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Mass Transfer in Evolved-Star Binary Systems: From Roche-Lobe Overflow to Bondi-Hoyle

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ABSTRACT

The goal of our work is to understand the mechanisms of mass transfer in evolved star binary systems. Our work is directly relevant to a number of essential issues in stellar astrophysics such as the end states of solar mass stars (Planetary Nebulae); the progenitors of Supernova Type Ia; the progenitors of compact binaries leading to mergers and gravitational wave generation. Understanding all of these phenomena begins with an understanding of the evolution of binaries in which one or more of the stars has evolved off the main sequence. In this study we begin by focusing on the lower stellar mass range with solar mass scale AGB stars and companions of different types (solar mass and below). Using a state-of-the-art AMR MHD multi-physics code developed by our group (AstroBEAR) we plan a campaign of simulations in which variations in orbital separation allow us to explore where transitions in the nature of mass capture by the secondary occurs. Previous local-scale studies supported by XSEDE allowed us to study Bondi-Hoyle accretion in detail. In this work we will use global scale (primary + secondary) simulations to explore transitions from Bondi-Hoyle accretion to a new mechanism called Wind Roche Lobe overflow. As the separation is further reduced we expect to see direct Roche Lobe overflow. In these studies we are particularly interested in the generation of circumbinary disks which have been observed in many evolved star binary systems and whose origin remains unexplained. Tracking the full hydrodynamics, MHD and radiation transfer mechanisms involved in these situations requires a fully 3-D AMR multiphysics code such as AstroBEAR. Our use of AMR will also allow us to begin investigation of the orbital evolution of the binary towards a Common Envelope which is considered a principal means of developing binary compact objects such as those responsible for gravitational waves.

To achieve this goal we request the support of 4.2 million SU's on Stampede at TACC, 3.9 million SU's on Comet at SDSC.

1 INTRODUCTION

The study of mass transfer in binary systems has a long and venerable history in astrophysics. However in spite of many years of work the fundamental time-dependent, 3-D, nonlinear radiation-MHD nature of the flows means that only a subset of possible behaviors have been explored. The need to understand the full range of possibilities has become ever more urgent for astronomers as binary star evolution *including mass transfer* has become a central issue for a number of domains at the frontiers of the field. For example Supernova Type Ia (which are a principle means of tracing Dark Energy) are the result of mass transfer on a white dwarf star which was once an AGB. Tracking the evolution of the binary - particularly through its late AGB stages when the outer regions of the AGB star are poorly bound - is an essential issue in accurately assessing SN Type Ia populations. A second example of the importance of mass transfer in binaries is the spectacular discovery of gravitational waves from merging black holes. The progenitors of the black holes were a high mass binary which must have interacted during its lifetime, most likely including mass transfer that led to a common envelope.

Planetary Nebula represent another example of a phenomena which depends on binary star mass transfer. The 'textbook' model of PN describes them as the last, dying gasps of single low and intermediate-mass (1-8 Mo) stars. Remarkable images of highly collimated PN flows and new measurements of their fundamental properties have, however, forced a dramatic reassessment of this paradigm (Figure 1, De Marco et al. 2011 and references therein). For example, measurements of the momentum in proto-PN (PPN) outflows show they cannot be driven by stellar radiation. Thus the power for the outflows must, in many cases, come from another source. Given the ubiquitous bipolarity and so-called 'momentum excess' in all measured PPN (Section 3), it appears that neither the launching nor collimation of PN can be considered well understood.

