series, V.66, pp 136-151 (1994).

21. A.G.Morozov: "Generation of Spiral Structures in Flat Galaxies with Double-Peaked Rotation Curves". Sov.Astron.Lett. 23, 278 (1979).

22. S.V.Bazdenkov, N.N.Morozov, O.P.Pogutse: in "Joint Varenna - Abastumani School and Workshop on Plasma Astrophysics" (Sukhumi, USSR), Europ.Space Agency, 1986, p.505.

23. M.Tomasini, N.Dolez, J.Leorat: "Instability of a Rotating Shear Layer in the Transonic Regime". J.Fluid.Mech. 306, 59-82 (1996).

24. G.P.Williams and T.Yamagata: "Geostrophic Regimes, Intermediate Solitary Vortices and Jovian Eddies", J. Atmos. Sci. 41, 453-478 (1984).

25. M.V.Nezlin, V.L.Polyachenko, E.N.Snezhkin, A.S.Trubnikov, A.M.Fridman: " Prediction of the Vortex Gas Motion Between Galactic Spiral Arms From the Laboratory Modeling". Sov.Astron.Lett. 12, 213 (1986).

26. V.L.Afanasyev, A.M.Fridman: Pis'ma v Astron.Jurn. (Sov.Astron. Lett.) 19, 787 (1993).

27. G.Contopoulos: Astron.Astrophys. 64, 323 (1978).

28. A.M.Fridman, A.G.Morozov, M.V.Nezlin, E.N.Snezhkin: Phys.Lett. A 109, 228 (1985).

FIGURE CAPTIONS

Fig.1. Zonal flows in Jupiter's atmosphere: the wind velocity, u, as a function of the latitude (eastward direction is positive) [2]. The coordinates of large, long-lived vortices are shown for the Great Red Spot (GRS), Little Red Spot (LRS), White Ovals (WO), Barges (B). Symbols in the brackets denote the vortex sign: a - anticyclone, c - cyclone.

Fig.2. Schematic drawing of the experimental set-ups [1] for exciting and studying single Rossby solitons in a free motion (left) and for the generating chains of Rossby vortices by the unstable zonal flows (right) : (1) Vessel of a nearly paraboloidal form (the diameter of the small vessel is 28 cm, that of the large vessel is 72 cm, the height of the vessel is equal to its radius); (2) free surface of the shallow water which spreads along the parabolic bottom when rotating; (3) a photographic camera rotating with a vessel or together with a vortex; (4) rotating "pumping disk"; (5) and (6)- rotating rings producing counterstreaming flows. The paraboloid rotates around a vertical axis counter clockwise with angular frequency Ωo. In the top views the solid arrows indicate the anticyclonic direction of the pumping disk rotation and the directions of the zonal flows for the case of anticyclonic vorticity; the dashed arrow shows the drift direction of the Rossby solitary vortex in the left layout (the vortex falls behind the global rotation of the fluid). The angle a is the local angle between the rotation axis of the vessel and the normal to the fluid surface.

Fig.3. An example of an anticyclonic Rossby solitary vortex visualized with the aid of test particles floating on the surface of water colored with $NiSO_4$ and photographed from above against the white background of the vessel bottom. The pumping disk, 3 cm in diameter, is indicated by "D"; the white areas show the location of the disk drive. The picture was taken with a camera corotating with the vessel, 2-3 s after the pumping disk had been switched off. The vortex drifts in the clockwise direction, i.e. contrary to the vessel rotation. (The small paraboloid, Fig.2,a [1].)

Fig.4. The fluid capture and transport by a drifting anticyclonic vortex. The vortex was created by the "pumping disk", D, in position 1, was colored with dye when in position 2, and subsequently drifted clockwise, counter to the vessel rotation. (The small paraboloid, Fig.2,a [1].)

Fig.5. Experimental configuration where a Rossby autosoliton was produced: (1) vessel with nearly parabolic bottom rotating at angular rate W = 10.85 rads/s; (2) free surface of the fluid which spreads evenly over the bottom as the vessel rotates; (3) camera rotating at at an adjustable angular rate W ; (4) ring rotating faster than the vessel; (5) ring rotating slower than the vessel; (6) bottom zone between the moving rings (11 cm wide along the meridian); (7) semi-transparent mirror; (8) rotoscope based on a Dauvet prism rotating at angular rate W/2 ; D = 28 cm [1].

