PHYSICAL REVIEW E **89**, 021004(R) (2014)

Nonlinear stability of laboratory quasi-Keplerian flows

E. M. Edlund and H. Ji
Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543, USA
(Received 5 August 2013; published 24 February 2014)

Experiments in a modified Taylor-Couette device, spanning Reynolds numbers of 10^5 to greater than 10^6, reveal the nonlinear stability of astrophysically relevant flows. Nearly ideal rotation, expected in the absence of axial boundaries, is achieved for a narrow range of operating parameters. Departures from optimal control parameters identify centrifugal instability of boundary layers as the primary source of turbulence observed in former experiments. By driving perturbations from a series of jets we demonstrate the robustly quiescent nature of quasi-Keplerian flows, indicating that sustained turbulence does not exist.

DOI: 10.1103/PhysRevE.89.021004 PACS number(s): 47.32.Ef, 47.27.Jv, 47.27.N−, 47.27.Rc

The sheared flows of dust, gas, and plasma in accretion disks are reservoirs of free energy with the potential to drive turbulence that enhances the outward transport of angular momentum. While theoretical studies indicate that magnetic fields play an important role in hot, well-ionized accretion disks through the magnetorotational instability (MRI) [1], colder accretion disks, like weakly ionized protoplanetary systems, are stable with respect to infinitesimal perturbations even in the limit of vanishing viscosity. Various mechanisms for enhanced transport in the hydrodynamic regions of protoplanetary disks have been proposed, including coupling to magnetohydrodynamic surface layers [2,3], compressible effects such as baroclinic instability [4] and Rossby wave instability [5], or a subcritical transition to turbulence [6]. This last mechanism, that is, sustained turbulence triggered in laminar flow by finite-amplitude perturbations, has been observed in rectilinear systems such as plane Couette flow [7] and pipe flow [8] and remains a candidate to explain enhanced transport in cold accretion disks. Prior experiments and simulations fall on both sides of the debate as to whether there exists a purely hydrodynamic pathway to sustained turbulence in rotating fluid systems like those of accretion disks. We demonstrate through a series of experiments that turbulence from boundary layers can obscure the inherent stability of the bulk flow in laboratory experiments and that remarkably quiescent, robustly stable flows develop when unstable boundary layers are mitigated, despite applications of large perturbations. These observations suggest that additional physics beyond that of incompressible hydrodynamics is necessary for enhanced angular momentum transport in accretion disks.

Synopses of recent discussions regarding the laboratory approach to studies of quasi-Keplerian flows, that is, flows with $d|\Omega|/dr < 0$ and $d|r^2\Omega|/dr > 0$, can be found in Refs. [9] and [10]. The primary experimental apparatus used for such studies is the Taylor-Couette device, in essence two coaxial cylinders capable of differential rotation with the working fluid between (see Fig. 1). A rich space of secondary motions exists when Taylor-Couette devices are operated at low Reynolds numbers of order 10^3 ($\mathrm{Re} \sim vL/\nu$ is the ratio of inertial to viscous forces, where v is a representative system velocity, L is a system length scale, and ν is the kinematic viscosity), with bifurcations and hysteresis between states [11,12]. Subcritical behavior has been observed in linearly stable, rotating flow [13–16], but in the astrophysically irrelevant regime of $d|\Omega|/dr > 0$. Using a Taylor-Couette apparatus with modified axial boundaries, Ji *et al.* [17,18] found large Re, quasi-Keplerian flows to have very low levels of fluctuations and measured the local transport of angular momentum to be orders of magnitude too small for astrophysical relevance. The latter paper [18] in particular claims that a subcritical transition likely does not exist, but does not prove this point directly with finite-amplitude perturbations. In contrast, Paoletti and Lathrop (PL) [19], using a Taylor-Couette device of the classical configuration, where the axial boundaries corotate with the outer cylinder, found enhanced torque on the inner cylinder in the quasi-Keplerian regime of operation and hypothesized that this was due to a sustained turbulent state, the result of hysteresis, and by implication, a sign of a subcritical transition to turbulence. However, the PL studies did not directly measure the rotation profiles and therefore could not distinguish the stability properties of the bulk flow from those of the boundary layers.

Numerical simulations of the Ji *et al.* and PL experiments conducted by Avila [20] attempted to reconcile differences in measured angular momentum transport. Avila concluded that the enhanced torque in the quasi-Keplerian regime of the PL experiments arose from boundary-layer turbulence near the inner cylinder. A highly turbulent state was also found for the Ji *et al.* experiments, contrary to observations of quiescent flows at large Re, although this may be consistent with lower-Re experiments in the range of 10^4 to 10^5 where enhanced Reynolds stress was measured [17]. Simulating accretion disk geometries, Balbus, Hawley, and Stone (BHS) [21] performed three-dimensional, finite-volume simulations for Re in the range of 10^3 to 10^4 and found that hydrodynamic instability is possible only when the rotational shear exceeds the limit for centrifugal stability. However, at lower values of rotational shear, for astrophysically relevant flows, BHS found only dissipation of the seed turbulence. In contrast, shearing box simulations have found both outward transport of angular momentum [22] and, in the simulations of Lesur and Longaretti (LL) [23], sustained turbulence based on extrapolations of turbulence lifetimes, with critical Re for a transition spanning the range of 10^6 to 10^{26}. In short, there is little agreement among numerical simulations as to whether subcritical turbulence exists and, if it does, what Re is needed for transition. Our studies seek to resolve this controversy and

