Protoplanetary Disk Gap Behavior as a Function of Planet Mass

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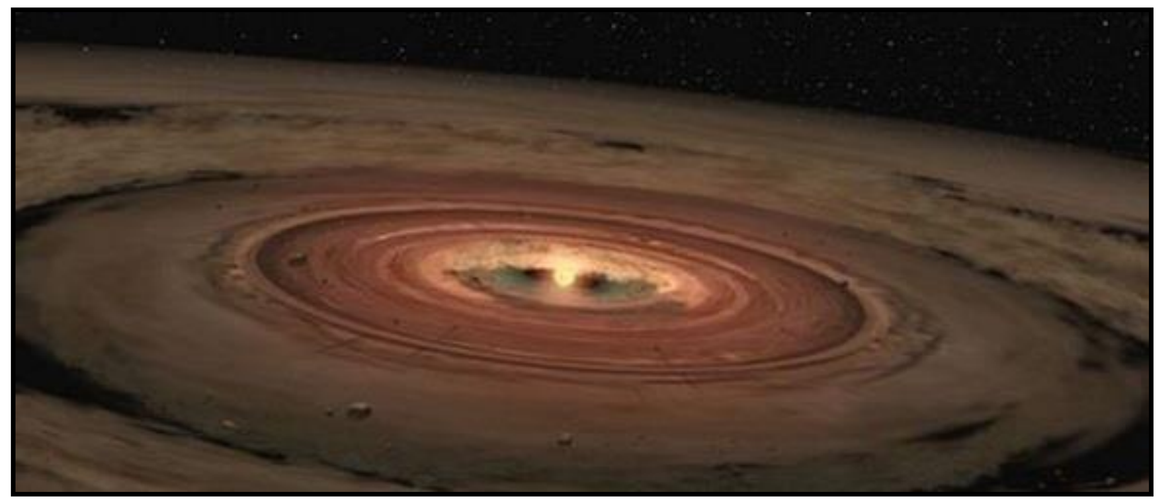


Figure 1: Artist's impression of a protoplanetary disk [1]

Introduction

Protoplanetary disks are the astrophysical site for planet formation. A protoplanetary disk is an accretion disk; meaning that as the disk spins, it accretes matter onto the central mass. In the case of protoplanetary disks, this central mass is a young star. Over the course of several million years, a protoplanetary disk can evolve from a torus-shaped cloud of gas and dust into a complex system of planets, moons, and asteroids (see Figure 3). This incredible phenomenon has been studied by scientists for decades, and even with new discoveries being made regularly, there is still a vast amount to be learned. The Center for Astrophysics, Space Physics, and Engineering Research (CASPER) is actively involved in researching the processes and phenomena that occur in protoplanetary disks. In studying protoplanetary disks, CASPER seeks to better understand the physics of planet formation and the science that it encompasses.

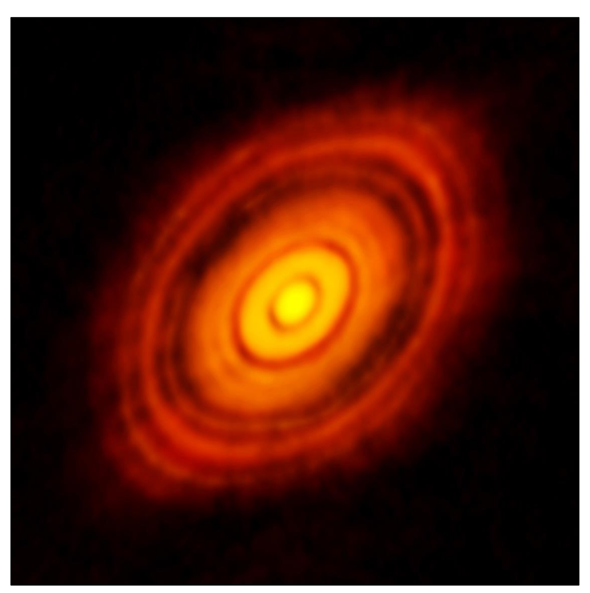


Figure 2: HL Tauri [2]

Protoplanetary disks begin as a cloud of hydrogen gas, dust, and trace amounts of other elements. Over time, the cloud will collapse under its own gravity, igniting a star in its core. Once the star is formed, gas and dust will continue to fall inward, forming an accretion disk that will orbit the star. In the dense areas of the disk, pebble accretion can take place, forming the building blocks of planets called planetesimals. Some of the gaps in the protoplanetary disk, HL Tauri (see Figure 2), are thought to have been created by newly formed planets, carving their way through the disk. Theory suggests that the disk will eventually disappear via dissipation and/or accretion on to the star, leaving behind a fully formed solar system with a central star, planets, and moons (see Figure 3).

