Magnetic Towers and Binary-Formed Disks

Martín Huarte-Espinosa, Adam Frank, Jason Nordhaus,
Baowei Liu, Jonathan J. Carroll-Nellenback

October 15, 2013

1 Abstract

Supersonic collimated outflows are observed emanating from Young Stellar Objects, Proto-Planetary Nebulae (PPN) and other astrophysical objects. Understanding the physics of these jets is a key challenge in plasma astrophysics, for they are powerful mechanisms of energy transport as well as probes of the unresolved central engine. One paradigm to explain the formation of jets in PPN is that of a binary stellar system. Jets may be formed in such an evolved system either by wind capture onto the secondary or via Common Envelope Evolution (CEE) in which the secondary is engulfed within the primary leading to the tidal disruption of the secondary and the formation of a disk around the primary's core. The rotational and magnetic energy of this disk will then lead to the launch and collimation of jets. Once launched, many questions about the physics of the magnetized jet remain unanswered such as the jets stability, the propagation of internal shocks within the jet beam and the observational consequences of the MHD jet dynamics.

In this proposal we plan to build on previous XSEDE allocations (TG-AST120029, TG-AST120060, TG-AST130036) and continue our study of both the evolution of binary driven disks and the propagation of MHD jets driven by such disks. Thus, 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 disks formed through the tidal shredding of a companion within a common envelope. In addition, we propose a series of simulations studying the 3-D dynamics of radiative MHD jets at previously unexplored resolutions.

Our computations will be performed AstroBear2.0 a highly parallelized AMR MHD multi physics code developed at the University of Rochester and currently used by research groups across the United States and Europe. We are in full production mode with AstroBEAR2.0 and require the numerical resources of XSEDE to make further progress on unraveling the mysteries of interacting binaries and their jets. To achieve this goal, we request 2.5 million SUs on Kraken and 2.9 million SUs on Stampede.

2 Introduction

Observations have shown that collimated supersonic outflow, or jets, are ubiquitous in astronomy. Young Stellar Objects (YSO), proto-Planetary Nebulae (PPN), X-ray binaries and distant active radio galaxies show jets. The "central engines" of these flows cannot be directly observed due to insufficient telescope resolution. Models suggest that jets are launched and collimated by accretion, rotation and magnetic fields (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). Disks may also form in such an evolved system either by wind capture onto the secondary or via Common Envelope Evolution (CEE) in which the secondary is engulfed within the primary leading to the tidal disruption of the secondary and the formation of jet-creating disk around the primary's core. (Nordhaus, Blackman & Frank 2007, Nordhaus et al. 2011)

For low-mass companions such as planets and M dwarfs, engulfment during post-main-sequence evolution leads to orbital decay during the common envelope phase which can not be halted due to insufficient orbital energy liberation. Instead, in-spiral proceeds until the companion is tidally shredded by the gravitational field of the giant star's core. The subsequent formation of an accretion disk deep in the interior of the giant star can amplify magnetic fields via dynamo action and has been proposed to explain the origin of highly-magnetized white dwarfs (Nordhaus et al. 2011).

In all cases, the disks are expected to be capable of producing magnetized jets (Ferreira et al. 2006). The physics of jet engines is difficult to constrain directly since the engines themselves may not be resolvable. Thus, observations of the jets on larger scales becomes the most promising means to understand aspects of the launch process. In addition, many questions about the physics of the magnetized jets remain unanswered such as the jet's stability, the propagation of internal shocks within the jet beam and the observational consequences of the MHD jet dynamics. In particular, the observational signature of the jets in different emission lines is of great interest in both proto-PN systems as well as YSOs. Variations in density or velocity at the base of the flow become shock waves which travel through the jet beam producing emission lines in variety of atoms and ions. The spatial pattern of the emission lines relative to the shock front provides critical information about conditions in the jet. The ability to model these emission line patterns however is hindered by the need for high resolution in simulations. Taking steps towards better resolution of the shock emission regions is necessary for making the essential contact between models and observations. The stability of magnetized jets is another open issue. Magnetically dominated structures such as nose-cones which appear in

2.5D axisymmetric simulations may be unstable in 3-D studies but answering this question requires higher resolution. We note that recently magnetized and radiatively cooling jets have been formed in laboratory experiments (Lebedev et al. 2005). Our group is a close collaborator in modeling the experimental studies (e.g. Ciardi et al. 2009, Huarte-Espinosa et al. 2012c).

