PREDICTING THE TRANSIENT SIGNALS FROM GALACTIC CENTERS

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EXECUTIVE SUMMARY

Active supermassive black holes (SMBHs) at the centers of galaxies are home to the most energetic phenomena in the universe and are systems of great interest for high-cadence sky surveys such as the Large Synoptic Survey Telescope (LSST). Insight into their transient nature is contingent on the community developing detailed simulations of electromagnetic emission from SMBHs and SMBH binaries (SMBHBs), which is our goal. With Blue Waters, we have learned how the electromagnetic fluctuations from SMBHBs depend on the mass ratio of the black holes and the disk's magnetic field. We have explored the stability properties of "mini-disks" about each black hole. Finally, we have begun exploring tidal disruptions of stars using our new "multi-patch" system for simulating dynamics at different temporal and spatial scales. Each set of runs advances the field's existing resolution and sophistication limits, thanks to the unique resources of Blue Waters.

INTRODUCTION

Black holes are exotic astrophysical objects that power some of the most energetic phenomena in the universe. The first direct detection of gravitational waves this past year has ushered us into an era of gravitational wave astronomy, and implies that the future space-based observatories will be rich in sources. Our work with Blue Waters will provide the community with the most advanced simulations of two kinds of systems of focus in transient surveys: SMBHB accretion disks and tidal disruption events (TDEs) of stars by SMBHs. Both projects offer the opportunity to test the strong-field limit of gravity, which benefits society fundamentally and provides new results on a topic of significant public interest: black holes and how they influence their environment.

METHODS & RESULTS

Our simulations on Blue Waters rely on the conservative, high-resolution shock-capturing code called HARM3d to solve the equations of general relativistic magnetohydrodynamics (GRMHD). Its coordinate-independent approach allows us to resolve the black holes in SMBHB simulations using a "dual fisheye" system that smoothly transitions from a local Cartesian-like high-resolution grid near each black hole to a spherical coordinate system further away where the circumbinary disk resides, all via a continuous coordinate transformation [1]. Also, HARM3d now accommodates a multi-program/multi-data mode, with which we may solve the equations independently, only interacting via boundary conditions. We call this approach "multi-patch" and it is being used for the **first time** in TDE simulations on Blue Waters, and will be used extensively for SMBHB simulations in the near future. It offers the ability to evolve the patches with different time steps, grid spacings, physics modules (e.g., gravity models), reference frames, and coordinate topologies—all to maximize the simulation's runtime performance and scalability.

We have expanded our earlier work on circumbinary disks [2,3], to consider SMBHBs of different mass ratio and magnetic field distributions. We find that once the mass ratio drops below 1/5, the binary's tidal torque diminishes to a degree that the disk's activity resembles that about a single black hole. Taking advantage of Blue Waters' large resources, we quadrupled the size of the initial reservoir of mass and magnetic field. This simulation confirms that a sustained source of magnetic field can mitigate the development of the circumbinary disk's electromagnetic signal. This work implies that these strong periodic signals may only arise from near-equal mass binaries in weakly magnetized environments.

Our new "mini-disk" initial data prescription, which is being demonstrated for the **first time** in 3D on Blue Waters, will allow us to bypass a large portion of the relaxation phase of the evolution and simulate the approximate steady-state of the circumbinary flow for longer. With Blue Waters, we have measured the tidal truncation radius of the mini-disks in the relativistic regime for the first time. We find that Newtonian predictions [4-6] remain valid down to binary separations of approximately 50M, but relativistic corrections are required for smaller separations.

The full TDE, from disruption to accretion, has not been simulated before because of the prohibitive expense of numerical methods which treat the problem in one computational domain. Our initial 3D hydrodynamic calculations are made affordable by using the multi-patch scheme, which is used for the first time for this project (Fig. 1). In addition to validating the multi-patch infrastructure, it paves the way for the **first ever** MHD TDE evolutions we hope to perform on Blue Waters soon.

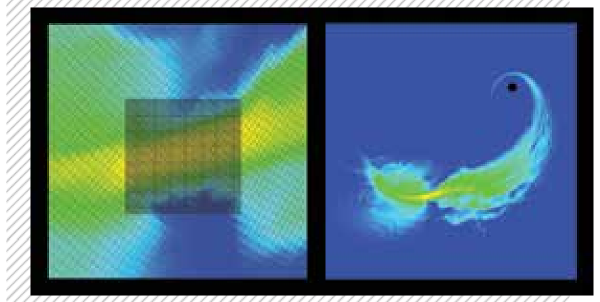

FIGURE 1: Logarithm of the density of debris from a star tidally disrupted by a black hole. Image credit: R. Cheng (JHU).

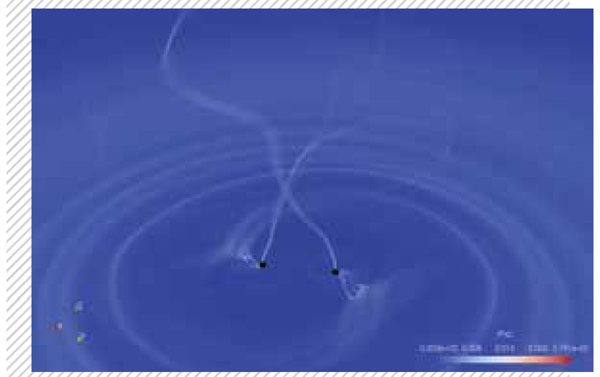

FIGURE 2: Magnetic field lines (white curves) emanating from two black holes. Equatorial slice of density of the accreting gas (background). Image credit: M. Vanmoer (NCSA).

WHY BLUE WATERS

Blue Waters provides a unique resource with which we may run at scales and core counts not possible on other systems. Using multiple patches multiplies the required core-count by the number of patches used. Further, our circumbinary disk calculations require tens of millions of time steps to cover the large range in time scales inherent to the problem.

An incredible resource made possible by our Blue Waters allocation is access to NCSA's visualization team. We have worked closely with Mark Vanmoer and Roberto Sisneros on how to best visualize magnetic field lines and volumetric ray-casts of density from our circumbinary accretion disk simulations (Fig. 2).

NEXT GENERATION WORK

To properly consider the effects of opacity and radiation pressure, the radiation's field equations must be evolved in tandem, adding extra dimensions to the problem and amplifying the workload dramatically. We look forward to the future generation of supercomputers for including radiation in our GRMHD simulations. In particular, we anticipate relying on graphics processing unit (GPU)/integer-core computing to relieve some of the extra computational burden, which will either require us to develop integer-core abilities into HARM3d or have the abilities automatically provided by the next generation of load balancing and distribution environments (e.g., Charm++ [7]).

Further, we expect to use the multi-patch scheme in a variety of new ways in the future. Since it uses the multi-program/multi-data program model, we may run microphysics codes (e.g., for local turbulence) alongside a global calculation to provide it with sub-cell-level input. Such calculations will again multiply the required resources and core-counts, and provide demand for the nation's continuing support of **cutting-edge** computing resources.