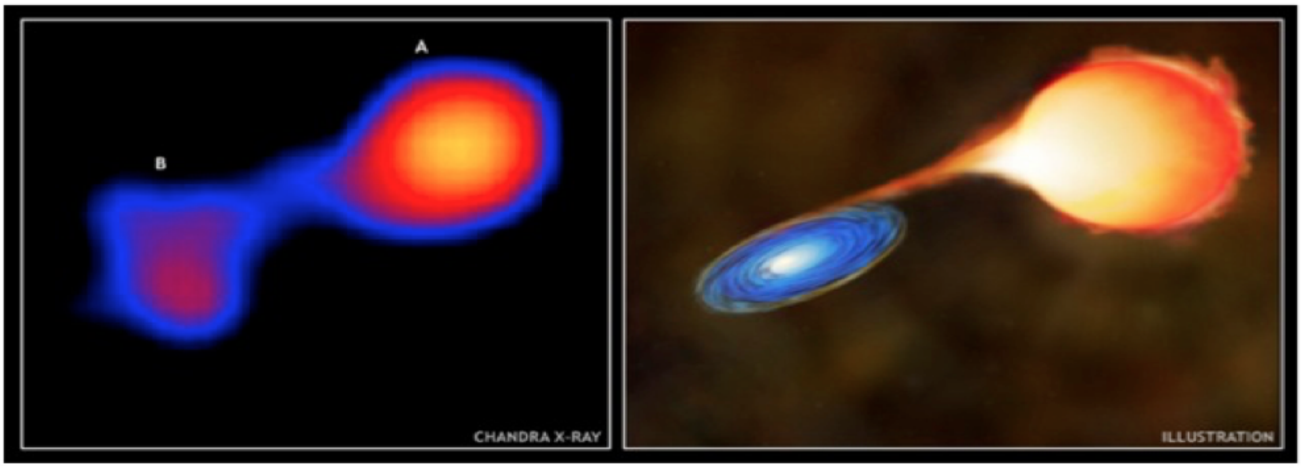

Figure 1. An example of mass transfer in the wide binary Mira. Left Chandra X-ray image. Right: Artists impression. Mira shows evidence for considerable mass transfer in spite of having an orbital separation of $\sim 70AU$. Wind Roche Lobe Overflow (WRLOF) is considered a viable mechanism to explain Mira's mass transfer.

In the wake of these studies, theorists have been forced to renew their understanding of PN and the evolutionary pathways of low and intermediate stars through models that focus on the role of binaries (Tocknell et al. 2014). Recently observers have begun accumulating direct measurements of these binary companions, and their disks. We are, therefore, in a particularly exciting time for the field as four decades of common wisdom are being critically re-evaluated.

In this proposal we wish to use our AMR MHD multi-physics code to continue work studying the mechanisms and consequences of mass transfer in evolved binary stars. This proposal focuses on lower mass evolved stars but the study will serve as entry into simulations of higher mass binaries since many of the mechanisms we explore in this work will be applicable to all binary systems.

Previous local-scale studies supported by XSEDE allowed us to study Bondi-Hoyle accretion in detail. In this work we seek to use global scale (primary + secondary) simulations to explore transitions from Bondi-Hoyle accretion to a new mechanism called Wind Roche Lobe overflow. As the separation is further reduced we expect to see direct Roche Lobe overflow. In these studies we are particularly interested in the generation of circumbinary disks which have been observed in many evolved star binary systems and whose origin remains unexplained. Tracking the full hydrodynamics, MHD and radiation transfer mechanisms involved in these situations requires a fully 3-D AMR multi-physics code such as AstroBEAR. Our use of AMR will also allow us to begin investigation of the orbital evolution of the binary towards a Common Envelope which is considered a principle means of developing binary compact objects such as those responsible for Gravitational Waves.

2 PREVIOUS ACCOMPLISHMENTS

Bondi-Hoyle Disk Studies: With our previous XSEDE allocation (AST120060) we have found significant new results related to the formation of disks in binaries. In (Huarte-Espinosa et al. (2013)) we determined that the BHL accretion solution has to be modified for its application to accretion from the primary wind onto an orbiting secondary. This comes because the wake that develops in this environment is not aimed towards the instantaneous position of the companion as in the "normal" BHL accretion. Instead, the captured material is accelerated towards a position between the companion's original and current positions. We have characterized this process via the "impact parameter"

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

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, finally, the AGB stellar wind speed. In (Huarte-Espinosa et al. 2013) we found that the formation of disks in 3-D simulations strongly depends on the proper resolution of the impact parameter b. 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 2).

In (Huarte-Espinosa et al. (2013)) we carried out two realizations 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 since the value of these accretion rates can help rule in, or out, the secondary as the engine powering outflows in PPN.

Circumbinary Disk Formation:

Recent observations of the L_2 Puppis system have suggested that its Asymptotic Giant Branch (AGB), Mira-like variable

