MINI-DISK DYNAMICS ABOUT SUPERMASSIVE BLACK HOLES BINARIES

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PI: Scott C. Noble[1]
Co-PIs: Manuela Campanelli[2], Julian H. Krolik[3]
Collaborators: Dennis Bowen[2], Stephane d'Ascoli[2], Vassilios Mewes[2], Hotaka Shiokawa[4]

[1]The University of Tulsa
[2]Rochester Institute of Technology
[3]Johns Hopkins University
[4]Harvard-Smithsonian Center for Astrophysics

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EXECUTIVE SUMMARY

The overall goal of our project is to provide the community with realistic predictions of electromagnetic (EM) signatures from supermassive black hole binaries (SMBHBs). These events are of much theoretical interest now since little is known about them, but they are ripe for discovery with current and future high-cadence large-sky observational campaigns (e.g., PAN-STARRS, Catalina Real-time Transient Survey, LSST), as well as future multi-messenger endeavors with spaced-based gravitational wave detectors. We paved the way toward this goal by performing a set of hydrodynamic and magnetohydrodynamic (MHD) simulations of these systems using the HARM3d code on the Blue Waters system. The simulations are frontier calculations and require incredible resources and significant effort to cover the large range in time and length scales inherent to their physical situation.

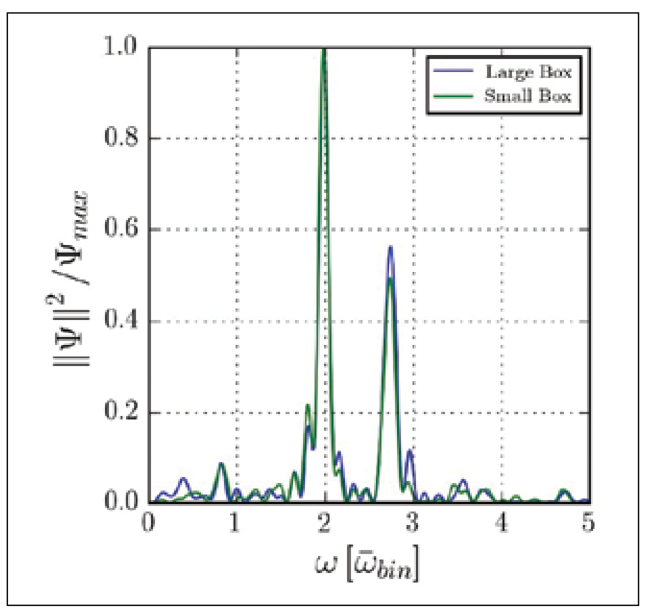

Figure 1: Fourier power spectrum of the fluctuating mass within the sloshing region from the 2D nonmagnetized simulation. The amount of light emitted from this region is expected to correlate with the mass, so the plot serves as a proxy for the predicted variability of the mini-disks' EM emissions. Such a signal could be used to learn properties of an observed system by comparing data to our predictions. Image credit: D. Bowen[2].

RESEARCH CHALLENGE

In previous years, we have performed 3D general relativistic MHD (GRMHD) simulations of the circumbinary disk that resides outside the orbit of the binary [1, 2]. These long timescale runs were affordable because we excised the binary from the evolution, which allowed us to take larger time steps yet maintain numerical stability. Unfortunately, the excision technique prevented us from learning about the gas dynamics that occurs near each black hole (BH) and the processes that develop between the "mini-disks" of gas that form there. These mini-disk simulations were the focus of our work on Blue Waters this past year, and provided us with first-of-a-kind comprehensive GRMHD simulations of accreting SMBHBs. Including the mini-disks is critically important to understanding the EM signatures because the mini-disks make up a large fraction of the total luminosity from the system, and they give rise to the most variable emission, which is a key means by which astronomers hope to characterize and identify SMBHBs.

In order to start from initial conditions closer to a steady-state and to save resources, Rochester Institute of Technology graduate student Dennis Bowen wrote a method to generate mini-disks around each BH. The initial data method was used first to explore how general relativistic terms affect the dynamics of 2D nonmagnetized disks [3].

METHODS & CODES

All the results reported here used the flux-conservative, high-resolution, shock-capturing GRMHD code called HARM3d [4]. Besides using modern computational fluid dynamics techniques and a solenoidal constraint transport scheme for the magnetic field's induction equation, GRMHD is written in a general covariant way so that any metric or coordinate system may be adopted. This last property has accommodated our implementation of a novel, time-dependent, nonuniform gridding scheme for resolving the small spatial scale features near each BH, and the larger spatial scale flow orbiting circularly that extends much further out beyond the SMBHB's orbit [5]. This coordinate system enabled us to perform the first 3D GRMHD simulations of SMBHB mini-disks already mentioned.