Fig.6. Flow pattern in free-surface shallow water for a smooth velocity profile and anticyclonic vorticity of the counter streaming flows; experimental configuration as in Fig.5.

Fig.7. Flow patterns in free-surface shallow water in the case of smooth velocity profile (a) for anticyclonic and (b) for cyclonic vorticity of counterflows (experimental configuration as in Fig.2,b [1]).

Fig.8. Flow patterns in free-surface shallow water in the case of steep velocity profile (a) for anticyclonic and (b) for cyclonic vorticity of counterflows (experimental configuration as in Fig.2,b [1].

Fig.9. Decrease in the number (m) of anticyclonic vortices in a chain with an increase in the velocity of counterstreaming flows (experimental configuration as in Fig.5 [1].

Fig.10. Rossby solitary vortex: three realizations for anticyclonic counterflows with smooth velocity profiles. The photographs were taken under the identical conditions of vortex generation and illustrate the dynamical behavior of the vortices as a function of time as they drift. This may be regarded as a quasi-stationary laboratory model of the GRS (experimental configuration as in Fig.5 [1]).

Fig.11. The set-up "Spiral": 1 - "core"; 2 - "periphery"; 3 - shallow water layer colored in green; 4 - incandescent lamp; 5 - red light filter; 6 - camera. First modification: D=28 cm, R=4 cm, the "periphery" is flat (horizontal) and immovable (see [1,19, and Refs. cited there). Second modification: D=60 cm, R=8 cm, the periphery is parabolic and rotating ([1, [20].

Fig.12, (a-d). Trailing spiral waves of surface density excited in differentially rotating shallow water: azimuthal modes m=3,2,1,0. The "core" and the spiral pattern are rotating clockwise, the "periphery" is at rest (the first setup modification---see caption to Fig.11). Black (white) parts of the pattern are the elevations (depressions) of the shallow water (see the Refs. pointed in caption to Fig. 11). From [1,20].

Fig.13. Trailing spiral waves of surface density excited in differentially rotating shallow water: mode m=2 with Ω_1 = 13 rad/s, Ω_2 = 2.6 rad/s, shallow water thickness H=0.35 cm. The core, the periphery, and the spiral pattern are rotating clockwise (the second setup modification---see caption to Fig. 11). The angular velocity of the pattern rotation is Ω_p = 6 rad/s. The dark circle intersected by the spiral arms is the line of the rotation velocity jump. From [1,20].

Fig.14. Right-hand limits for the existence of spiral patterns with different number of arms, m, with a changing (increasing) flow velocity shear between the core and the periphery under the experimental conditions of Fig. 12 ([1,20]).

Fig. 15, Spiral-vortex structures excited in differentially rotating shallow water; the camera rotates with the pattern; experimental configuration as in Fig. 12.

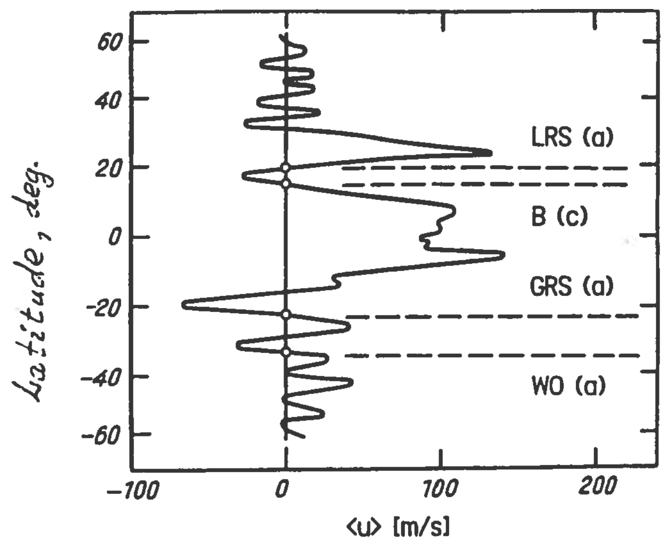
60
40
20
0
-20
-40
-60
Latitude, deg.
-100
0
100
200
<u> [m/s]
LRS (a)
B (c)
GRS (a)
WO (a)

