# Study of Colliding Flows and Feedback in Star Formation

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## 1 Abstract

The question of star formation feedback has risen in importance as data from NASA missions such as the HST and SST have yielded fruitful global studies of young star clusters. Feedback represents a suite of processes in which the flux of mass, momentum and energy (both kinetic and radiative) from newly formed stars affects the assembly of other stars in the cluster.The issue of feedback between newly formed stars and their environment represents one the the major challenges to the next generation of star formation studies. In order to track the role of feedback in star forming clusters we must first build reasonable models of a star forming cluster. Using the AMR multi-physics capabilities of AstroBEAR we will use global simulations to create a cloud environment with a spectrum of proto-cluster (so-called "clump") masses. Clusters of appropriate mass will then become initial conditions for further ultra-high resolution simulations where stars can form via collapse (sink particles) and outflow conditions can be applied to those stars to track feed back.

Based on novel results that obtained with our previous start-up XSEDE allocation (TG-AST120029) we propose to to carry out a series of three-dimensional Adaptive Mesh Refinement parallel numerical simulations to study the cloud collapse and cluster formation under various conditions. This will include colliding flows with/without MHD and with different shear angles, different magnetic field strength and angles.

We are in full production mode with AstroBEAR2.0, but the powerful numerical resources of the XSEDE that we are requesting are needed to make further progress on unraveling the mysteries of feedback process in star formation. To achieve this exciting goal we request the support of 7.1 million SU's on Kraken at NICS..

## 2 Introduction

Over the last decade rapid progress in the study of star formation has allowed astronomers to move from studying the assembly of single stars to a more detailed exploration of stellar birth in an environmental context meaning the study of clustered star formation (Fig 1). The density of young stellar clusters can vary considerably, from $N = 10^2 pc^{-3}$ in low mass versions such as Taurus, to $N = 1000 pc^{-3}$ in high density clusters such as Orion. In both low and high mass clusters however, stars form with siblings in close proximity. While much is understood about isolated star formation, the opposite is true for star formation in an environmental context. In particular, the mechanisms by which

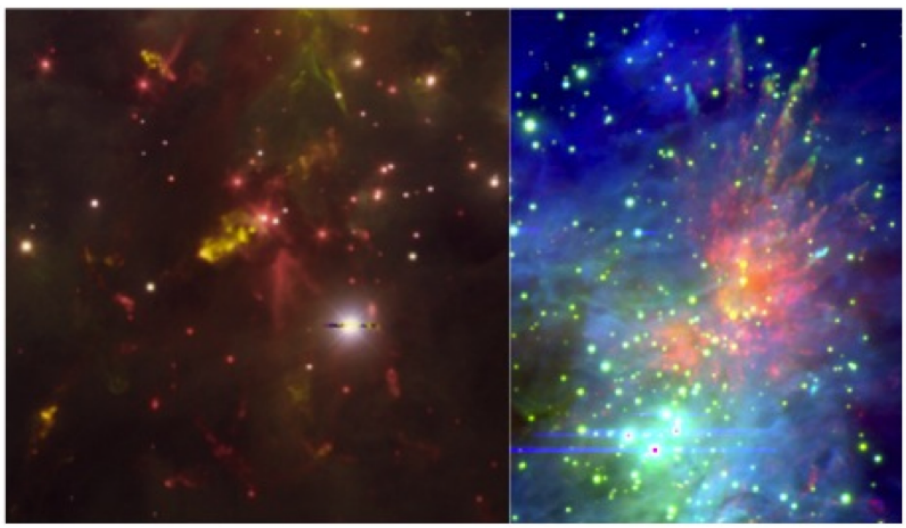

Figure 1: Feedback in star forming clusters. Right (1a): Low mass cluster NGC 1333 (Combined mosaic CCD:green and SST: red). Note the presence of multiple outflows oriented in a variety of directions. Left (1b): OMC 1 outflow (combined HST and NIR H2: FeII). Note the semi-collimated eruption that has broken up into various "fingers" interacting with the surrounding cluster gas.

