A Study of Colliding Flows and Feedback in Star Formation

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ABSTRACT

Observational evidence from local star-forming regions mandates that star formation occurs shortly after, or even during, molecular cloud formation. Models of the formation of molecular clouds in large-scale colliding flows have identified the physical mechanisms driving the necessary rapid fragmentation. They also point to global gravitational collapse driving supersonic turbulence in molecular clouds. In this work we propose exploring the effect of *magnetic fields* and *shear* in the colliding flow on the resulting clouds and the ensuing gravitational collapse. We also explore the role of triggering in star formation, namely the ability of supersonic flows to drive stable pre-existing clouds into collapse. We are particularly interested in the formation of (planet forming) accretion disks in the aftermath of triggering and the role of fields in inhibiting or altering collapse.

Three new publications came from results obtained with our previous XSEDE allocation (AST130036) and we now seek resources to continue and expand our work. To achieve this goal we request the support of 5.0 million SU's on Stampede at TACC, 2.5 million SU's on Gordon at SDSC.

1. Introduction

1.1. Large-scale Converging Flows and Formation of Molecular Clouds

The concept of flow-driven cloud formation (Vázquez-Semadeni et al. 1995; Ballesteros-Paredes et al. 1999; Hartmann et al. 2001) can explain two observational constraints on how molecular clouds form stars, derived from local star-forming regions. First, all local molecular clouds form stars. Second, the observed stellar age spreads are on the order of $1-2$ Myr, several times shorter than cloud crossing times (see summary in Hartmann et al. 2001; Ballesteros-Paredes & Hartmann 2007). The first constraint suggests that star formation sets in immediately (or even during) molecular cloud formation, and that the second constraint is trivially fulfilled in a scenario where the clouds themselves form in large-scale "converging" flows. The immediate ("rapid") onset of star formation in the forming clouds and the fact that the star formation efficiency is only a few percent (Evans et al. 2009) mandates that the clouds are highly structured: local collapse must set in before global collapse can overwhelm the dynamics. The notion of cloud formation in converging flows has led to a series of numerical experiments investigating the physical processes relevant for the rapid fragmentation and for the control of the star formation efficiency. There is agreement across the models on the following results: (1) Rapid fragmentation is induced by strong radiative losses during the flow collision and by dynamical instabilities (Hueckstaedt 2003; Audit & Hennebelle 2005; Vázquez-Semadeni et al. 2006; Heitsch et al. 2008b) (2) Turbulence in molecular clouds is a natural result of dynamical instabilities during the cloud formation, and is driven by global gravitational collapse at later stages of the cloud evolution (Vázquez-Semadeni et al. 2007). Some evidence for this is seen in the filamentary nature of some clouds (Figure1). (3) Strong, non-linear density contrasts can also be driven by self-gravity in finite clouds, due to geometry (or "edge") effects (Burkert & Hartmann 2004). (4) Although the rapid fragmentation can keep the star formation efficiency low, eventually, feedback or cloud dispersal is needed to prevent a large percentage of the gas to participate in gravitational collapse (Vázquez-Semadeni et al. 2010).

While significant progress has been made in understanding the colliding flow paradigm for forming cloud,s significant open questions exist. In this study we seek to explore the combined effects of magnetic fields and shear in the colliding flows as both can significantly alter the dynamics of post-shock flows and the properties/statistics of the clouds formed there.

1.2. Triggered Star Formation

Triggered star formation (TSF) occurs when supersonic flows generated by distant supernova blast waves or stellar winds (wind blown bubbles) sweep over a stable cloud. In realistic environments, this is likely to occur when such a flow impinges the heterogeneous regions within molecular clouds (Robe H. (1968), Hill et al. (1997), Kothes et al (2006), Bonnell et al (2006), Leao et al (2009)). While it is unclear if TSF accounts for a large fraction of the star formation rate within the galaxy, the concept has played an important role in discussions of the formation of our own solar system because it offers a natural way of injecting short lived radioactive isotopes (SLRI's) like ^{26}Al into material which will then form planetary bodies.

