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Observation of standard magnetorotational instability in the laboratory

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Astronomical accretion disks consist of gas or plasma orbiting a compact massive object such as a black hole or protostar, and slowly spiraling inward (accreting) by surrendering orbital angular momentum to other material in the disk or in an out flow. Driven by gravity, the angular velocity profile in a Keplerian flow has a decaying power-law dependence on cylindrical radius, $\Omega(r)\propto r^{-q}$, with $q=3/2$. According to Rayleigh's criterion[1], purely hydrodynamic rotation profiles with $0<q<2$ ("quasi-Keplerian") are linearly stable to perturbations[2], thus cannot excite the turbulence required to explain the astronomically observed rapid accretion. The standard magnetorotational instability (SMRI)—a unique magnetohydrodynamic (MHD) instability in a conducting Keplerian flow in the presence of an axial magnetic field—is thus regarded as one of the most promising mechanisms for unraveling the origin of turbulence in accretion disks[3]. However, unlike other fundamental plasma processes such as Alfvén waves and magnetic reconnection which have been subsequently detected and studied in space and in the laboratory, SMRI remains unconfirmed even for its existence long after its proposal, despite its astrophysical importance. Its direct detection has been hindered in observations due to its microscopic nature at astronomical distances, and in the laboratory due to stringent requirements and interferences from other processes.

In this talk, I will present direct evidence for the axisymmetric SMRI from a combined experimental and numerical study of a magnetized quasi-Keplerian liquid-metal flow in a Taylor-Couette cell, where the inner cylinder, outer cylinder, and upper (lower) conducting endcaps corotate independently at angular velocities Ω_1, Ω_2, and Ω_3, respectively[4]. When a uniform vertical magnetic field B_i is applied along the rotation axis, the measured radial magnetic field B_r on the inner cylinder increases linearly with a small magnetic Reynolds number Rm due to the magnetization of the residue Ekman circulation. Onset of the axisymmetric SMRI is identified from the nonlinear increase of Br beyond a critical Rm in both experiments and nonlinear numerical simulations. The axisymmetric SMRI exists only at sufficiently large Rm and intermediate B_i, a feature qualitatively consistent with theoretical predictions. On the other hand, the required minimum Rm is below the predictions of linear analyses with periodic axial boundaries, which is caused by the imperfect bifurcation nature of the axisymmetric SMRI in our closed system. Our simulations further show that the axisymmetric SMRI causes the velocity and magnetic fields to contribute an outward flux of axial angular momentum in the bulk region, just as it should in accretion disks.

In the meantime, the SMRI is found to be accompanied by a global nonaxisymmetric MHD instability[5], which has an exponential growth at its onset and an azimuthal mode number m=1 with a moderate frequency $\Omega_1-\Omega_3<f<\Omega_1-\Omega_2$ in the corotating frame of the inner cylinder. Further analysis also suggests that it is unlikely to be the hydrodynamic Rayleigh instability or the Stewartson-Shercliff layer instability, implying that it could be a nonaxisymmetric form of SMRI that breaks the rotational symmetry of the system. The experimental results are reproduced by nonlinear three-dimensional numerical simulations, which further show that the nonaxisymmetric instability is generated linearly from the primary axisymmetric flow modified by the applied axial magnetic field.

References

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