3 Previous Accomplishments

3.1 Summary of Scientific Discoveries

Our principle scientific discoveries are as follows

- We have completed an initial study of wind capture disks providing initial limits as to disk formation, mass accretion rates and disk structure.
- We have complete a study of magnetized jets in 2.5-D (axisymmetry) at extremely high resolution. Our simulations capture the dynamics of both the global magnetic field structure in the jet as well as the emission patterns in the cooling zone behind internal working surfaces. The simulations are the first to resolve and predict predict both H_α as well as [SII] emission patterns.
- We have completed an initial study of disks formed from the disruption of a binary companion during common envelope evolution. Our simulations have presented an initial view of instabilities occurring at the disk/envelope interface which lead to mixing and disk dispersal.

3.2 Details of Previous Accomplishments

During the tenure of the last grant, we used 100% of our allocation pursuing a study focused on the evolution of evolved binary stars and the outflows they generate. Highly collimated outflows in the form of planetary nebulae (PNe) and proto-planetary nebulae (pPNe) represent the observational signatures of what are believed to be winds driven by magnetic processes from a central engine that dominated by the interaction of an AGB star with a companion. Using the Adaptive Mesh Refinement (AMR) Multi-physics code AstroBEAR (developed by our group Cunningham et al 2009, Carroll et al 2012, Frank et al 2014) we have carried out high resolution simulations that shed light on a number of aspects of the jet and binary interaction problem.

Our studies (Huarte-Espinosa et al 2012a, 2012b, 2013) of binary stars interactions focused initially on the evolution of disks around the secondary via AGB wind capture (Bondi-Hoyle or BH flows). While previous works found significant enhancements over theoretical BH accretion rates onto the secondary, the resolutions were insufficient to fully model the disk. Our studies provided a better account of the accretion rates as well as resolving the critical disk impact parameter which controls disk formation. Newer work focuses on exploring a broader range of orbital parameter for the binaries. In particular we have pushed to find the upper limits on orbital radii at which a disk will still form via the BH process. (Frank et al 2014).

We have also used our allocation to begin exploring binary interactions and disk formation where the binary separation is much smaller. Our eventual goal is to model Common Envelope evolution where the secondary is engulfed by the expansion of the AGB star and then plunges inward to the core (via dynamical friction with AGB envelope material). Such simulations hold many computational challenges and as a step forward, we modeled disks which can form around the primary core due to the disruption of the secondary (Nordhaus et al 2014). These initial test models allowed us to gain an understanding of the stability properties and longevity of disks embedded within an extended stellar envelope.

We have also carried out simulations of both magnetized jets and (episodic ejections) "bullets" relevant to pPNe and PN. Detailed high resolution simulations of MHD jets with a full compliment of microphysics allowed us to resolve the "cooling regions" behind internal shocks in the jet beam. These studies which will be useful for both PN studies and jets from young stars have, for the first time, resolved the MHD regions where observed emission lines (Hα and [SII]) form allowing for direct contact with Hubble Space Telescope Images (Hansen et al 2014).

4 Research Objectives

4.1 MHD Jet Studies

Collimated flows are a ubiquitous phenomena in astrophysics occurring in contexts as diverse as young stars (YSOs), evolved stars (PN) and the environments of supermassive blackholes. In almost all instances the jets are thought to be launched via a combination of rotation (often via an accretion disk) and magnetic fields. The role of the fields is to tap the rotational energy much like a drive belt and convert it into directed kinetic energy of the outflow as well as pinch forces (via magnetic tension) to collimate the outflow into a jet-like beam. The outflows/jets associated with planetary and proto-planetary nebulae appear as both low and high density flows. When the flows are low density the jets may be characterized as Poynting Flux dominated magnetic towers which we have used previous XSEDE allocations to explore (Huarte Espinosa et al 2012). When the densities are higher the fields may still be important (particularly for the collimation of the flow).

