Coherent Structures in Planetary Polar Vortices: A Laboratory View

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Introduction

Polar vortices are a key element in the atmospheric dynamics of planets. These structures are observed in all planets with atmospheres, including the Earth, Mars, Venus, Jupiter and Saturn. Earth's polar vortices in the stratosphere appear to have a fairly circular shape that is mostly stable, except during episodes of breaking that cause the "sudden stratospheric warming" phenomenon. The polar vortices on Venus, on the other hand, show extremely rich dynamics, as recent observations by ESA's Venus Express spacecraft have revealed [1]. They most often exhibit a double-lobed shape, as first observed by NASA's Pioneer Venus spacecraft in the late 1970s [2], but have recently been found to vacillate rapidly among 1-, 2- and 3-lobed configurations. At the same time, observations of Saturn's north polar vortex by the NASA/ESA Cassini spacecraft have shown the complexity of an extraordinary six-sided geometric figure encircling the entire north pole [3].

Hypothesis

There is not yet a fully comprehensive explanation for the variety of polar vortices in the atmospheres of the planets. Many factors have been invoked to set a theoretical framework that could describe their bizarre dynamics. Different kinds of instabilities could arise at the edge of the vortices, where the wind shear between the circumpolar jet and the vortex interior is strongest. In the case of Venus, the possibility of barotropic instabilities in the polar jets is supported by calculations made from radio occultation observations from Pioneer Venus [4], and by results of numerical models [5, 6, 7]. Linear stability analysis suggests that the zonal wind profile on Saturn might be barotropically unstable at the latitudes of the North Polar Hexagon [8].

A necessary (though not sufficient) condition for barotropic instability is the *Rayleigh-Kuo criterion*, which states that the gradient of total absolute vorticity must change sign within the domain of interest, namely:

$$\partial q/\partial y = df/dy - \partial^2 u/\partial y^2 \leq 0 \qquad (1)$$

where y is the northward coordinate, u is the zonal wind, f is the Coriolis parameter, and $q = f - \partial u/\partial y$ is the total absolute vorticity.

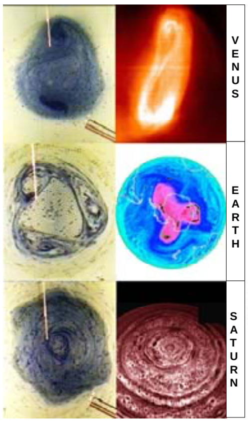


Figure 4: ***Left panels****: mode-2 (dipole), mode-3 (tripole) and mode-6 (hexagon) patterns obtained in the laboratory analogue of a polar vortex. The diameter of the vortex is approximately 1-m.* ***Right panels****: the same configurations observed in Nature: mode-2 in Venus' south polar vortex (ESA/Venus Express), mode-3 in the Earth's south polar vortex (ECMWF and VORCORE), and mode-6 in Saturn's north polar vortex (NASA-ESA/Cassini).*

The Laboratory Experiment

We studied the barotropic instabilities forming at the edge of a polar vortex in a laboratory experiment performed in June/July 2008 at the Norwegian University of Science and Technology in Trondheim, using their 5-m diameter "Coriolis" rotating tank (Fig. 1). In this experiment, we used a source-sink technique to create a central vortex in homogeneous water (Fig. 2). Water was pumped out of a source ring (radius=2 m) at a given flux rate Q, and was sucked from a central, circular sink region (maximum radius=0.45 m). This colander-like sink region had a parabolic shape to account for the γ–effect at the pole of a planet, i.e. the quadratic term of the expansion of the Coriolis parameter f=2Ωsinφ near the pole. We were able to use different configurations of the sink region, by covering parts of it with specifically designed annular masks (Fig. 3), each of them 0.09 m wide, and a central, circular mask of 0.09 cm diameter..

