GRAVITATIONAL AND ELECTROMAGNETIC SIGNATURES FROM BINARY BLACK HOLE–NEUTRON STAR MERGERS: A JET ENGINE FOR SHORT GAMMA-RAY BURSTS

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EXECUTIVE SUMMARY

Recently, the LIGO/Virgo scientific collaboration reported the detection of gravitational waves likely produced by a black hole–neutron star (BHNS) system (source S190426c). No electromagnetic counterparts were linked to this event. Using general relativistic magnetohydrodynamic simulations of a BHNS undergoing merger, the research team surveyed different configurations that differ in the spin of the BH ($a/M_{BH} = -0.5,0,0.5,0.75$); in the mass ratio ($q = 3:1$, $q = 5:1$); and orientation of the magnetic field (aligned and tilted by 90° with respect to the orbital angular momentum). Only for configurations with $a/M_{BH} >= 0.5$ and aligned magnetic fields did the team find collimated, magnetically confined jets whose luminosity was consistent with typical short gamma-ray bursts and significant mass outflows that can induce detectable kilonova. By contrast, in case $q = 5:1$ the remnant disk and magnetic field were too small to drive a jet and generate significant mass outflows or counterpart electromagnetic luminosity. High mass ratio BHNSs may therefore be the progenitors of S190426c.

RESEARCH CHALLENGE

Inspiraling and merging black hole–neutron star binaries are not only important sources of gravitational waves (GWs) but are also promising candidates for coincident electromagnetic (EM) counterparts. In particular, these systems are thought to be progenitors of short gamma-ray bursts (sGRBs) [1–4].

Coincident detection of GWs with EM signals from compact binary mergers containing neutron stars (NSs) could give new insight into their sources: GWs are sensitive to the density profile of NSs and their measurement enforces tight constraints on the equation of state of NSs [5]. Postmerger EM signatures, on the other hand, can help to explain, for example, the phenomenology of sGRBs and the role of BHNS mergers in triggering the nucleosynthesis processes in their ejecta.

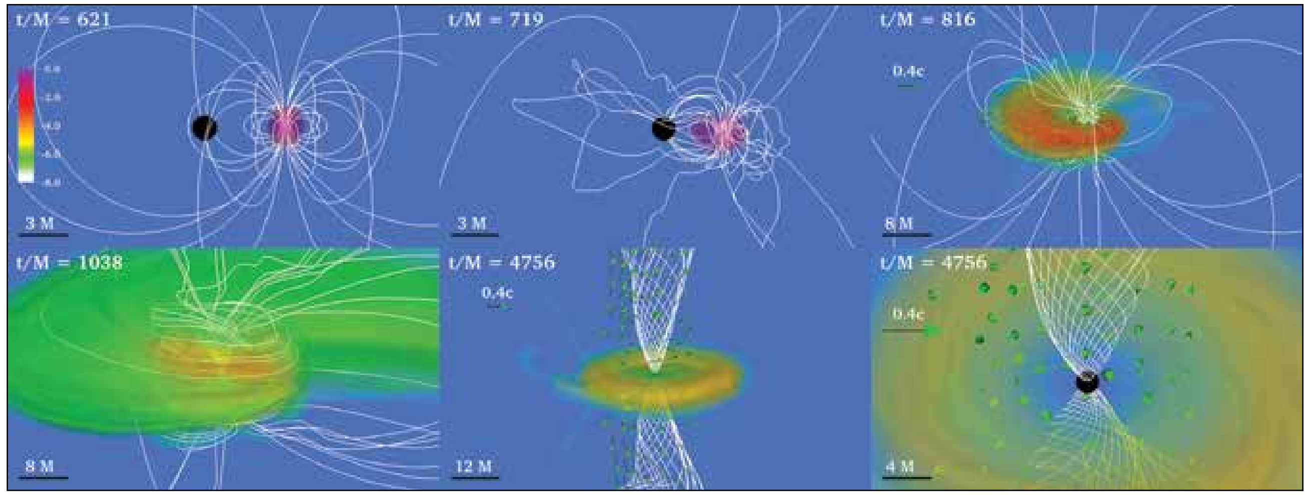
BHNS scenarios have attracted a great deal of attention recently because of the first-ever candidate detection of GWs from a BHNS system (90% confidence) reported by the LIGO/VIRGO scientific collaboration [6]. As a crucial step to solidifying the role of BHNSs as multimessenger systems, the research team reported results from general relativity simulations of BHNS configurations undergoing merger that differ in the spin of the BH ($a/M_{BH} = -0.5,0,0.5,0.75$); in the mass ratio ($q = 3:1$, $q = 5:1$); and in the orientation of the magnetic field (aligned and tilted by 90° with respect to the orbital angular momentum), to determine their impact in the EM luminosity, ejecta, and other EM counterparts [7,8].

