Magnetic Towers and Binary-Formed Disks

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1 Abstract

Several supersonic collimated outflows have been observed emanating from Young Stellar Objects, Proto-Planetary Nebulae (PPN) and other astrophysical objects. Understanding the physics of these so-called jets is a key challenge in plasma astrophysics, for they are the most powerful natural mechanisms of energy transport. One paradigm to explain the formation of jets in PPN is that of a binary stellar system in which material from the wind of an AGB star is gravitationally pulled onto an intermediate-mass companion. A hot magnetized rapidly rotating plasma disk will be formed about the companion star. The rotational and magnetic energy of this disk will then lead to the launch and collimation of jets. Several key fundamental questions remain open in this picture however. E.g. which binaries, i.e. for which separations and mass ratios, form stable accretion disks? Do all disks form jets? What affects the stability of jets?

Based on novel results that obtained with our previous start-up XSEDE allocation (TG-AST120029) we propose a plan to carry out a series of three-dimensional Adaptive Mesh Refinement parallel numerical simulations to study the formation, structure and stability, and observational implications, of interacting stellar binaries. This will include (1) accretion from the primary AGB wind onto a secondary star and (2) launch and propagation of strongly magnetized jets. Our computations will be performed with higher resolution and longer time-scales than ever before, using our local and well tested code AstroBear2.0. Binary-formed accretion disks will be investigated for stellar separations of 10, 20, 30, 40 astronomical units, for mass ratios of 1.5. On the other hand, strongly magnetized jets will be investigated for adiabatic and cooling plasmas, against toroidal-to-poloidal magnetic component ratios of .1, 1, 10, 100.

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. To achieve this exciting goal we request the support of 4 million SU's on Kraken at NICS and 4 million SU's on Ranger at TACC.

2 Introduction

Astronomical observations have established that collimated supersonic outflow, or jets, are ubiquitous. Young Stellar Objects (YSO), proto-Planetary Nebulae (PPN), X-ray binaries and distant active radio galaxies show jets. The "central engines" of these flow cannot be directly observed due to insufficient telescope resolution. Models suggest that jets are launched and collimated by accretion, rotation and magnetic mechanisms (Pudritz et al. 2007). One paradigm to explain the formation of jets in PPN is that of a binary stellar system in which material from an AGB star wind is accreted (captured gravitationally) onto an intermediate-mass companion (Soker & Rappaport 2000; Nordhaus, Blackman & Frank 2007). The process of accretion from a primary wind onto a secondary star is a specific case of Bondi-Hoyle-Lyttleton (BHL) accretion (e.g. Edgar 2004 for a review) and is now observed to play a direct role in the phenomenology of some asymmetric PPN; the best studied example is the Red Rectangle (Witt et al. 2009).

Disk formation around the secondary via AGB wind capture was first studied computationally with SPH calculations 14 years ago (Mastrodemos & Morris 1998), then by Podsiadlowski & Mohamed (2007) using GADGET), and more recent 2D FLASH simulations of BHL accretion were performed by De Val-Borro et al. (2009). These studies found significant enhancements, by 1-2 orders of magnitude, over BHL accretion rates onto the secondary. Such result however must be tested in 3-D using high resolution simulations because the implications for the maximum outflow (jet) power are dramatic; the answer could rule in, or out, the secondary as the engine powering jets in PPN.

In the case of magnetized jets, assumed to be launched from accretion disks in binaries, plots of specific angular momentum vs. jet speed are distinct for different MHD engines (Ferreira et al. 2006). This fact can help constrain the physics of jet engines. The importance of the magnetic field relative to the flows' kinetic energy, divides jets into (i) Poynting flux dominated (PFD; Shibata & Uchida 1986), in which magnetic fields dominate the jet structure, (ii) magnetocentrifugal (MC; Blandford & Payne 1982), in which magnetic fields only dominate out to the Alfvén radius. The observable differences between PFD and MC jets are unclear, as are the effects of cooling and rotation on these jets. Recently, cooling magnetized jets have been formed in laboratory experiments (Lebedev et al. 2005). Such studies, along with high resolution 3-D MHD numerical simulations (e.g. Ciardi et al. 2009, Huarte-Espinosa et al. 2012c), have proven to play a key role in the understanding of the physics of jet launch and stability.

