**Motivation**

The accretion of gas, dust, and plasma orbiting a strong gravitational source is responsible for the observed luminosity of systems such as binary star systems and active galactic nuclei. Accretion disk dynamics also set the timescale for star and planet formation in protostellar disks. The rate of accretion is governed by how quickly angular momentum can be transported through the disk. Inferred rates of accretion suggest that this transport is inefficient, thus turbulence models are invoked to explain observations. The mechanism responsible for turbulent transport in these accretion disks is the Magnetorotational Instability (MRI), a linear instability caused by the Maxwell stress introduced by an ambient magnetic field coupled to the Keplerian sheared flow. The MRI is sufficiently generic that it should be observable in any hydrodynamically stable rotating shear flow with a radially-decreasing angular velocity for sufficiently high magnetic Reynolds number with an externally applied axial magnetic field. The Princeton MRI experiment was designed to study the stability of rotating shear flow in a magnetized conducting fluid. The unique design of this experiment allows the generation of quiescent shear flow at high Reynolds number (Re > 10^5) as demonstrated by Reynolds stress measurements using water. The experiment has been filled with a gallium eutectic alloy and operated with an applied axial magnetic field of up to 5 kG. The most recent measurements show the emergence of nonaxisymmetric MRI modes from magnetized turbulent shear flow using an array of radially-aligned induction coils. The modes process toroidally and display a frequency splitting which scales as the rotation speed, a characteristic of MRI waves in rotating systems.

**The MRI Mechanism**

Magnetic tension between fluid elements can lead to a runaway instability creating an effective radial flux of angular momentum. As two fluid elements are displaced, the one moving to lower orbit feels a drag from the field line tension (depicted as a spring) and falls to lower orbit. Likewise, the element moving to higher orbit feels a tug from the field and rises farther. The resulting instability is:

- Asymmetric
- Derives its free energy from the flow shear
- Resistively limited (minimum Rm)
- Stabilized by a sufficiently strong magnetic field

**Linear Stability Analysis of magnetized Taylor-Couette flow**

The flow between two concentric rotating cylinders (a Taylor-Couette experiment) can be used to explore both hydrodynamically and MRI instabilities related to accretion disk turbulence. Disk flows follow a Keplerian profile $\Omega = r^{-1/2}$, but more generally are characterized as being anti-cyclonic and centrifugally stable.

$$\frac{d\Omega}{dr} < 0, \frac{d\Omega}{dr} > 0$$

Such flows are referred to as quasi-Keplerian. Both the nonlinear hydrodynamic instability and MRI are present in incompressible fluids so that we can explore them by generating rotating shear flows in either water or a liquid metal.

**Axisymmetric fluctuations increase with flow shear**

For infinitely long cylinders, the rotation profile is the ideal Couette profile

$$\Omega(r) = \frac{b}{r^2}$$

Adjustment of the inner and outer cylinder speeds allow us to explore both hydrodynamically and MRI stable and unstable regimes.

Three regions of stability:

1. Centrifugally unstable, but can be stabilized by the magnetic field
2. Centrifugally stable, but can be destabilized by the magnetic field
3. Always stable

**Boundary effects in finite cylinders**

Since the endcaps of the apparatus rotate with outer cylinder, a pressure imbalance creates a boundary layer that drives radial flow at the endcaps. The flow circulates into the bulk flow creating large Ekman circulation cells. This secondary circulation is quite effective at transporting angular momentum and causes the rotation profile to deviate from the ideal Couette profile.

**Mitigation of secondary circulation using segmented endcaps**

By splitting up the endcaps into independently-driven differentially rotating rings, the flow profiles can be tailored to fit the ideal Couette profile, thereby minimizing the residual secondary circulation. Fluctuations in the bulk flow were found to be extremely small and insignificant for angular momentum transport (see E. Schartman’s poster).

**Nonaxisymmetric modes observed**

Nonaxisymmetric fluctuations were observed in hydrodynamically unstable flows:

- Dominant m=1 mode
- Higher harmonics
- Mode rotates at 1/6 speed of inner cylinder
- Mode appears to be due to beating waves
- Frequency splitting of m=2 mode proportional to rotation rate

**Magnetocoreolis (MC) waves**

A rapidly rotating conducting fluid subject to a strong magnetic field can support waves where the restoring force is a combination of the Lorentz and Coriolis forces. The Alfven wave branch is split between a fast and slow MC wave:

- Fast MC wave: Lorentz and Coriolis restoring forces are in phase
- Slow MC wave: Lorentz and Coriolis restoring forces are out of phase

These waves are also present in rotating shear flow.

**Liquid metal rotating shear flow**

Machine Parameters:

- Liquid metal: Gallium eutectic alloy (melts at 10°C)
- $r = 6.361$ gcm$^{-3}$
- $\eta = 24.30$ cm$^2$/s
- $v = 3.462 \times 10^{-2}$ cm$^2$/s
- $v / 2 \pi = h / (R_i - R_o) = 2.1$
- Geometry: $R_i = 7.06$ cm, $R_o = 20.30$ cm, $h = 27.9$ cm
- Max Speeds: $\Omega_i = 418.9$ rad/s (at 4000 rpm or 66.7 Hz), $\Omega_o = 55.6$ rad/s (at 533 rpm or 8.8 Hz)
- $R_m = (R_i - R_o) / 2 \pi \Omega_i / \Omega_o / \Omega_i$
- Applied Field: $B_i$ ranges from 50G to 500G

$S = B_i / (R_i - R_o) / \eta (4\pi)^{1/2}$ ranges from 0.3 to 3

**Liquid metal rotating shear flow experiments**

Example run: the motors are turned on and the flow is allowed to equilibrate for about 2 minutes. Then the magnetic field is turned on and the pickup coils observe the perturbed magnetic field.

**Diagonistics in development:**

- RI Probe and pressure sensors mounted in a hydrodynamic wing for internal Reynolds and Maxwell stress measurements
- Potential probe measurements
- Ultrasound Doppler Velocimetry