# Planetary Polar Vortices: Instabilities in Nature and in the Laboratory


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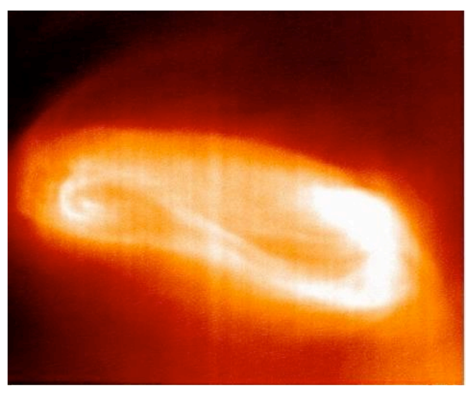
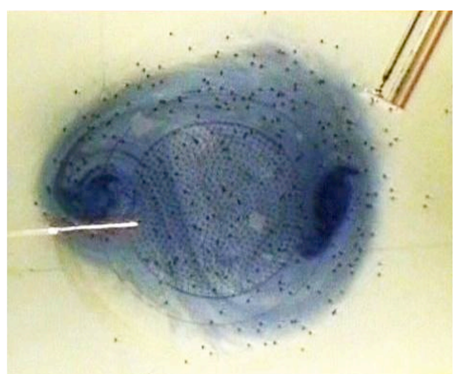
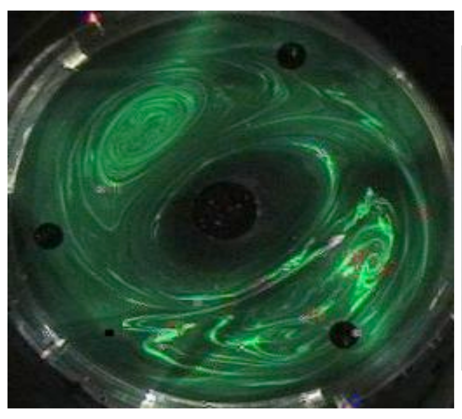
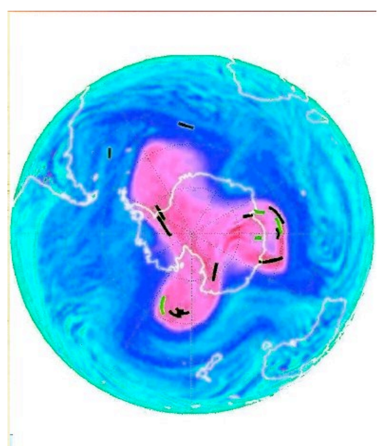
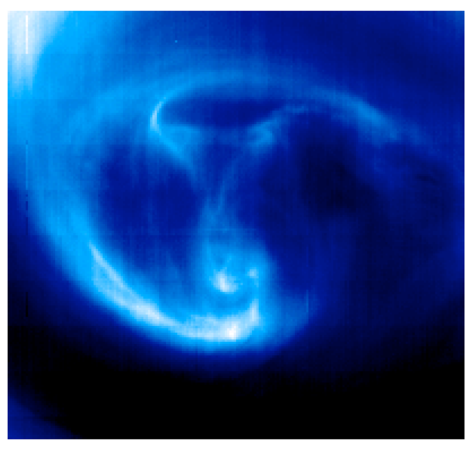