3 Accomplishments and the way forward

With our previous start-up XSEDE allocation (TG-AST120029) we have found very interesting, new results on the formation of disks in binaries. In [Huarte-Espinosa et al. , 2012d] we explained that the BHL accretion solution has to be modified for its application to accretion from the primary wind onto an orbiting secondary; the wake that develops in this process is not aimed towards the instantaneous position of the companion as in the BHL accretion. Instead, the captured material is accelerated towards a position between the companion's original and current positions. We have characterize this process via the "impact parameter"

$$\frac{v_s^3(2Gm/v_w)^2}{2r_s(v_s^2+v_w^2)^{3/2}} \tag{1}$$

where v_s, m, r_s and v_w are the orbital speed of the secondary star, the mass of the secondary star, the distance between the binary center of mass and the secondary and the AGB star's wind speed. In [Huarte-Espinosa et al. , 2012d] we found that the formation of disks in 3-D simulations strongly depends on the proper resolution of the impact parameter. We were also able to resolve, for the first time, bow shocks formed by the interaction of stable disks and the AGB wind (see Figure 1).

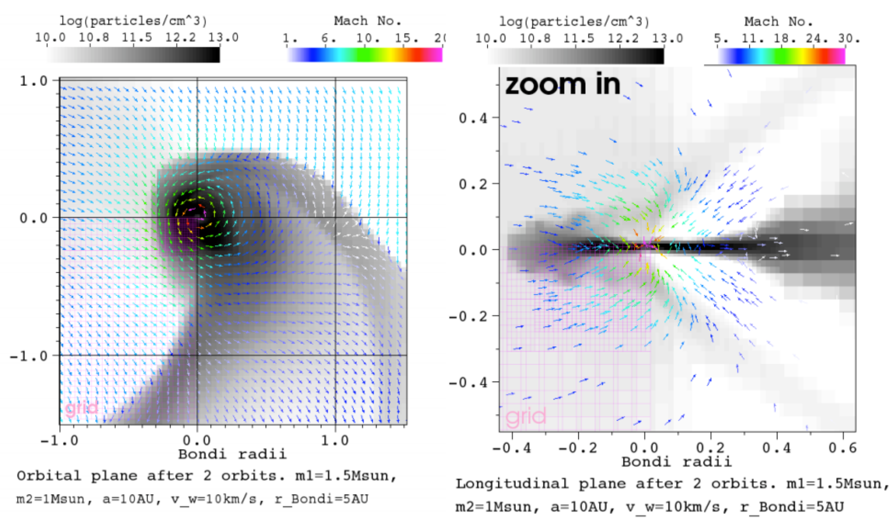

Figure 1: Density and velocity field distribution of the binary-formed accretion disk. Left: slice through the orbital plane. Note the disk (dark, round region) around the origin and the accretion "tail" (gray wide region) on the bottom right part of the domain. Right: zoom in at a longitudinal slice through the disk. The primary AGB star has a mass of $1.5\,\mathrm{M}_\odot$ and is located outside the grid. The AGB's wind enters the grid from the left and top (left panel) domain faces. The secondary star has a mass of $1\,\mathrm{M}_\odot$ and is located at the origin. The domain follow the orbit of the secondary. A quarter of the grid is shown in pink color.

In [Huarte-Espinosa et al. , 2012d] we carried out two realization of the problem: one for a binary separation of 10 AU and another one for a separation of 20 AU. A parameter survey is very important for the numerical characterization of the accretion rates onto the companion; the value of these accretion rates relative to the BHL solution might rule in, or out, the secondary as the engine powering jets in PPN.

On the other hand, in Huarte-Espinosa et al. 2012a we have carried out 3D-MHD AMR numerical simulations of stellar PFD jets. These outflows where launched via magnetic pressure gradients of the initial conditions and the continuous injection of magnetic energy. We assumed that the initial magnetic field had been wound by a binary-formed accretion disk at sub-resolution scale. The novel part of this study was the exploration of the effects that cooling and rotation have on PDF jets. One of our motivations was the important fact that the observations cannot clearly distinguish between PFD and MC jets.

