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SHEDDING LIGHT ON SUPERMASSIVE BINARY BLACK HOLE MERGERS

Allocation: NSF PRAC/10,200 Knh
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EXECUTIVE SUMMARY

Observing electromagnetic and gravitational waves from supermassive binary black holes and their environments promises to provide important new information about both strong-field gravity and galaxy evolution. Since little theoretical understanding about the details of these accreting binary black hole systems exists, the aim of this project is to continually advance the realism and rigor of simulations of these systems. The problem is complicated because dynamical general relativity, plasma physics, and radiation physics all must be calculated together over vast spatial and temporal scales.

This past year, the research team finished performing the first magnetohydrodynamics (MHD) simulations of black holes with their own minidisks surrounded by a circumbinary disk. The team also created the first detailed electromagnetic predictions consistent with simulations using postproduction radiation transport. These predictions will be critical to the success of electromagnetic searches and source characterization leading up to the launch of the Laser Interferometer Space Antenna (LISA), which is planned for 2034.

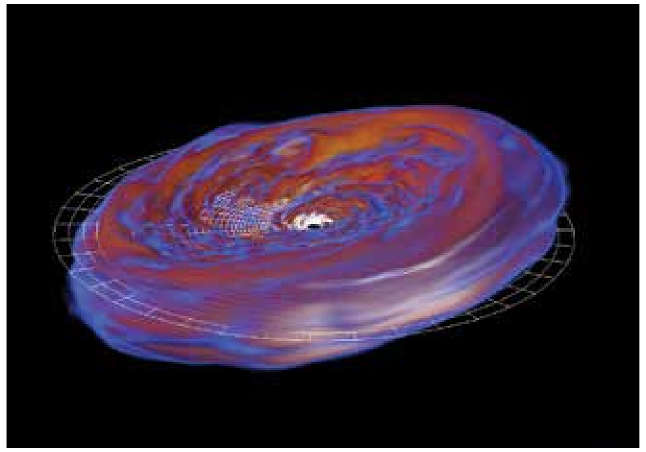

Figure 1: This simulation snapshot shows a partially evolved disk with a 12° tilt with respect to the binary supermassive black hole orbital plane. (Credit: Mark J. Avara)

RESEARCH CHALLENGE

Realistic accretion disk simulations are particularly challenging because they involve a multitude of physical processes interacting over large dynamic ranges in space and time. In actual systems, gas is collected at scales a million times larger than the black holes themselves, yet many cells per black hole width must be used to capture the relativistic plasma dynamics in their vicinity. Reliable angular momentum transport of gas through the disk requires solving the MHD equations of motion at sufficiently high resolution to adequately resolve the responsible internal magnetic stresses. Consistency between the gas's thermodynamics and radiation model is desirable to produce self-consistent predictions of the light produced by the modeled systems, which is the ultimate goal of this program.

Then, transporting the produced light to a distant observer requires researchers to calculate how light moves in the curved time-dependent spacetime of the black hole binary, and how it scatters and is absorbed by intervening gas; *i.e.*, investigators must solve the general relativistic geodesic and radiative transfer equations. All this sophistication is built so scientists may confidently predict what electromagnetic counterparts may exist to the extremely bright gravitational wave sources LISA will see over cosmological distances. Since LISA is planned to launch in more than a decade, researchers can begin to search for these systems with predictions in hand. The research group's simulations may discover features that are unique to binaries and inform the search for them.

METHODS & CODES

The research team used the flux conservative GRMHD code called HARM3D. It is written in a covariant way such that arbitrary spacetime metrics and coordinate systems may be used without the need to modify core routines. The team also tested and used the new code PatchworkMHD coupled with HARM3D to enable the most sophisticated and longest simulations yet. This allowed the placement of meshes with different refinement/coordinates and topologies in a way ideal for the system, increasing the efficiency of the simulations and extending them by an order of magnitude in time. It enabled the team to capture the behavior of a region between the black holes that was excluded in prior 3D simulations and to achieve a resolution unprecedented in magnetized 3D simulations of accreting binaries.