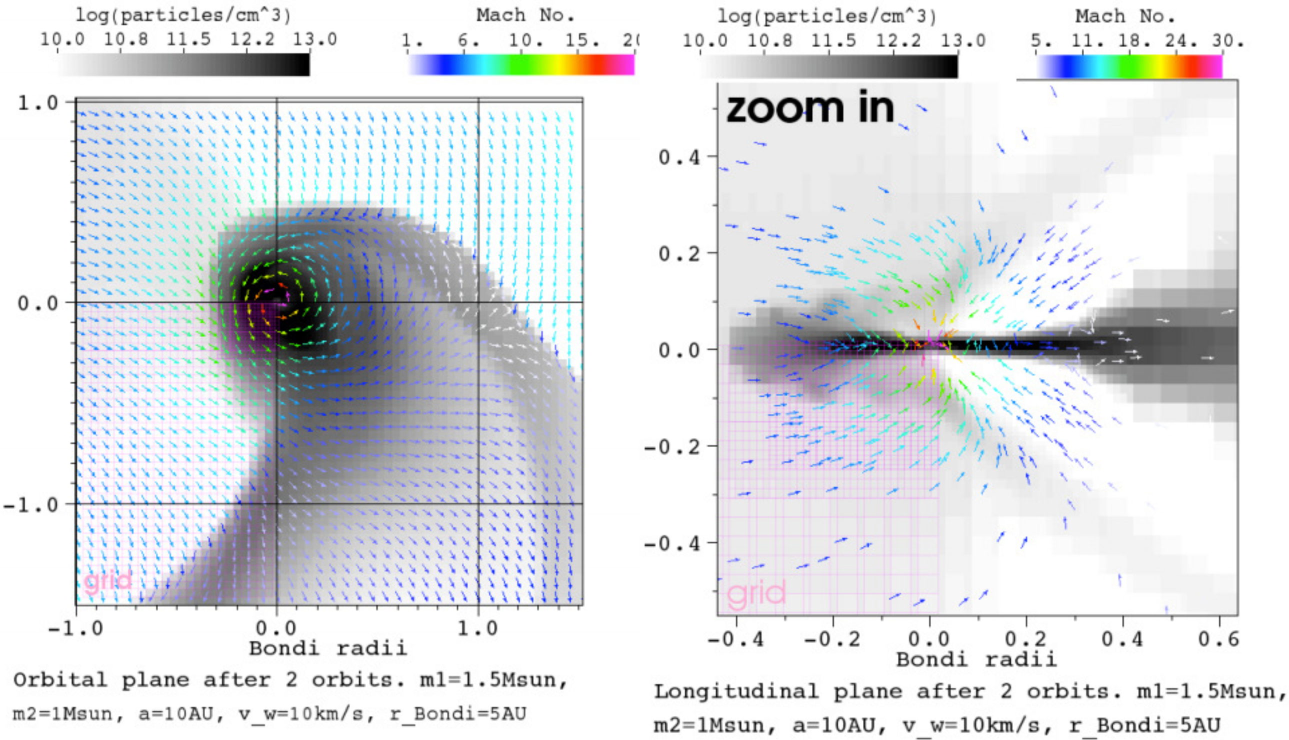

Figure 2. Density and velocity field distribution of the binary-formed accretion disk. Left: slice through the orbital plane. Note the disk (dark, round region) around the origin and the accretion "tail" (gray wide region) on the bottom right part of the domain. Right: zoom in at a longitudinal slice through the disk. The primary AGB star has a mass of $1.5\,M_{\odot}$ 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 $1\,M_{\odot}$ and is located at the origin. The domain follow the orbit of the secondary. The AMR grid structure is shown in pink.

may be in the early stages of transitioning to a planetary nebula (PN) Kervella et al. 2015b,a. At a distance of 64 *pc*, L_2 Puppis is one of the nearest and brightest AGB stars. It seems to be orbited by a close binary companion, and thus represents a unique laboratory in which to test models of the late-stages of stellar evolution.

L_2 Puppis has a large lobe structure that extends more than 10 *AU* to the northeast of the disk in L-band images (Kervella et al. 2014), likely due to the interaction of an AGB wind with the secondary star. A recent result by Kervella et al. (2015b) supports this hypothesis, revealing evidence of a close-in secondary source at a projected separation of 2 *AU*. In addition, the existence of an optically-thick circumstellar dusty disk hints at the presence of a secondary.

To explore if L_2 Puppis may be surrounded by a disk in (Chen et al. 2016a) we presented fully 3-D hydrodynamic simulations that modeled a pulse of dense wind followed by constant stellar wind in a binary system. Our simulation self-consistently showed how a circumbinary disk with wide-bipolar outflows can form with the L_2 Puppis system parameters as initial conditions (Figure 3). Throughout the computational domain, we tracked the fluid to determine whether flows were gravitationally bound. We found that the bulk of the bound material was in fact located in a thin keplerian circumstellar disk. In addition along the poles, a wide angle low velocity outflow emerges with measured velocities of $\sim 20\ km/s$, a value well supported by observations.

Using the output of hydrodynamic modeling we also produced synthetic observations of broad-band photometric and imaging data that significantly improved upon previous non-dynamical, morphological studies of L_2 Puppis . Synthetic observations constructed by post-processing our hydrodynamic simulation with the radiation transfer code RADMC-3D showed strong morphological similarity to the V-band and N-band observations. The broad-band SED computed from our results also matches the observations well, reproducing the "flat" range from $1\mu m$ to $4\mu m$ and the infrared excess seen long-ward of $10\mu m$. The top-down synthetic images show that the polar direction is optically thin and the dust in the disk has low temperature.

Thus our simulations showed one mechanism by which a circumbinary disk could be produced in evolved star binary systems.