Huarte-Espinosa et al. 2012a found that cooling and jet base rotation amplify current-driven perturbations in PFD jets. This is clear in Figure 2 which contains maps of the magnetic field lines in our jets for three cases: one unperturbed version (left); one only affected by base rotation (middle); one only affected by cooling (right). The top panel shows side-on views while the bottom panel shows upper (pole-on) views. Colors represent magnetic field strength. As a consequence of the kink perturbations amplified by cooling or rotation, the PFD jets become a series of collimated clumps, the magnetization properties of which vary over both time and distance from the engine. PFD flows may thus eventually evolve into hydro jets at large distances from their host stars. This is very relevant for observations of Young Stellar Objects and proto-Planetary Nebulae (Hartigan et al. 2007). Our calculations are thus the fists steps towards distinguishing between different launch mechanisms by providing descriptions of asymptotic flow characteristics where observations might be possible, specially with the next generation of telescopes, e.g. ALMA. Moreover, the evolution of our PFD jets is in very good agreement with plasma laboratory astrophysics experiments Huarte-Espinosa et al. [2011]. Hence the laboratory experiments and the simulations support each other as well as the conclusion that both are revealing generic properties of PFD jets.

A future avenue for this investigation is a systematic comparison of the magnetic energy flux distribution between our PFD jets -where magnetic fields dominate the entire jet structure- and MC jets -where magnetic fields only dominate near the engine (e.g. Krasnopolsky et al. 1999, 2003). Finally, the parameter survey is very important future work, since we have only solved three PFD jet cases. We note that while one of our principle interests are kink instabilities in these jets, such instabilities are also very relevant for plasma columns is solar flares and devices that confine plasmas using magnetic fields.

4 Research Objectives

We will focus on simulations and observational implications of interacting binaries. This will include (1) accretion from the primary wind onto a secondary star