In recent studies by Boss and collaborators (Boss et al (2008), Boss et al (2010), Boss et al. (2013)) shock conditions needed for successful triggering and mixing were mapped out. In general, the higher the Mach number of the shock, the more difficult it is to trigger collapse. Faster shocks can shred and disperse the clump material before it has time to collapse. While these studies have done much to reveal the details of TSF, they have been restricted to the early stages of the resulting flow evolution. The full evolution leading to a collapsed object (a star) and its subsequent gravitational interaction with the surrounding gas have not been to be studied. These leaves open questions such as what is the mass accretion rate of such a star formed by triggering? What is the accretion history of such a star? Does a trigger-formed star also has a disk when rotation in present in the cloud? If so, is the disk stable?

2. Previous Accomplishments

Over the tenure of the last proposal we have carried out studies leading to 3 papers (Carroll et al 2014; Li et al 2014; Kaminski et al 2014) . We have also begun studies of magnetized colliding flows with shear. Below is a summary of our accomplishments

2.1. Summary of Scientific Discoveries

- We completed a high resolution study of hydrodynamic self-gravitating converging flows with realistic cooling properties to explore the effect of heterogeneities on the formation of molecular clouds (Carroll et al 2014)

- We began a low resolution study of MHD self-gravitating converging flows with realistic cooling focusing on the effect of field tension and initial shear on the formation of bound cloud complexes (Figure 1).

- We completed studies of the effect of ambient gas (either static or supersonic) on the collapse of pre-existing clouds. In particular we completed the first high resolution studies of triggered star formation to track the formation of a star and a surrounding accretion disk (Figure 2 (Li et al 2014; Kaminski et al 2014))

2.2. Details of Previous Accomplishments

In (Carroll et al 2014) we studied the evolution of flow-driven cloud formation with and without substructure in the flow. Our goal was to explore how pre-existing heterogeneities would alter the ability of converging flows to drive post-shock regions into gravitational collapse. We compared two extreme cases, one with a collision between two smooth streams, and one with streams containing small clumps. Our analysis showed how structured converging flows lead to a delay of local gravitational collapse ("star formation". Thus, more gas has time to accumulate, eventually leading to a strong global collapse, and thus to a high star formation rate.

New low resolution studies of the effects of magnetic fields and shear on these flows has laid the groundwork for the current proposal (Figure 1). Our initial work shows that the presence of shear in the colliding flows leads to the generation of substantial vorticity which alters the creation of dense proto-clouds. Magnetic field tension restricts motion lateral to the field lines which can either enhance or destabilize local structures depending in the shear angle.

In (Kaminski et al 2014; Li et al 2014) we studied the effects of the ambient gas on the collapse of pre-existing cloud cores. In particular we explored how either a dense ambient gas or a passing supersonic flow could drive stable Bonner Ebert spheres into gravitational collapse. Using our codes sink particle capacities we modeled the collapse past the point of the formation of a condensed object (a star). For non-rotating clouds we found robust triggered collapse and little bound circumstellar material remaining around the star. When we added initial cloud rotation we observed the formation of disks around the star which then interact with the post-shock flow (Figure 2). Our results indicated that these circumstellar disks are massive enough to form planets and are long-lived, in spite of the ablation driven by post-shock flow ram pressure. We also tracked the time evolution of the accretion rates and particle mixing between between the ambient wind and cloud material.

3. Proposed Work

3.1. The Formation of Molecular Clouds

Given our successful study of hydrodynamic cloud formation by colliding flows we and our low resolution validations of the MHD/shear set-up we now need to move on to production runs to explore the effects of field tension and the oblique shocks/vorticity production that can be expected when shear is included in the flow collision. The expense of higher resolution flows is justified because we are interested in both the global statistics of clouds that form in the collisions and their morphologies. The clouds form via a two step process in which the colliding flows trigger shocks when they cool sufficiently to allow for gravitational collapse. Thus it is vital that we are able to resolve the regions behind shocks where cooling occurs. The inclusion of magnetic fields can be expected to change the dynamics of the flows in the post shock regions which also necessitates higher resolutions. The goal is to effectively characterize the effects of field tension, $(\mathbf{B} \cdot \nabla \mathbf{B})$, as flows cross the oblique shocks and vorticity is generated.

