DISKS AROUND MERGING BINARY BLACK HOLES: FROM GW150914 TO SUPERMASSIVE BLACK HOLES

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EXECUTIVE SUMMARY

The coincident detection of gravitational waves (GWs) with electromagnetic (EM) signals from the coalescence of black hole binaries is a new observational challenge. Combining GW and EM observations offers a unique probe to understanding black hole cosmological evolution and accretion processes. We report results from general relativity simulations of circumbinary magnetized disks accreting onto nonspinning merging black holes. We survey different disk models to quantify the robustness of previous simulations on the initial disk model. Scaling our simulations to LIGO (Laser Interferometer Gravitational-Wave Observatory) GW150914 we find that such systems could explain possible gravitational wave and electromagnetic counterparts, such as the Fermi GBM hard X-ray signal reported 0.4 seconds after GW150915 ended. Scaling our simulations to supermassive binary black holes, we find that the observable flow properties such as accretion rate periodicities and the emergence of jets throughout inspiral, merger, and postmerger we reported in earlier studies display only modest dependence on the initial disk model.

RESEARCH CHALLENGE

Accreting black holes are central in explaining a range of high-energy astrophysical phenomena that we observe in our universe, such as X-ray binaries, active galactic nuclei (AGN), and quasars. Recently, substantial theoretical and observational effort has gone into understanding accretion onto binary black holes, and the emergent electromagnetic (EM) signatures these systems may generate, because they are anticipated to exist at the centers of distant AGNs and quasars [1,2]. The bulk of the research so far has focused on supermassive black hole binaries (SBHBHs), and about 150 candidate accreting SBHBHs have been identified in quasar surveys [3,4]. Depending on the physical properties of the above systems, such as the mass ratio and orbital period, some of these candidates may bein the gravitational-wave (GW)-driven regime [5]. However, in addition to accreting SBHBHs, there may exist black hole binaries (BHBHs) of a few tens of solar masses that could be accreting matter from a circumbinary disk. This scenario has attracted a lot of attention recently because of the direct detection of GWs by the LIGO/VIRGO collaboration. As a crucial step toward solidifying the role of BHBHs as multimessenger systems, we report results from general relativity simulations of circumbinary magnetized disks accreting onto merging BHBS, starting from relaxed disk initial data. We evolve the systems after binary-disk decoupling through inspiral and merger, and analyze the dependence on the binary mass ratio and initial disk model.

METHODS & CODES

Magnetohydrodynamic (MHD) numerical simulations in full general relativity (GR) require the solution of the Einstein field equations to determine the gravitational field, the relativistic MHD equations to determine the flow of matter, and the electromagnetic fields. Together, the equations constitute a large system of highly nonlinear, multidimensional, partial differential equations in space and time.

We solve the above equations through our completely independent "Illinois GRMHD" code, which has been built over many years on the Cactus infrastructure and uses the Carpet code for adaptive mesh refinement but employs our own algorithms and coding [6]. This code utilizes state-of-the-art high resolution shock capturing methods to evolve scenarios involving either vacuum or matter spacetimes, with or without magnetic fields. It utilizes the Baumgarte–Shapiro–Shibata–Nakamuraformulation of the Einstein field equations with puncture gauge conditions. It solves the magnetic induction equation by introducing a vector potential, and employs a generalized Lorentz gauge condition to reduce the spurious appearance of strong B-fields on refinement level boundaries [6].

RESULTS & IMPACT

We performed MHD simulations of binary black holes with different mass ratios that accrete magnetized matter from a circumbinary accretion disk. We considered three initial disk models that differ in their scale heights, physical extent, and in their magnetic field content, in order to test whether previous properties of MHD accretion flows onto binary black holes are sensitive to the initial disk model [7]. We find that the presence of periodicities in the accretion rate, the emergence of jets, the time delay between merger, and the boost in the jet luminosity that we previously discovered [1,8–9] are all robust features and largely insensitive to the choice of initial disk model (see Fig.1).

As in our previous studies, we ignored the disk self-gravity and adopted a simplified Γ-law equation of state (Γ=4/3), which allows us to scale the binary black hole mass and disk densities to arbitrary values. Thus, our results have implications both for LIGO black hole binaries and for supermassive black hole binaries at centers of luminous AGNs and quasars. Scaling our simulations to LIGO GW150914 we find that magnetized disk accretion onto binary black holes could explain both the GWs detected from this system and the EM counterpart GW150915-GBM reported by the Fermi GBM team 0.4 seconds after LIGO's GW150915.When scaling to supermassive black hole binaries, we find that at late times flow properties, temperatures, and thermal frequencies are all robust, displaying only modest dependence on the disk model. Nevertheless, the range of disk thickness and ratio of magnetic-to-gas pressure in our survey is limited by what we can achieve with current computational resources and methods. As computational resources grow and numerical techniques advance we will be able to probe wider ranges of these parameters.