Fig. 1

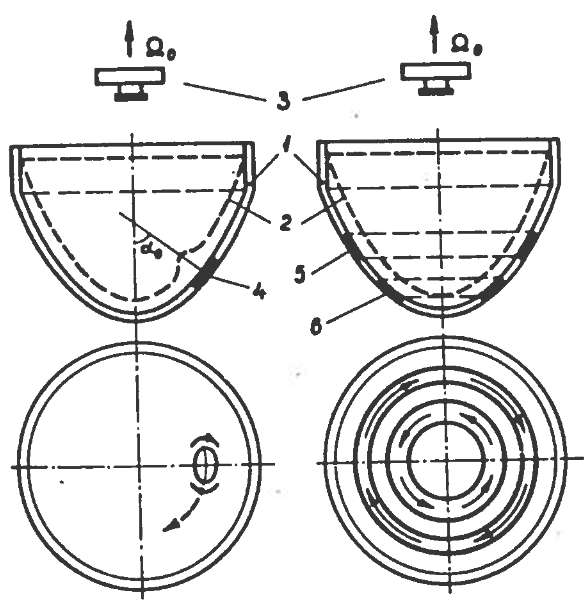
Ω₀
Ω₀
3
1
2
4
5
6
α₀

Fig. 2

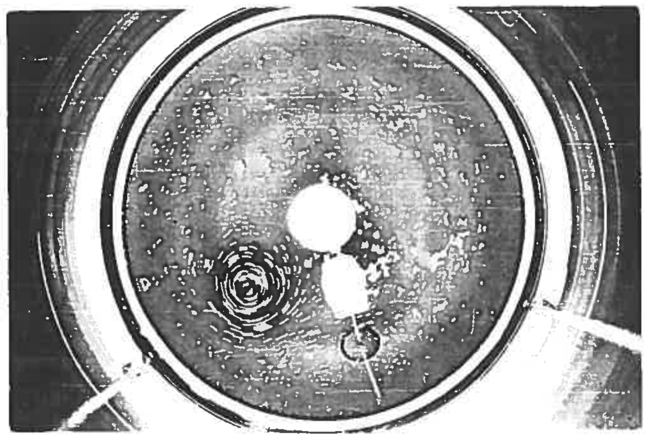

Fig. 3

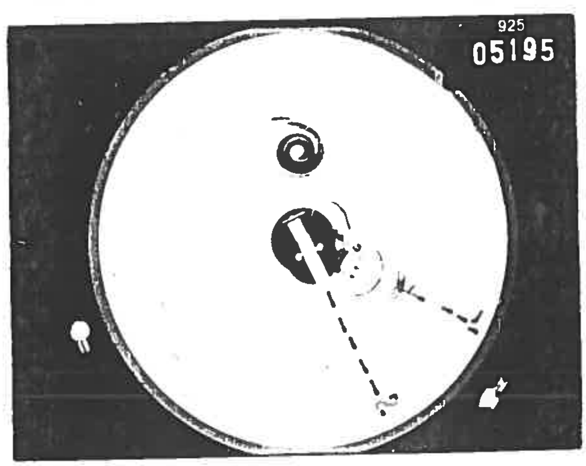

Fig. 4