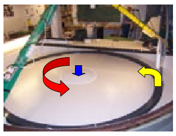


Figure 1

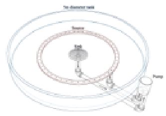


Figure 2

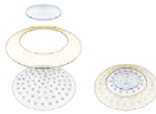


Figure 3

Results and conclusions

We were able to establish the presence of a central ("polar") vortex by conservation of angular momentum associated with the poleward flux in a rotating frame. We observed barotropic instabilities forming at the edge of the central jet, which led to the formation of coherent satellite vortices. These vortices organized themselves into different minimum-energy configurations (including dipole, tripole, quadrupole and hexagon). The stability of a given configuration was dependent on two key experimental parameters: the Rossby number and the poleward volume flux Q. The Ekman number (i.e. bottom friction) also plays an important role, but in our experiments we didn't vary the depth of the water (H=0.4 m) and we mostly used only two rotation rates for the tank, so the dependence on the Ekman number is less clear. In general, previous studies spanning a large range in the parameter space observed higher modes as the Rossby number decreases (our experiments confirmed this tendency), and lower modes as the Ekman number decreases, although the dependence on Ekman is less strong than on Rossby [see, e.g., 8].

Our experiments confirm that barotropic instability is a plausible physical mechanism for the formation of the multi-lobed coherent structures observed around the poles of several planetary atmospheres, including Venus and Saturn. These results strengthen the conclusions of previous laboratory experiments on shear induced by a solid rotating disk [8].

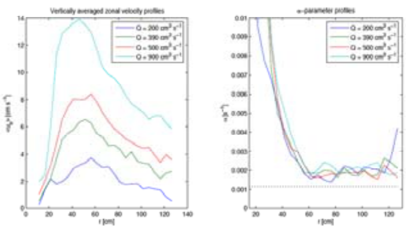


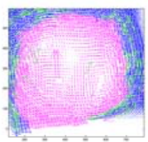
Figure 5: ***Left panel****: the curves represent the (vertically averaged) profiles of zonal (azimuthal) velocity as a function of the distance from the centre of the tank. Different curves are for different values of the poleward flux Q. The velocity components (averaged over one minute time interval) are measured with a Doppler velocity probe, after the flow has reached a steady state. The rotation period of the tank was in this case T=30 s, and the diameter of the sink region was 0.27 m. The jet formed at about r=0.5 m (Ro=0.67 - 0.19). Plots of the second derivative of the zonal velocity are quite noisy (not shown here), but they show that the gradient of the total absolute vorticity changes sign several times.*

Right panels*: we evaluated the eddy damping of angular momentum in the form of angular momentum damping parameter α(r). Calculating this parameter is of fundamental interest, as it allows us to measure how effective the eddies (coherent structures) are at removing energy from the zonal flow. The calculation was made assuming that the rate of change of angular momentum is given by the sum of the torques due to the Coriolis (spin-up) effect and the damping (Ekman+eddy), where the latter is simply given by* $\tau_d = -\alpha L_z$ *(*L_z *being the angular momentum vertical component). Therefore, an expression can be derived for the parameter α(r) as a function of known quantities (Q, Ω,* U_θ*)*

Ongoing and Future Work

The result of these experiments are only preliminary and we have planned to perform a detailed analysis of all cases. A complete linear stability analysis can tell us which competing mode is most likely to attain a steady state after the onset of the barotropic instability Comparison between the theoretical predictions and the experimental results, as well as the analysis of the real atmospheric zonal wind mean profiles can shed a light on the mechanisms of formation of the coherent structured observed in the planetary polar vortices.

Since in Trondheim we didn't have a technique to measure Eulerian velocity fields, we repeated this experiment very recently (March 2009) in the 14-m diameter rotating tank of the Coriolis/LEGI laboratory in Grenoble, where high resolution *Particle Image Velocimetry* is available to measure the velocity of the flow in an Eulerian framework. The velocity field on the right is an example of the quality of the results we can obtain with this last experiments (here showing a dipole in experimental conditions comparable to those in Fig. 1. Credits to M. Manfrin, University of Turin).



References

[1] Piccioni G. et al. (2007), *Nature, 450,* 637–640. [2] Taylor F. W. et al. (1980), *J. Geophys. Res., 85,* 7963-8006. [3] Fletcher L.N. et al. (2008), *Science, 319,* 79-81. [4] Newman M. et al. (1984), *J. Atmos. Science 41*, No12, 1901-1913. [5] Elson L. S. (1982), *J. Atmos. Sci. 39*, 2356-2362 [6] Michelangeli D. V. et al. (1987), *J. Atmos. Sci. 44*, 2031-2041. [7] Limaye, S. S. et al. (2009) *Geophys. Res. Lett., 36,* L04204 [8] Aguiar A. et al. (2009) *Icarus,* submit.