3.2. Triggered Star Formation

As discussed in the introduction Triggered Star Formation is thought to be the means that SLRI's are delivered to our solar system. Considerable work has gone into determining the range of shock wave parameters which can both trigger a cloud to collapse and maximize mixing of processed elements from the shock into the newly formed cloud.

There is however another critical constraint that needs to be studied to assess the efficacy of triggered star formation in the context of protoplanetary disk systems. For the range of Mach numbers and cloud masses that allow both collapse and mixing, can disks form *and* survive the blast wave for initially rotating clouds? For clouds with different rotation directions relative to the shock what are the dynamics in the post triggering flow that allow the trinity of star formation, sufficient SLRI mixing, and sustained sufficiently massive protoplanetary disks to form? In addition all clouds are expected to include some magnetic flux. How will the amplification of fields due to collapse effect disk formation and mixing? Because our simulations are able to follow the MHD of shock-cloud interactions for millions of years and not just the early stages that others have considered, we can answer this question.

We will extend our work beyond Li et al. (2014) by carrying out high resolution simulations with with different cloud rotation orientations and magnetic field strengths. In this way we can determine the processes that set star formation, mixing and disks survival. Moreover, by using particle tracers, we will be able to see exactly where the SLRI tagged material mixes with material that remains bound to the post-triggered cloud core.

4. Research Objectives

Our proposal embraces two well-defined objectives:

- Carry forward a campaign of high resolution MHD simulations of colliding flows including self-gravity, radiative cooling and treatment of sink-particles. The simulations are designed to study the effect of magnetic fields and shear on subsequent cloud formation. We will not only study the dynamics of the resulting flows but also produce detailed analysis of the statistics of the cloud properties which can be compared with observations.

- Carry forward a targeted set of simulations to determine the effect of rotation and magnetic fields on triggered collapse. Triggering occurs when a supersonic flows impinges on a pre-existing cloud. We are particularly interested in the formation of (planet forming) accretion disks in the aftermath of triggering and the role of fields in inhibiting/altering collapse and changing mixing.

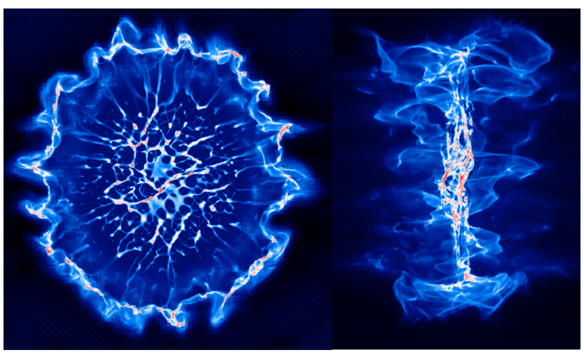

Fig. 1.— Plot showing column density integrated along flow axis (left) and perpendicular (right) for the MHD model of colliding flows

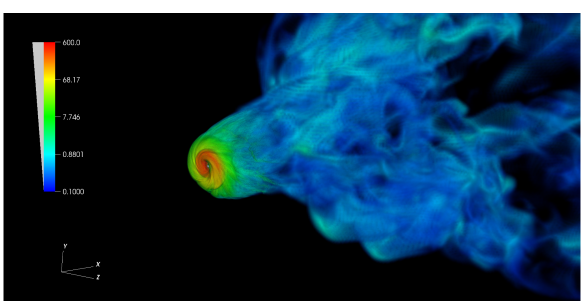

Fig. 2.— 3D volume rendering of Triggered Star Formation simulation showing evolution after the disk formed at 0.6 million years.