3 RESEARCH OBJECTIVES

Mass transfer rates in binary systems can control many aspects of the system's evolution. Mass transfer will determine the maximum power for outflows from the accretor. It will control the angular momentum transfer and hence changes in orbital

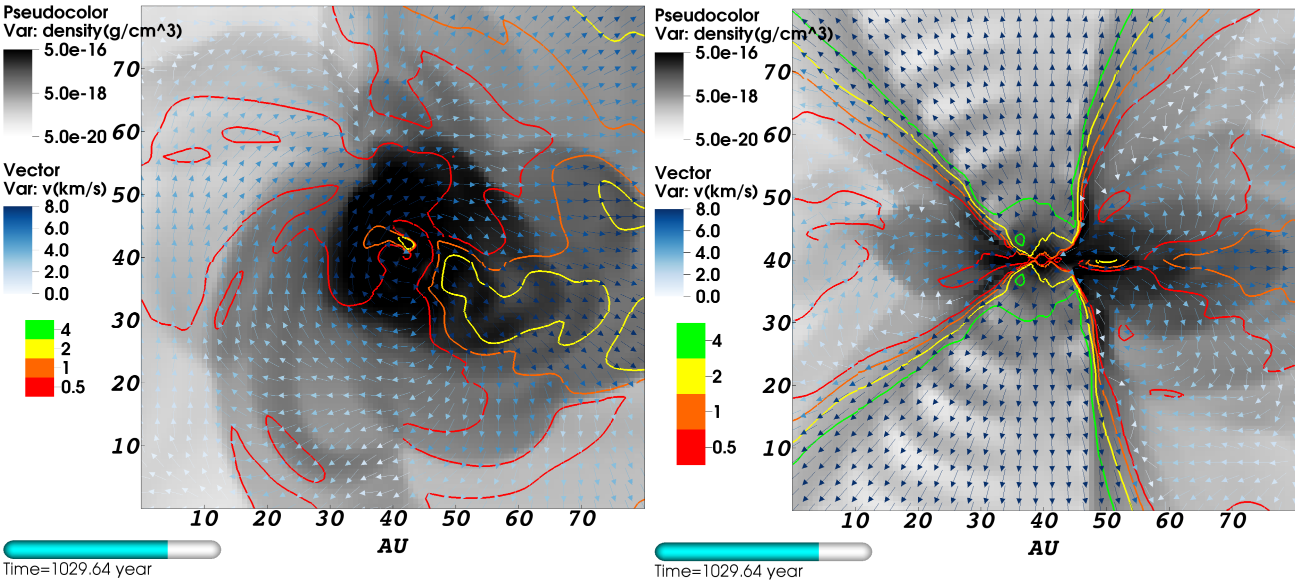

Figure 3. Left: Face-on density cut of the 3-D L_2 Puppis simulations (x-y plane). Right: Edge on density cut of the 3-D L_2 Puppis simulations (x-z plane). Density values are shown with a gray-color map, while velocity vectors are shown in white and blue at the end of the simulation. Four contours of q delineate the bound and unbound regions. Note the presence of both a disk and an outflow in the images

configuration of the system. Mass transfer will also determine the ability of disks to form around either or both stars. Thus characterizing mass transfer in binary systems across a range of initial conditions is essential for understanding the evolution and impact of these systems.

Previous studies have only been able to focus on particular domains of binary mass transfer behavior like, for example, the limits of standard Bondi-Hoyle-Lyttleton (BHL) accretion. This was shown for example by Soker & Rappaport 2000 in their analytic application of BHL accretion via wind capture to PPN/PN in which they only explored the ability to binaries to lower power outflows. For the highest power outflow systems some combination of accretion on a WD, Roche lobe overflow, or accretion within a Common Envelope (CE) must be considered. These other mechanisms will also change the mechanisms for the formation of disks. Other simulations studies have, for example, been tuned to only focus on Roche lobe overflow. What has been lacking has been a global study with a single code that can explore the transitions between different modes of mass transfer for binaries with a range of input parameters. This is required to understand the limits of mechanisms that have been explored before such as Roche lobe overflow and Bondi-Hoyle as well as new mechanisms such as Wind Roche Lobe Overflow (WRLOF).

The WRLOF mechanism was recently discovered by Mohamed & Podsiadlowski 2012. WRLOF occurs because the subsonic region of an accelerating wind acts like an extended atmosphere and can, therefore, become significantly distorted by tidal forces leading to a region of enhanced density flowing through the L1 point. Thus the structure of the wind in WRLOF systems can be significantly altered leading to accretion rates onto the secondary that are a factor of 100 or more higher than that predicted by BHL theory. Higher accretion rates onto the secondary will lead to higher outflow rates. Thus WRLOF offers a means of accounting for at least some of the more powerful outflows observed and creating disks around the secondary or both stars.

Thus an initial goal of our study is to assess what mechanisms determine the mass transfer rates for a range of companion separations, and to quantify these rates. Because outflow power serves as a proxy for mass transfer rates, as the catalog of objects with measured outflow powers increase (e.g. via ALMA) our calculations will provide crucial quantitative constraints on the viability of these different models. Note that in this project we focus on the case of accretion onto companions when the companion is outside the primary's envelope.

