Planet Embryos in Vortex Wombs

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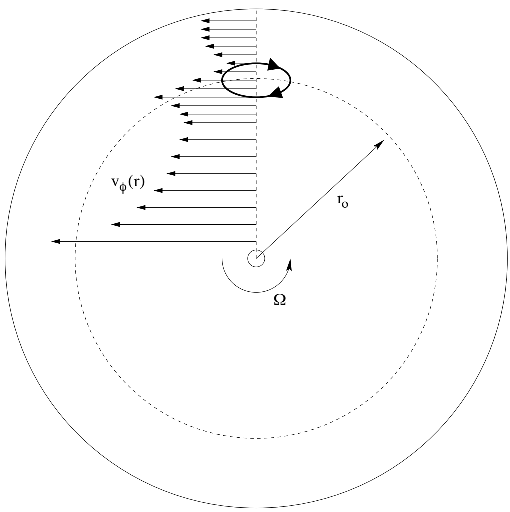
Abstract. One of the enduring puzzles in the formation of planetary systems is how millimeter-sized dust grains agglomerate to become kilometer-sized, self gravitating planetesimals, the "building blocks" of planets. One theory is that the dust grains settle into the mid-plane of the protoplanetary disk (thin, cool disk of gas and dust in orbit around a newly forming protostar) until they reach a critical density that triggers a gravitational instability to clumping. However, turbulence within the disk is likely to stir up the dust grains and prevent them from reaching this critical density. A competing theory is that dust grains grow by pair-wise collisions, forming fractal structures. It is unclear, however, how robust such structures would be to successive collisions. A new and exciting theory is that vortices in a protoplanetary disk may capture dust grains at their centers, "seeding" the formation of planetesimals. We are investigating the dynamics of 3D vortices in protoplanetary disks with a parallel spectral code on the Blue Horizon supercomputer. Some of the lingering questions we address are: What is the structure of 3D vortices in a protoplanetary disk? Are they columns that extend vertically through the disk, through many scale heights of pressure and density? Or are they more "pancake-like" and confined to the mid-plane? Are the vortices stable to small perturbations, such as vertical shear? Are 3D vortices robust and long-lived coherent structures? Do small vortices merge to form larger vortices the way vortices on Jupiter do?



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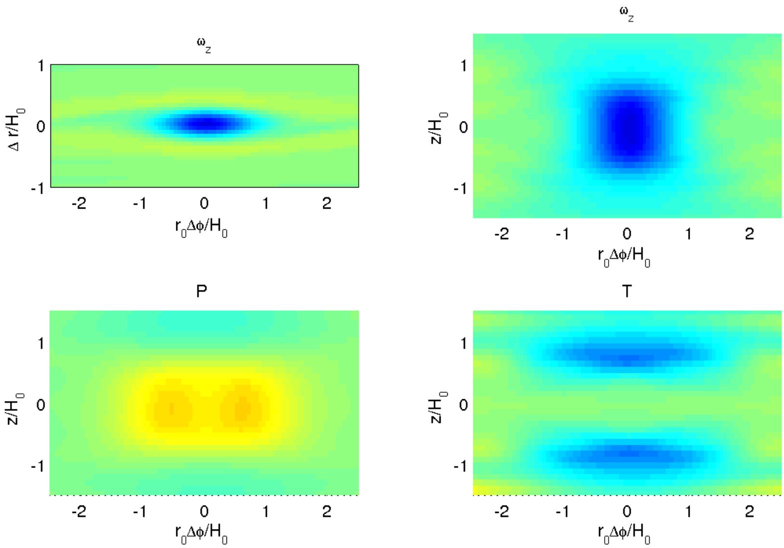

FIGURE 1. Slices through a 3D vortex located at $r = r_0$ in a protoplanetary disk. Vortex turn-around time is roughly 3 years. Clockwise, from upper left: z-component of vorticity in the midplane; z-component of vorticity in ϕ-z plane; temperature in ϕ-z plane; pressure in ϕ-z plane. Anticyclones are regions of high pressure. Note the "cold lids" which are needed to vertically confine the vortex: buoyancy balances vertical pressure gradient.

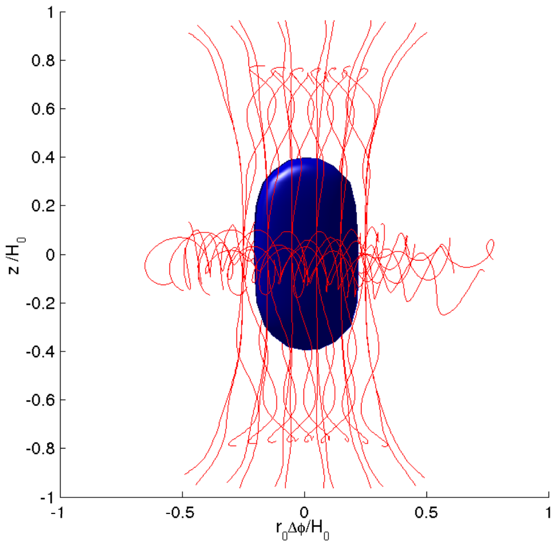

FIGURE 2. Same vortex as in Figure 1. Surface is an isovorticity surface for z-component of vorticity; lines are vortex lines which are everywhere tangent to the vorticity vector.