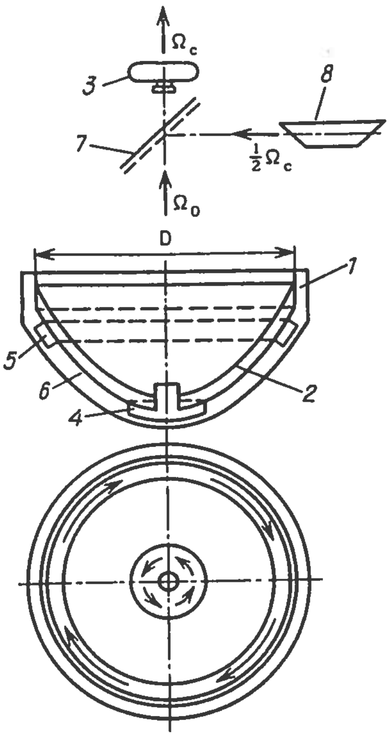

Fig. 5

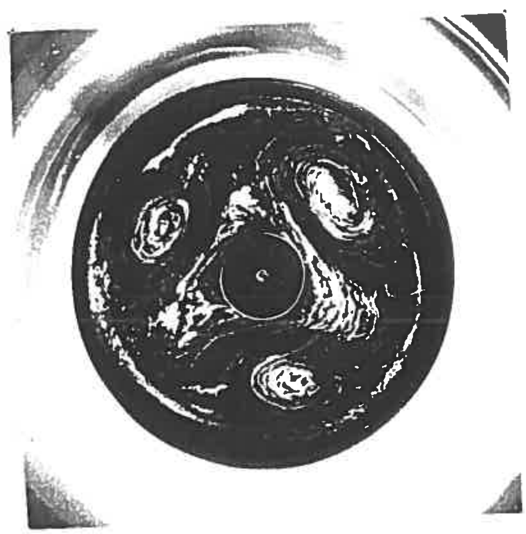

Fig. 6

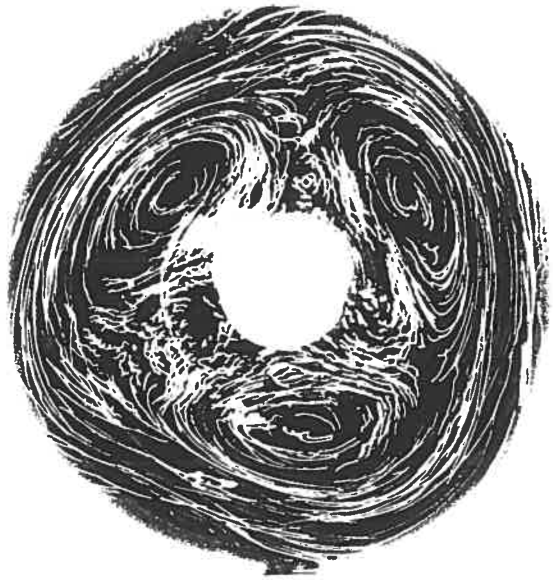

Fig. 7, a

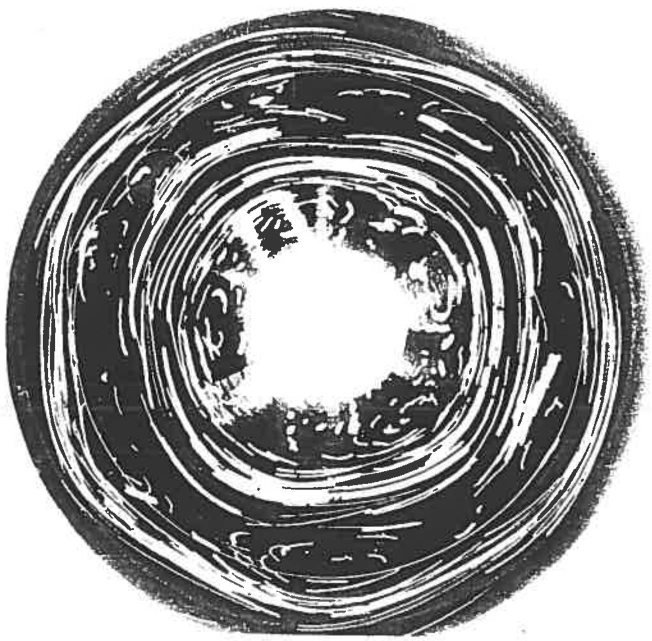

Fig. 7, b