In carrying forward this work we plan on giving considerable attention to WRLOF studies. There are only a handful of papers studying the basic dynamics of WRLOF and these have covered on a small region of the parameter space. This has hampered the application of WRLOF studies to astrophysical objects. For example, in an analytic study, Abate et al. (2013) attempted to use the WRLOF mechanism to explain carbon-enhanced metal-poor stars via WRLOF by considering its properties as a function of, among other things, binary mass ratio q. The enhanced WRLOF accretion rates were written as $\beta_{acc} = \beta(M_d)/\beta(M_w)$, the ratio of the disk accretion rate to AGB wind mass loss rate (which is a measure of the fraction of the wind which is captured).However since only a single value of q has been used in published simulations, Abate et al. (2013) were forced to extrapolate the q dependence (Figure 4). Our first order of work will be to fill out the parameter space for WRLOF simulations to determine the true form of the curve in Figure 4. This will be by running high-resolution simulations for a broader range orbital separations with particular emphasis on exploring the role of the ratio of sonic point

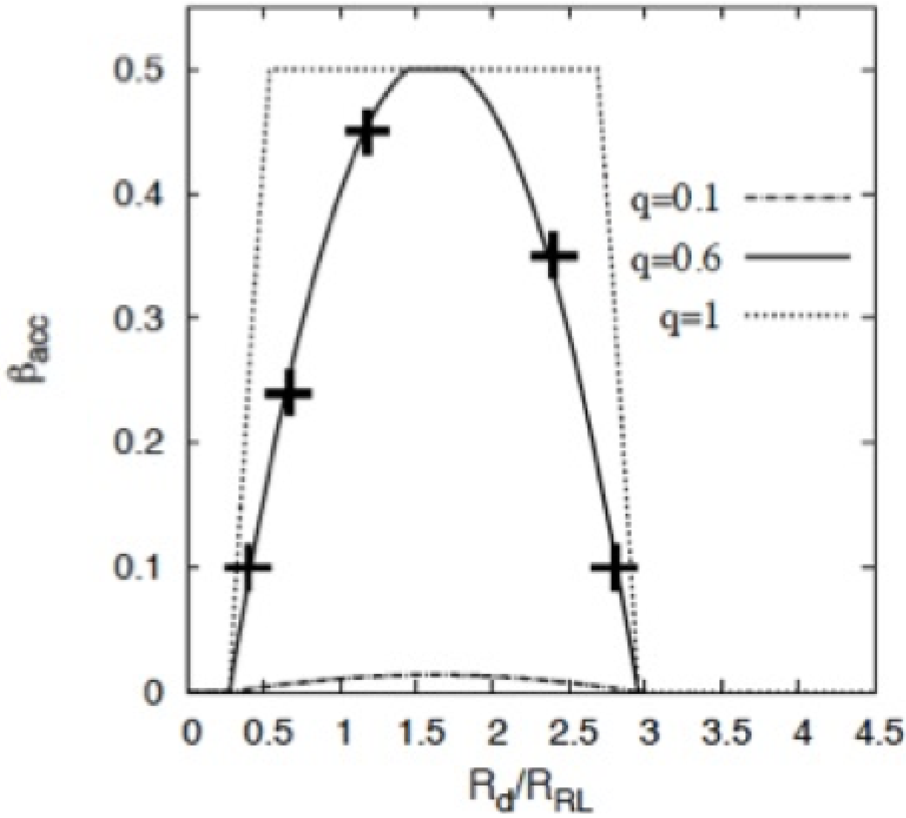

Figure 4. Ratio of wind accretion rate on secondary to wind mass loss rate from primary in WRLOF systems. In WRLOF close to 50% of the AGB wind can be captured in the disk around the secondary. Typical values for this ratio in Bondi-Hoyle systems are factors of 50 lower. Note that only the mass ratio $q = 0.6$ has been directly simulated. The other curves are extrapolations. From Abate et al. (2013)

in the accelerating wind to the L1 point between the binaries. [Note that the sonic radius is close to the dust condensation radius Rd (Rs∼Rd) and $Rd \sim R * (Teff/Tcond)^{2.5}$,Höfner (2008)] .

Thus we plan a suite of studies in which we vary the orbital separations of binaries expecting to see transitions between BHL at the largest separations, then WRLOF for intermediate separations and then Roche lobe overflow for the smallest separations. In this way we will carry out a comprehensive 3-D AMR numerical exploration of accretion rates and flow geometries for evolved star binaries. The use of 3-D AMR will allow us not only to compute the accretion rates, but also assess when an accretion disk forms around the secondary. Figure 5 shows an example of a low resolution version of one of our simulations.

We note that our models self-consistently drive the AGB winds via radiation pressure on dust. The dust forms when the temperature in the winds drops below its condensation radius. Some of this dust is expected to be expelled to larger radii and form spiral shocks (Mohamed & Podsiadlowski 2012). These spiral shocks are important because they yield specific morphological signatures of binaries (Edgar et al. 2008; Kim & Taam 2012; Kim et al. 2013). They can also produce accretion rate variability whose time scales we will determine as a function of the binary parameters. Careful interpretation of these simulations can thus greatly help connect theoretical predictions with observations.