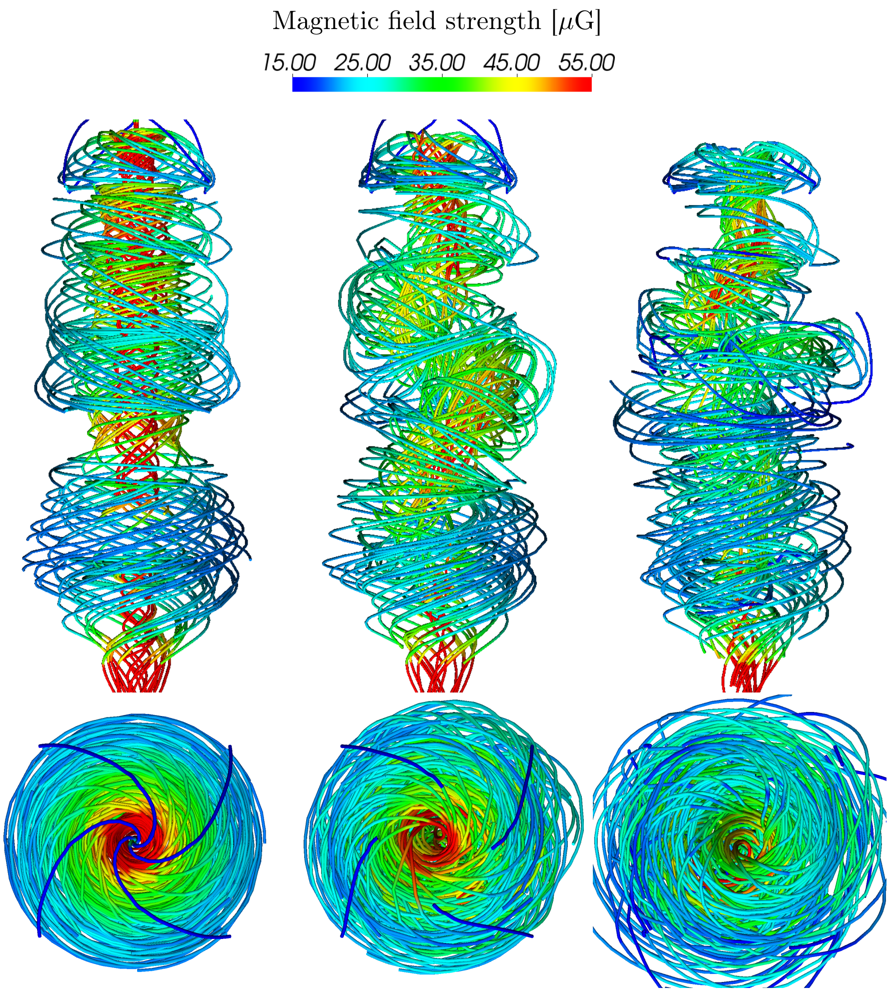

Figure 2: Central PFD jet magnetic field lines at $t = 118$ yr. From left to right these are the adiabatic, non-rotating jet, the one with base rotation and the cooling one, respectively. Bottom panels show an upper view, pole-on. Open field lines are a visualization effect.

and (2) launch and propagation of strongly magnetized jets. Our computations will be carried out using AstroBear2.0.

Accretion from the primary wind onto a secondary star. We will start by extending our previous models of wind capture in binaries with co-rotating reference frames (Huarte-Espinosa et al. 2012d, in prep.). The aim will be to perform a comprehensive 3-D exploration of (1) the nature of disk formation, (2) the outcome of wind accretion, (3) determination of accretion rates and disk geometries, and (4) a comparison to the BHL accretion rate. We will investigate using a range of binary stellar masses, stellar separations and grid resolution setups using the power of AstroBear2.0's AMR (see section 6). We seek to obtain data in 3-D and with higher grid resolutions than ever before. We will also do a comparison with the semi-analytical models on accretion disk long term evolution of Perets & Kenyon (2012) who have found consistently raising gradients in their evolution profiles of both the disk mass and the secondary accretion (see their Figure 1). In Huarte-Espinosa et al., 2012d, in prep) we have found different profile gradients; ones that become flat much faster than the analogous profiles of Perets & Kenyon (2012).

Launch and propagation of strongly magnetized jets. Once the above simulations are running and producing data we will start working on the magnetized jets. Our starting point will be the initial conditions and setup that we used Huarte-Espinosa et al. (2012a), but with a larger grid, more spatial resolution and longer evolution times. The aim of these models will be a comparison of PFD jets with simulations of MC launching in which the flow is cold and gas pressure can be ignored and show typical values of magnetic-to-kinetic energy flux ratios ~ 0.7 at observationally-resolved distances from the engine (Krasnopolsky et al. 1999, 2003).

After that we will focus on investigating the structure and propagation of PFD jets as a function of position in the parameter space defined by (1) the initial magnetic field geometry, (2) the initial and injected magnetic-to-kinetic energy flux ratio, (3) the plasma cooling strength and (4) the jet base rotation profile. The focus will be understanding the nature and non-linear evolution of current-driven instabilities that produce such a suggestive correspondence between simulations, laboratory experiments and astrophysical observations (Lebedev et al. 2005; Ciardi et al. 2007; Huarte-Espinosa et al. 2012a). Of particular interest to us is the effect that the above parameters have is the time-dependent distribution of the magnetic-to-kinetic energy flux ratio of PFD jets. This has important fundamental implications for both observations of jets and the jet launch models (see Section 1).

We note that the these proposed investigations have never been done before.

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 2012ab).

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 scaling results for AstroBEAR. In Figure 3, we report scaling test results on Kraken at NICS. Each compute node of Kraken has two six-core AMD Opterons, so we use 12, 1200, 4800, and 12000 cores. These tests are done with 4 level AMR and different load balancing schemes. The running efficiency only drops about 30% up to 12000 cores on Kraken, which shows the excellent scaling of AstroBEAR.

Figure 4 shows the scaling results for AstroBEAR on Ranger at TACC. For these tests, we run with 0 level and 1 level of AMR. For each level of AMR, we see flat scaling curves which again shows us excellent scaling results.

