The astrophysical and geophysical flows group

Astrophysical and geophysical fluid flows are usually dominated by large lengths and velocities, so the flows are often turbulent. The 2000 Summer Program focused on the late stages of star formation, planet formation, sediment transport, and turbulence in the upper ocean. Modeling and computing the turbulence within a protostar's thin accretion disk, in which the primary flow is near-Keplerian, are made complicated by the strong rotation and shear, the compressibility, and a small overall aspect ratio. The group's work in star formation was motivated by an unsolved problem in mass and momentum transport: to form a star, gas must move radially inward from the outer edge of the disk and accrete onto the central object, but it also must maintain a nearly-Keplerian azimuthal velocity as it moves. Therefore, the inward mass transport requires that the moving parcels of gas give up some of their angular momentum (and energy) to the ambient gas. The disk must, therefore, create a secondary flow to transport this angular momentum radially outward. There is no known way to do this. The traditional astrophysical literature suggests that turbulence within the disk is responsible for this angular momentum transport, despite the fact that the required transport is in the *same* direction as the mean angular momentum gradient of the disk (which is contrary to our usual expectation: turbulence usually transports quantities into regions where their densities are relatively low). The group's goal was to determine how a secondary flow, turbulent or otherwise, might carry out this transport and still allow mass to accrete onto the central star fast enough to agree with observations.

Our group's motivation for our work in planet formation was inspired by the recent discoveries of planets outside our solar system. Their large sizes and proximity to their suns violate accepted scenarios of planet formation and bring into question much of what has been previously written. Our group focused on the question of how turbulence and coherent vortices within the protoplanetary disk could promote or inhibit the accumulation of dust grains into planetesimals (objects of sufficient mass that their own self-gravity allows them to accrete mass in the turbulent disk environment).

The motivation for the work in sediment transport was the understanding of how pollutants such as heavy metals and pesticides, which bind to sediment particles, spread through harbors and rivers. The work in turbulence in the upper ocean was inspired by recent observations that vertically propagating, internal wave packets in the upper thermocline of the ocean may be important for sustaining turbulent mixing.

The research group of Barranco, Marcus & Umurhan was faced with the difficulties of unknown equations of energy and state in the disk (which in some parts is optically thin and in others thick) and unknown boundary conditions (since the gas is in-falling at the outer edge and joins at the inner edge onto the star through a boundary layer in which magnetic fields are likely to be important). The group concentrated on formulating a well-posed problem that was numerically tractable. They found that through judicious use of asymptotic expansions, the boundary conditions and equations of state and energy could be easily parameterized. Their analyses were based on the premise that turbulence alone was not likely to solve the transport problems and that coherent vortices were needed. This premise was bolstered by Orlandi's numerical calculations of cross-stream mass transport in a shearing channel, which showed that coherent and numerically-resolvable flow structures can account for this type of mass/momentum transport. Since previous calculations as well as calculations by others indicated that subsonic vortices with order-unity Rossby numbers (ratios of the inertial to the Coriolis forces) would be the most long-lived, the asymptotics were developed in this parameter regime. Formal asymptotics were carried out, and three sets of self-consistent equations were found. It was shown that all three sets had the same boundary condition requirements as the anelastic Euler equation. It was shown analytically that a barotropic protoplanetary disk obeying any one of these asymptotic equations could not solve the transport problem. A small amount of baroclinicity was required. The analysis showed that the vortices were efficient transporters of mass and angular momentum and that only two or three vortices at each radial location were sufficient for observed star formation rates. The asymptotics were formulated for calculations in a thin, annular section of the protoplanetary disk, so the equations could be mapped into a Cartesian domain. Although the equations were periodic in the mapped azimuthal coordinate, they were not in the radial coordinate. By applying a Rogallo transform to the equations, Shariff was able to make them periodic in the radial direction as well and modify an existing code to solve the asymptotic equations.

Barranco & Marcus considered the role of vortices in the process of aggregating dust grains into large planetesimals. They found that grains moving initially in non-circular and/or non-planar orbits with respect to the disk quickly moved into planar, near circular orbits due to the drag of the gas within the disk when the flow was laminar. They showed numerically that dust grains were attracted to vortices within the disk and could create large (and strongly self-gravitating) density perturbations. This seems paradoxical since it would be expected that the centrifugal force of a vortex would eject grains. However, Barranco derived a simple physical argument why this is not so and went on to numerically compute the attracting regions of the dust in or near the vortex. As a function of the grain-stopping time, the attracting region changes from a single point within the vortex to a ring within the vortex and then to a large ring around the vortex (and in the plain of the disk).

Boersma numerically examined sediment transport by carrying out direct numerical calculations of three-dimensional flow in a channel. The wavy bottom boundary was designed to simulate both a rippled river or ocean bottom and previous wind tunnel experiments. Like the experiments, the calculations of the fluid motion and the particle paths showed that Langmuir-like vortices were created that were aligned in the longitudinal direction. The particles tended to concentrate downstream of the wave tops.

Carnevale & Orlandi used two-dimensional numerical simulations to examine internal waves in the upper ocean thermocline. In their numerical experiments, wave packets propagated vertically in a manner that was consistent with the observed vertical scales in the ocean. Strong packets generated turbulence that formed a continuous ‘scar’ of small-scale perturbations in their wakes that were much longer than the size of the packets themselves. The results are important due to their implications for turbulent mixing in the upper ocean.

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