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Baroclinic vorticity production in protoplanetary disks

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Long-lived anti-cyclonic vortices in protoplanetary disks assist planetary formation by concentrating matter at the vortex core. Here we investigate vortex formation and longevity in protoplanetary disks using a reduced, coupled set of equations for vorticity and temperature which include baroclinic vorticity production and thermal damping. These equations are derived from conservation of momentum, energy, and mass in the anelastic limit, and are vertically integrated to produce a two-dimensional model. The numerical model is pseudo-spectral with Fourier-Chebyshev basis functions on an annulus, where the influence matrix technique is used to enforce stress-free boundary conditions.

Numerical simulations with initial temperature perturbations and zero initial vorticity produce coherent, long-lived vortices within several orbital periods. This study identifies regions of parameter space where shear due to differential rotation inhibits vortex formation, as well as regions of parameter space where strong vortices form. Conditions to overcome shear to form vortices include strong initial temperature perturbations and large radial temperature or density gradients.

Vortex longevity is strongly affected by the rate of radiative cooling. Strong radiative cooling enhances the baroclinic feedback and maintains vortices for over 120 orbital periods. A lack of radiative cooling produces a stratified temperature field and no baroclinicity after ten orbital periods, so that vortices are not reinforced and dissipate away.

Angular momentum transport due to turbulence and vortices is often negative (inward), as shown by numerical simulations and a simple vortex model.