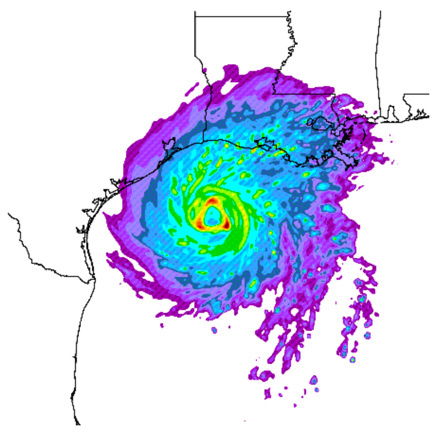
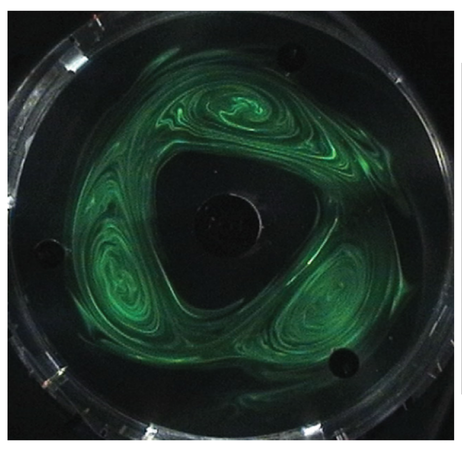
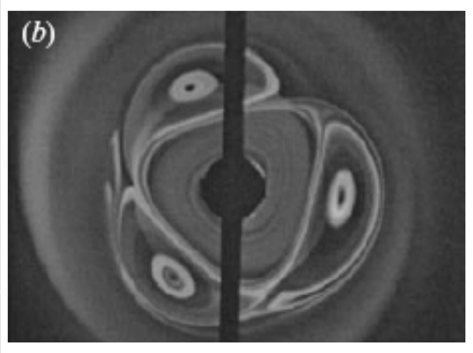
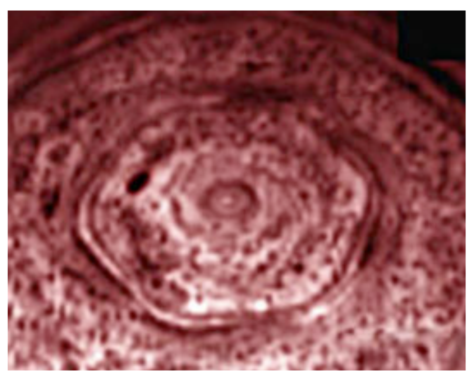
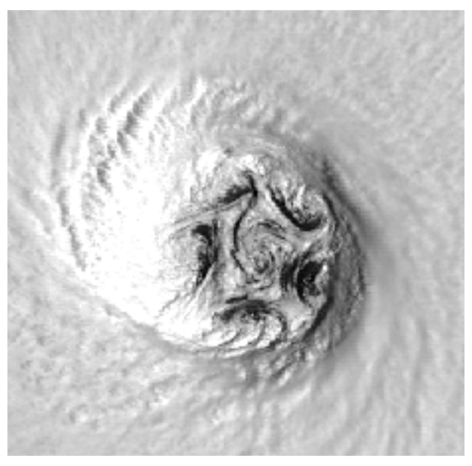
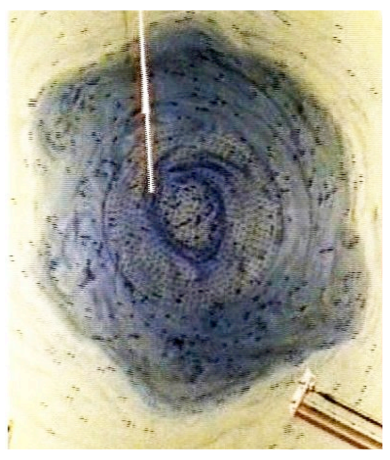
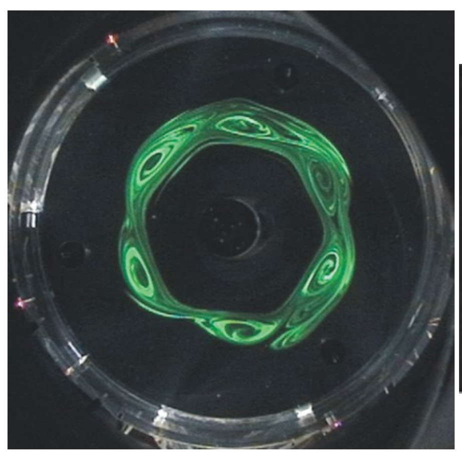
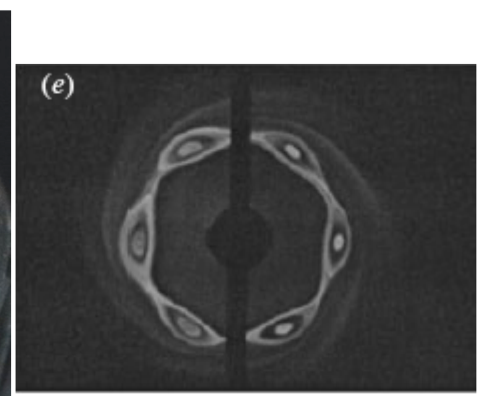
## Introduction