many stars, having formed roughly coevally, affect their parent cloud environment remain poorly characterized. Fundamental questions, such as the nature of the interplay between multiple outflows, ionization fronts and turbulence are just beginning to be fully articulated (Klein et al 2005). The issue of feedback between newly formed stars and their environment represents one of the major challenges to the next generation of star formation studies. In particular issues such as the lifetime of molecular clouds, clumps and cores may require a full characterization of feedback as it remains uncertain if clouds are transient or equilibrium structures (Ballesteros-Parades et 1999b, Elmgreen 2000). The critical issue of Star Formation Efficiency (SFE) in clouds of different types will also require an understanding of feedback from newly forming stars as material which may collapse can become unbound via stellar energy inputs (Krumholtz et al 2005). Many clouds show SFE of less than 25% and it remains unclear what processes restrict a more efficient conversion of cloud mass into stars. Feedback

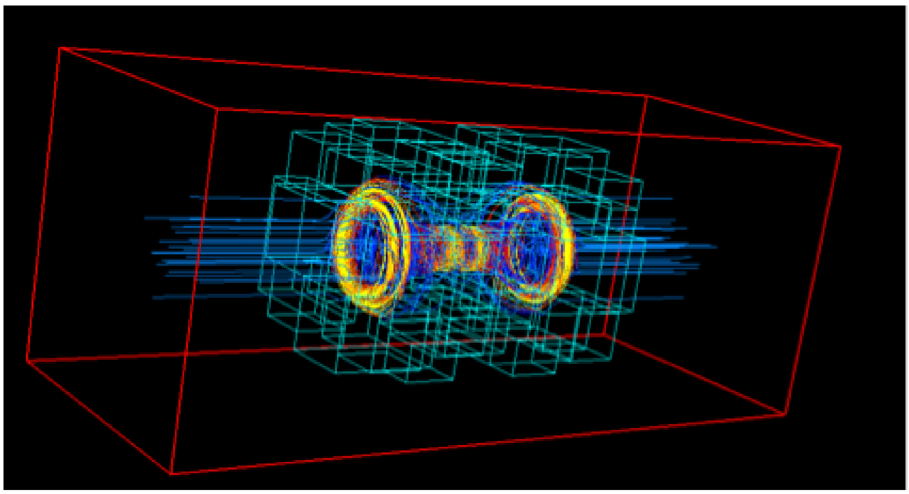

Figure 2: Bipolar Jet Simulation Using AstroBEAR MHD AMR code. Bipolar jet (yellow isosurfaces) expands from center of computational domain. Blue = magnetic fields. Jet field is dominated by toroidal component. Green boxes show adaptive placement of high resolution grids (Cunningham et al 2009)

represents a suite of processes in which the flux of mass, momentum and energy (both kinetic and radiative) from newly formed stars affects the assembly of other stars in the cluster. The nature of feedback will however differ depending on the nature of the cluster. Lower mass clusters without O stars will tend to be dominated by collimated outflows from newly formed low and intermediate mass stars (Bally 2011a,b). Massive clusters with one or more O stars will be dominated by both ionization fluxes from those stars and highly energetic mass outflows via both collimated and uncollimated winds, non-terminal eruptions and, finally, supernova. Thus one can think of a feedback ladder in which the nature of the feedback processes changes for clusters of different potential well depths (Smith et al 2010, Bally 2001). Characterizing feedback and its effect on clusters of different masses is a critical step in assessing its overall role in clustered star formation.

The question of star formation feedback has risen in importance as data from NASA missions such as the HST and SST have yielded fruitful global studies of young star clusters. Thus it is now time to push deeper in developing detailed "ecological studies" of star formation where the parent molecular cloud, newly formed stars and stellar feedback are seen as a coherent interacting system. We