5. Computational Approach

AstroBEAR is an Adaptive Mesh Refinement (AMR), multi-physics code for astrophysics. AMR

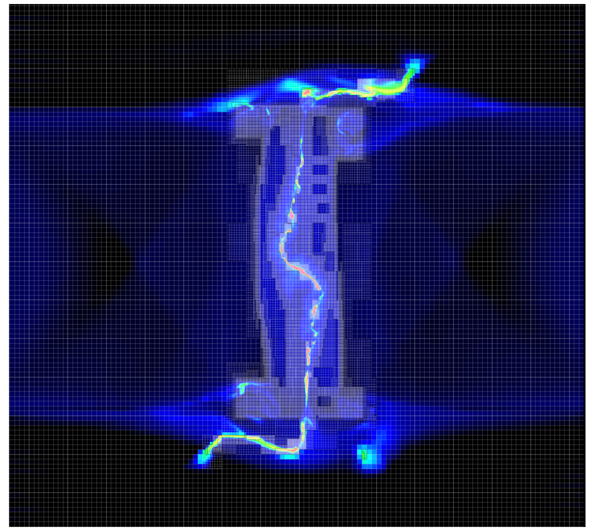

Fig. 3.— Slice showing log density from 3D Colliding Flows simulation performed with AstroBEAR. Also shown is the AMR mesh which contains 4 additional levels of refinement

remains at the cutting edge of computational astrophysics. AMR simulations adaptively change resolution within a computational domain to ensure that the most important features of the dynamics are simulated with highest accuracy. By allowing quiescent regions to evolve with low resolution, AMR simulations achieve order of magnitude increases in computational speed.

The UR astrophysics group successfully constructed and tested AstroBEAR, a fully parallelized, multi-dimensional AMR MHD code. The success of this effort is evidenced both in the code's completion (Cunningham et al 2009) and the papers published using AstroBEAR as it was developed through its radiation-hydrodynamic and MHD versions (a partial list includes: Poludnenko et al 2004ab; Cunningham et al 2005; 2006ab, Hartigan et al 2007, Dennis et al 2008, Yirak 2009, 2010, Li et al 2012, Huarte-Espinosa et al 2012).

The multi-physics capabilities of AstroBEAR have been significantly expanded by including solvers for elliptic and parabolic equations. Adapting the linear system solver HYPRE, we now routinely simulate systems in which self-gravity, heat conduction and magnetic resistivity are important. Radiation transfer in the diffusive limit is currently being added. In addition, AstroBEAR can treat gravitationally interacting point particles which accrete mass.

5.1. AstroBEAR Scaling

AstroBEAR is designed for 2D and 3D adaptive mesh refinement (AMR) simulations which require algorithms that are highly parallelized and manage memory efficiently. AstroBEAR uses a hierarchical approach to parallelization suitable for multicore architectures in which large-scale patches of data are distributed to nodes using MPI and the work for an individual patch is distributed across the cores on a node using OpenMP directives. AstroBEAR also employs new techniques such as load balancing by threading the grid advances on each level with preference going to the finer level grids.

We performed strong scaling tests on Stampede at TACC shown in the top panel of Figure 4. These tests were done at a resolution of $320 \times 192 \times 192$ with 3 additional levels of AMR for an effective resolution consistent with our planned production runs. The strong scaling shows a slope -0.83 out to 1024 cores and -0.69 out to 4096 cores. (Perfect scaling corresponds to a slope of -1). This demonstrates good scaling of AstroBEAR on Stampede for the simulations we seek to perform. We also performed weak scaling tests shown in the bottom panel of Figure 4 to study how the code performed when the workload per core was held constant at 64^3 zones. In general this helps to determine how the communication scales. Our weak scaling results show a drop in efficiency of 15% out to 1024 cores and 27% out ro 4096 cores. More results and details about the performance of AstroBEAR can be found in the report of "Code Performance of AstroBEAR2.0".

