Rossby autosoliton

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A new nonlinear physical entity, a "Rossby autosoliton," has been produced experimentally. It is an undamped, solitary, drifting, anticyclonic vortex which self-organizes in oppositely directed streams in rotating shallow water. It may be thought of as a steady-state soliton model of the Great Red Spot of Jupiter, developed experimentally for the first time.

The "Rossby autosoliton"[1)] produced in this study has three properties that distinguish it in a fundamental way from the solitary geostrophic vortices which we have studied previously.[1–3] First, it is not subject to viscous damping, and it exists for an unbounded time (by way of comparison, the viscous-damping time of a Rossby soliton in the experiments of Refs. 1–3 did not exceed 20 s). Second, like the global vortices in planetary atmospheres,[4] it is an isolated formation, not an element of a closed chain of vortices such as we have observed previously.[2–4] Third, its production does not require a special source: The autosoliton is generated by the nonlinear evolution of unstable, oppositely directed streams in rotating shallow water; it restructures their spatial profile in such a way that the new profile corresponds to the steady-state structure of the soliton that is generated. This autosoliton is thus the result of the nonlinear self-organization of a Rossby soliton in a system of geostrophic streams.

The experimental apparatus uses the same vessel, 28 cm in diameter, with a parabolic bottom profile, as that in which Rossby solitons were observed in previous experiments,[1–3] in a layer of shallow water rotating along with the vessel. The results of those previous experiments agreed qualitatively with the theory of Petviashvili.[5] The working liquid (water in a layer 0.5 cm thick) is subjected to two oppositely directed streams that propagate along a "parallel" around the axis of the system. The streams with respect to the vessel are created by a differential motion of two parts of the bottom, which are rotated with respect to the vessel in opposite directions and which entrain the layers of liquid above them. The inner part is the entire central part of the bottom, 10 cm in diameter, while the outer part is a ring 2.5 cm wide separated from the inner part by 11 cm along a "meridian" on the paraboloid (between these two parts is a part of the paraboloid that rotates as a whole). The experimental results can be summarized as follows.

1. In this arrangement with two streams separated by a considerable distance, their instability gives rise to large-scale vortex structures [with dimensions exceeding the Rossby-Obukhov radius, given in expression (1) below], as in Refs. 2 and 3, only if the streams are in the anticyclonic direction, and the curl of their velocity is antiparallel to the angular-velocity vector of the paraboloid. If the curl of (well-separated) streams is instead cyclonic, then large-scale vortex structures are not generated. This cyclonic-anticyclonic asymmetry, a fact of fundamental importance, stems from the circumstance that large anticyclones can be Rossby solitons, while large cyclones can-

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FIG. 1. Representative visualization of a Rossby autosoliton (top view). The center of the layer of shallow water is rotating more rapidly than the periphery. The white lines are tracks of tracer particles floating on the surface of the liquid, seen against the black bottom of the paraboloid ($\Omega_0 = 12.6$ s^{-1}; the camera exposure time is 1/3 s; the distance from the center of the vortex to the rotation axis is about 6 cm).

not (they decay rapidly). The latter can be steady-state formations only if they are generated by streams with an extremely sharp velocity profile, for which the scale dimension is smaller than Rossby-Obukhov radius (1). Such vortices are forced modes and not solitons.[4]

2. Figure 1 shows the pattern of streams (of anticyclonic direction) and the vortex structure that they generate on photographs taken by a camera rotating along with the vortex under study. The major feature of this pattern is a vortex of approximately elliptical shape that exists for an arbitrarily long time, drifting opposite the direction of the global rotation of the system. It is an anticyclone: a rise of the liquid which is rotating in the direction opposite the rotation of the vessel. The dimensions of the vortex along the parallel and along the meridian are about 6 cm, i.e., about (3–4)r_R, where

$$r_R = (g^* H_0)^{1/2} / 2\Omega_0 \cos \alpha \qquad (1)$$

is the Rossby-Obukhov radius, H_0 is the depth of the liquid, Ω_0 is the angular rotation velocity of the system, g^* is the acceleration due to gravity (the centrifugal force from the global rotation is taken into account), and α is the inclination of the local normal (vertical) with respect to the rotation axis of the system. The drift velocity of this vortex is about 8 cm/s, approximately equal to the Rossby velocity.[1]