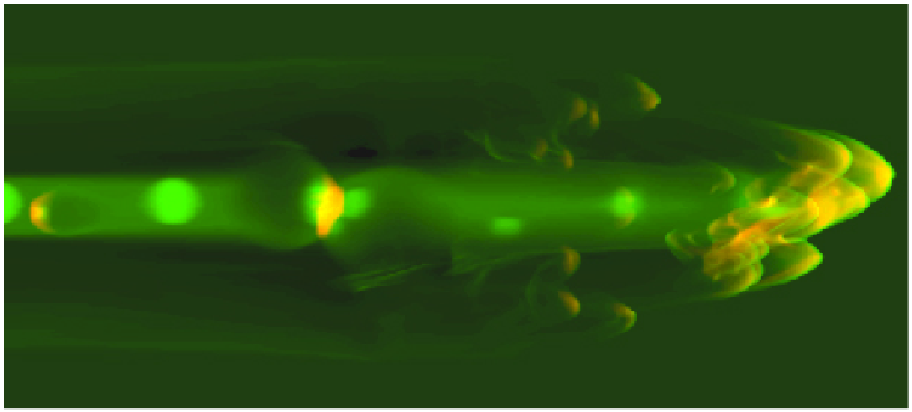

Figure 3: Comparison with Data: AstroBEAR Synthetic Observations. Ha (green) and [SII] (yellow) image of clumpy jet simulation. Code has microphysics routines to model all HST relevant wavelength bands.

seek to carry forward a focused theoretical study of feedback in both low mass and high mass cluster environments with direct connections to observations. Using the Adaptive Mesh Refinement MHD multiphysics code called AstroBEAR developed by our group we plan to do two computational studies: (1) multiple, interacting outflows and their role in altering the properties of a parent low mass cluster (2) Poorly collimated outburst/outflows from massive star(s) and their effect on high mass cluster star forming environments. In both cases we will use initial conditions derived from high-resolution AMR MHD simulations of cloud/cluster formation. An example from our computation can be found at (4).

In this proposal we seek to carry out a series of three-dimensional Adaptive Mesh Refinement parallel numerical simulations to study the cloud collapse and cluster formation under various conditions. This will include colliding flows with/without MHD and with different shear angles, different magnetic field strength and angles (see Table 1).

# 3 Accomplishments and the way forward

3D Simulations of Feedback and Its Consequences: Left: Density cut of 3D jet feedback model. Outflow collisions (red) “stir” ambient gas (blue). Right: Turbulent energy spectra for models with outflows only (blue), injected turbulence only (red) and with both (green). Note that outflows always alter characteristics of turbulent spectra producing both steeper slopes and a “knee” characteristic of the outflow interaction length (see Carroll et al 2010 for a discussion of relevance to current observations).

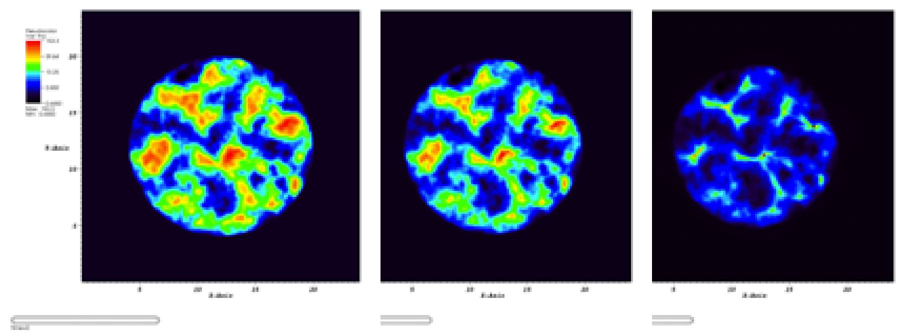

Figure 4: Simulations of cloud collapse and cluster formation (density). An initial Bonner Ebert sphere with density perturbations collapses (left to right) forming a dense proto-clusters. Note the creation of a few sink particles (dots) in the last frame. By identifying these structures prior to collapse we can select out clusters of different mass and follow their subsequent evolution at much higher resolution for our feedback simulations.

# 4 Research Objectives

We will focus on simulations and observational implications of colliding flows. This will include (1) colliding flows with different shears and (2) colliding flows with different magnetic fileds. Our computations will be carried out using AstroBear2.0.