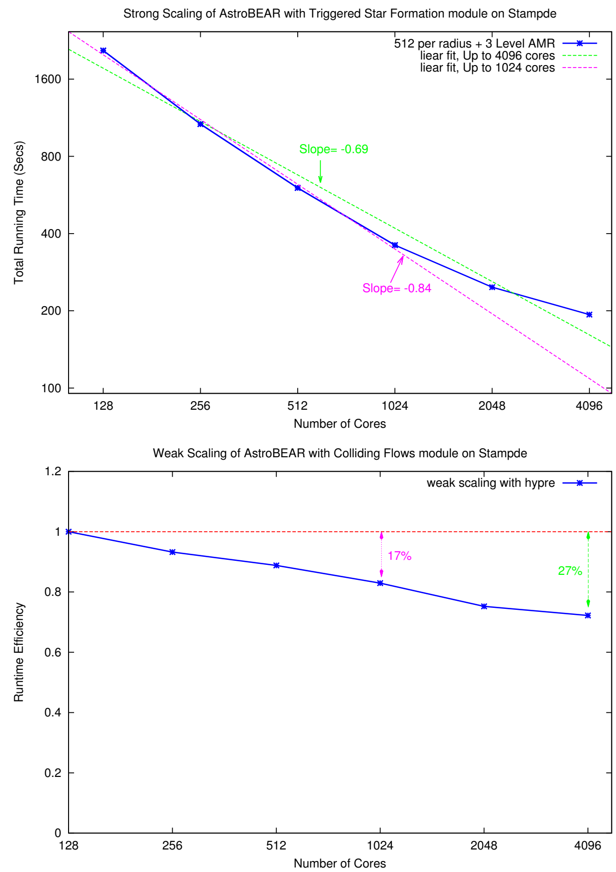

Fig. 4.— Top: Strong scaling behavior of AstroBEAR with a base resolution of $320 \times 192 \times 192$ and 3 additional levels of AMR on Stampede at TACC. Running time is plotted versus the number of cores in log scale. It has a slope of -0.84 out to 1024 cores and a slope of -0.69 out to 4096 cores (a slope of -1 corresponds to "perfect scaling). Bottom: Weak scaling behavior of AstroBEAR with self-gravity and 64^3 zones per processor on Stampede. The runtime efficiency($1/t$ where t is the running time) is plotted versus the number of cores in log scale. The efficiency drops only 15% running on 1024 cores and 27% on 4096 cores.

6. Justification of Runs

The formation of turbulent molecular clouds from supersonic colliding flows involves transferring the large scale bulk motion to smaller scale turbulence primarily via several instabilities including the thermal instability (TI), nonlinear thin shell instability (NTSI), and Kelvin Helmholtz instability (KHI), and Jeans instability (JI) (Heitsch & Hartmann 2008). The thermal instability (which is stable above scales of .1 pc) produces density fluctuations along the interface that become the seeds for the growth of other instabilities. In addition, the molecular cloud can undergo global gravitational contraction due to the accumulation of dense gas at later times and on larger scales (40 pc). Resolving both the thermal instability and the gravitational instability require at a bare minimum a resolution of order 1000^3. Our proposed resolution of 40^3+5 levels of AMR gives an effective resolution of 1280^3 zones. In addition the timescale for global gravitational instability is approximately 20 times the dynamical time scale, which corresponds with our proposed runtime and frame count.

The introduction of shear can dramatically enhance the growth of KH instabilities compared to the TI and NTSI. This is expected to alter the rate of core formation and potentially the angular momentum of the cores that due form. Performing simulations with shear angles of 0, 15, and 30, will allow us to study this effect in detail. We also propose to study the effect that magnetic fields play in the evolution of these clouds. Magnetic fields (provided they are strong enough) can suppress the NTSI and the KHI, and alter the evolution of the TI. They are also expected to alter the overall structure of the molecular cloud. Performing the set of simulations with a beta of 1 and 10 will allow us to investigate these effects in more detail.