It has long been theorized that protoplanetary disks are turbulent environments [4]. Since matter in the disk is continuously accreted on to the star, there must be one or more mechanisms by which angular momentum is transferred radially outward in the disk. The prevailing theory for the generation of turbulence in a protoplanetary disk is the Magnetorotational Instability (MRI).

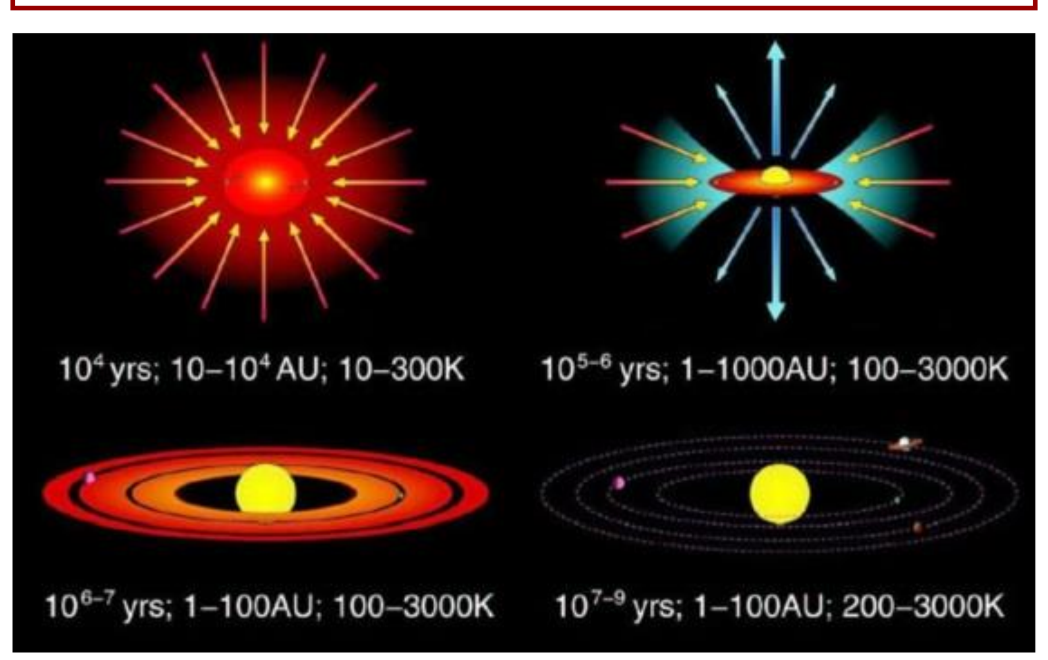


Figure 3: Shu et al. (1987) [3]

While the MRI causes turbulence, it acts fundamentally as a source by which angular momentum can be transferred radially outwards as mass is accreted on to the central star. MRI is produced from the combination of ionization, weak magnetic fields and differential rotation. Because of the ionization in the disk, it is theorized that magnetic field lines could couple to the disk in fixed regions. This would allow the field lines to act as tethers between different regions of the disk, thereby transferring angular momentum. If the magnetic field lines were stretched to the point that they break, this would release an enormous amount of tension and contribute to the turbulence in the disk.

Methods

The study of protoplanetary disks focuses heavily on a model called the "shearing box." A shearing box is a two or three dimensional box that defines the region in the disk being observed. The box moves with the disk, tangent to the orbital velocity of the region being observed. It is called a shearing box because of the shearing interaction within the box due to differential rotation in the disk. In order to accurately model such an enormous and complex system, CASPER required the use of high-power computational engines. In modeling the evolution of protoplanetary disks, CASPER used Kodiak [5] and Stampede [6], two different supercomputers located at Baylor University and the University of Texas at Austin, respectively.

Protoplanetary disk simulations were done on these engines using a program called Athena [7]. Athena is a C-based, magnetohydrodynamics (MHD) code used to model astrophysical phenomena and is particularly useful for shearing box analysis.

