Induction of vortex structures in the Jovian atmosphere by fragments of Comet Shoemaker–Levy 9

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Possible perturbations of the Jovian atmosphere caused by the incidence of fragments of Comet Shoemaker–Levy 9 are analyzed. The energy released as a result of the destruction of the largest fragments in the atmosphere is sufficient for the formation of long-lived vortex structures in the upper layers of the atmosphere. The primary mechanism for the formation of large-scale vortices is a horizontal baroclinity. The conclusions reached here are supported by astronomical observations of the collision of the comet with Jupiter. The subsequent evolution of the vortices which are formed is predicted on the basis of a model of a 2D baroclinic Jovian atmosphere. © *1994 American Institute of Physics.*

1. A significant astronomical event occurred in July of 1994: the incidence of the massive comet Shoemaker–Levy 9 on Jupiter. Observations of the comet showed that by the time of the collision it consisted of a chain of fragments stretched out along the trajectory. The fragments ranged in size from a few hundred meters up to 1 or 2 km. They approached Jupiter at a velocity of 65 km/s. Their kinetic energy was estimated to range from 10^{29} to 10^{31} erg, respectively. During the stopping and destruction of the cometary fragments, the energy which they carried (aside from a fraction on the order of 10% which was expended on the emission of electromagnetic radiation) was transferred to the surrounding atmosphere. This energy transfer created a unique opportunity to study the evolution of planetary-atmosphere processes over a broad range of ultrahigh values of the energy deposition.

One of the most interesting phenomena observed in the atmospheres of rapidly rotating planets such as Jupiter is the existence of long-lived vortex formations: Rossby vortices. The vorticity in these formations is less than the rotational angular velocity of the planet, ω_0, so these vortices can be described in the quasigeostrophic approximation.[1] It is currently believed that such well-known structures in the Jovian atmosphere as the Great Red Spot and the White and Brown Ovals fall in the category of Rossby vortices. Under the conditions at the earth, analogs of such vortices are cyclones and anticyclones in the atmosphere, as well as the synoptic vortices which are observed in large numbers in the ocean. The transverse dimension of the Rossby vortices is many times the height of the atmosphere. The pressure corresponds to the hydrostatic approximation; the horizontal pressure gradient is maintained by a Coriolis force. These vortices can therefore be described highly accurately in the shallow-water approximation.[2,3] A horizontal length scale of these processes in the atmosphere of a planet is the Rossby–Obukhov radius $R_r = c_s/2\omega_0 \sin\alpha$, where c_s is the sound velocity, and α the latitude. For Jupiter, at the latitude at which the comet was incident, this radius is estimated to be 6000 km. The phase velocity of linear Rossby waves, v_r, for this latitude is ≈ 40 m/s; the time scale of the evolution (rotation) of the vortices can thus be estimated to be $\tau = R_r/v_r \approx 30$ h. However, highly nonlinear vortices may evolve considerably more rapidly, and larger ones more slowly.

One of the most complicated problems involved here, and one which has received comparatively little study, is the mechanism by which vortices form. It has been suggested that one of the most fundamental sources of geostrophic vorticity in the atmosphere is a baroclinity, specifically, a situation in which the pressure gradient is not collinear with the temperature gradient.[4] From this standpoint, observations of effects stemming from the incidence of Comet Shoemaker–Levy 9 on Jupiter can provide unique experimental material on the reaction of a planetary atmosphere to perturbation by an essentially point, instantaneous, and very intense source of heat.

2. In an effort to predict the results of the incidence of the cometary fragments on the dynamics of the Jovian atmosphere, calculations were carried out on the process on the basis of a 2D model of a baroclinic dynamics of the atmosphere.[4] This model incorporates the basic assumption that the vertical length scales of the process are small in comparison with the horizontal ones. The hydrodynamic equations are integrated on a rotating sphere along the vertical coordinate. The motion of the medium is treated in the β plane. This approach is completely legitimate if the length scales of the process are much smaller than the radius of the planet.

The primary distinction between the model of Ref. 4 and the well-known barotropic models, e.g., the Charney–Obukhov model,[1,5] is the conservation of the so-called horizontal baroclinity of the atmosphere. The physical meaning here is the assumption that there is a change in the specific entropy in the horizontal plane. It thus becomes possible to offer a correct description of the baroclinic mechanism for the generation of vorticity. The dimensionless equations for a baroclinic atmosphere[4] are

$$\partial_t q + \mathbf{V}_g \cdot \nabla_q = \mathbf{V}_g \cdot \nabla \Theta, \tag{1}$$

