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Abstract

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Stewartson layers, inertial waves and wave instabilities in a spherical-gap flow: Laboratory experiments with full optical access

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We experimentally study linear and nonlinear inertial waves and modes as well as Stewartson layers in a spherical gap with a radius ratio of $\eta = r_\mathrm{i}/r_\mathrm{o} = 1/3$. Inertial waves and wave modes are Coriolis-restored linear waves which often arise in rapidly rotating fluids. To excite and investigate these features, two forcing systems are considered: (i) inner-sphere libration for which the sphere globally rotates at Ω_0 around its vertical axis, and a time-periodic variation of the inner sphere's angular speed in the interval $0 < \omega_\mathrm{lib} < 2\Omega_0$ is overlaid, and (ii) steady differential rotation for which the inner sphere and the outer shell rotate at different speeds (spherical Couette flow), i.e. $\Omega_\mathrm{i} \neq \Omega_\mathrm{o}$ with $\Omega_\mathrm{o} \neq 0$. To visualise and measure the flow, two methods based on a laser-light-sheet technique have been used: (i) qualitative measurements in the meridional plane using Kalliroscope tracer particles, and (ii) quantitative co-rotating particle-image-velocimetry (PIV) measurements in the horizontal plane using spherical tracer particles.

In the first part, we discuss the structure of the Stewartson layer in both systems. The Stewartson layer is a vertical shear layer tangential to the inner sphere's equator. For a critical shear, it becomes unstable due to shear instability. These instabilities are characterised by low-frequency wavy structures that correspond to Rossby wave instabilities. Some of these are travelling retrograde and are trapped near the Stewartson layer, others are travelling prograde filling the whole gap outside of the Stewartson layer. Since libration can be seen as a time periodic variation of differential rotation, we found the flow behaviour to be similar in both systems. The experimental results confirm theoretical, numerical, as well as other experimental studies on Stewartson-layer instabilities.

In the second part, we investigate plane inertial waves. The influence of the libration amplitude and the libration frequency on the waves and further the efficiency of the forcing to excite inertial waves are discussed. A simple 2D ray-tracing model is applied for the meridional plane to interpret the visualisations with respect to energy focusing and wave attractors. Further, nonlinear wave interactions with Rossby waves are examined.

In the third part, we investigate inertial modes in the spherical Couette flow. Recent experimental work has shown that inertial modes exist in a spherical Couette flow for $\Omega_\mathrm{i} < \Omega_\mathrm{o}$. A finite number of particular inertial modes has previously been found. By scanning the Rossby number from $-2.5 < Ro = (\Omega_\mathrm{i} - \Omega_\mathrm{o})/\Omega_\mathrm{o} < 0$ at two fixed Ω_o, we report the existence of similar inertial modes. However, the behaviour of the flow described here differs much from previous spherical Couette experiments. We show that the kinetic energy of the dominant inertial mode dramatically increases with decreasing Rossby number that eventually leads to a wave-breaking and an increase of small-scale structures at a critical Rossby number. Such a transition in a spherical Couette flow has not been described before. The critical Rossby number scales with the Ekman number, $E = \nu/(\Omega_\mathrm{o}\, d^2)$, as $E^{1/5}$. Here, ν is the kinematic viscosity and d the gap width. Additionally, the increase of small-scale features beyond the transition transfers energy to a massively enhanced mean flow around the tangent cylinder. In this context, we discuss an interaction between the dominant inertial modes with a geostrophic Rossby mode exciting secondary modes whose frequencies match the triadic resonance condition. Results of preliminary numerical simulations confirm the experimental results.