Methods (cont.)

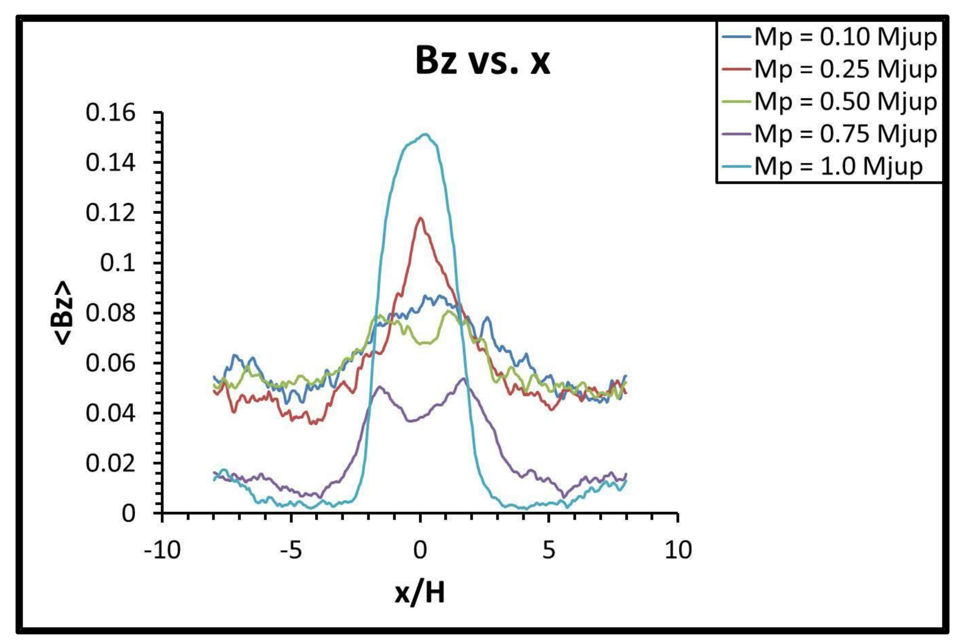
Two particular problems were studied using Athena: 1.) A vertically unstratified accretion disk problem modeled after conditions described in "Local Three-dimensional Magnetohydrodynamic Simulations of Accretion Disks" by Hawley et al. [8], and 2.) A vertically stratified accretion disk problem resembling conditions described in "Three-dimensional Magnetohydrodynamic Simulations of Vertically Stratified Accretion Disks" by Stone et al. [9]. These two problems were run with a variety of different input conditions. The input conditions that were most often varied were the planetary mass, and the magnetic field arrangement. For the purposes of this poster, the primary focus will be on data obtained from the vertically unstratified problem. The vertically stratified problem is addressed in the discussion and conclusion section of this poster.

Results

Five trials were done with various planet masses. While other magnetic field configurations are available, the vertical non-zero flux configuration was used exclusively in the trails presented here. Values for planet mass are represented as a fraction of Jupiter's mass. All five of these trials are analyzed graphically below and two of these trials were chosen to be displayed visually using VisIt generated images of the density and magnetic field. Each trial is listed below in Table 1.

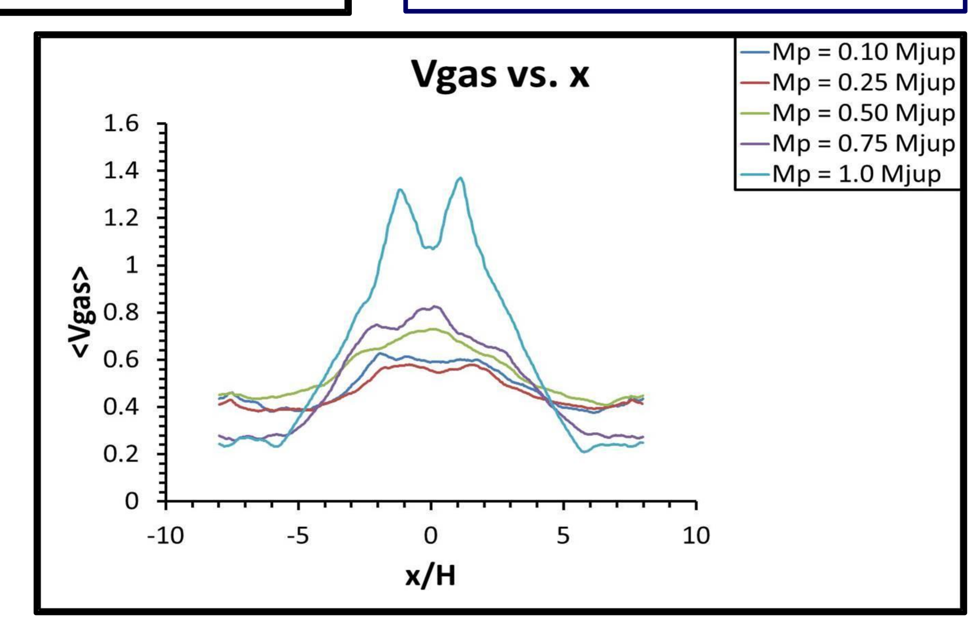
Table 1: Trial Input Values and Calculation Parameters

