SHEDDING LIGHT ON INSPIRALING BINARY BLACK HOLES WITH MAGNETIZED MINI-DISKS

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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, our project's aim 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. Our 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). This past year, we finished performing the first magnetohydrodynamics simulations of black holes with their own mini-disks surrounded by a circumbinary disk. We have recently finished creating the first detailed electromagnetic predictions consistent with simulations using postproduction radiation transport.

RESEARCH CHALLENGE

Realistic accretion disk simulations are particularly challenging as 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 magnetohydrodynamics 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 our program. Then, transporting the produced light to a distant observer requires us to calculate how light moves in curved, time-dependent spacetime to the black hole binary, and how it scatters and is absorbed by intervening gas; i.e., solving the general relativistic geodesic and radiative transfer equations.

All of this sophistication is built so we can confidently predict what electromagnetic counterparts may exist to the extremely bright gravitational wave sources LISA will see over cosmological distances. The first truly multimessenger event last year, GW/GRB 170817, provided a glimpse of the rich and varied information we can discover when gravitational waves accompany more conventional astronomical messengers such as light. Accreting supermassive binary black holes at the centers of galaxies are the only promising scenario for seeing light and gravitational waves from binary black holes, as stellar-mass systems in the local universe are unlikely to have any appreciable mass left over from their earlier stellar life. Since LISA is expected to launch in more than a decade, we can begin to search for these systems with our predictions in hand. Our simulations may discover features that are unique to binaries and, thus, inform the search for them.

METHODS & CODES

Our team uses the flux-conservative General Relativistic Magnetohydrodynamic (GRMHD) code called HARM3d. It is written in a covariant way such that arbitrary spacetime metrics and coordinates of systems may be used without the need to modify core routines. We exploit this property for the sake of time-dependent fixed mesh refinement to resolve the large range in spatial scales present in our systems of interest.

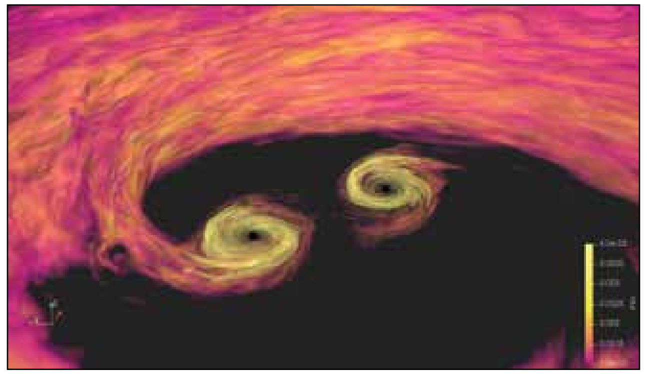

Figure 1: Volume rendering of the accretion flow's rest-mass density from the magnetized mini-disk simulation. (Credit: M. Van Moer, NCSA)

RESULTS & IMPACT

Our 3D magnetohydrodynamics simulation of mini-disk and circumbinary disk interactions advanced the field in a number of ways (Fig. 1). First, the inclusion of magnetic stresses provides greater realism to how gas is brought in from large distances and how it dissipates its orbital energy. The resolutions and run-times required to adequately describe this process are only possible on Blue Waters. Second, we discovered a new phenomenon in which the irregular circumbinary flow can modulate the rate of accretion onto the mini-disks. Because our black holes are relatively close, in that they are approaching the nonlinear merger phase of their evolution, the mini-disks drain faster than expected from standard Newtonian accretion disk theory. The fast depletion rate of the mini-disks leads them to be depleted, and then refilled, as they pass by the over-density feature in the circumbinary disk, suggesting a means to generate periodic electromagnetic emission.

In order to predict the electromagnetic emission from this simulation, we performed first-of-a-kind radiative transfer calculations in time-dependent general relativity using the simulation's data as an emitting source. 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. Our calculation resulted in the first electromagnetic spectrum of accreting supermassive black holes in the inspiral regime. Simulated images of the accreting black hole binary are shown in Fig. 2.

We are now exploring how 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. We have completed a first survey and are analyzing the results now.

WHY BLUE WATERS

The 3D GRMHD mini-disk simulation ran for three orbital periods and used 18 million floating-point-core-hours or 1.2 million node-hours on Blue Waters. The simulation used 600 × 160 × 640 or approximately 60 million cells on about 3 million timesteps using 600 nodes or 19,200 Blue Waters cores. Our latest tilted circumbinary disk simulations use up to 500 Blue Waters nodes at a time, with more than half the number of cells as the mini-disk simulation. NCSA Blue Waters staff, David King and Jing Li, were helpful in arranging reservations for our runs.