Polar vortices are a key element in the atmospheric dynamics of planets. These structures are observed in all planets of the Solar System with an atmosphere, 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], which has been stable for at least 30 years since the first observation by Voyager. Finally, instabilities similar to those observed in planetary polar vortices beyond Earth have also been observed in the central core of hurricanes on Earth [4], as well as in small and large-scale laboratory experiments, thus encompassing a range of scales varying by a factor of over 100 million.

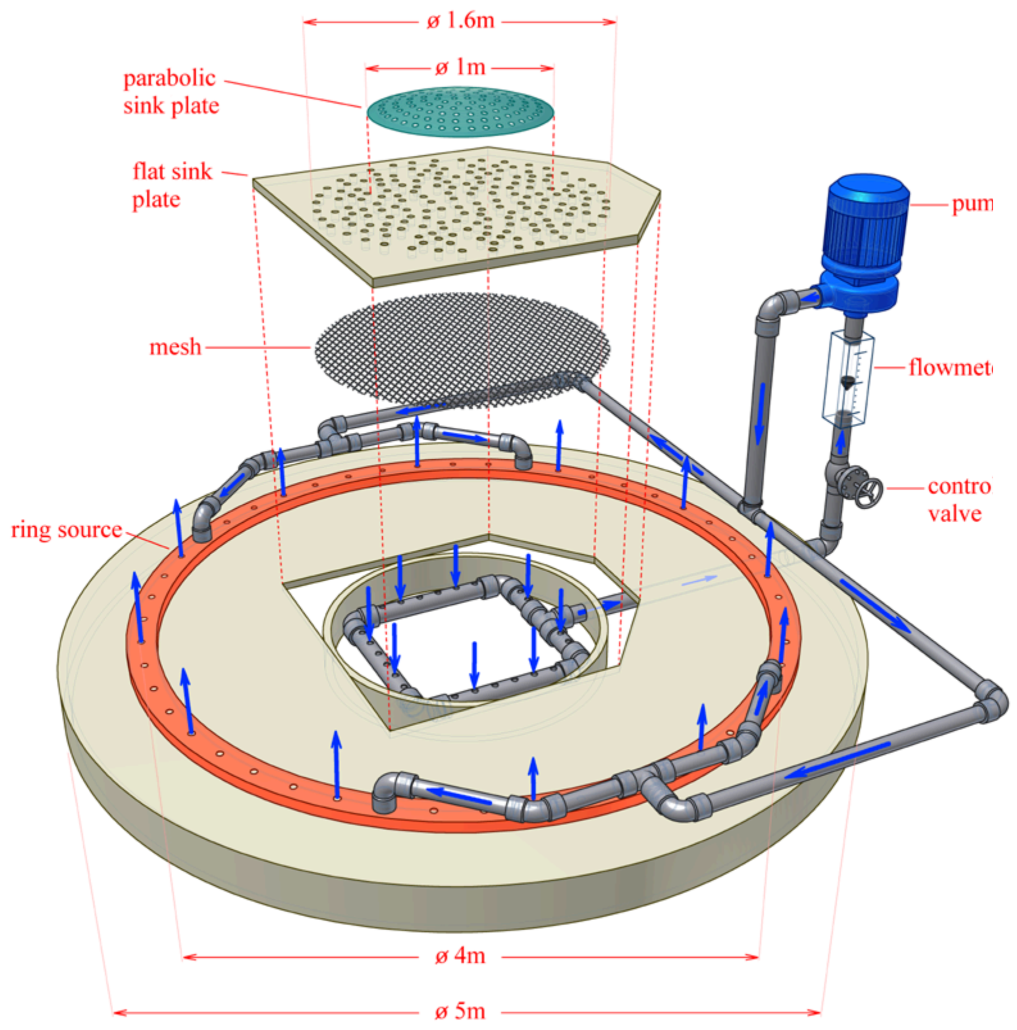
| | ~25·10⁶ m | ~5·10⁶ m | ~3·10⁶ m | ~10⁵ m | ~1 m | ~0.30 m | ~0.20 m |
|---|---|---|---|---|---|---|---|
| **Dipole (mode-2)** | | |  | |  |  |  (a) |
| **Tripole (mode-3)** | |  |  |  |  |  |  (b) |
| **Multipole (mode-5,6)** |  | | |  |  |  |  (e) |
| | Saturn's hexagon at the north pole. Infrared image (5.1 μm) from VIMS/CASSINI (credit to NASA) | Earth's sudden stratospheric warming at the south pole on 3rd Dec 2005. ECMWF 430K potential vorticity and VORCORE balloons. | Venus' south polar vortex. Dipole and tripole-like vortex core seen as brightness temperatures in the IR at 5.1 μm (corresponding to ~65 km altitude). | Upper picture: polygonal eyewall of hurricane Rita (2005) showing a tripole in the precipitable water map. Lower picture: eyewall of hurricane Isabel (2003), showing 5 mesovortices. | Source-sink laboratory experiment in a 5-m diameter rotating tank [5]. Blue dye is used for visualisation, together with black surface tracers. | Shear-flow laboratory experiment in a 0.6-m diameter rotating annulus [6]. Green dye is used for visualisation | Shear-flow laboratory experiment in a 0.6-m diameter rotating annulus [7]. Dye is used for visualisation. |