4 COMPUTATIONAL APPROACH

AstroBEAR 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.

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. (2004); Cunningham et al. (2005, 2006, 2009); Yirak et al. (2012); Carroll-Nellenback et al. (2013); Huarte-Espinosa et al. (2013); Li et al. (2014); Kaminski et al. (2014); Hansen et al. (2015); Hartigan et al. (2016); Chen et al. (2016a,b); Fogerty et al. (2016)).

The multi-physics capabilities of AstroBEAR have been significantly expanded by including solvers for elliptic and

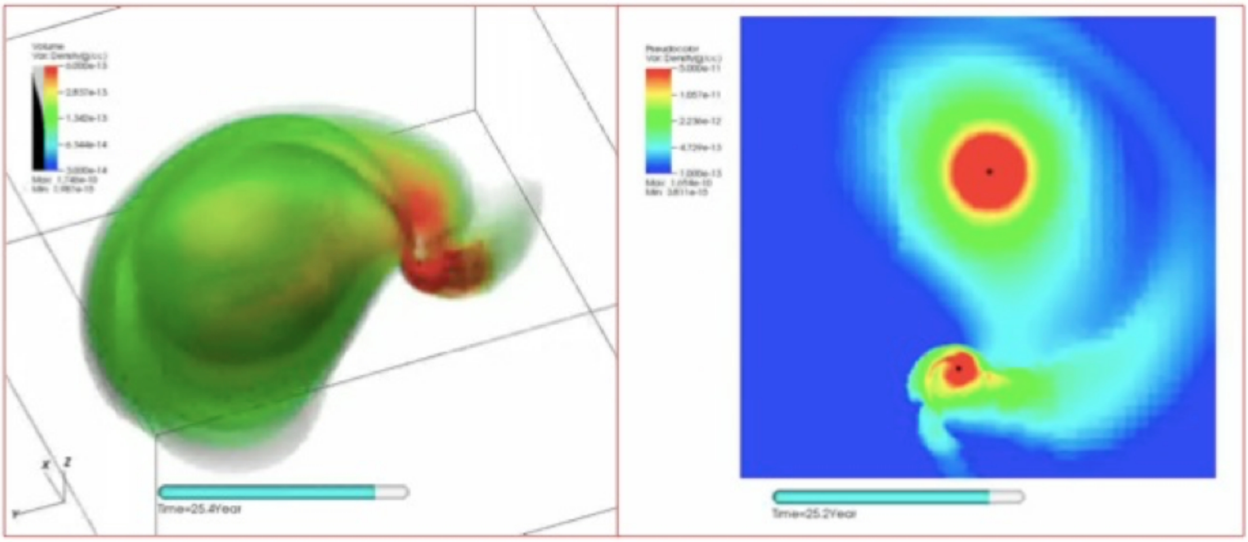

Figure 5. AstroBEAR AMR simulation of WRLOF disk formation. Left: Volume rendered image of density showing iso-contours of wind leaving the AGB star (green) and being captured by the secondary to form both a disk and a complex wake (red). Right: density map of same simulation in the equatorial plane

parabolic equations. Adapting the linear system solver HYPRE, we now routinely simulate systems in which self-gravity, heat conduction, magnetic resistivity and radiation transfer are important. In addition, AstroBEAR can treat gravitationally interacting point particles which accrete mass.

4.1 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 left panel of Figure 6. These tests were done with Model 7 ($d = 6AU$) at a resolution of $80 \times 80 \times 30$ with 7 additional levels of AMR for an effective resolution consistent with our planned production runs. The strong scaling shows a slope -0.78 out to 1728 cores on Comet and -0.86 out to 1024 cores and -0.73 out to 4096 cores respectively on Stampede. (Perfect scaling corresponds to a slope of -1). This demonstrates very good scaling of AstroBEAR on both Comet and Stampede for the simulations we seek to perform. We also performed weak scaling tests shown in the right panel of Figure 6 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 to 4096 cores on Stampede. More results and details about the performance of AstroBEAR can be found in the report of ”Code Performance of AstroBEAR2.0”.

5 JUSTIFICATION OF RUNS

Our goal of work will be to explore the transition between forms of mass transfer and,in the process, fill out the parameter space for WRLOF simulations to determine the true form of the curve in Figure 4. We plan to carry out a suite of studies for a broader range orbital separations between $3AU$ and $10AU$, specifically we plan to run high-resolution simulations with orbital separation $3AU$, $4AU$(with various q), $6AU$ and $10AU$. (Table 2).