Fig. 8, a

Fig. 8, б

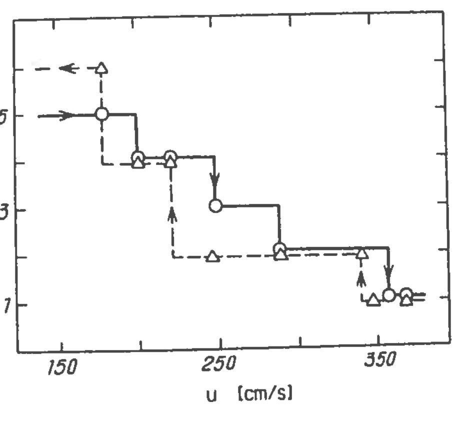

Fig. 9

Fig. 10, a

Fig. 10, b

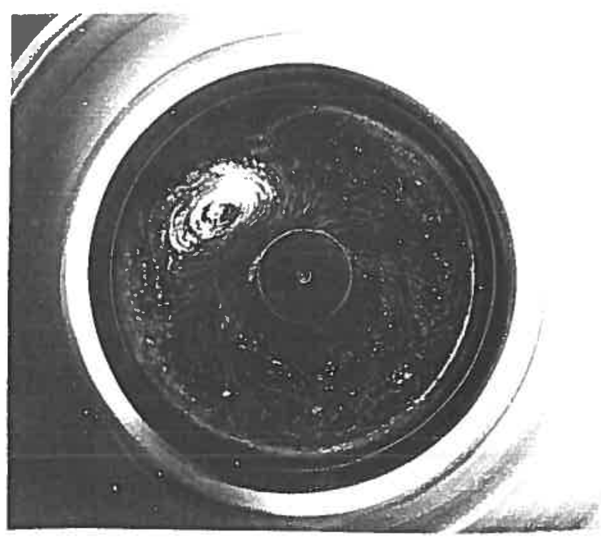

Fig. 10, c

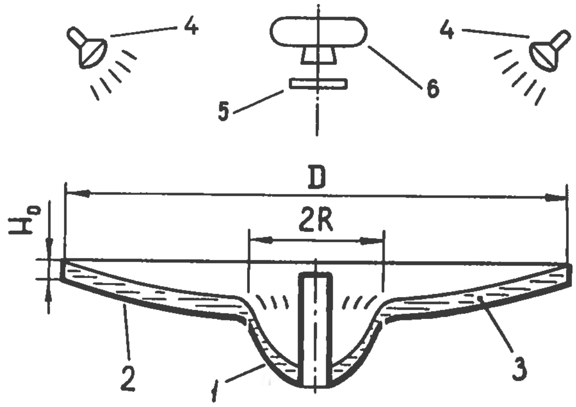