METHODS & CODES

Magnetohydrodynamic (MHD) numerical simulations in full general relativity require the solution of the Einstein field equations to determine the gravitational field as well as 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. The researchers solved the above equations through their 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 the team's own algorithms and coding [9]. 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–Nakamura formulation 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 magnetic fields on refinement level boundaries [9].

RESULTS & IMPACT

In agreement with the researchers' earlier calculations, where the star is seeded with a dipole magnetic field that extends from the interior to the stellar exterior [4,10], they found that the BHNS mergers listed above led to a disk + BH remnant with a rest-mass ranging from$\sim 10^{-6}$Msun to $\sim 10^{-3}$Msun, and dimensionless spin ranging from $a/M_{BH} \sim 0.33$ to ~ 0.85. The early evolution, tidal disruption, and the merger phases are unaltered by the dynamically weak initial magnetic field. In the postmerger phase, the research team found that by around $\Delta t \sim 3500M \approx 88(M_{NS}/1.4M_{sun})$ms after the GW peak emission a magnetically driven jet is launched in the case where the initial spin of the BH companion is equal or larger than $a/M_{BH}= 0.5$. The lifetimes of the jet [$\Delta t \sim 0.7(M_{NS}/1.4M)$ s] and outgoing Poynting luminosity [$L_{jet} \sim 10^{52}$ erg/s] are consistent with observations of typical sGRBs [11], as well as with the Blandford–Znajek [12] mechanism for launching jets and their associated Poynting luminosities. In contrast, by the time the team terminated its simulations, they did not find any indication of an outflow in the other cases; in the nonspinning case ($a/M_{BH}= 0$) and mass-ratio $q = 3:1$, a persistent fallback debris toward the BH was observed until the end of the simulation, the magnetic field above the BH poles was wound into a helical configuration, but the magnetic pressure gradients were still too weak to overcome the fallback ram pressure, and thus it is expected that a longer simulation will be required if a jet were to emerge. However, if the fallback debris timescale is longer than the disk accretion timescale [$\Delta t \sim 0.36(M_{NS}/1.4M)$s], the launching of a jet in this case may be suppressed. In the counter-rotating $q = 3:1$ BHNS configuration ($a/M_{BH} = -0.5$) the star plunges quickly into the BH, leaving an "orphan" BH with a negligibly small accretion disk containing less than 1% of the rest-mass of the NS. Similar behavior was observed in the BHNS configuration with mass ratio $q = 5:1$. Finally, in the tilted magnetic field case, the team did not find a coherent poloidal magnetic field component remaining after the BHNS merger; hence, the key ingredient for jet launching was absent. The dynamical ejecta produced in the nonspinning $q = 5:1$ and the counter-rotating BHNS configurations were too small to be resolved ($\sim 10^{-5}$Msun) and it may indicate that high mass-ratio BHNS or counter-rotating BHNS configurations may not be accompanied by either kilonovae or short gamma-ray bursts because they unbind a negligible amount of mass and form negligibly small accretion disks onto the remnant BH. The researchers have concluded that these two configurations may be the progenitors of the BHNS candidate S190426c.



Volume rendering of rest-mass density ρ_0 normalized to the initial NS maximum value (log scale) at selected times for a black hole (BH) with spin 0.5 and an irrotational neutron star. White lines denote the magnetic field while the arrows denote fluid velocities. The BH horizon is shown as a black sphere.

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 message-passing interface (MPI)-based code, scalability on multicore machines has improved greatly. With the Blue Waters high-performance interconnect and processors, the team's hybrid OpenMP/MPI code exhibits greater scalability and performance than on any other supercomputer they have used. Recently, the researchers were able to build their code with the Blue Waters Intel compilers. This resulted in a significant boost of the code's performance by about 30%, making Blue Waters unique for tackling the astrophysical problems the team wants to address.

PUBLICATIONS & DATA SETS

M. Ruiz, A. Tsokaros, V. Paschalidis, and S. L. Shapiro, "Effects of spin on magnetized binary neutron star mergers and jet launching," *Phys. Rev. D*, vol. 99, no. 8, p. 084032, Apr. 2019.

L. Sun, M. Ruiz, and S. L. Shapiro, "Magnetic braking and damping of differential rotation in massive stars," *Phys. Rev. D*, vol. 99, no. 6, p. 064057, Mar. 2019.

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L. Sun, M. Ruiz, and S. L. Shapiro, "Simulating the magnetorotational collapse of supermassive stars: Incorporating gas pressure perturbations and different rotation profiles," *Phys. Rev. D*, vol. 98, no. 10, p. 103008, Nov. 2018.