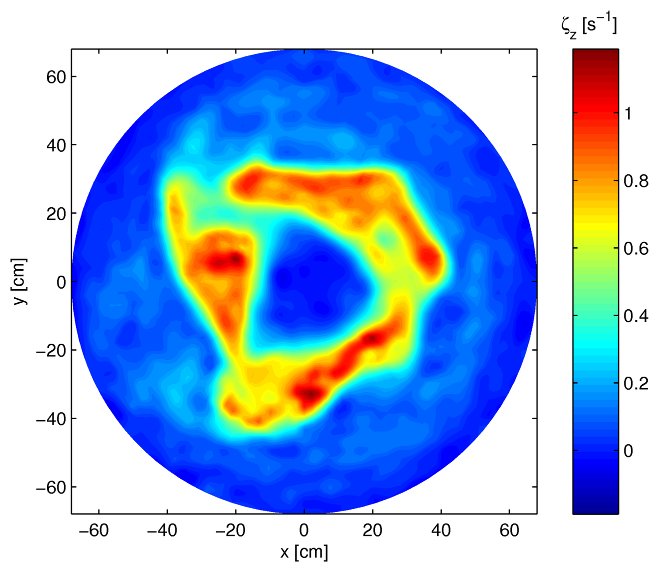
## Hypotheses

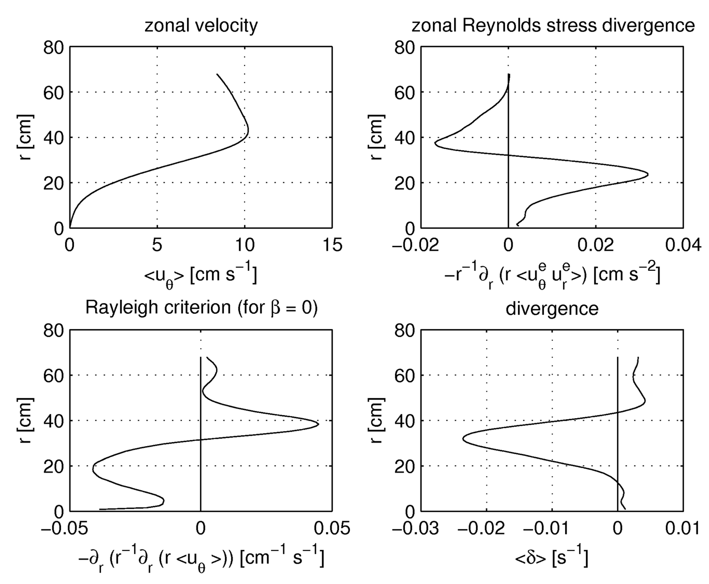
There is not yet a fully comprehensive explanation for the variety of polar vortices in the atmospheres of the planets. Many factors have been invoked to set a theoretical framework that could describe their bizarre shapes and account for their dynamics. Different kinds of instabilities could arise at 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 [8], and by results of numerical models [9, 10, 11]. Linear stability analysis suggests that the zonal wind profile on Saturn might be barotropically unstable at the latitudes of the North Polar Hexagon [6]. For the Earth, planetary wave breaking is often indicated as a cause of sudden stratospheric warming, particularly in the northern hemisphere. Small-scale waves (e.g. gravity waves) are also suggested as additional forcing mechanism facilitating the vortex breaking [12].

## Testing the barotropic instability hypothesis in the laboratory

We studied in the laboratory the possibility that barotropic instabilities at the edge of a polar vortex could lead to the formation of lobed coherent structures. The experiments were performed in the 5-m diameter rotating tank of the Norwegian University of Science and Technology in Trondheim (Norway) and in the 13-m diameter rotating tank of the Coriolis laboratory/LEGI in Grenoble (France). We used a source-sink technique to create a central vortex: water was pumped out of a source ring at a given flux rate Q, and was sucked from a central, circular sink region.




**Left:** plan of the experimental setup. The platform was positioned in the centre of the 13-m diameter tank at the Coriolis laboratory in Grenoble. A similar set-up was used in the 5-m diameter tank in Trondheim.

**Centre:** Vertical vorticity component 40 minutes after the setting of the initial conditions for the case of the experiment with T = 60 s and Q = 0.8 l/s.

**Right:** zonal (azimuthal) velocity, divergence of Reynolds stress, vorticity gradient and horizontal divergence for the same case. A necessary (but 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 $\partial q/\partial y = df/dy - \partial 2u/\partial y2 \leq 0$, where y is the northward coordinate, u is the zonal wind, f is the Coriolis parameter (neglected in this plot), and $q = f - \partial u/\partial y$ is the total absolute vorticity.

## References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