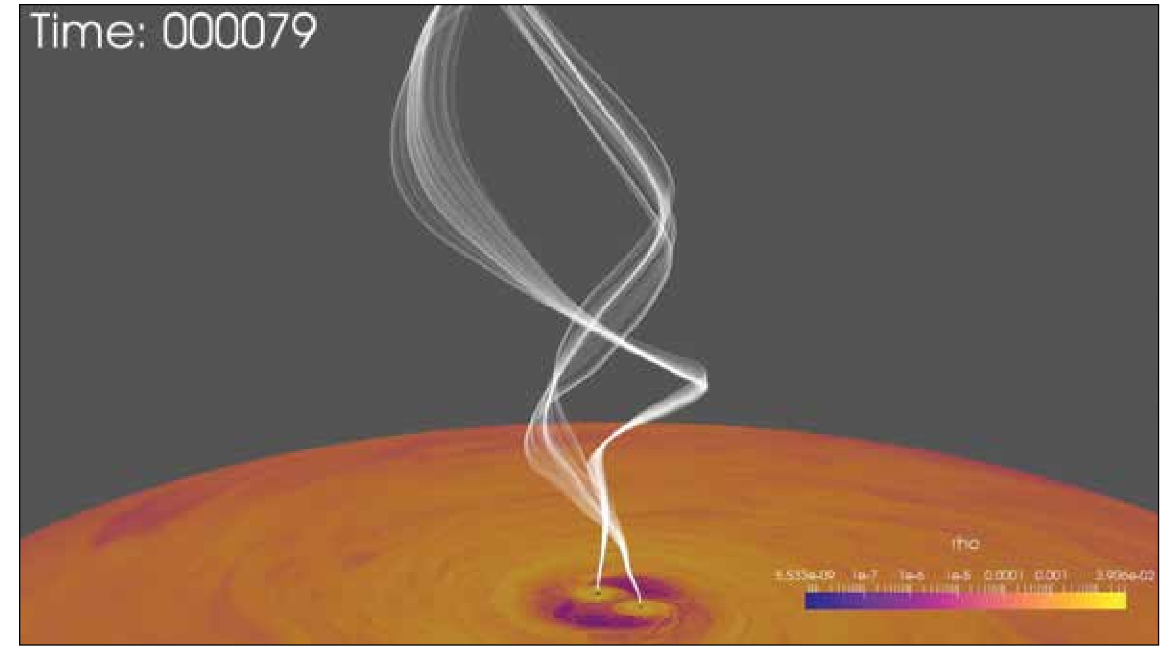

Figure 2: Magnetic field lines (white curves) emanating from two magnetized black holes from the 3D magnetized simulation. An equatorial slice of density of the accreting gas is also shown (background). Image credit: M. Van Moer (NCSA).

We are extending this idea of mesh refinement to one involving multiple coordinate patches, which we call "Patchwork." The scheme is able to solve the MHD equations of motion using multiple, overlapping coordinate system patches. We validated the method on various machines using a variety of tests, which are described in detail in [6]. After passing these tests, we performed a production-level science run of a star's disruption by a black hole from approach all the way to disruption and fallback.

RESULTS & IMPACT

In the 2D hydrodynamic simulations, we found that significant mass exchange, or "sloshing," of material occurred between the two mini-disks. The fluctuations of the mass in the sloshing region resulted in a high-quality and characteristic signal, which we would expect to produce a similarly characteristic periodic EM signal because of the high rate of dissipation there. We further found that the amount of material in the sloshing region increases as the binary shrinks, suggesting that the sloshing emission will become brighter as the BHs grow closer and proceed to the relativistic limit. Our findings suggest that binaries near merger will be bright and periodic at a time scale associated with the SMBHB's orbital period—a key to extracting information about an observed binary's orbit.

Continuing our use of the new mini-disk initial data, we have performed the first full 3D MHD evolution of mini-disks about black hole binaries in the relativistic regime, including the accretion from the circumbinary disk. This full run will begin to address the importance of spiral shocks in the overall angular momentum budget relative to internal MHD stresses. Additionally, we will be able to explore the effects of accretion streams from the circumbinary on the overall structure of the mini-disks. Our results from this simulation will be submitted soon.

WHY BLUE WATERS

The 3D GRMHD mini-disk simulation ran for two orbital periods and used 12.9 million floating-point-core-hours, or 0.806 M node-hours, on Blue Waters. The simulation used 600x160x640, or approximately 60 million cells, on about 2 million time steps using 600 nodes or 19,200 Blue Waters cores. The simulation is challenging because of the large dynamic range of time scales between the fast behavior near the black holes and the relatively slow orbital velocity of the binary, resulting in a month-long run time. Members of the NCSA Blue Waters team, e.g., David King and Jing Li, were very helpful in arranging a reservation for our run during a busy time on the cluster. The reservation allowed us to finish the simulation before the end of the allocation period.

PUBLICATIONS AND DATA SETS

Zilhao, M., S. Noble, M. Campanelli, and Y. Zlochower, Resolving the relative influence of strong field spacetime dynamics and MHD on circumbinary disk physics. *Physical Review D*, 91:2 (2015), 024034.

Bowen, D., et al., Relativistic Dynamics and Mass Exchange in Inspiraling Binary Black Hole Mini-Disks. *Astrophysical Journal*, 838 (2017), p. 42.

Shiokawa, H., R. Cheng, S. Noble, and J. Krolik, PATCHWORK: A Multipatch Infrastructure for Multiphysics/Multiscale/Multiframe Fluid Simulations. *Astrophysical Journal*, arXiv:170105610, under review (2017).