6 Resource Request

Using AstroBEAR2.0, we have found very interesting new results on the formation of disks in binaries (Huarte-Espinosa et al. 2012c, 12d) and on stellar PFD jets (Huarte-Espinosa et al. 2011, 12a, 12b), We plan to carry out a series of three-dimensional Adaptive Mesh Refinement parallel numerical simulations

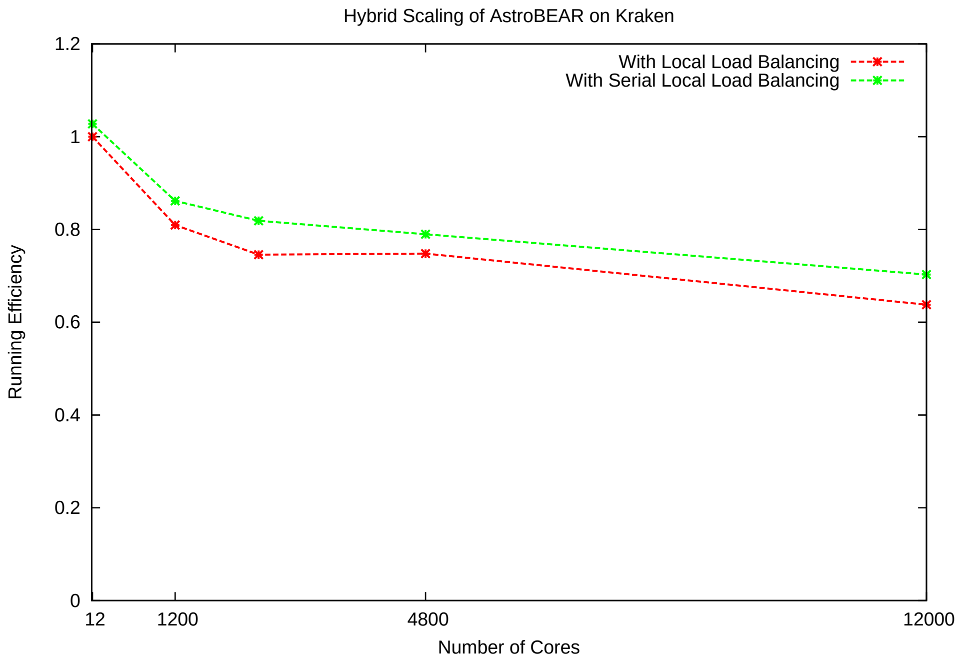

Figure 3: Hybric scaling behavior of AstroBEAR on Kraken at NICS.Running efficiency with different load balancing schemes is ploted versus the number of cores. The curve is expected to be flat for perfect scaling.

with with higher resolution and longer time-scales than ever before to study the formation, structure and stability, and observational implications, of inter- acting stellar binaries. This will include (1) accretion from the primary AGB wind onto a secondary star and (2) launch and propagation of strongly magne- tized jets. Binary-formed accretion disks will be investigated for stellar separations of 10, 20, 30 and 40 astronomical units, for mass ratios of 1.5. On the other hand, strongly magnetized jets will be investigated for adiabatic and cooling plasmas, against toroidal-to-poloidal magnetic component ratios of .1, 1, 10, 100.

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 20au Binary Disk Simulation with resolution $64^3 + 3AMR$ took about 100,000 SUs for 3 orbits. In Tables 1 and 2 we summary the computing resources we require. In total we require 8 million CPU-hours (4 million on Kraken and 4 million on Ranger), 99.2% of which will be used for production runs and 0.8% for testing runs and continue development of our code. We need about 10,000