$$\partial_t \Theta + \mathbf{V}_g \cdot \nabla \Theta = 0. \tag{2}$$

$$q = \nabla_\perp^2 P - P + \beta y,$$

$$\nabla_\perp^2 = \partial_x^2 + \partial_y^2,$$

$$\mathbf{V}_g = \mathbf{e}_z \times \nabla P,$$

where $\Theta = P^{1/\gamma}/\rho$ is a potential temperature, which is a single-valued function of the entropy; P is the pressure; ρ is the density; q is a generalized vorticity; $\mathbf{V}_g$ is the geostrophic velocity; the coordinate X runs along latitude; and the coordinate Y runs along a meridian. Equations (1) and (2) have been put in dimensionless form in accordance with[4]

$$\begin{aligned}
&x,y\rightarrow R_r x,R_r y,\\
&t\rightarrow tR_f/c_s\\
&\rho\rightarrow \rho\rho_0 R_r/R_f,\\
&P\rightarrow PP_0 R_r/R_f,\\
&\Theta\rightarrow \Theta\Theta_0 R_r/r_f,
\end{aligned}\qquad (3)$$

where $R_f \approx 70\ 000$ km is the length scale of the variation in the Coriolis parameter, and P_0, ρ_0, and Θ_0 are characteristic background parameters of the Jovian atmosphere for the observable cloud layer, which contains most of the thermal energy. According to space-probe data, this layer corresponds to a pressure of roughly 3 bar and a temperature of about 200 K.

Numerical calculations were carried out on the basis of model (1), (2) for the Jovian latitude band at the coordinate of 45° S, which is close to the predicted latitude of incidence of the comet. The calculations incorporated a zonal mass transfer in the atmosphere, with velocities from -5 to 5 m/s, which are characteristic of this band.

Estimates of the effect of the cometary fragments on the Jovian atmosphere in the first stage of the process, which includes the slowing of the fragment, its breakup, and the formation and subsequent rise of a thermal, suggest that a perturbation with length scales on the order of hundreds of kilometers, with a temperature rise $\Delta T \approx 5$ K above the surrounding medium, forms in the atmosphere of the planet over half an earth hour for the fragments with sizes of a few hundred meters. These figures correspond to an energy release $\sim 10^{29}$ erg (this is a lower limit on the energy of the effect). For the fragments 1 or 2 km in size, the corresponding length scales are a thousand kilometers, and the corresponding temperature rise is $\Delta T \approx 30$ K. The latter figures correspond to an upper limit $\sim 10^{31}$ erg on the energy release. The reason for the spread in the estimates of the initial perturbations for a given interaction energy is that different models of the initial stage of the process lead to slightly different results. Furthermore, neither the composition of the comet nor the density of the fragments is totally certain. Perturbations with properties lying in this range were selected as the starting points for the calculations on vortex formation.

Analysis of the results of the calculations showed that the versions with $\Delta T \approx 5$ K do not yield the excitation of a long-lived vortex, regardless of the zonal flow velocity. The entire effect on the atmosphere reduces to an excitation of wave packets, which disappear rapidly because of dispersion but which may nevertheless lead to a significant perturbation of the zonal flow over a time on the order of an earth day. Figure 1 shows a typical calculation for the parameter value $\Delta T = 5$ K and a zonal flow velocity of -3 m/s. The coordinate system is moving with the zonal flow. The pressure perturbations are seen to be insufficient to give rise to closed streamlines; i.e., a vortex does not form.

In contrast, for the versions with $\Delta T \approx 30$ K, which corresponds to a perturbation of the dimensionless potential temperature Θ by an amount on the order of unity, we clearly observe the formation of a vortex structure. The length scales of this structure in the initial stage, which lasts a few earth days, are on the order of 15 000–20 000 km, depending on the intensity of the original perturbation and on the zonal flow velocity. Figure 2 shows the results of calculations for the parameter value $\Delta T = 30$ K and for a