We have further benefited from Mark Van Moer's efforts over the past three years to produce state-of-the-art visualizations of our simulations. Recently, these included volume renderings of the gas density (Fig. 1) and a method to advect the seed points used to integrate the magnetic field lines using the fluid's velocity so that the lines are consistent across several frames in the animation.

PUBLICATIONS & DATA SETS

Bowen, D., et al., Quasi-periodic Behavior of Mini-disks in Binary Black Holes Approaching Merger. *Astrophysical Journal*, 853 (2018), DOI:10.3847/2041-8213/aaa756.

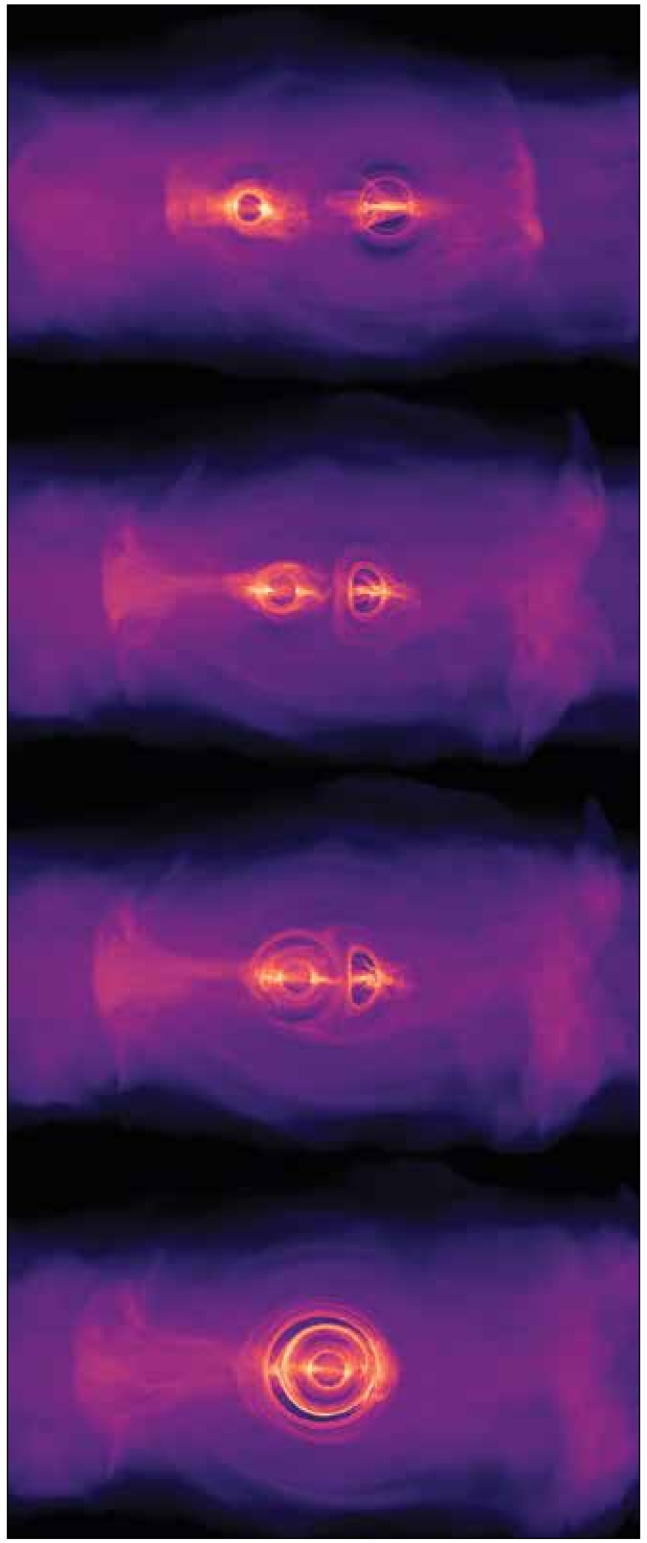

Figure 2: General relativistic ray-traced image of emission from magnetized gas accreting onto a binary system of black holes. The intensity of light is represented by the intensity of the hue. (Credit: S. Noble, University of Tulsa and NASA–GSFC)