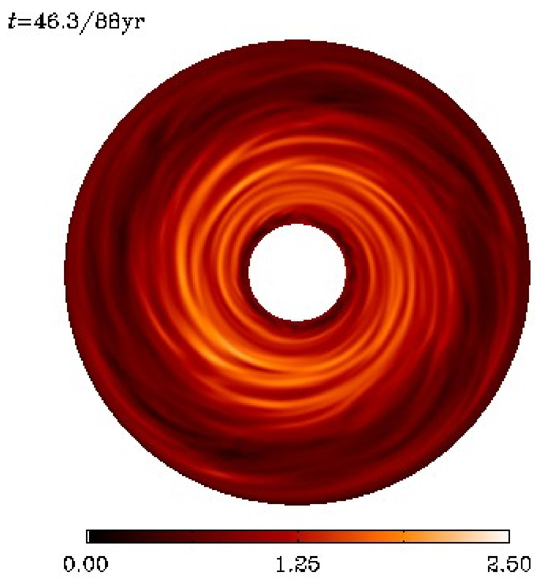
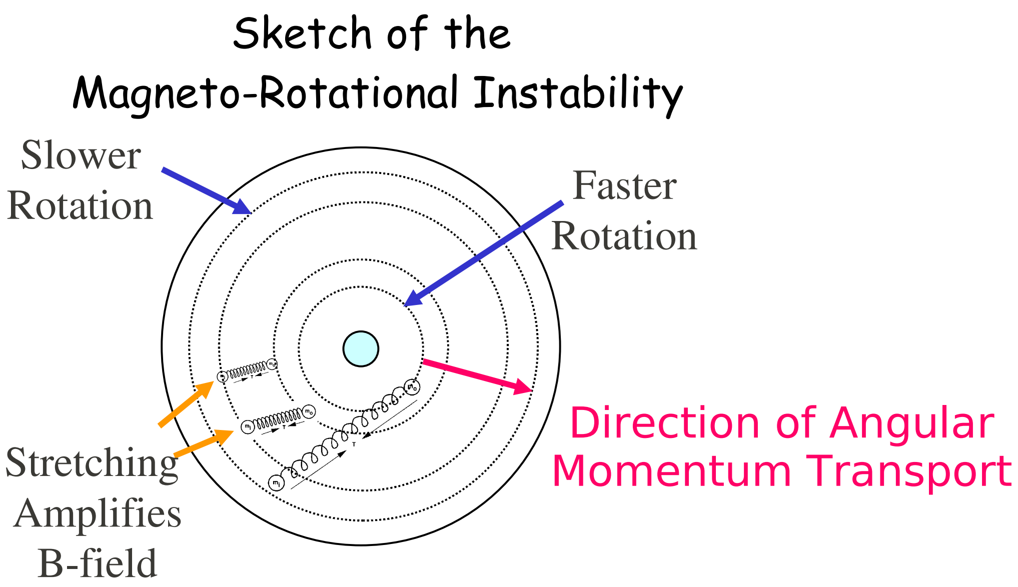
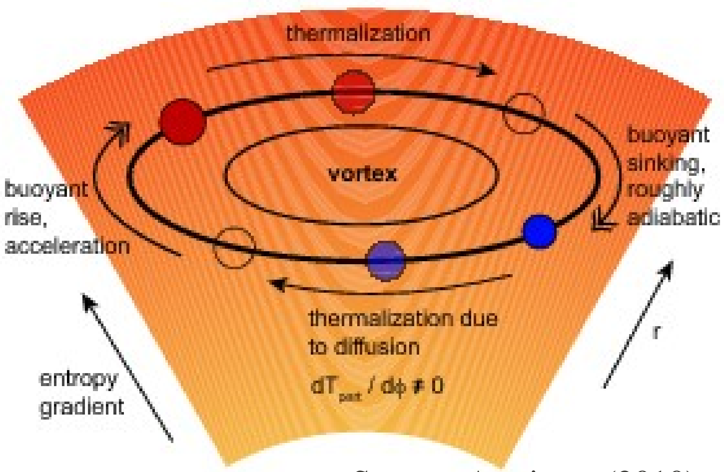
Planet formation in layered accretion flow