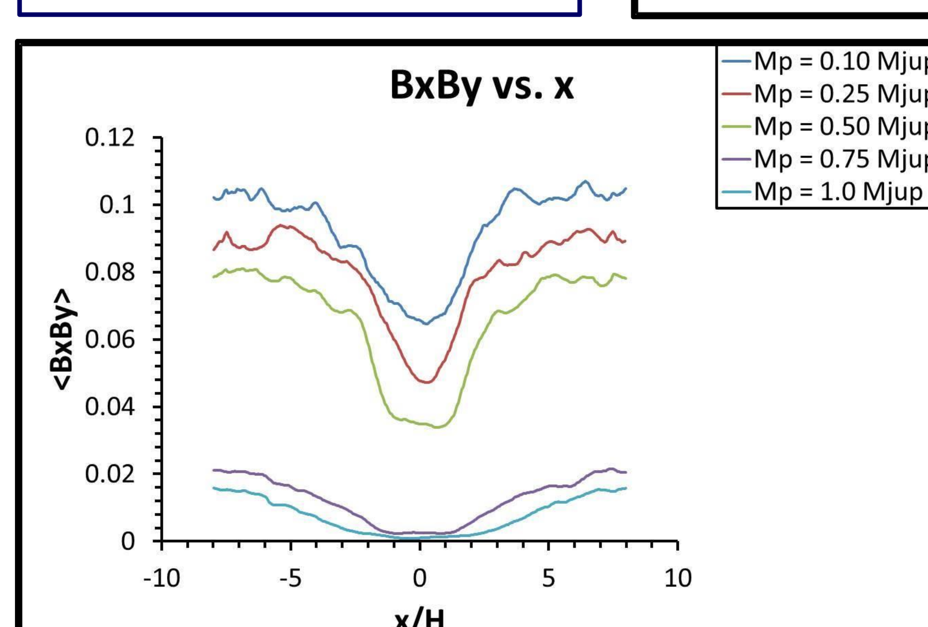
Trial Number	Planet Mass	B-Field	Duration	Averaged Over
A1	Mp = 0.10 Mj	Vertical, Non-Zero, Flux	87 Orbits	Orbit 50-87
A2	Mp = 0.25 Mj	Vertical, Non-Zero, Flux	100 Orbits	Orbit 50-100
A3	Mp = 0.50 Mj	Vertical, Non-Zero, Flux	160 Orbits	Orbit 100-160
A4	Mp = 0.75 Mj	Vertical, Non-Zero, Flux	70 Orbits	Orbit 40-70
A5	Mp = 1.00 Mj	Vertical, Non-Zero, Flux	60 Orbits	Orbit 40-60



Graph 1: This graph depicts the vertical (z) component of the magnetic field in the shearing box, averaged over y, z, and time. The horizontal axis (x/H) represents the axis in the shearing box parallel to the radius of the protoplanetary disk. It is in units of scale height. The vertical axis (<Bz>) is in code units defined in Athena. The planet is located at x = 0.

Graph 2: This graph depicts the average gas velocity in the shearing box, averaged over y, z, and time. The horizontal axis (x/H) represents the axis in the shearing box parallel to the radius of the protoplanetary disk. It is in units of scale height. The vertical axis (<Vgas>) is in units of sound speed. The planet is located at x = 0.





Graph 3: This graph depicts the product of the x and y components of the magnetic field in the shearing box, averaged over y, z, and time. The horizontal axis (x/H) represents the axis in the shearing box parallel to the radius of the protoplanetary disk. It is in units of scale height. The vertical axis (<BxBy>) is in code units defined in Athena. The planet is located at x = 0.