# 5 Computational Approach

AstroBEAR2.0 is an Adaptive Mesh Refinement (AMR), multi-physics code for astrophysics. AMR remains at the cutting edge of computational astrophysics. AMR simulations adaptively change resolution within a computaional 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 computaional speed. After a decade of development only a handful of AMR-MHD codes exist for astrophysics: (e.g. FLASH, ENZO RAMSES, ORION, CASTRO).

The UR astrophysics group successfullly 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 2012a).

The multiphysics 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 exploys new techniques such as load balancing by threading the grid advances on each level with preference going to the finer level grids.

Here we present strong scaling results for AstroBEAR. In Figure 5, we report scaling test results on Kraken at NICS. Each compute node of Kraken has two six-core AMD Opterons, so we use 120, 240 and 480 cores. The resolution we used for these test are $128^3 + 4$ level AMR which is same as the computation we are plannning to do. The strong scaling test plot of the current code shows a slope $-0.764$ (Figure 5 (a)) while the slope for perfect scaling is $-1$. This shows AstroBEAR has an excellent scaling on Kraken. All AMR codes have redundant calculations coming from ghost zones. The redundant calculations portion gets bigger as the refinement zones gets smaller. Ideally if we get rid of all redundant calculations, the AstroBEAR scaling will be a straight with slope $-0.971$ (Figure 5 (b)). We are trying to get closer to this slope by optimizing the code and decreasing the redundant calcuations.

## 6 Resource Request

Using AstroBEAR2.0, we have found very interesting new results on the feedback (Quillen et al 2005, Carroll et al 2009, 2010, Carroll et al 2012) and on colliding flows (Cunningham et al 2009, Carroll et al 2013), We plan to carry out a series of three-dimensional Adaptive Mesh Refinement parallel numerical simulations with different shear angle and magnetic field to study the star-forming properties of a cluster. This will include (1) colliding flows with shear angle $0°$, $30°$ and $60°$ (2) colliding flows with MHD and magnetic field with strengh $\beta = 1$ and $\beta = 2$ and direction $\theta = 0°$, $\theta = 30°$ and $\theta = 60°$. AstroBEAR2.0 is presently performing well with multiple 6+ levels of AMR refinement. The tractability of a given run then becomes more a question of the number of needed cell updates, which is mainly determined by the fraction of the volume where mesh refinement is employed. And the volume filling fraction depends on the specific problem/simulation. The computing resources we require are based on our previous runs on XSEDE machines. For example, Our hydro calculation