Turbulence in disks is enabled by the magneto-rotational instability (MRI), whereby the Keplerian rotation is de-stabilized by weak (subthermal) magnetic fields. Through most of the disk, however, the gas is only weakly ionized, being too cold and too dense to be ionized by either collisions or stellar X-rays. An MRI-dead zone should exist in the midplane of the disk, sandwiched by MRI-active layers. Accretion proceeds in the active layers and is stalled in the dead zone. A possible source of turbulence in the dead zone is the *Baroclinic Instability*.

Sketch of the Baroclinic Instability



Source: Armitage (2010)

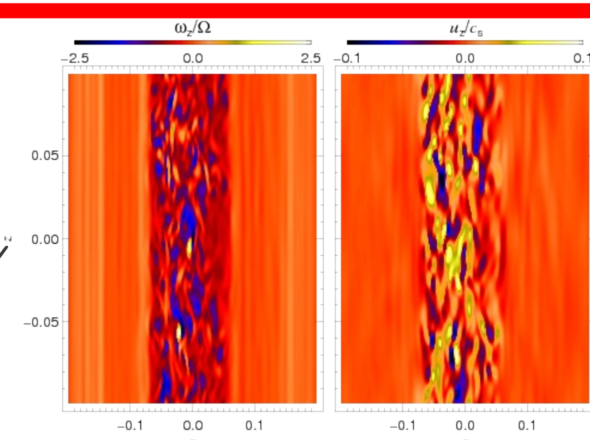
The recipe for the Baroclinic Instability:

- *Thermal diffusion or relaxation*
- *Finite amplitude perturbations*
- *Long evolution times*
- *High resolution*

Thermal diffusion is needed to establish the azimuthal temperature gradients. **Finite amplitude** is needed because the perturbations have to be strong enough to not be sheared away by the Keplerian motion. The instability is ***non-linear***. **Long evolution** times are needed for the same reason. The growth rate is proportional to *(H/r)^2*. A **resolution** requirement of at least 32 points per H is found to capture the instability in numerical simulations with the **Pencil Code**.

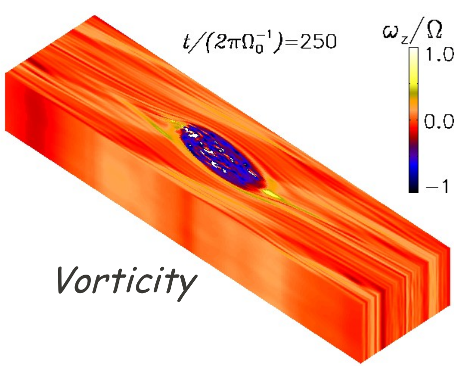
The sketch above illustrates how the instability works. In the presence of a radial temperature gradient, a buoyant gas parcel rising reaches its outer orbit with a higher temperature than the gas around it. When thermalized, the gas parcel is denser than the surrounding gas and thus sinks. When it reaches the lower orbit, it is colder than the surrounding gas, and the eddy swing works toward thermalizing it, closing the cycle. An azimuthal temperature gradient is established around the eddy. The radial and azimuthal gradients lead to a non-zero baroclinic vector, which promotes enstrophy generation. The saturated state is dominated by large scale vortices that have cores showing 3D turbulence due to the elliptic instability, as shown aside.