In our recent work we have focused on the higher density magnetized outflow problem. In these cases, most appropriate to the critical proto-planetary nebula phase, radiative cooling behind strong shock waves will significantly alter jet dynamics. The radiation emitted in the cooling process (including Hα and [SII] lines) serves as an excellent observational diagnostic for conditions in the flow. Thus performing simulations with appropriate microphysics to track Hα and [SII] excitation (via collisions) is essential to building realistic models of jets relevant to both PPN and YSOs. We have already carried out axisymmetric simulations of radiative MHD jets and found new behaviors in terms of the way Hα and [SII morphologies change with input magnetic beta (Figure 1). The next step is to remove the constraints of 2.5D simulations and attempt to study these flows in 3-D.

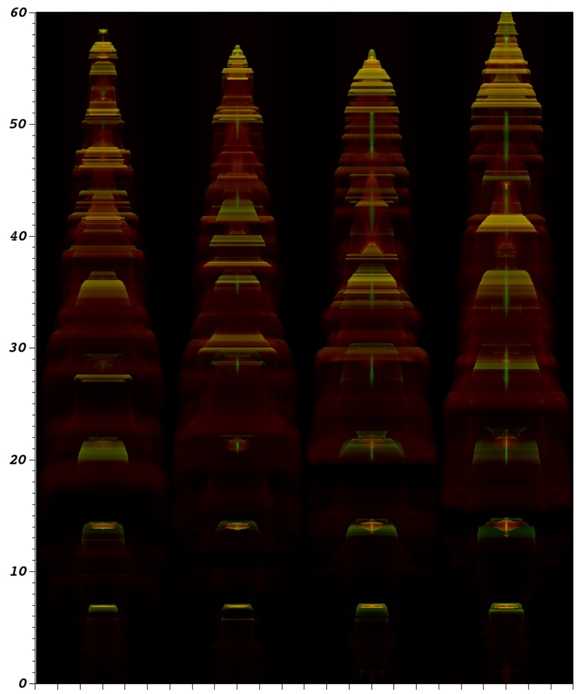


Figure 1: Emission maps of Hα and [S II] for the hydrodynamic and $\beta = 5, 1, 0.4$ models (from *left* to *right* respectively). Green corresponds to Hα emission and red is the [S II]. Each emission line is scaled to its maximum value at that time (t = 500 yr for these images). Also, the entire RGB scale (0 to 255) spans six orders of magnitude for each emission line.

Open questions that can only be understood with fully 3-D simulations include stability of the jet head and internal shocked regions within the jet beam. In 2.5D magnetic forces lead to streamlined features called "nose cones". In 3-D it is possible such features will become destabilized by kink modes which should also operate within the jet beam. The role of heterogeneity within the beam is also a critical subject to be studied with 3-D simulations. Any clumps that form with differential velocity will generate shocks and collide with pre-existing shocks crested by global flow variations. Mapping the emission patterns from these clumps will serve as an important point of contact between our jet simulations and multi-epoch Hubble Space Telescope observations.

Thus we request resources for high resolution radiative MHD simulations of time variable jets. Our goal is to run a series of models that allow for at least moderate resolution of thin cooling zones behind internal shock waves which also capturing the global evolution of the entire jet-ambient medium interactions. We are therefore requesting 2.9 million SUs on Stampede to perform high-resolution simulations of 3D jets. These simulations will be run with different values of the initial magnetic field strength.

4.2 Binary Disk Studies

The ultimate fate of low-mass companions to main-sequence (MS) stars is of interest as substellar and stellar companions to intermediate-mass stars are plentiful (Raghavan et al. 2010). During post-MS evolution, dynamical interactions induced by radial expansion of the primary, strong mass loss via stellar winds, and tidal interactions can occur. For planets and M dwarfs initially orbiting within a few AU of the main-sequence star, post-MS expansion of the primary will result in a common envelope phase in which the companion is engulfed by the giant star. Most of these engulfed companions are not massive enough to eject the envelope of the giant and thereby emerge as short-period binary systems (Nordhaus & Spiegel 2013). Instead, these planetary companions inspiral inside until they are tidally disrupted deep in the interior of the star by the gravity of the proto-WD core. The disrupted material, possesses angular momentum and forms a dense and relatively cold accretion disk. Such disks have been proposed as a way to amplify magnetic fields and explain the origin of isolated highly-magnetized white dwarfs. Despite promising analytic estimates, such a system has never been simulated. We are requesting ∼2.5 million SUs on Kraken to perform high-resolution production-run simulations of such disks. Figure 2 shows an AstroBEAR snapshot of a test run low-resolution simulation we performed. These simulations will provide insight into accretion rates, angular momentum transport processes and the stability properties of such disks.