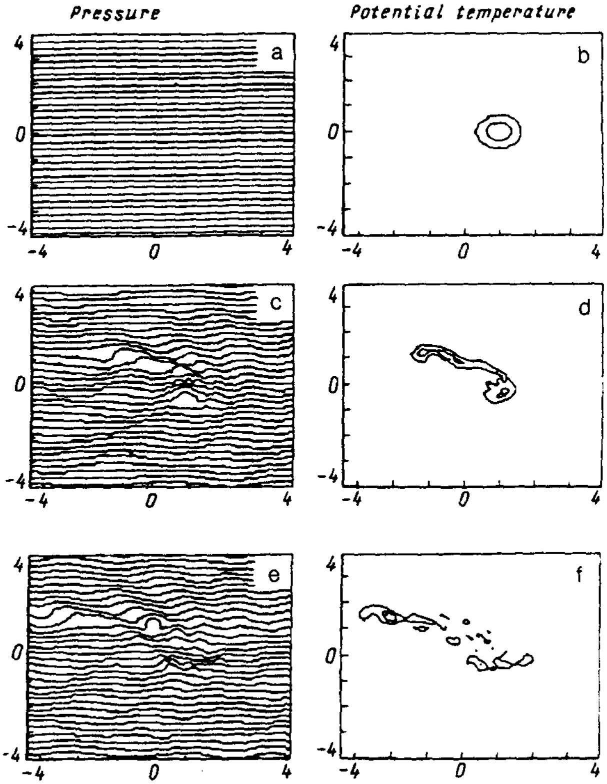

FIG. 1. Pressure perturbations in a zonal flow with a velocity of -3 m/s (a, c, e) and contour map of the potential temperature in the vortex (b, d, f), as generated by the incidence of a fragment with a size on the order of 100 m ($\Delta T = 5$ K). a,b—$t=2$ earth days; c,d—$t=4$ earth days; e,f—$t=6$ earth days. The upper boundary in the figures corresponds to the poleward direction, while the upper boundary corresponds to the equatorward direction. Distances are given in units of the Rossby radius.

zonal flow velocity of -3 m/s. A similar vortex was observed by astronomers on 18 July in the Jovian atmosphere after the incidence of the first of the large fragments. This observation apparently confirms the applicability of this theoretical model and the results of the numerical analysis. The subsequent time evolution of the vortex was studied in the numerical simulation. This study revealed that the vortex is clearly of a dipole nature in the initial stage of the evolution, as can be seen in Fig. 2, c and d. Prolonged calculations showed that there is a tendency toward an intensification of the anticyclonic vortex (the left side of the vortex structure in Fig. 2, c and d), while there is a degradation of the cyclonic vortex.

The induction of stable vortex structures by the incidence of the largest fragments is observed in the calculations for all selected values of the zonal flow velocity. With increasing value of this velocity, we see an intensification of the vortex-formation process. This intensification is easy to understand on the basis of model (1), (2). The sizes found for the vortex structures in the calculations are close to or slightly greater than the Rossby radius, so these structures, can be regarded as long-lived structures with a typical lifetime on the order of several earth days.

3. In the model used here, the uncertainty in the parameters of the turbulent viscosity in the Jovian atmosphere restricted us to a consideration of only the dissipation due to a slight heat transfer between a vortex and the surrounding medium. However, the mecha-

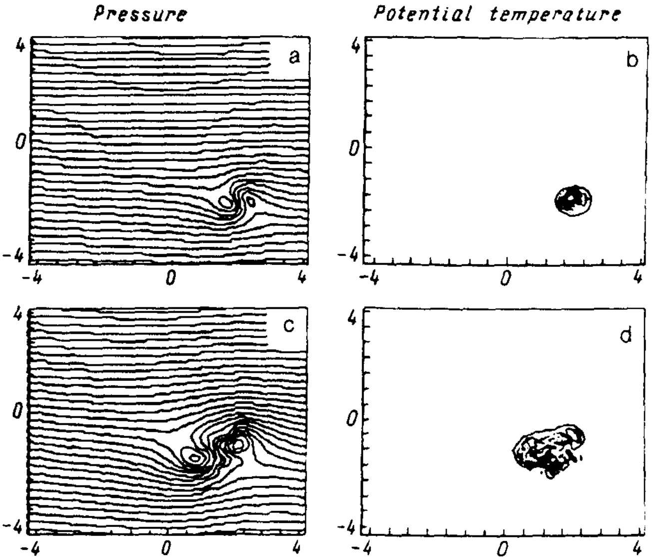

FIG. 2. Pressure perturbations in a zonal flow at a velocity of -3 m/s (a,b) and contour map of the potential temperature in a vortex (c,d), as generated by the incidence of a large fragment, with a size on the order of 1 km ($\Delta T = 30$ K). a,b—$t = 3$ earth days; c,d—6 earth days. The upper boundary in the figures corresponds to the poleward direction, and the lower boundary to the equatorward direction. Distances are given in units of the Rossby radius.

nism of turbulent exchange, ignored in this model, could act in two directions. Along with the process of energy dissipation in a vortex, there could be an inverse transfer from small atmospheric vortices to a larger vortex.[6] The effect would be to increase the lifetime of the latter vortex. The observations of large-scale vortices in the atmospheres of Jupiter and Saturn available at this point reveal that the lifetime of these vortices is extremely long. For example, the Brown Ovals on Jupiter, which are cyclonic and which have dimensions close to those of the vortices resulting from the incidence of the cometary fragments, exist for a time on the order of 30 yr. Accordingly, predictions of the lifetime of the vortices which form need not at the outset be limited to the time scale mentioned above.

This opportunity to directly observe vortices generated at Jupiter by cometary fragments should undoubtedly lead to information important for further refinements of the theory of the nonlinear interactions of vortex structures with a microscopic atmospheric turbulence.

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