Vorticity

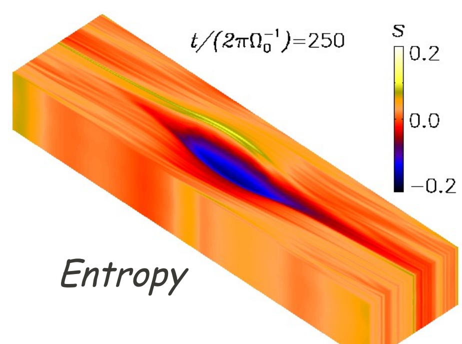


Kinetic Energy

Source: Lyra & Klahr (2010)

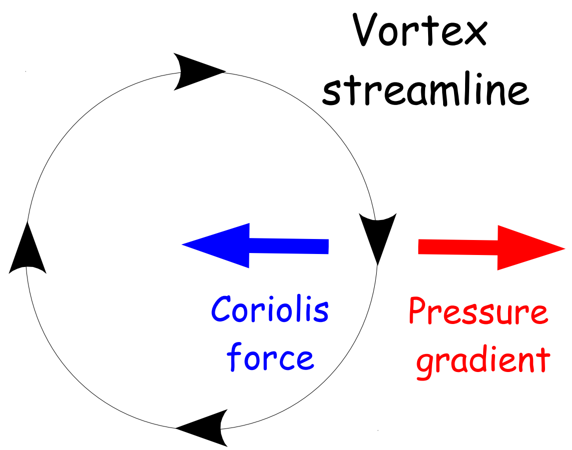


Vorticity



Entropy

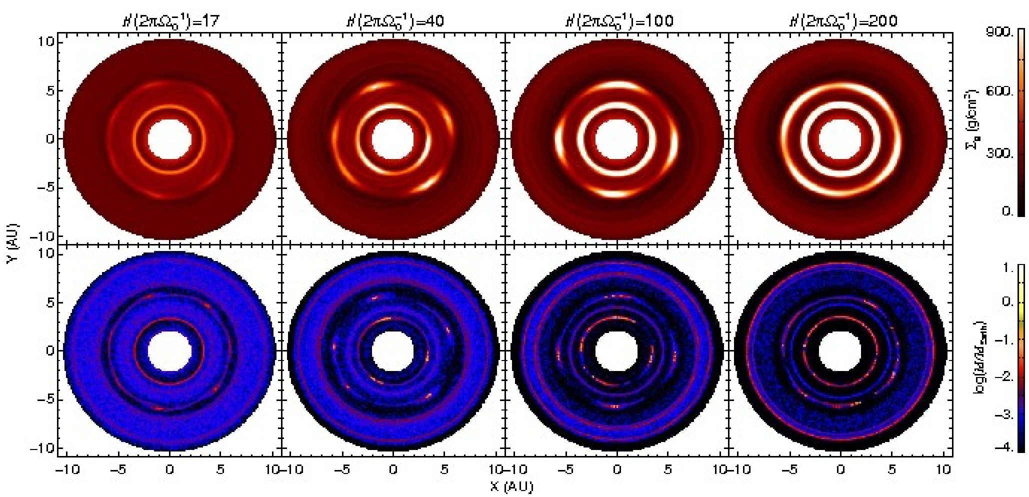
Vortices and planet formation

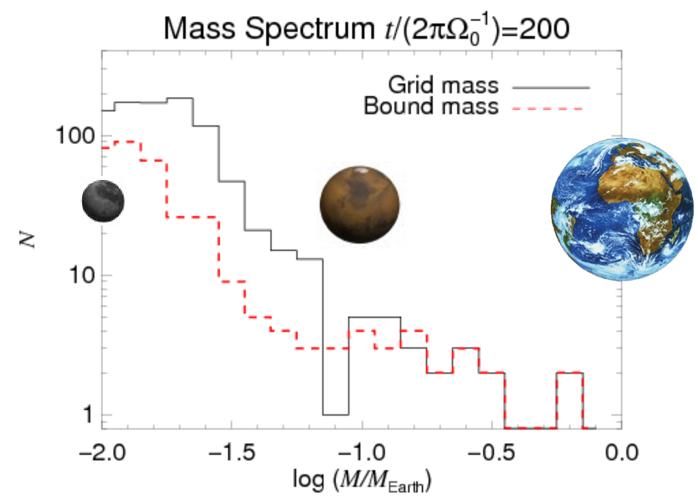


Geostrophic equilibrium

$$2\boldsymbol{\Omega}\times\boldsymbol{u}=-\rho^{-1}\nabla p$$

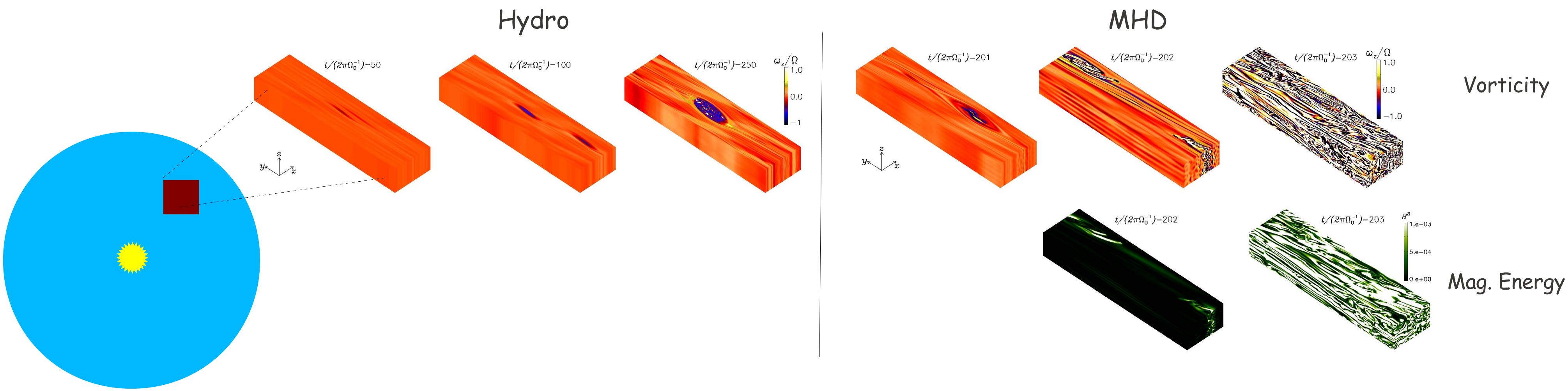
Anticyclonic vortices are very interesting sites for planet formation, because ***a).*** they are in ***geostrophic balance***, meaning that the Coriolis force is matched by the pressure gradient. The equilibrium configuration makes them persistent structures, that survive for many turn-over times. One example is the Great Red Spot, a giant vortex that exists in the Jovian atmosphere since the first telescope observations of the planet; and ***b).*** embedded solid particles do *not* feel the pressure gradient. Subject only to the Coriolis force, they sink to the center of the vortex, that therefore behaves as a particle collector, sweeping them up and increasing the number density of particles to high enough values to allow the concentration of solids to get *gravitationally bound*. When this happens, the ensemble of particles collapses into objects of planetary mass.





In the simulation shown above, vortices excited at dead zone boundaries collect particles until critical density is achieved. A burst of planet formation occurs, leading to the initial mass function show in the right. Over 300 gravitationally bound clumps are formed, 20 of them more massive than Mars.

The baroclinic instability in layered accretion flow.



We show, however, that vortices do not survive magnetization. In the hydro case, a balance is achieved between baroclinity and stretching, i.e., between the baroclinic and elliptic instabilities. The end result is coherent vortices with subsonic core turbulence, at the level of 10% of the sound speed. On the other hand, in the magnetic case, the horizontal modes of the magneto-elliptic instability are far more violent. Channel flows are excited, and a powerful core turbulence produces enough strain to break the vortex apart. The conclusion is that the baroclinic instability is relevant in the dead zone only.

My project as a Sagan fellow is to examine this process in a global calculation, establishing the large scale phenomenology of weakly ionized disks with baroclinic dead zones, and decisively answering the questions of whether large-scale vortices aid planet formation.

Coming soon....