Fig. 11

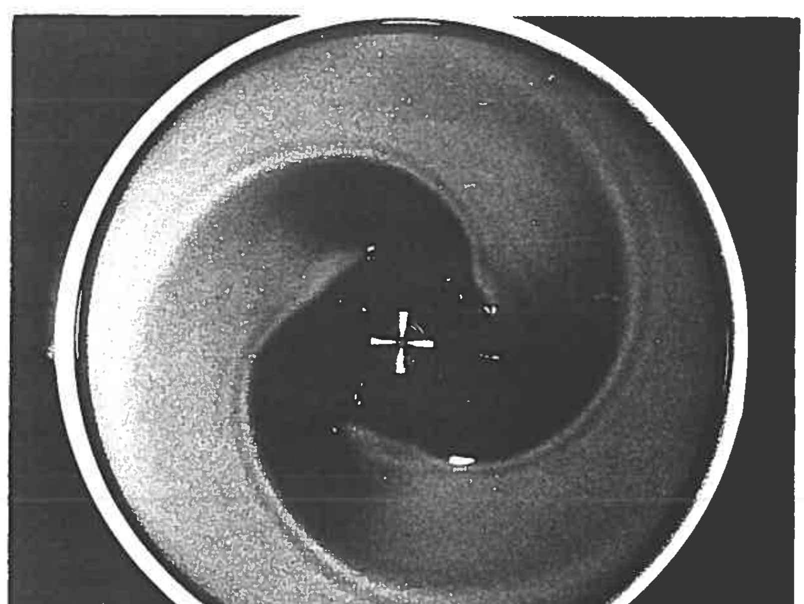

Fig. 12, a

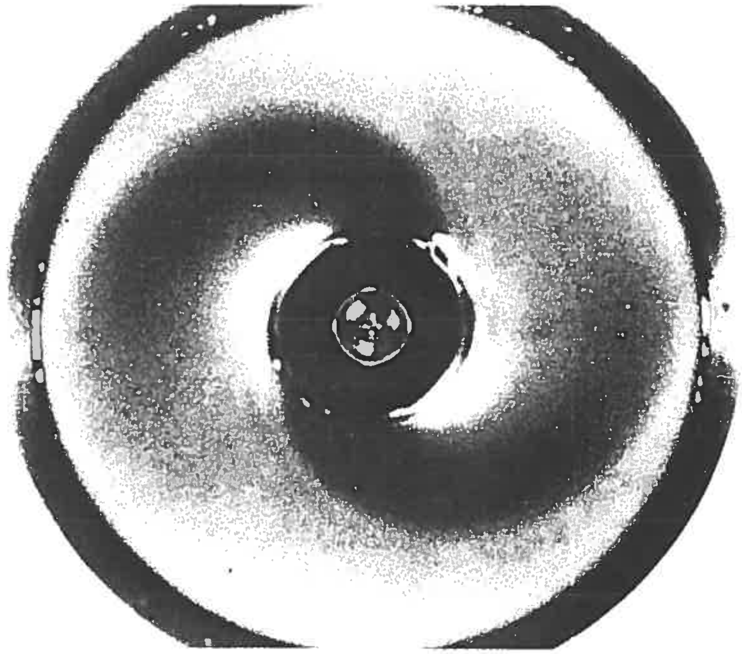

Fig. 12, b

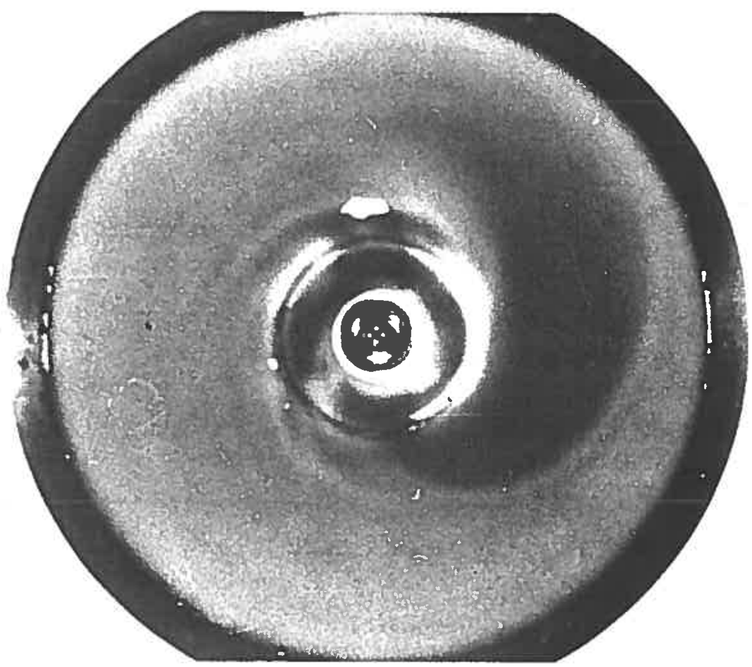

Fig. 12, c