- **Proposed Simulation Zone** The hydrodynamic behavior of our low-resolution testing runs suggest that the minimum physical size of the simulation zone would be $64AU \times 64AU \times 48AU$ and $96AU \times 96AU \times 48AU$ for orbital separation $d = 3AU$ and $d = 4AU$ runs respectively. The grid scales are set based on fall back timescales and our desire to explore the formation of circumbinary disks. For runs with larger separation distance, the simulation domains are scaled based on estimate fall-back times from low resolution models (See details in Table 2).
- **Proposed Resolution** To see the structure of the disk as shown in Figure 5, we will need the finest grid to be $0.05AU$ or less. So for the $d = 3AU$ (Model 1) runs this will need the resolution to be at least $1280 \times 1280 \times 960$. With AMR we can get the same resolution with $40 \times 40 \times 30+$ 5 levels of AMR. For our production runs, our proposed resolutions for Model 1 is $40 \times 40 \times 30+$ 7 levels of AMR which will enable us to study the more detailed structure of the disk.

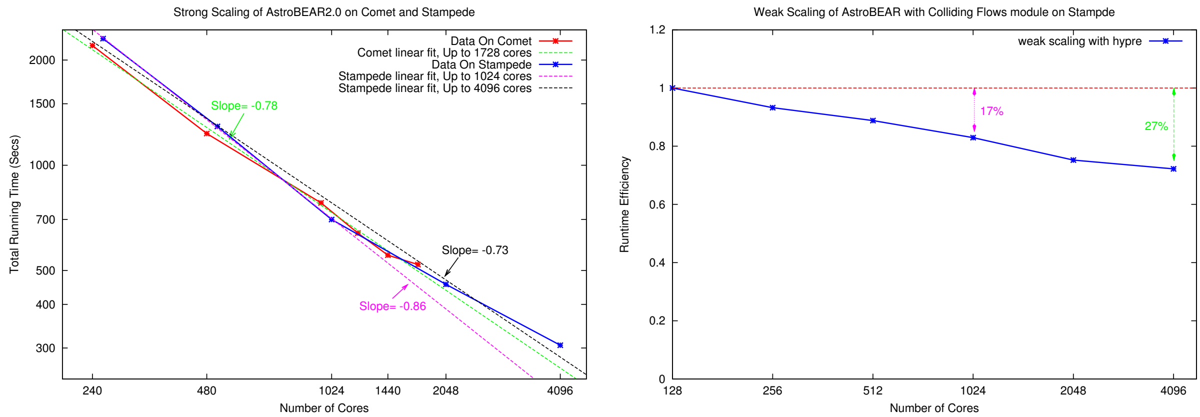

Figure 6. Left: Strong scaling behavior of AstroBEAR with a base resolution of $80 \times 80 \times 30$ and 7 additional levels of AMR on Comet at SDSC and Stampede at TACC. Running time is plotted versus the number of cores in log scale. The test result on Comet has a slope of -0.78 out to 1724 cores, while on Stampede the slope is -0.86 out to 1024 cores and -0.73 out to 4096 cores(a slope of -1 corresponds to "perfect scaling). Right: 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.

- **Proposed Run-time and Frame Counts** The pulsation period for AGB stars is $\sim$ 1 year. Thus to properly resolve the mass loss rate, we will need at least 10 frames/outputs per pulsation period. We propose to run the simulation up to 50 years so we would need 500 frames for each run.

6 RESOURCE REQUEST

6.1 CPU-hours Request

For our production runs, our estimate CPU-hours is based on the strong scaling tests we've done (with Model 7 or $d = 6AU$) which has the same resolution but running for only 1/10 of one frame (we are planning to obtain 500 frames of the data). For our scaling test on 1024 cores on Stampede, it takes about $700 seconds$ or $200 CPU - hour$ to run 1/10 of one frame. So the total CPU-hours for one production run is about 1,000,000 CPU-hours on Stampede. (See Table 1). For other runs, we expect longer and shorter run-time based on the resolution. For example, for Model 8 the estimated run-time will be slightly longer than $120^2 \times 50/(80^2 \times 30) = 3.75$ million CPU-hours since the most refined zone will be larger comparing with Model 7. Base on this information we estimate the total CPU-hours needed will be 7,970,000 (Table 2).

In total we require 4.2 million CPU-hours on Stampede and 3.9 million CPU-hours on Comet (for Model 8 runs), 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.

6.2 I/O Requirements, Analysis, and Storage

Based on Table 1, we expect to save 500 frames of data with an average size of 3GB 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 with 7 levels of AMR. So the total data size for our project is about 12 TB. We are planning to run these simulations on Stampede and Comet. we expect to need $\sim$ 8 TB of storage on Ranch of TACC and $\sim$ 4 TB of storage on Data Oasis of SDSC. 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. We will also use our local visualization resources for analyzing the data (See Section 7).

6.3 Choice of Computational Clusters

The AstroBEAR code has been running successfully and productively on many powerful Supercomputers like Kraken, Ranger, Stampede, Gordon, Comet etc. for the past several years. Especially AstroBEAR scales very well on Stampede and runs most efficiently on 1024 cores (see Figure 6 or the scaling test report attached). We estimate one of our proposed production runs (Model 8) will require more memory usage. So we would like to run it on Comet nodes to take the advantage of the 128GB memory per node.