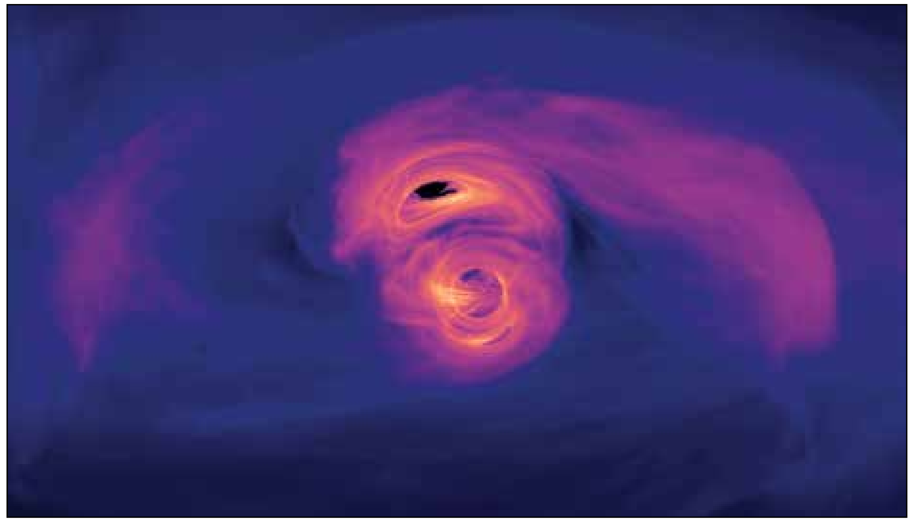

Figure 2: General relativistic ray-traced image of emission from magnetized gas accreting onto a binary system of black holes. The intensity of light is represented by the intensity of the hue. (Credit: S. Noble)

RESULTS & IMPACT

The research team's continued research program focused on 3D MHD simulations of the black hole minidisks and circumbinary disk interactions has advanced the field in a number of ways. During a previous allocation period, the team discovered a new phenomenon in which the irregular circumbinary flow can modulate the rate of accretion onto the minidisks in a quasiperiodic fashion, causing them to be depleted and then refilled as they passed by the over-density feature in the circumbinary disk [1]. During the most recent allocation period, the team continued the simulation of three binary black hole orbits to 12 orbits [3]. This allowed the team to probe the minidisks quasiperiodic behavior deeper into the late stages of the relativistic binary black hole inspiral. The research group showed that the quasiperiodicity in the minidisk evolution is driven by the interaction of the individual black holes with a localized over-density feature in the circumbinary, which orbits the binary at a well-defined beat frequency with respect to the orbiting black holes. Since the mass inflow times onto each black hole during the late stages of inspiral are comparable to the variability of the mass supply owing to the over-density, the minidisk masses and accretion rate onto each black hole are strongly modulated at this beat frequency. This constitutes a distinctive electromagnetic signature, the sort that could distinguish supermassive black hole binary systems from typical accreting single supermassive black holes. The research team subsequently explored how all this changes when the disk is tilted with respect to the binary's orbit, since the gas fed to the system need not always be aligned. The team has completed a first survey and are analyzing the results as of August 2019 (Fig. 1).

The team performed first-of-its-kind radiative transfer calculations in time-dependent general relativity using the simulation's data as an emitting source in order to predict the electromagnetic emission from the minidisk simulation. A range of viewing angles and observation frequencies were surveyed for all time slices of data to explore the energy, time, and angle dependence of the emission [2]. This calculation resulted in the first electromagnetic spectrum of accreting supermassive black holes in the inspiral regime. These results were shared with the community with the help of several news releases [4–6], which included high-resolution movies and images (Fig. 2).

WHY BLUE WATERS

The 3D GRMHD mini-disk simulation ran for three orbits and used 1.125 million node hours on Blue Waters. The simulation used a 600 x 160 x 640 grid, or approximately 60 million cells, and evolved through about three million timesteps using 600 nodes. The follow-up simulation, which extended this to 12 orbits, used 148 days of wall-clock time running on 600 nodes for a total of 2.13 million node hours. The tilted circumbinary disk simulations ran on 500 Blue Waters nodes at a time, but required a long duration. NCSA staff members were helpful in arranging reservations for the runs. Without the vast resources available on Blue Waters, the research team would not have been able to perform this work.

PUBLICATIONS & DATA SETS

D. B. Bowen, V. Mewes, S. C. Noble, M. J. Avara, M. Campanelli, and J. H. Krolik, "Quasi-periodicity of Supermassive Binary Black Hole Accretion Approaching Merger," *Astrophys. J.*, vol. 879, no. 2, p. 76, July 2019, doi: 10.3847/1538-4357/ab2453.

S. d'Ascoli, S. C. Noble, D. B. Bowen, M. Campanelli, J. H. Krolik, and V. Mewes, "Electromagnetic emission from supermassive binary black holes approaching merger," *Astrophys. J.* vol. 865, no. 2, p. 140, Oct. 2018.

D. B. Bowen, V. Mewes, M. Campanelli, S. C. Noble, J. H. Krolik, and M. Zilhão, "Quasi-periodic behavior of mini-disks in binary black holes approaching merger," *Astrophys. J. Lett.*, vol. 853, no. 1, p. L17, Jan. 2018.