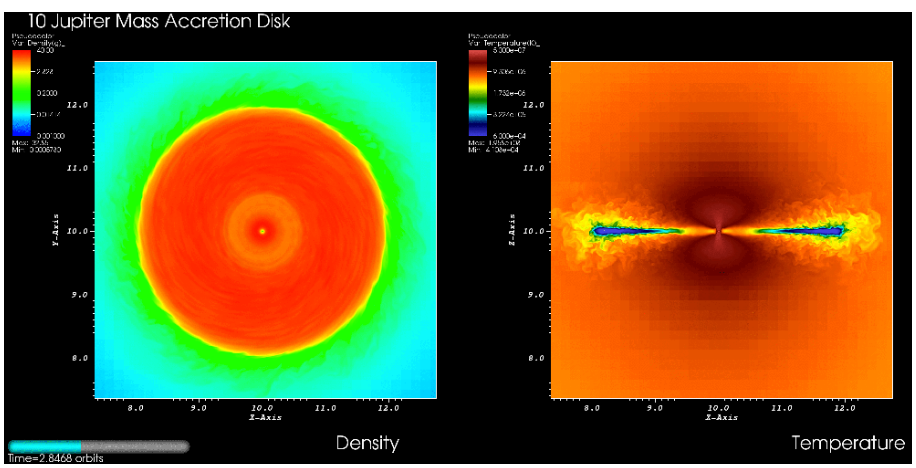


Figure 2: AstroBEAR snapshot of a test run low-resolution simulation.

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 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. After a decade of development only a handful of AMR-MHD codes exist for astrophysics: (e.g. FLASH, ENZO RAMSES, ORION).

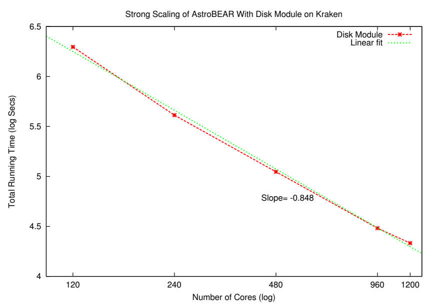
The UR astrophysics group successfully constructed and tested AstroBEAR, a fully parallelized, multi-dimensional AMR MHD code. The success of this effort is evidenced both in the code's completion (Cunningham et al 2009) and the papers published using AstroBEAR as it was developed through its radiation-hydrodynamic 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 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.

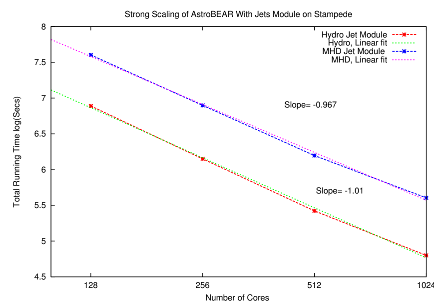
5.1 AstroBEAR Scaling

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 employs 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 3(a), we report scaling test results (with Disk module) on Kraken at NICS. Each compute node of Kraken has two six-core AMD Opterons, so we use 120, 240, 480, 960 and 1200 cores. The resolution we used for these test are $128^3 + 5$ level AMR which is same as the computation we are planning to do. The strong scaling test plot of the current code shows a slope -0.848 (Figure 3(a)) while the slope for perfect scaling is -1. This shows AstroBEAR has an excellent scaling on Kraken. In Figure 3(b), we report scaling test results (with 3D Jet module) on Stampede at TACC. Each compute node of Stampede has two Intel E5 8-core (Sandy Bridge) processors and an Intel Xeon Phi 61-core (Knights Corner) coprocessor, so we use 128, 256, 512, and 1024 cores. The resolution we used for these test are $21 \times 105 \times 21 + 5$ level AMR which is same as the computation



(a) Disk Module on Kraken



(b) Jet Module on Stampede

Figure 3: Strong scaling behavior for AstroBEAR with Disk module on Kraken(a) and Jet on Stampede (b). For these tests we run with the exact same resolution as our proposed production runs (128^3 + 5 levels AMR for Disk and $21 \times 105 \times 21$ + 5 levels AMR for Jet), but for much shorter final time (1% of one frame while the production runs need 100 frames) and without IOs. The current code with the Disk and Hydro and MHD Jet modules shows excellent scaling on Kraken and Stampede (with slope$=-0.848$, -1.01 and -0.967 respectively while the perfect scaling has a slope -1).

we are planning to do. The strong scaling test plot of the current code shows a slope -0.101 for Hydro jet and -0.967 for MHD jet (Figure 3(b)) while the slope for perfect scaling is -1. This shows AstroBEAR has an excellent scaling on Stampede also.