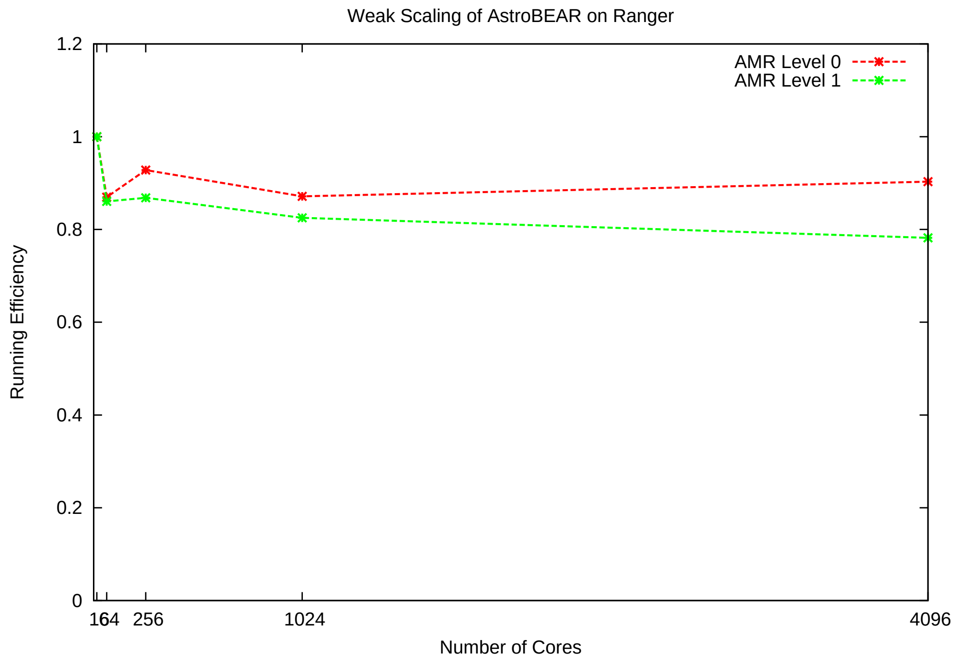

Figure 4: Weak scaling behavior of AstroBEAR with 0 and 1 AMR level on Ranger at TACC. Running efficiency is ploted versus the number of cores. The curve is expected to be flat for perfect scaling.

cores for a typical production run.

6.1 I/O Requirements, Analysis, and Storage

For each of the four runs of our Binary disks simulation, we expect to save 200 frames of data with size 1-5GB for each frame. So the total data size for our binary disks project is about 800GB-4Tbytes. We also expect the similar size of storage for our tower simulation. In total we expect to need ∼8 Tbytes of storage on Ranger and Kraken.

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; 8/15/2009 - 8/14/2012) and the National Science Foundation, NSF AST-1109285 entitled "From Central Engine to Bipolar

Table 1: Expected CPU-hours for Binary Disk Simulations

Size	Resolution	Time	Expected SUs
10au	$64^3 + 5AMR$	10 orbits	50,000
20au	$128^3 + 5AMR$	10 orbits	245,000
30au	$128^3 + 5AMR$	10 orbits	850,000
40au	$256^3 + 6AMR$	10 orbits	4,350,000
Total			5,495,000

Table 2: Expected CPU-hours for Magnetic Towers Simulations

t/p magnetic component ratios	Resolution	Expected SUs
0.1	$128 \times 128 \times 320 + 3AMR$	500,000[a] / 600,000[b]
1.0	$128 \times 128 \times 320 + 3AMR$	350,000[a] / 450,000[b]
10.0	$128 \times 128 \times 320 + 3AMR$	150,000[a] / 240,000[b]
100.0	$128 \times 128 \times 320 + 3AMR$	55,000[a] / 95,000[b]
Total		2,440,000

[a] Adiabatic Plasmas
[b] Cooling Plasmas

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 - 2/21/2013).

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 jets – the most powerful natural mechanisms of energy transport. 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 time-scales than ever before to study the formation, structure and stability and observational implications of inter-acting stellar binaries.

- Study of accretion from the primary AGB wind onto a secondary star. Resources requested: 5,495,000 SUs; 68.7% of total request.
- Study of launch and propagation of strongly magne- tized jets. Resources requested: 2,440,000 SUs; 30.5% of total request.
- Testing and continue development of our code. 65,000 SUs; 0.8% of total request.

To achieve these goals, we request 4,000,000 SU's on the NCIS Cray XT5 (Kraken) and 4,000,000 SU's on the TACC Sun Constellation Linux Cluster (Ranger)

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