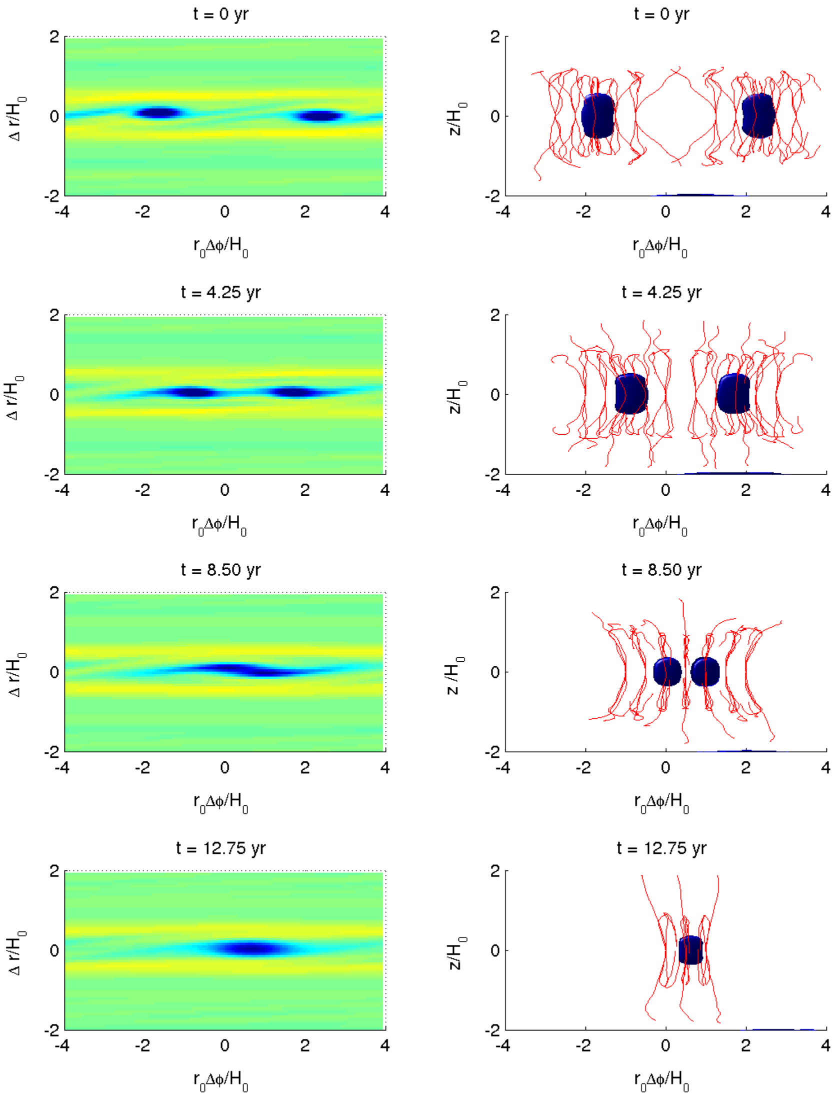

FIGURE 3. Two vortices in the midplane merging to form a new vortex. First column shows z-component of vorticity in the midplane. Second column shows isovorticity surface for z-component of vorticity, and vortex lines.

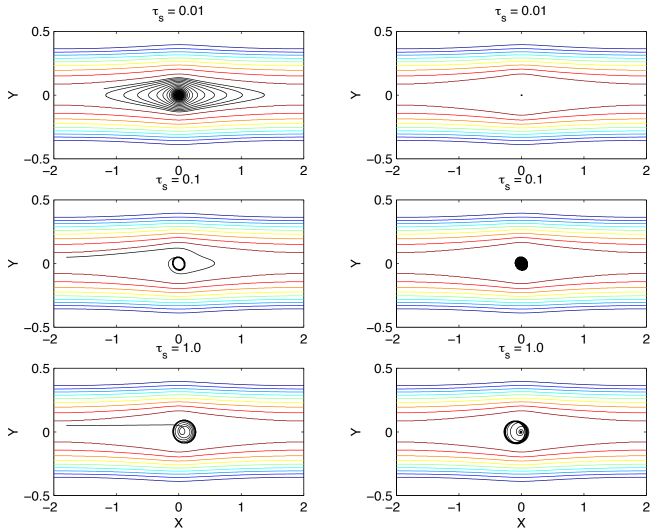

FIGURE 4. Trajectories (projected into the midplane) of individual grains within a vortex in a shear flow. The gray lines of various shades indicate the streamlines of the gas flow around the vortex. The vortex itself is not shown for clarity. Solid black lines are the trajectories of individual grains. $\tau_s \equiv t_s/T_{orb}$ is the stopping time normalized by the orbital period. From top–down, $\tau_s = 0.01, 0.1, 1.0$. First column shows trajectories of grains that were started outside the vortex on Keplerian orbits. Second column shows trajectories of grains started at the center of the vortex.

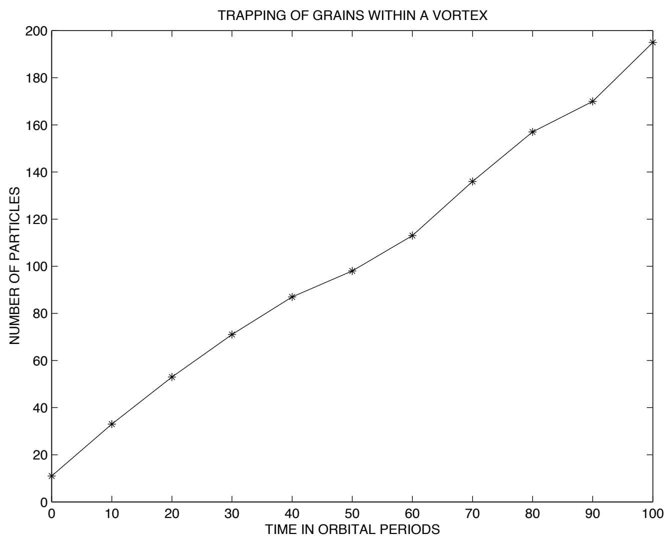

FIGURE 5. Number of particles trapped within vortex as a function of time. The vortex boundary is defined by the boundary of the patch of constant vorticity.