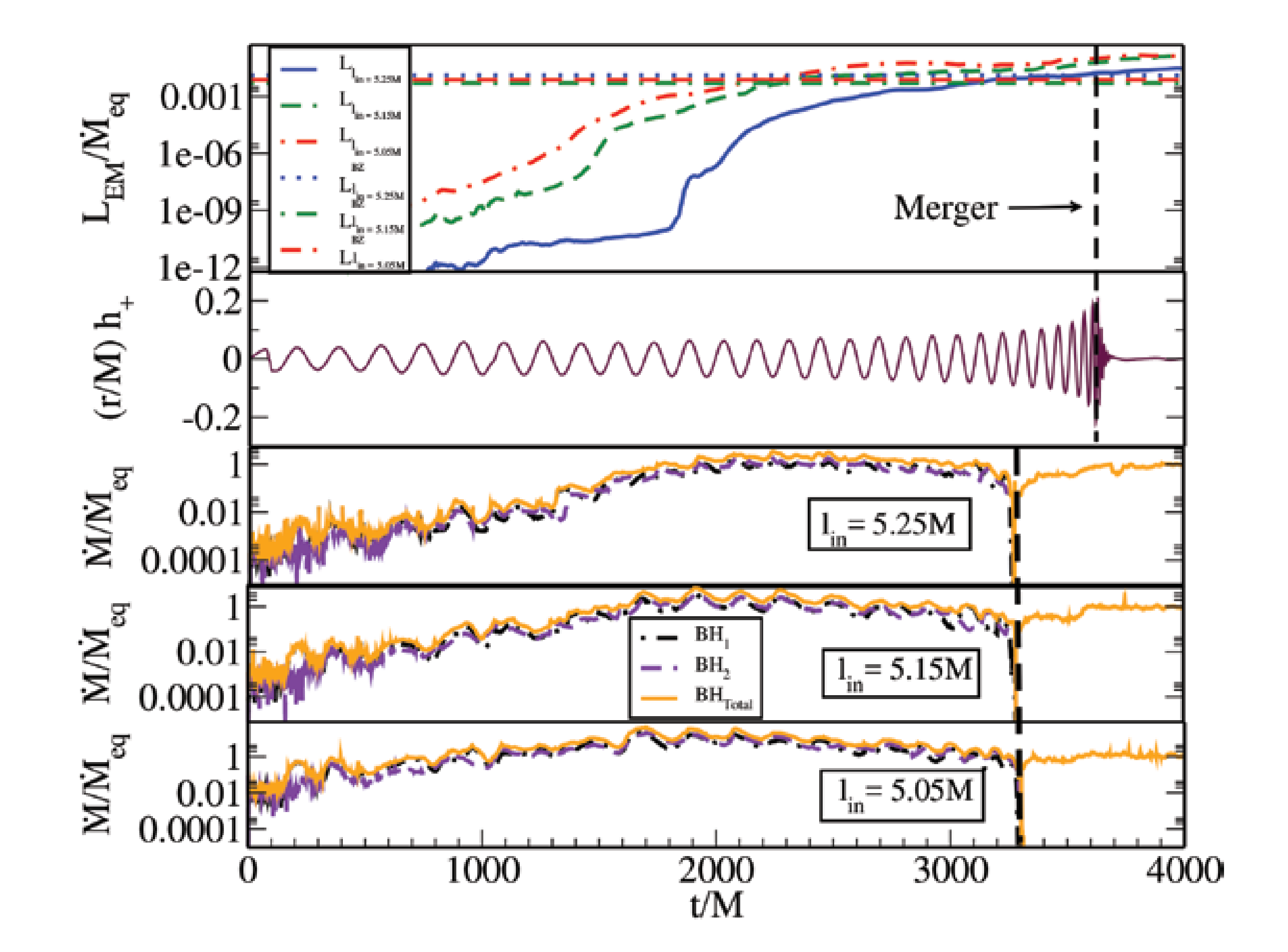

Figure 1: Poynting luminosity, accretion rate, and the strain of the gravitational waveform ("plus" polarization) vs. time for different disk models (see [7]). The displacements in the dashed vertical merger line in the luminosity and GW plots with respect to the merger lines in the accretion plots account for the light travel time.

WHY BLUE WATERS

Blue Waters provides the required computational power to simulate these cosmic sources in a timely manner. By adding OpenMP support to our MPI-based code, scalability on multicore machines has improved greatly. With the Blue Waters next-generation interconnect and processors, our hybrid OpenMP/MPI code exhibits greater scalability and performance than on any other supercomputer we have used. Recently, we were able to build our code with the Blue Waters Intel compilers. This resulted in a significant boost of our code's performance by about 30%, making Blue Waters unique for tackling the astrophysical problems we want to address.

Blue Waters is also used by our undergraduate research team to make visualizations (Fig. 1) and movies of our simulations with the VisIT software.