6 Resource Request

Based on the strong scaling test Figures (3(a) and 3(b)), we estimate the SUs we need on Stampede and Kraken for our production runs (Table1 and Table2). When doing the estimate we consider 1) the real running time for each frame may vary; 2) the production runs include IO times; 3) the MHD jet runs with $\beta = 1$ and $\beta = 5$ are slightly faster than the $\beta = 0.4$ run.

In total we require 2.5 million CPU-hours on Kraken and 2.9 million CPU-hours on Stampede, about 98% of which will be used for production runs and 2% 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.

6.1 I/O Requirements, Analysis, and Storage

For each of the eight runs of our disk simulation, we expect to save 150 frames of data with sizes between 1-5GB for each frame. The total data size for our disk project is about 1.2TB-6.0TB. And For each of the four runs of our 3D jet simulation, we expect to save 100 frames of data with size 4-20GB. So the

Table 1: Expected CPU-hours for Disk Inside Star Simulations

mass($M_{jupiter}$)	Resolution	Expected SUs on Kraken
1	128^3 + 5 AMR	300,000
3	128^3 + 5 AMR	300,000
5	128^3 + 5 AMR	300,000
10	128^3 + 5 AMR	300,000
15	128^3 + 5 AMR	300,000
20	128^3 + 5 AMR	300,000
25	128^3 + 5 AMR	300,000
30	128^3 + 5 AMR	300,000
Total		2,400,000

Table 2: Expected CPU-hours for 3D Pulsed Jets Simulations

Hydro/MHD	Resolution	Expected SUs on Stampede
Hydro	$21 \times 105 \times 21$ + 5 AMR	400,000
MHD $\beta = 5$	$21 \times 105 \times 21$ + 5 AMR	800,000
MHD $\beta = 1$	$21 \times 105 \times 21$ + 5 AMR	800,000
MHD $\beta = 0.4$	$21 \times 105 \times 21$ + 5 AMR	850,000
Total		2,850,000

total data size for our 3D jet project is about 1.6TB-8.0TB. In total we expect to need ∼6 Tbytes of storage on Kraken and ∼8 Tbytes on Stampede. Most of the analysis will be done using parallelized tools built into the AstroBEAR package that can be performed at runtime or in post processing.

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 binary driven disks and the propagation of MHD jets driven by such disks. With our previous XSEDE allocations (TG-AST120029, TG-AST120060, TG-AST130036) and our local computing resources including the Top500-listed Blue Gene/Q system at the University of Rochester, 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 disks and MHD jets.

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 accretion rates, angular momentum transport processes and the stability properties of the disks and the propagation of MHD jets driven by these disks.

- Study of the evolution of binary driven disks. Resources requested: 2,400,000 SUs on Kraken.

- Study of the propagation of MHD jets driven by disks. Resources requested: 2,850,000 SUs on Stampede.

- Testing and continue development of our code. 50,000 SUs on Kraken and 50,000 SUs on Stampede.

To achieve these goals, we request 2,500,000 SU's on the NCIS Cray XT5 (Kraken) and 2,900,000 SU's on the TACC Dell PowerEdge C8220 Cluster (Stampede)

References

[1] Miszalski, B., Jones, D., Rodríguez-Gil, P., Boffin, H. M. J., Corradi, R. L. M., Santander-García, M., 2011, AAP, 531, A158

[2] Blandford, R. D., & Payne, D. G., 1982, MNRAS, 199, 883

[3] Carroll-Nellenback, J. J., Frank, A., Shroyer, B., & Ding, C., 2011, arXiv:1112.1710

