ACCRETION DISK BOUNDARY LAYER

Mikhail Belyaev | Roman Rafikov | James Stone

Berkeley

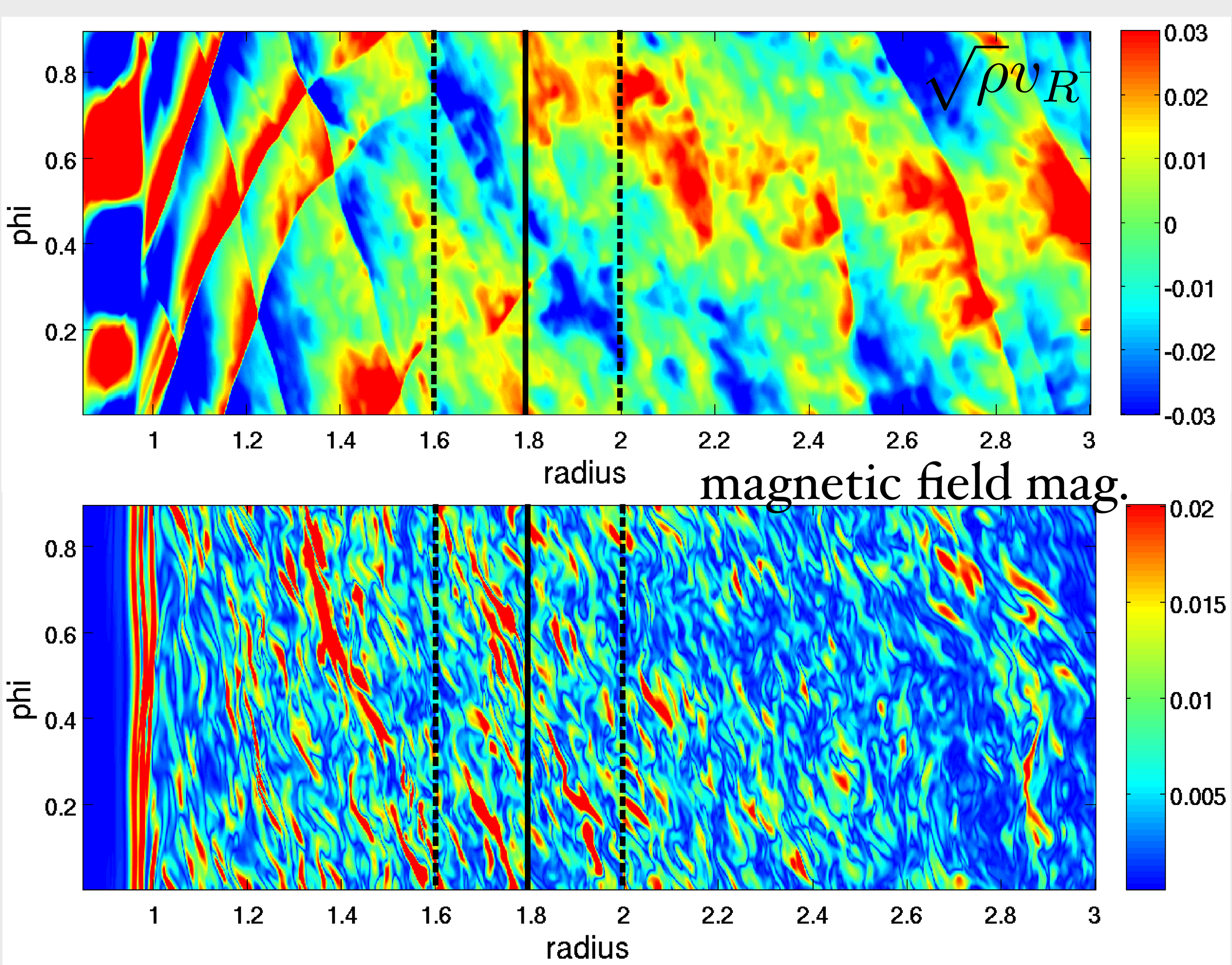
Introduction

The boundary layer (BL) is the region between the disk and the star. We study BLs around an idealized weakly-magnetized star such that the disk extends down to the surface without being disrupted by the stellar magnetic field. We present analytical theory and results from 2D and 3D hydro and MHD simulations with isothermal equation of state, using the code *Athena*.

Boundary Layer Modes & Instability

The angular velocity increases with radius in the BL, in contrast to the disk, which has an angular velocity profile is declining with radius. Thus, unlike the disk, the BL is (linearly) stable to the magneto-rotational instability (MRI). However, the BL is unstable to a shear instability, which we call the sonic instability. The sonic instability arises for globally supersonic flows and differs fundamentally from the more commonly studied Kelvin-Helmholtz shear instability. It is related to the class of Papaloizou-Pringle instabilities (PPI). However, the sonic instability is more vigorous than PPI in disks, because the radial extent of the BL is small compared to the stellar radius, meaning the shear there is more intense there than in the disk.

The sonic instability shows up clearly, even in 3D MHD simulations that have well-resolved MRI in the disk. The figure below is a snapshot in the disk midplane from a cylindrical simulation (R-phi-z). The star is located at R<1 and the Keplerian disk is located between 1<R<6. The BL, which is well-resolved numerically, is located at R~1. The lower panel shows the magnetic field magnitude and depicts MRI turbulence in the disk. The upper panel shows the density-weighted radial velocity. A sound mode excited in the BL due to the sonic instability is visible. This mode propagates into both the star and the disk. The dashed lines show the Lindblad radii, and the black line shows the corotation radius in the disk. The pattern of intersecting shocks is caused by reflection of the mode off the forbidden region between the Lindblad radii.



Angular Momentum Transport by Waves

One of our most surprising results is that waves, rather than turbulent stresses, transport angular momentum in the BL. This is true even when stresses due to MRI turbulence account for the angular momentum transport in the disk. A major difference between how waves transport angular momentum compared to turbulent stresses is that stresses act locally, but waves are delocalized and can transport angular momentum large distances from where they are excited before redepositing it. In fact, in an ideal disk with zero viscosity, angular momentum exchange between a small-amplitude wave and the disk fluid can only occur at a corotation resonance. In practice, we find that modes excited by sonic instability steepen into shocks as they propagate away from the BL into the disk. Thus, deposition of angular momentum is controlled by shock dissipation physics in the disk. In the star, damping of the modes depends on stellar physics, and radiative diffusion damping is a possibility.

Angular momentum transport by waves can be seen in spacetime diagrams (see figures below). The x-axis in the panels gives time in units where t=2pi is one Keplerian orbit at R=1; the y-axis gives radius in units where R=1 is the stellar radius (at t=0). The upper panel shows the stress angular momentum current (averaged over phi and z) in a 3D MHD simulation with MRI. The bottom panel shows the density (averaged over phi and z) in the same simulation. The stress is positive in the disk (R>1), since MRI turbulence transports angular momentum outward. However, striations due to passing waves emitted from the BL are also apparent in the disk stress. In the BL and in the star (R<1), the stress angular momentum current is negative, meaning that angular momentum is transported inwards. In this region, angular momentum transport is dominated by waves. The BL modes that transport angular momentum are excited stochastically (two dark blue regions in the upper panel). Excitation of modes “flushes out” the mass in the inner part of the disk, as can be seen by the dip in surface density (lower panel) when BL stresses are large. The stochastic nature of the excitation is likely due to a mismatch in the rates at which angular momentum is transported by waves in the BL (fast) vs. MRI in the disk (slow).