For the triggered star formation, the proposed effective resolution is equivalent to 1024 cells per cloud radius. This is competitive compared to previous works done by Boss (512 cells per radius), and at a 2x resolution compared to our own work on TSF ((Li et al 2014)). This resolution allows us to study in more detail the accretion disc that forms during the collapse as seen in Li et al (2014). The choice of $\beta = 1$ is realistic for the interstellar medium, and will change the evolution considerably based on our low resolution prototype simulations. The toroidal and poloidal cases are two fundamental cases of self-contained magnetic fields which yield very different morphology upon being shocked (Li et al 2013). We seek to address how these differences affect the star formation. In particular, when the rotation axis is parallel to the shock normal case, it is likely that the process of collapse give rise to magneto-centrifugal acceleration of the bound material around the center of the disc therefore lead to jets (confirmed by our low resolution simulations) which is crucial in determining the likeliness of the triggering mechanism compared to observations.

7. Resource Request

7.1. CPU-hours Request

For our colliding flows project, our estimate CPU-hours is based on the strong scaling tests we've done which has the same resolution but running for only 0.1% of one frame (we are planning to obtain 200 frames of the data). For our scaling test on 1024 cores, it takes about $144 seconds$ or $41 CPU - hour$ to run 0.1% of one frame. So the total CPU-hours for one production run is about $820,000$ CPU-hours on Stampede. (See Table 1).

When doing strong scaling tests for our triggered star formation project, we start from a point where the stars have just formed and where the mesh is refined to level 3. It took about 361 seconds to get 20% of one frame from the starting points on 1024 cores which is about 103 CPU hours. We estimate the running time will be 8 times longer when running with 4 levels of AMR and the MHD runs will be twice as long as the the hydro runs. Based on this information we estimate the total CPU-hours needed will be 412,000 for each of the hydro runs and 824,000 for each of the MHD runs.(See Table 1).

In total we require 5.0 million CPU-hours on Stampede and 2.5 million CPU-hours on Gordon, about 99% of which will be used for production runs and 1% for testing runs and continue development of our code. We can use anywhere from 500-5000 cores for a typical production run, depending on queue limitations.

7.2. I/O Requirements, Analysis, and Storage

Based on Table 1, we expect to save 200 frames of data with an average size of 10GB for each frame (the size of the each frame depends how many zones trigger the highest level of AMR) for each of the six runs of our colliding flows simulation with 5 levels of AMR. So the total data size for our colliding flows project is about 12 TB. We are planning to run these simulations on Stampede and we expect to need ~12 TB of storage on Ranch of TACC. For each of of the four runs of our triggered-star-formation simulations, we expect to save 100 frames of data with size about 6GB, So the total data size for our triggered-star-formation project is about 2.4TB. These simulations will be done on Gordon. So we request ∼ 3 TB on Gordon. Most of the analysis will be done using parallelized tools built into the AstroBEAR package that can be performed at run time or in post processing.

7.3. Choice of Computational Clusters

We've been using Kraken and Stampede (before Ranger) for the past two very productive years. With Kraken decommissioned this April, we've had to shift most of our production runs to Stampede while seeking for opportunities on other machines. AstroBEAR scales very well on Stampede (see the scaling tests attached) and since Gordon has a similar architecture, we expect the code to scale on Gordon as well. For our Triggered Star Formation project, we propose to run with higher levels of AMR than before, which will require more memory usage and Gordon has 64GB of memory per node. We are also planning to optimize the code on the Xeon Phi coprocessors(5110P) of our local BlueHive system. So we expect the code will take the advantage of the MIC architecture and run even better on Stampede.

8. Local Resources and Research Team

Research Team Our research group consists of PI Professor Adam Frank two senior computational science staff members, one post-doc, 3 graduate students and two undergraduate students. Together the group has developed and maintained the AstroBEAR and applied it to problems ranging from star formation to evolved star winds. The code is also being used by other groups internationally and our group oversees their training.

Local Computing Resources The UR has two computational platforms available for our research. The Center of Integrated Research Computing(CIRC) hosts a Blue Gene/Q system called BlueStreak. BlueStreak consists of 1,024 nodes,16 TB of RAM, and 400 TB of storage. Each node consists of a 16-core A2 processor with 32MB of cache and access to 16GB of RAM. CIRC also hosts a Linux cluster with 200 nodes of IBMs iDataPlex architecture. Each node houses 2 x 12-core Intel Ivy Bridge processors, with a range in memory from 64 GB to 256 GB. These machines are available to researchers across the University and both systems are highly over-subscribed.