[4] Ciardi, A., et al. 2007, Phys. of Plasmas, 14, 056501

[5] Ciardi, A., Lebedev, S. V., Frank, A., et al., 2011, ApJL, 691, L147

[6] Cunningham A. J., Frank, A., & Hartmann, L., 2005, APJ, 631, 1010

[7] Cunningham A. J., Frank, A., Quillen, A. C. & Blackman, E. G., 2006a, APJ, 653, 416

[8] Cunningham A. J., Frank, A., & Blackman, E. G., 2006b, APJ, 646, 1059

[9] Cunningham A. J., Frank, A., Varnière, P., Mitran, S., & Jones, T. W., 2009, ApJS, 182, 519

[10] de Val-Borro, M., Karovska, M., & Sasselov, D., 2009, ApJ, 700, 1148

[11] Ferreira, J., Dougados, C., & Cabrit, S., 2006, AAP, 453, 785

[12] Frank, A. et al, in preparation

[13] Hansen, E. et al, in preparation

[14] Huarte-Espinosa, M., Frank, A., & Blackman, E., 2011, arXiv:1111.4223

[15] Huarte-Espinosa, M., & Frank, A., 2012, Planetary Nebulae: An Eye to the Future, Proceedings of the International Astronomical Union, IAU Symposium, 283, p. 164-167

[16] Huarte-Espinosa, M., Frank, A., Blackman, E. G., Carroll-Nellenback, J. J. & Nordhaus, J. 2012, American Astronomical Society Meeting 219, 404.06

[17] Huarte-Espinosa, M., Frank, A., Blackman, E. G., et al., 2012c, arXiv:1204.0800

[18] Huarte-Espinosa, M., Carroll-Nellenback, J. J., Nordhaus, J., Frank, A. & Blackman, E. G., 2013, MNRAS, 433, 295 , (in prep)

[19] Krasnopolsky, R., Li, Z.-Y., & Blandford, R., 1999, APJ, 526, 631

[20] Krasnopolsky, R., Li, Z.-Y., & Blandford, R. D., 2003, APJ, 595, 631

[21] Lebedev, S. V., et al. 2005, MNRAS, 361, 97

[22] Mastrodemos, N., & Morris, M., 1998, ApJ, 497, 303

[23] Mohamed, S., & Podsiadlowski, P., 2007, Asymmetrical Planetary Nebulae IV

[24] Nordhaus, J., Blackman, E. G., & Frank, A., 2007, MNRAS, 376, 599

[25] Nordhaus, J. et al, in preparation

[26] Nordhaus, J., Wellons, S., Spiegel, D. S., Metzger, B. D., & Blackman, E. G. 2011, Proceedings of the National Academy of Science, 108, 3135

[27] Nordhaus, J. Spiegel D. S., 2013 MNRAS 432, 500

[28] Perets, H. B., & Kenyon, S. J., 2012, arXiv:1203.2918

[29] Poludnenko, A., Mitran, S., & Frank, A., 2004a, APJ, 613, 387

[30] Poludnenko, A., Danneburg, K., Drake, P., Frank, A., Knauer, J., 2004b, APJ, 604, 213

[31] Pudritz, R. E., Ouyed, R., Fendt, C., & Brandenburg, A., 2007, Protostars and Planets V, 277

[32] Shibata, K., & Uchida, Y., 1986, PASJ, 38, 631

[33] Soker, N., & Rappaport, S., 2000, APJ, 538, 241

[34] Witt, A. N., Vijh, U. P., Hobbs, L. M., et al., 2009, APJ, 693, 1946

[35] Edgar, R. 2004, New Astron. Rev., 48, 843

[36] Dennis T. J., Cunningham, A. J., Frank, A., Balick, B., Blackman, E. G. & Mitran, S. 2008, ApJ 679 1327

[37] Yirak, K., Frank, A., Cunningham, A.J., & Mitran, S. 2008, ApJ 672 996

[38] Yirak, K., Frank, A., & Cunningham, A.J. 2010, ApJ 722 412

[39] Li, S., Frank, A., & Blackman, E.G. 2012, ApJ 748 24

[40] Hartigan P., Frank A., Varnière, P. & Blackman, E. G. 2007, ApJ 661 910

[41] Raghavan, Deepak; McAlister, Harold A.; Henry, Todd J.; Latham, David W. 2010, 190, 1