Krista L. Martocci: Research Statement

I am a computational astrophysicist who is interested in performing large-scale, three-dimensional magneto-hydrodynamic (MHD) and hydrodynamic simulations of astrophysical systems. I am most interested in making a connection between astrophysical theory and laboratory experiments. My current work focuses on simulating MHD turbulence to understand how it affects magnetic field generation in astrophysical systems, so that we can begin to answer the following questions about astrophysical accretion disks: Can turbulence in a magnetized medium allow for efficient accretion in astrophysical disks? If so, can the turbulent disk self generate the magnetic fields which initially caused the turbulence? In other words, can these disks sustain dynamo action?

Background and Motivation

These questions are universal to all accretion disks, which are present in many astrophysical systems such as active galactic nuclei (AGN), binaries, and protoplanetary disks. The disk mediates the flow of material onto a central object assisting in powering AGN, forming the core of a Type Ia supernova, and forming protostars and their surrounding planetary systems. As the material slowly spirals inward, gravitational energy is released powering some of the most energetic phenomena in the universe. An outstanding problem of all disks is that they must accrete mass inward efficiently to account for the relatively short timescales of formation and the releases of energy. In the theory of accretion disks angular momentum transport is the crucial quantity, since it determines the efficient accretion rates and the structure of the disk.

The idea that the material in an accretion disk must be turbulent was originally proposed by Shakura and Sunyaev (1973) to explain this efficient transport. They predicted that turbulent motions would cause an effective or turbulent viscosity, which is responsible for the efficient angular momentum transport. This proposed effective viscosity is necessary in a typical astrophysical disk, since the disk's molecular viscosity is many orders of magnitude too small to be responsible for efficient transport. Their "alpha disk" prescription has been successful in predicting disk accretion rates, but does not describe how turbulence arises nor how it is driven. Astrophysical disks are Keplerian, since they rotate around a compact object such as a star or black hole. A Keplerian disk's velocity profile is one where the velocity decreases and the angular momentum increases with an increasing radius. This has been shown both analytically by Lord Rayleigh and experimentally by Ji et al. (2006) to be hydrodynamically stable to perturbations, and therefore they should not be turbulent.

Since Keplerian disks are hydrodynamically stable, there must be another mechanism responsible for the presence turbulence in accretion disks. Balbus and Hawley (1991) proposed turbulent motions could arise due to the magneto-rotational instability (MRI). The MRI arises in a Keplerian ionized disk that is threaded by a weak, vertical magnetic field. If magnetized, an otherwise hydrodynamically stable disk is now hydromagnetically unstable, and therefore turbulent. The MRI explains how turbulence is driven by the rotation and shearing of the fluid in the presence of a vertical field, but does not explain whether this turbulence can also be responsible for the self-generation of the magnetic fields which can caused the turbulence. A self-generating magnetic field in a dynamo is necessary to keep the field from decaying over the lifetime of a disk.

Currently, most of the data used for answering the questions of dynamo action and turbulence are from numerical simulations--either global calculations or local approximations. Local approximations typically use the shearing box approximation with periodic boundary conditions. I use global simulations for my calculations, since the periodic shearing boxes have been shown to suffer from the "convergence problem". If the shearing box has periodic boundary conditions in all three directions the angular momentum transport decreases as the resolution is increased (or viscosity decreased). A dynamo dependent on the molecular viscous scale is a small-scale dynamo and not applicable to astrophysical disks, since the molecular viscosities are negligible. However, a large-scale dynamo has a magnetic field with scales comparable to the size of the system and is independent of viscosity, and therefore relevant to astrophysical accretion disks.

Global Numerical Simulations of Magnetized Taylor-Couette Flow

To study the problem of disk accretion and angular momentum transport, I use three-dimensional, global MHD computer simulations of Taylor-Couette (TC) flow, which is the flow of electrically conducting fluid between two differentially rotating, cylindrical walls. The TC rotational profile is considered "quasi-Keplerian", since it has similarities with the rotational profile of a Keplerian disk. Both are hydrodynamically stable to perturbations unless magnetized. One reason for choosing a TC flow instead of simulating a fully realized accretion disk is because it is mathematically well defined. This problem of field generation and turbulence is formulated in a way that allows for a more thorough understanding of the direct effects on the transport and self-magnetization without confusion from other mechanisms present in typical astrophysical disks. An additional reason is because these types of flow may be experimentally verified. For example, TC flow will be used to study similar questions in the MRI experiment at the Princeton Plasma Physics Laboratory.

My simulations are calculated using an MHD version of Nek5000 developed by Paul Fischer et al. (2008) in the Mathematics and Computer Science Division at Argonne National Laboratory. This is a spectral element code that solves the three-dimensional, incompressible, MHD equations. This code was chosen because it can properly incorporate wall-bounded flows and scale to a large number of processors. To be properly resolved, our largest simulation currently uses almost 100 million gridpoints. Therefore, it is necessary to run calculations with up to a few tens of thousand processors, so efficient scaling is crucial. I have run these calculations on a variety of computational architecture including the IBM BlueGene/P *Jügene* and BlueGene/Q *JüQueen* at the Institute for Advanced Simulation (Jülich Supercomputing Centre, Germany), the Cray XE6 *Beagle* at the Computation Institute (University of Chicago, IL), and the Cray XE5 *Kraken* at the National Institute for Computational Sciences (Oak Ridge National Laboratory, TN).

My calculations successfully simulate a dynamo in a TC setup using the ingredients of a vertical, seed field, differentially rotating walls, appropriate boundary conditions, and large Reynolds number. A toroidal magnetic field is generated and sustained over time. The mean toroidal field that is generated is a significant fraction of the fluctuations in the toroidal direction.

In the saturated phase of the dynamo, the behavior of the system is cyclic, which is seen in synchronous oscillations of the magnetic energy and torques on the inner and outer walls. The angular momentum transport is dominated by Maxwell stresses except at the walls where thin viscous boundary layers couple the rotating walls to the fluid driving the rotation.

Geometric effects were explored by flattening the cylinder from an aspect ratio of unity to an eighth. The qualitative behavior as it is flattened is that more of the fluid loses touch with the boundaries. Therefore, the more disk-like the system, the more it becomes a disk where the transport is driven completely by Maxwell stresses and the boundaries have less influence on the behavior of the system. In all calculations there is an effective viscosity due to the turbulence present in the disk that significantly larger than the molecular viscosity.

These simulations of dynamos are sensitive to the boundary conditions applied to the system. Käpylä & Korpi (2011) find that a shearing box's angular momentum transport is independent of viscosity if the vertical boundary conditions are stress-free. It is thought that the reason these boundaries are successful in sustaining dynamo action independent of the viscosity is related to the conservation of magnetic helicity, which measures the "twistedness" of the field lines. Vishniac & Cho (2001) conclude that a disk must have an outflow of magnetic helicity to have a successful dynamo, which is satisfied with these stress-free, vertical boundaries. Currently, I have started exploring the various vertical boundary conditions in this system. This will contribute to a better understanding of magnetic helicity conservation effects on the dynamo action and angular momentum transport.

These numerical simulations are applicable to studying both astrophysical accretion disks and laboratory experiments due to its global treatment and the option of realistic walls. While they currently have these idealized vertical boundaries, which are thought to be necessary for successful dynamo action, they can be altered to mimic the physical boundaries that are necessary for the prediction of experimental result. I am interested in continuing to study of the physical mechanisms present in astrophysical systems by making the connection between theoretical astrophysical systems with laboratory experiments through large-scale numerical simulations.

References:

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