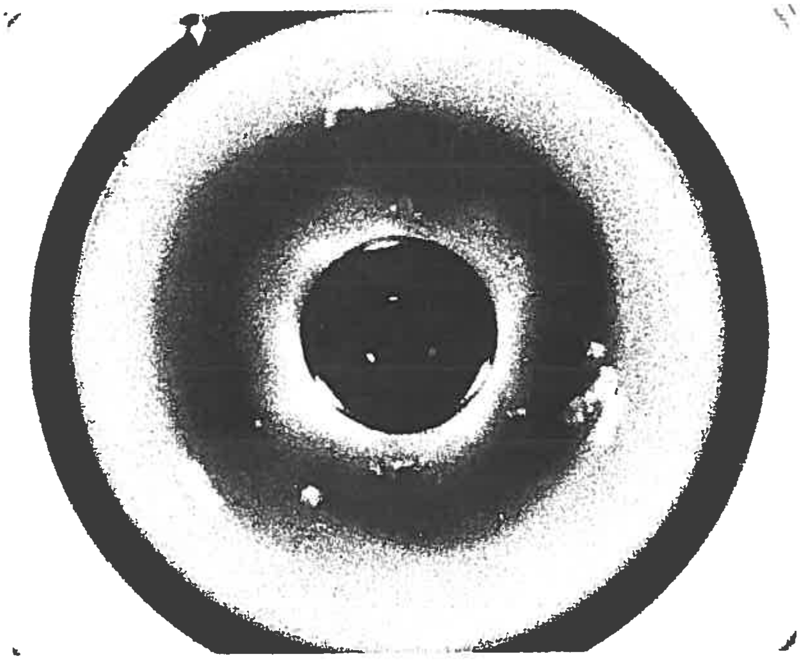

Fig. 12, d

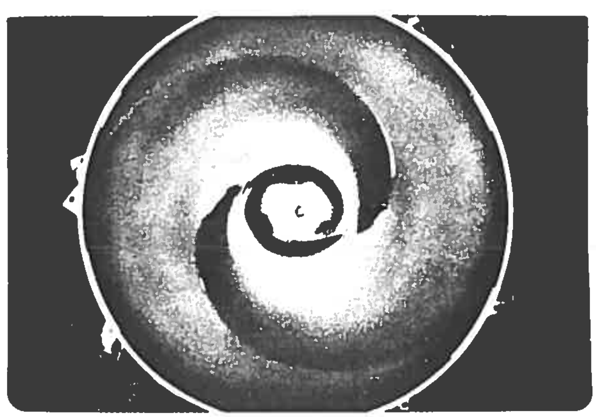

Fig. 13

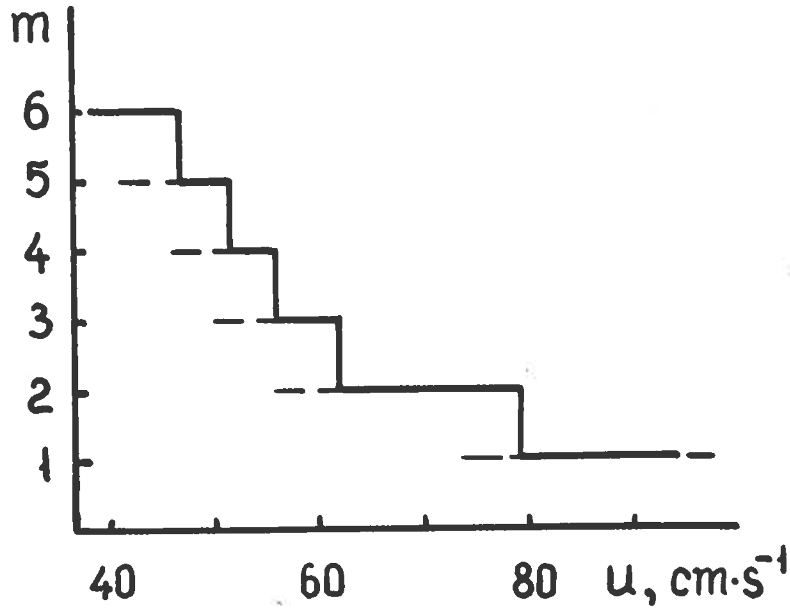

Fig. 14

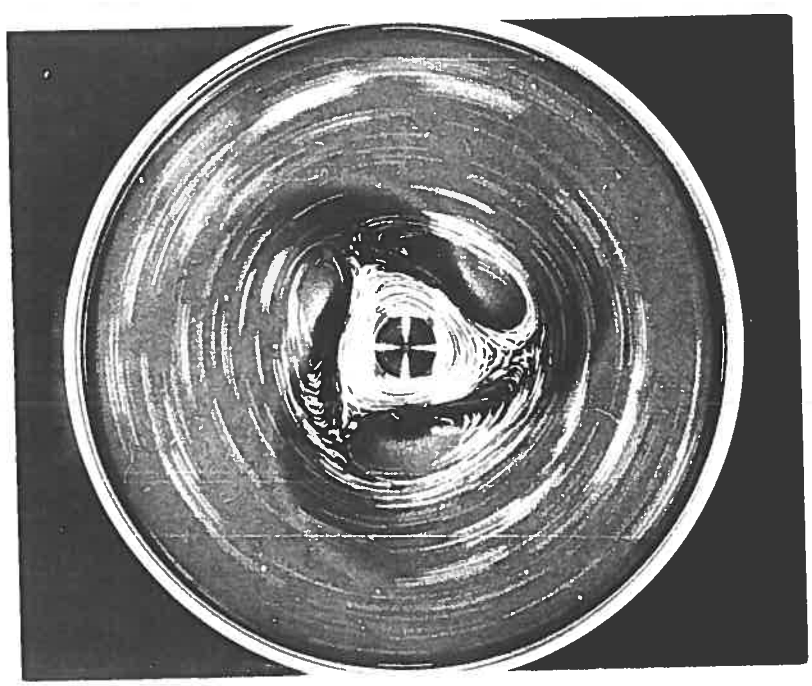

Fig. 15