HIGH-RESOLUTION SIMULATIONS OF MAGNETOHYDRODYNAMIC TURBULENCE IN ACCRETION DISKS

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EXECUTIVE SUMMARY

Accretion disks are rings of gas that orbit black holes, white dwarfs, neutron stars, young stars, and planets. Disks lie at the heart of many important astrophysical problems, including planet formation and the central engine of quasars. Disk evolution is likely driven by turbulent diffusion of angular momentum. We studied turbulence in differentially rotating, magnetized disks at **unprecedented** resolution using a graphics processing unit (GPU)-accelerated code. Our goal was to decide between earlier, contradictory claims about convergence of disk turbulence. We found, surprisingly, that the intensity of turbulence does not converge.

INTRODUCTION

Accretion disks are rings of gas that orbit black holes, white dwarfs, neutron stars, and young stars and planets. The release of gravitational energy in disks around supermassive black holes powers the quasars, luminous objects in galactic nuclei that outshine all the stars in their parent galaxies. Disks are also the sites of planet and moon formation. Disk evolution is likely driven by turbulent diffusion of angular momentum within the disk. The leading candidate for producing turbulence in disks is the magnetorotational instability (MRI) [1]; our goal in this project was to investigate saturation of MRI-driven turbulence and, with groundbreaking resolution, decide between claims that MRI-driven turbulence in stratified disks is converged [2] and not converged [3] in implicit large eddy simulation (ILES) studies.

METHODS & RESULTS

We studied a model disk problem known as the *stratified shearing box* using the hybrid (MPI+CUDA) ramses-GPU ideal magnetohydrodynamics (MHD) code developed by our collaborators [4]. Using Blue Waters, we were able to integrate at an **unprecedented** resolution of 768 x 512 x 3072 for the hundreds of dynamical times necessary to obtain a statistically significant measurement of turbulent intensity. Our linear resolution **surpassed** all earlier models by nearly a factor of 2. Figure 1 shows the effect of increasing resolution on the density and magnetic field structure in our main series of models.

The result of our **record-breaking** integration was surprising. Although some measures of turbulent intensity did converge, others did *not*. In particular, we found that the characteristic size of turbulent eddies (the correlation length) scales with the number of zones per disk scale height N as $N^{-1/2}$. Figure 2 shows the run of correlation length with a vertical position in the disk over a factor of 16 in resolution, illustrating the weak nonconvergence. This result suggests that many numerical models of MHD turbulence in disks that use ILES, rather than explicit dissipation models, may not be convergent. Our results differ from earlier results showing nonconvergence of ILES in certain ("zero net field") unstratified shearing boxes [5], which show correlation length scaling directly with the grid scale, i.e. as N^{-1}. Confirmation of our results will be required using alternate numerical schemes (and therefore alternate ILES closures), such as athena. Our results also motivate further high-resolution investigation of models with explicit dissipation.

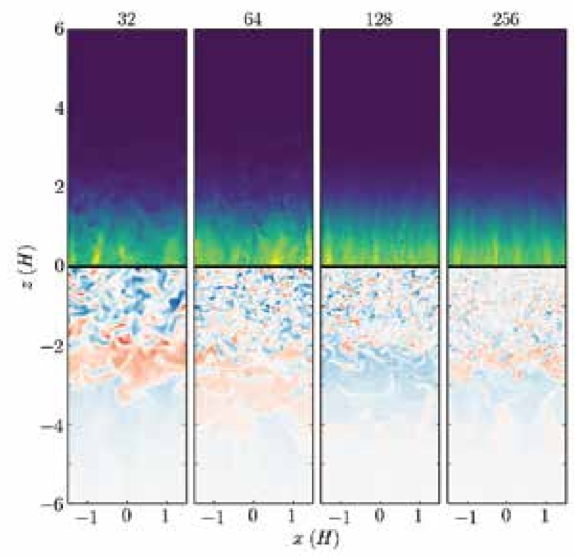

FIGURE 1: Slices through a 3D simulation of the fluid density and azimuthal magnetic field strength over the range of resolutions surveyed in this work. Increasing resolution dramatically decreases the length scale of the magnetic field structure, with a corresponding decrease in turbulent intensity.

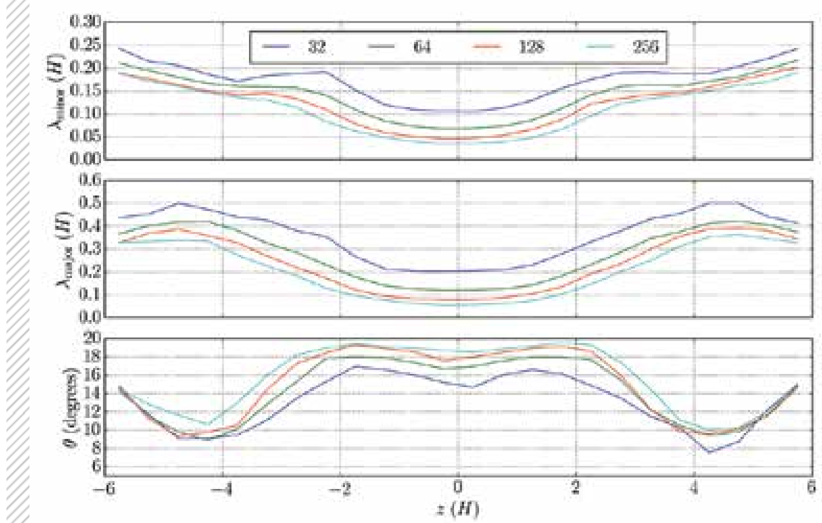

FIGURE 2: Magnetic field correlation function for disk turbulence, from 32 zones per disk scale height H to a record-breaking 256 zones/H. The correlation function in the plane of the disk is characterized by a minor axis correlation length (top panel), major axis correlation length (middle panel) and the angle between the semimajor axis and the orbital velocity vector (bottom panel). While the change in angle with resolution is consistent with convergence, the change in correlation lengths near the midplane of the disk is not.

WHY BLUE WATERS

Blue Waters is the only available facility capable of running this problem. We were able to exploit the large number of GPUs available on Blue Waters, which run our GPU-based code at a factor of about three faster per node over a CPU-based version of the code.

NEXT GENERATION WORK

Supercomputers like Blue Waters now commonly integrate models of hydrodynamic turbulence with explicit dissipation (DNS model) with a several decade inertial range between the outer scale and inner (dissipation) scale. MHD turbulence, by contrast, has both a resistive and a viscous dissipation scale. The ratio of these scales is an important dimensionless parameter of the problem that varies over many orders of magnitude in astrophysical settings. Studies of MHD turbulence in DNS models with a clear separation of viscous and resistive length scales will require next-generation facilities.