In the graphs above there are three basic regions of behavior to be noted: the behavior on either side of the gap region (-8<x<-5 U 5<x<8), the behavior at the edges of the gap, and the behavior at and around the planet. Also note how certain masses group in their behavior, even though mass was varied evenly (with the exception of 0.10) from 0 to 1. For some planet masses, values seem to "pile up" near the edges of the gap and then drop around the planet. For other masses however, the planet's location appears to be a local extrema. Lastly, there are three other notable segregations to note: the gap between Mp = 0.75 and 1.00 on Graph 1, between Mp = 0.75 and 1.00 on Graph 2, and between Mp = 0.50 and 0.75 on Graph 3.

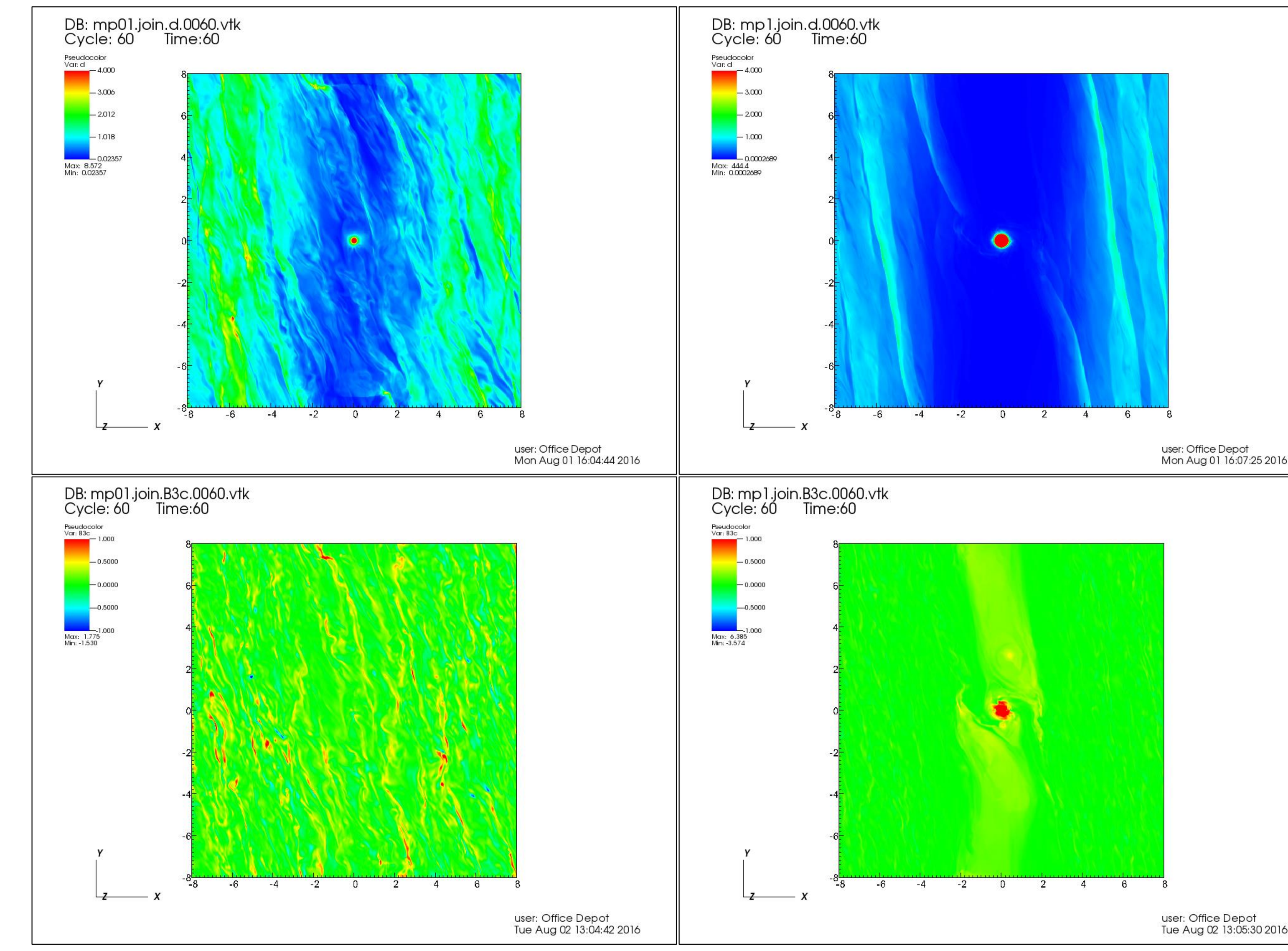


Figure 4: VisIt VTK Density and B-Field Plots

The images above are from the 60th orbit of the 0.10 Mj and 1.00 Mj trails. The left images correspond to the 0.10 mass trial and the right images to the 1.00 mass trial. The top two images are density plots and the bottom two images plot the vertical (z) component of the magnetic field. Density plots range from blue (low density) to red (high density). Magnetic field plots range from blue (negative field) to red (positive field).Both axis on each graph are in units of scale height. Note the difference in gap width on the two density graphs. Also, take note of how the magnetic field varies in intensity and arrangement between the two masses. These images were created from VTK output files using VisIt.

Discussion and Conclusion

It can be concluded from the graphs, images, and papers previously mentioned that an increase in planet mass contributes to an increased gap width. That being said, a strictly linear correlation has not yet been established (at least not in this poster). Furthermore, the behavior of the magnetic field surrounding and within the gap is also dependent on the mass of the planet. General trends can be observed with each of the three variables discussed. For each of the planet masses tested: there is a net increase in the vertical component of the magnetic field (Bz) around and through the gap, there is a net increase in the average gas velocity (Vgas) around and through the gap, and there is a net decrease in the product of the x and y components of the magnetic field (BxBy) around and through the gap. While these general trends exit, some masses produce drops in Bz and Vgas close to the location of the planet and increases near the edges of the gap. This behavior will be investigated in future research. In addition, future trials may be done to determine why certain planet masses (like 0.75 and 1.00) appear to segregate in their behavior for certain variables. Future trials may be done with planet masses intentionally chosen to decrease the increment between the trails completed. A decrease in the difference between each trial may reveal that a non-linear relationship is causing certain variables to appear the way they do.