3. Figure 2a shows height profiles of the liquid (1) outside the vortex (at the side of the vessel diametrically opposite the vortex) and (2) inside the vortex. Figure 2b shows velocity profiles in the vortex and in the streams. We see that the vortex (which arises from an instability of the streams) causes radical changes in the profiles of the streams: While before the appearance of the vortex the profile of the streams is the step function 1, in the regime with a vortex the profile becomes a smooth curve 2. The velocity profile in the vortex itself is represented by the two curves 3 in Figs. 2b and 2a; in the

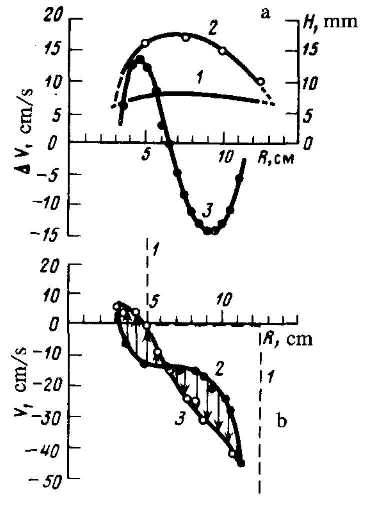

FIG. 2. a: Depth profiles of the liquid in a meridional cross section of the rotating paraboloid, i.e, plot of the depth of the liquid versus the distance from the rotation axis (as usual, the depth is measured along the normal to the surface of the bottom at the given point). 1—In the region diametrically opposite the vortex; 2—in the region of the vortex; 3—velocity profile in the vortex (the velocity is measured with respect to the stream, as shown by the arrows in Fig. 2b). b: Profiles of the linear azimuthal velocity of particles on the surface of the liquid in the system of the rotating vessel, i.e., plots of the velocity versus the distance from the axis of the vessel. 1—In the absence of a vortex; 2—in the vortex-generation regime, in the region diametrically opposite the vortex; 3—in the vortex.

latter case the velocities of the particles in the vortex (denoted by Δv) are measured with respect to the stream, as shown in Fig. 2b by the arrows between curves 2 and 3 (as usual,[2,3] the positive direction of the velocity is that in the rotation direction of the system). Since the vortex under study is formed in the region between the streams, where their velocity crosses zero, the streams with the new profile are matched with the spatial structure of the vortex and maintain its steady state, "untwisting" the vortex and compensating for its viscous loss (and perhaps other types of losses).

4. The maximum rotation velocity of the vortex with respect to the streams is about 15 cm/s, considerably greater than the vortex drift velocity; this is precisely the situation that corresponds to the presence in the vortex of a clearly defined region of trapped particles, as can easily be seen in Fig. 1 (Ref. 1). The maximum vorticity (the curl of the velocity) in the vortex is five or six times the value of the vorticity in the stream outside the vortex (on the diametrically opposite side of the vessel); this is precisely the same situation as is found for the large vortices in planetary atmospheres.[6]

5. This vortex differs in an extremely nontrivial way from the chain of steady-state anticyclones that we observed in Refs. 2 and 3 in that it is the only one along the entire perimeter of the paraboloid.

The solitary vortex produced in these experiments thus combines all the properties of a Rossby soliton (dimensions, drift direction, direction of internal rotation, and drift velocity) in the absence of damping. It may thus be suggested that this vortex is a

Rossby autosoliton or an example of a steady-state laboratory model of the Great Red Spot of Jupiter, adding substantial support to the soliton theory for this remarkable natural phenomenon.[7,5,4,8]

The Rossby autosoliton is generated by a centrifugal instability of the streams which arises when the interior part of the "shallow water" is rotating more rapidly than the peripheral part; i.e., the instability involved here is the same as that which, under other experimental conditions,[9] models the mechanism for the formation of the spiral structure of galaxies.

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[1)]We are using the term "autosoliton" to mean a self-sustaining (undamped) soliton, following B. S. Kerner and V. V. Osipov.

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