8.1. Financial Support

We have been granted financial support from the NSF, DOE and NASA. Specifically Space Telescope Sci Institute grant HST -AR-12128.01-A entitled "STSci - Hubble Telescope - The Reel Deal: Interpreting HST Multi-Epoch Movies of YSO JetsSpace" (PI, A. Frank; 10/1/2010 - 9/30/2014); DOE grant DE-SC0001063 entitled "The dynamics of magnetized Astrophysical Jets through Pulsed Power DEDP lab Studies" (PI, A. Frank; 8/15/2012 - 8/14/2015) and the National Science Foundation, NSF AST-1109285 entitled "From Central Engine to Bipolar Outflow: Binaries, MHD and the Evolution of Planetary Nebulae" (PI, A. Frank; 9/1/2011 - 8/31/2014).

9. Summary

Given our successful work with our parallelized AMR MHD multiphysics code AstroBEAR on studies of star formation we propose to carry forward 2 studies. The first is a campaign of high resolution MHD simulations of colliding flows including self-gravity, radiative cooling and treatment of sink-particles. The simulations are designed to study the effect of magnetic fields and shear on subsequent cloud formation. We will not only study the dynamics of the resulting flows but also produce detailed analysis of the statistics of the cloud properties which can be compared with observations. The second study is a targeted set of simulations to determine the effect of rotation and magnetic fields on triggered collapse. We are particularly interested in the formation of (planet forming) accretion disks in the aftermath of triggering and the role of fields in inhibiting/altering collapse and changing mixing.

- Study of colliding flows with MHD 4,920,000 SU's on Stampede.
- Study of triggered star formation with/without MHD 2,472,000 SUs on Gordon.
- Testing, and continue development of our code. 40,000 SU's on Stampede; 1% of total request.
- Testing and continue development of our code. 40,000 SU's on Stampede; 2% of total request.

To achieve these goals, we request 5,000,000 SU's on the Stampede of TACC and 2,500,000 SUs on Gordon of SDSC.

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Table 1: Estimate CPU-hours needed for each run (based on 1024 cores of Stampede)

Project	Colliding Flows	Tiggered Star Formation
AMR levels for (Scaling VS Production)	5 VS 5	3/2 VS 4
Num of frames (Scaling VS Production)	0.1% VS 200	20% VS 100
WallTime/CPU-hour for Strong Scaling(1024 cores)	144 Secs/41	361 Secs/103
Data size of each frame	5-20 GB	3GB (6-12GB with 4 AMR)
Total Estimate CPU-hours	820,000	412,000

Table 2: Expected CPU-hours for Continuing Colliding Flows 3D Simulations

Shearing Angle(θ)	Resolution	Magnetic Field (β)	Expected SUs on Stampede
0	40^3 + 5 AMR	1	820,000
15	40^3 + 5 AMR	1	820,000
30	40^3 + 5 AMR	1	820,000
0	40^3 + 5 AMR	10	820,000
15	40^3 + 5 AMR	10	820,000
30	40^3 + 5 AMR	10	820,000
Total			4,920,000

Table 3: Expected CPU-hours for 3D Triggered Star Formation Simulations

Hydro/MHD	Resolution	Rotation	Expected SUs on Stampede
Hydro	$320 \times 192 \times 192$ + 4 AMR	axis parallel to shock normal	412,000
Hydro	$320 \times 192 \times 192$ + 4 AMR	axis perpendicular to the shock normal	412,000
MHD $\beta = 1$,Toroidal	$320 \times 192 \times 192$ + 4 AMR	axis parallel to shock normal	824,000
MHD $\beta = 1$,Poloidal	$320 \times 192 \times 192$ + 4 AMR	axis parallel to shock normal	824,000
Total			2,472,000