PLANET EMBRYOS IN VORTEX WOMBS. J. A. Barranco, *NSF Astronomy & Astrophysics Postdoctoral Fellow, Center for Astrophysics, Cambridge, MA 02138 (jbarranco@cfa.harvard.edu)*, P. S. Marcus, *Dept. of Mechanical Engineering, University of California, Berkeley, CA 94720 (pmarcus@me.berkeley.edu)*.

We present the results of high-resolution, three-dimensional (3D) hydrodynamic simulations of the dynamics and formation of coherent, long-lived vortices in stably-stratified protoplanetary disks. Tall, columnar vortices that extend vertically through many scale heights in the disk are unstable to small perturbations; such vortices cannot maintain vertical alignment over more than a few scale heights and are ripped apart by the Keplerian shear. Short, finite-height vortices that extend only 1 scale height above and below the midplane are also unstable, but for a different reason: we have isolated an antisymmetric (with respect to the midplane) eigenmode that grows with an e-folding time of only a few orbital periods; the nonlinear evolution of this instability leads to the destruction of the vortex. Serendipitously, we observe the formation of 3D vortices that are centered not in the midplane, but at 1-3 scale heights above and below. Breaking internal gravity waves create vorticity; anticyclonic regions of vorticity roll-up and coalesce into new vortices, whereas cyclonic regions shear into thin azimuthal bands. Unlike the midplane-centered vortices that were placed *ad hoc* in the disk and turned out to be linearly unstable, the off-midplane vortices form naturally out of perturbations in the disk, and are stable and robust for many hundreds of orbits.

We have also investigated the formation of 3D vortices from random vorticity and/or temperature fluctuations. In the unstratified region near the midplane (where the Brunt-Väisälä frequency ω_B is less than the Coriolis frequency $\omega_C = \Omega_0$), the turbulence is essentially 3D in nature: vorticity fluctuations are randomly oriented and tend to rip each other apart as energy cascades from large scales down to small scales where it is dissipated via (hyper)viscosity. In the stratified regions away from the midplane (where $\omega_B > \omega_C$), the turbulence is more 2D in nature: vorticity fluctuations that are aligned with the rotation axis merge to form larger vortices, characteristic of an inverse cascade of energy. These vortices survive for as long as we have run the simulations (of order a thousand orbits).

Dust grains get trapped and concentrated in off-midplane vortices. Grains are prevented from falling into the midplane by vertical drag forces, in much the same way that large hail stones can be suspended in the Earth's atmosphere until they reach a critical size and rain out. We propose that grains will accumulate in off-midplane vortices, where they can grow via collisions and agglomeration, or via a local gravitational instability within the vortex core. Once the grains reach a critical size, they will rain out into the midplane of the protoplanetary disk.

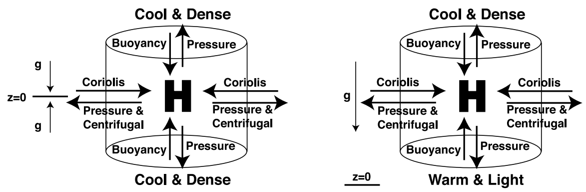

Figure 1: Balance of forces in an anticyclone with Rossby number less than unity.

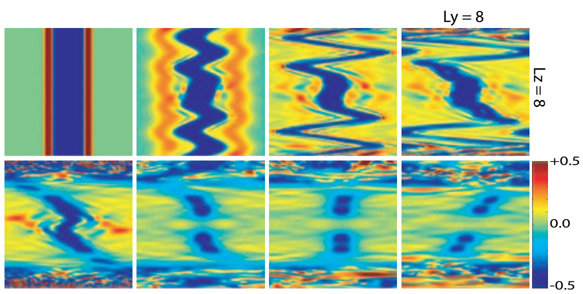

Figure 2: Tall, columnar vortex: $y-z$ slices at $x=0$ of the z-component of vorticity $\tilde{\omega}_z$. Blue = anticyclonic vorticity; red = cyclonic vorticity. The initial elliptical column had aspect ratio $\chi = 4$ and vorticity $\tilde{\omega}_z = 0.625$, corresponding to a Rossby number $Ro = 0.3125$. The times corresponding to each frame are: $t/\tau_{orb} = 0.0, 2.1, 4.2, 6.4, 51, 102, 153, 204$.

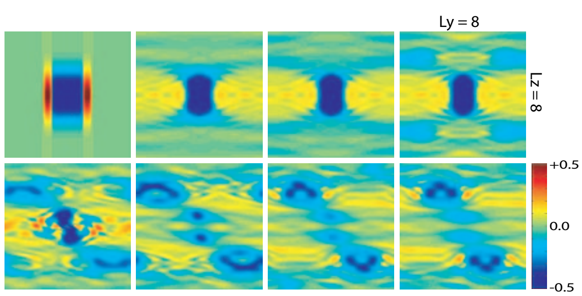

Figure 3: Finite-height cylindrical vortex: $y-z$ slices at $x=0$ of the z-component of vorticity $\tilde{\omega}_z$. Blue = anticyclonic vorticity, red = cyclonic vorticity. The initial elliptical cylinder had aspect ratio $\chi = 4$ and vorticity $\tilde{\omega}_z = 0.625$, corresponding to a Rossby number $Ro = 0.3125$. The time between frames is $\Delta t/\tau_{orb} \approx 60$.

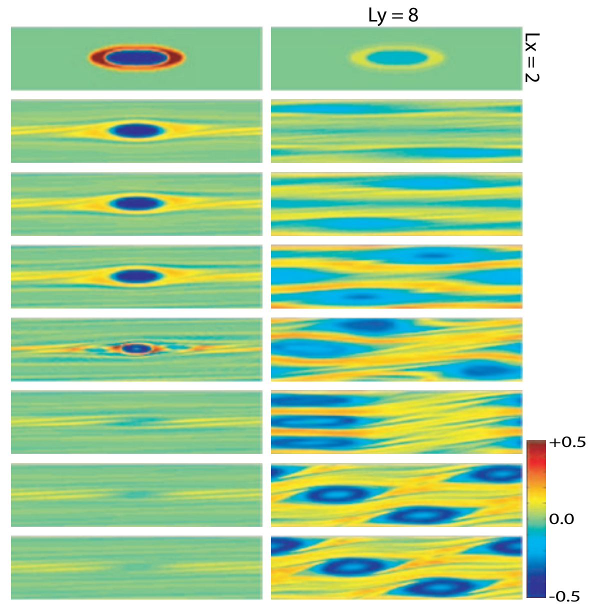

Figure 4: Finite-height cylindrical vortex: $x-y$ slices at $z=0$ (first column) and $z=2$ (second column) of the z-component of vorticity $\tilde{\omega}_z$. Blue = anticyclonic vorticity, red = cyclonic vorticity. The initial elliptical cylinder had aspect ratio $\chi = 4$ and vorticity $\tilde{\omega}_z = 0.625$, corresponding to a Rossby number $Ro = 0.3125$. The time between frames is $\Delta t/\tau_{orb} \approx 60$.

Figure 5: Dust particles trapped inside the core of an off-midplane vortex.