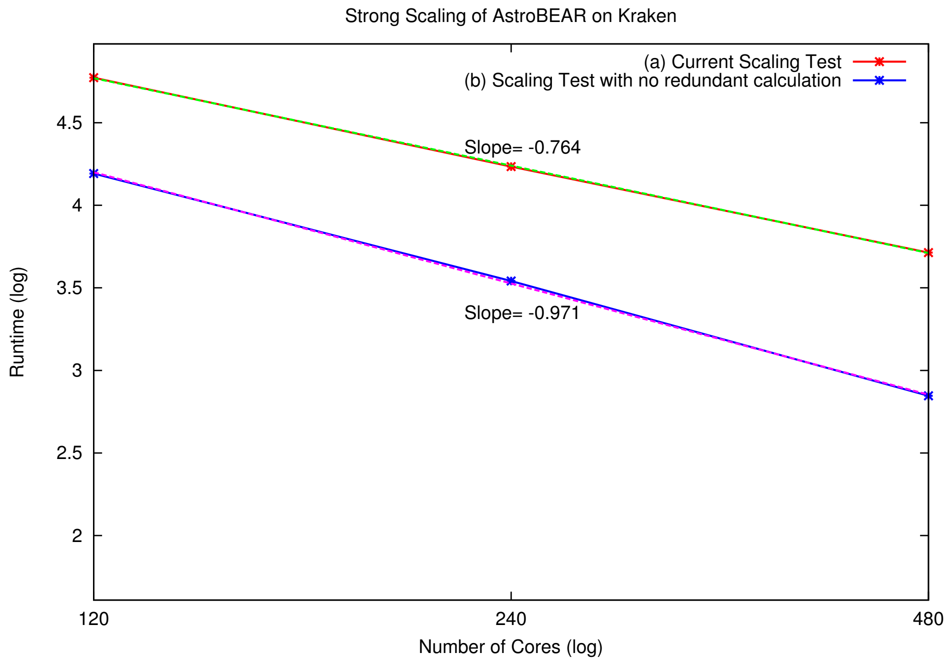


Figure 5: Strong scaling behavior of AstroBEAR with $128^3 + 4AMRlevel$ resolution on Stampede at TACC. Running Time is ploted versus the number of cores in log scale. (a) shows the scaling test result of current revision of AstroBEAR. It has a slope $-0.764$ which shows excellent scaling. (b) is the scaling test after we remove all redundant calculations. It has a almost perfect scaling slope $-0.971$. This is the scaling we are aiming to.

with $0^\circ$ shear and with resolution $128^3 + 4AMR$ took about 6,000 SUs for 1 frame. In Tables **??** we summary the computing resources we require. In total we require 7.1 million CPU-hours, 99.3% of which will be used for production runs and 0.7% for testing runs and continue development of our code. We need about 4,000 cores for a typical production run.

## 6.1 I/O Requirements, Analysis, and Storage

For each of the seven runs of our simulation, we expect to save 150 frames of data with size 1-5GB for each frame. So the total data size for our colliding flows project is about 850GB-4.5Tbytes. In total we expect to need $\sim$5 Tbytes of storage on Kraken and Stampede.

Table 1: Expected CPU-hours for Colliding Flows Simulations

| Hydro/MHD | Shear Angle | $\beta$ | Field Orientation | Resolution | Frames | Expected SUs |
|---|---|---|---|---|---|---|
| H | 30° | 0 | 0° | $128^3 + 4AMR$ | 150 | 900,000 |
| H | 60° | 0 | 0° | $128^3 + 4AMR$ | 150 | 900,000 |
| MHD | 60° | 1 | 0° | $128^3 + 4AMR$ | 150 | 1,050,000 |
| MHD | 0° | 2 | 0° | $128^3 + 4AMR$ | 150 | 1,050,000 |
| MHD | 60° | 2 | 0° | $128^3 + 4AMR$ | 150 | 1,050,000 |
| MHD | 0° | 1 | 30° | $128^3 + 4AMR$ | 150 | 1,050,000 |
| MHD | 0° | 1 | 60° | $128^3 + 4AMR$ | 150 | 1,050,000 |
| Total | | | | | | 7,050,000 |

### 6.2 Financial Support

Financial support for this project will come from the 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 - 9/30/2013) and the Department of Energy grant DE-SC0001063 entitled "The dynamics of magnetized Astrophyiscal Jets through Pulsed Power HEDP 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). DOE, Award no. R17081, entitled "Rice - Clumpy Environments & Interacting Shock Waves: Realistic Laboratory Analogs of Astrophysical Flows", (PI: A. Frank, 2/22/2011 - 2/21/2014) and the Space Telescope Sci Institute grant HST-AR-12832.01-A entitled "Hubble Telescope Cycle 20 - Climbing the Ladder of Start Formation Feedback", (PI A. Frank, 11/1/2012 - 10/31/2015).

## 7 Summary

With the advent of our efficient 3D AMR MHD code AstroBEAR2.0 and state of the art HPC facilities, we are on the doorstep of significant breakthroughs in understanding the physics of the feedback process in the clustered star formation. With our previous start-up XSEDE allocation (TG-AST120029), we have already found and are in the process of publishing very important results. We are in full production mode with AstroBEAR2.0, but the powerful numerical resources of the XSEDE that we are requesting are needed to make further progress on unraveling the mysteries of interacting binaries.

If granted this allocation, we will perform a series of 3D Adaptive Mess Refinement parallel numrical simulations with higher resolution and longer timescales than ever before to study the formation, structure and stability and observational implications of inter-acting stellar binaries.

- Study of colliding flows with/without MHD 7,050,000 SUs; 99.3% of total request.
- Testing and continue development of our code. 50,000 SUs; 0.7% of total request.

To achieve these goals, we request 7,100,000 SU's on the NCIS Cray XT5 (Kraken).

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