As was previously mentioned, a vertically stratified case is also available in Athena. Currently, Athena does not offer a way to run trials with a planet submerged in a vertically stratified disk. This is currently being worked on and great progress has been made. At the time of this poster, edits to the Athena code have been made so that extremely small planet masses can be used and represented by a spherical (rather than cylindrical) gravitational potential. Protoplanetary disks are, by nature, three-dimensional. Should the vertically stratified case become fully operational, it would increase the physical accuracy and realism of the experiments dramatically. Lastly, simulations with a magnetohydrodynamic, vertically stratified shearing box containing a planet have never been done before, so there is much to be explored.

Sources

1. Artist's impression of a protoplanetary disk around the brown dwarf OTS44, Credit: NASA, http://www.daviddarling.info/encyclopedia/P/protoplandisk.html
2. Webb, Johnathan (6 November 2014). "Planet formation captured in photo". BBC News. Retrieved 3 November 2016, http://www.eso.org/public/images/eso1436a/
3. Shu et al. (1987), Credit NASA, http://jwst.nasa.gov/birth.html
4. Philip J. Armitage, "Dynamics of Protoplanetary Disks", 2011, ARA&A, 49, 195-236
5. The author acknowledges the Academic & Research Computing Services (ARCS) at Baylor University for providing HPC resources that have contributed to the research results reported within this presentation. URL: http://www.baylor.edu/lib/factech/index.php?id=39613
6. The author acknowledges the Texas Advanced Computing Center (TACC) at The University of Texas at Austin for providing HPC resources that have contributed to the research results reported within this paper. URL: http://www.tacc.utexas.edu
7. James M. S., Thomas A. G., Peter T., John F. H., Jacob B. S., "A New Code for Astrophysical MHD", 2008, The Astrophysical Journal Supplement Series, 178, 137-177
8. Hawley, J. F., Gammie, C. F., & Balbus, S. A., "Local Three-dimensional Magnetohydrodynamic Simulations of Accretion Disks", 1995, Astrophysical Journal v.440, p.742.
9. Stone, J. M., Hawley, J. F., Gammie, C. F., Balbus, S. A.,"Three-dimensional Magnetohydrodynamical Simulations of Vertically Stratified Accretion Disks", 1996, Astrophysical Journal v.463, p.656