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

	Scaling Test	Production Run
AMR levels	7	7
Num of frames	1/10	500
WallTime/CPU-hour for Strong Scaling(1024 cores)	700 secs	$\sim$ 200 hrs
Data size of each frame	2-4 GB	1-2 TB
Total Estimate CPU-hours		1,020,000

7 LOCAL RESOURCES AND RESEARCH TEAM

- **Research Team** Our research group consists of PI Professor Adam Frank, two computational scientists, one post-doc, three graduate students. Together the group has developed and maintained the AstroBEAR and applied it to problems ranging from binary disk 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 called BlueHive which has 200 nodes of IBM's iDataPlex architecture interconnected with FDR10 Infiniband. Each BlueHive computing node houses 2X12-core Intel "Ivy Bridge" processors, with a range in memory from 64 GB to 505 GB. The Visualization nodes on BlueHive has OpenGL capable GPUs that can be used for accelerated 3D rendering. CIRC also hosts the Visualization-Innovation-Science-Technology-Application (VISTA) Collaboratory which is a state of the art visualization lab capable of displaying massive datasets in real time. VISTA is equipped with a 50 mega-pixel display and 10 Gbps direct fiber connection back to BlueHive and BlueStreak. These cutting edge resources are available to researchers across the University and both systems are highly over-subscribed.

7.1 Financial Support

We have been granted financial support from the NSF, DOE and NASA. Specifically the National Science Foundation, NSF AST-1515648 entitled "From Core to Outflow: The Dynamics of Binary Interactions and the Generation of Collimated Flows in Evolved Stars" (PI, A. Frank; 9/15/2015 - 8/31/2018); Space Telescope Sci Institute grant HST -AR-12832.01-A entitled "HST Cycle 20: Climbing the Ladder of Star Formation Feedback " (PI, A. Frank; 1/1/2012 - 10/31/2016); Space Telescope Sci Institute grant HST -AR-12892.001 entitled "STSCI-Hubble Telescope Cycle 22: The Reel Deal In 3D: The Spatio-Temporal Evolution of YSO Jets " (PI, A. Frank; 1/1/2015 - 10/31/2017) and DOE grant DE-SC0001063 entitled "Resolving the Issue:The dynamics of magnetized Astrophysical Jets through Pulsed Power DEDP laboratory Studies" (PI, A. Frank; 8/15/2012 - 8/14/2015).

8 SUMMARY

Given our successful work with our parallelized AMR MHD multiphysics code AstroBEAR on studies of Bondi-Hoyle disk (Huarte-Espinosa et al. 2013) and circumbinary disk formation (Chen et al. 2016a) we propose to carry forward a study of mass transfer mechanism in the evolved-star binary system with various orbital separations. We will run a series of high-resolution simulations with the AstroBEAR binary module and carry out a comprehensive 3D AMR numerical exploration of accretion rates and assess when an accretion disk forms around the secondary.

- Runs for Model 1-7: 4,120,000 SU's on Stampede.
- Run for Model 8: 3,850,000 SUs on Comet.
- Testing, and continue development of our code. 80,000 SU's on Stampede; 1% of total request.
- Testing and continue development of our code. 50,000 SU's on Comet; 1% of total request.
- The total data set is $\sim$ 12 TB

To achieve these goals, we request 4,200,000 SU's on the Stampede of TACC together with 8TB of storage on Ranch and 3,900,000 SUs on Comet of SDSC together with 4TB of storage on Data Oasis.

Table 2. Expected CPU-hours for Binary Simulations

Model	q	d	Simulation Zones	Resolution	Expected SUs
1	0.5	3AU	$64 \times 64 \times 48AU$	$40 \times 40 \times 30$ + 7AMR	250,000
2	0.1	4AU	$96 \times 96 \times 48AU$	$60 \times 60 \times 30$ + 7 AMR	570,000
3	0.3	4AU	$96 \times 96 \times 48AU$	$60 \times 60 \times 30$ + 7 AMR	570,000
4	0.5	4AU	$96 \times 96 \times 48AU$	$60 \times 60 \times 30$ + 7 AMR	570,000
5	0.7	4AU	$96 \times 96 \times 48AU$	$60 \times 60 \times 30$ + 7 AMR	570,000
6	0.9	4AU	$96 \times 96 \times 48AU$	$60 \times 60 \times 30$ + 7 AMR	570,000
7	0.5	6AU	$128 \times 128 \times 48AU$	$80 \times 80 \times 30$ + 7 AMR	1,020,000
8	0.5	10AU	$192 \times 192 \times 64AU$	$120 \times 120 \times 50$ + 7 AMR	3,850,000
Total					7,970,000

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