HIGH-RESOLUTION SIMULATIONS OF MAGNETOHYDRODYNAMIC TURBULENCE IN ACCRETION DISKS

Allocation: Illinois/440 Knh
PI: Charles F. Gammie
Co-PI: Ben Ryan, Sebastien Fromang, Pierre Kestener

1University of Illinois at Urbana-Champaign
2Service d’Astrophysique
3CEA/IRFU

EXECUTIVE SUMMARY

Accretion disks are rings of gas that orbit black holes, white dwarfs, neutron 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 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 results, 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 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 H 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^0. 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.

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.