Laminar to turbulent transition in librating spheres

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Celestial bodies, such as moons, may undergo forced libration in longitude as a result of gravitational interactions with their orbital counterparts. This simple harmonic oscillation in their rotation rate induces complex fluid flow within their liquid metal cores (e.g., Ganymede, the Moon) or subsurface oceans (e.g., Europa, Enceladus).[1] Understanding the fluid response to this forcing mechanism is essential for elucidating the dynamics and structure of these bodies.[2] Mechanical energy is transferred from the solid shells to the fluid regions and mainly dissipated within the boundary layer. To correctly estimate the viscous torque, it is important to know the type of boundary layer, i.e., whether it is laminar or turbulent. In this talk, we present the development of boundary layer instabilities induced by libration in a full sphere. To address the non-linear problem numerically, we employ XSHELLS, a highly parallelized solver for spherical shells.[3] We conduct an extensive parametric study, systematically varying the Ekman number and the libration amplitude. This results in local Reynolds numbers ranging from less than one to 700. In the laminar regimes, the numerically computed torque is presented against different theoretical models [4] [5]. Achieving substantial agreement in the limit of vanishing Ekman numbers. Then, the focus is directed towards the spatio-temporal evolution of the boundary layer as a function of the local Reynolds number. In this part, we prevent the direct forcing of inertial waves by setting a libration frequency that exceeds twice the rotation frequency. We verify the existence of three distinct regimes[6]: (1) At low forcing amplitudes, a stable boundary layer is present, extending across all latitudes. (2) For a local Reynolds number larger than 50, a secondary flow in the form of longitudinal rolls develops near the boundary at equatorial latitudes. These Görtler vortices remain axisymmetric and smooth for intermediate local Reynolds numbers. At higher latitudes, the boundary layer remains laminar. The angular extent of the band affected by the longitudinal rolls increases with the forcing amplitude. (3) For sufficiently high forcing, shear instabilities destabilize the rolls, leading to boundary layer turbulence. Most notably present in the retrograde phase, when maximum shear is exerted. In the prograde phase, the boundary layer experiences relaminarization. The attached figure, which displays the azimuthal velocity distribution close to the boundary layer, illustrates the various stages and their complex dynamics. At the equator, we see a turbulent band of fluid that consistently rotates prograde, regardless of the time-dependent forcing. The latitude-dependent delay in the fluid's response serves as a source of shear instability. By accurately quantifying the latitudinal extent of the equatorial band, novel models for torque estimation are proposed for the transitional and turbulent regions.

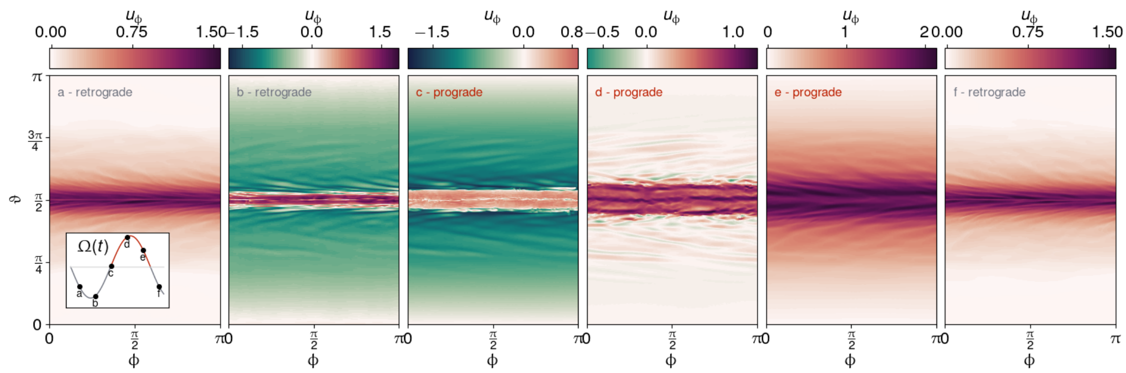

Figure 1: Surface plot of the azimuthal velocity at $r = 0.99$, at different stages in the libration cycle. $Re = 400$, $Ek = 10^{-4}$. Only half spherical surface is shown.

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