RELATIVISTIC JET FORMATION IN BLACK HOLE–NEUTRON STAR MERGERS

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EXECUTIVE SUMMARY:

Merging black hole–neutron star binaries will be prominent sources for advanced gravitational-wave detectors. They are also thought to produce relativistic jets and serve as engines that power short-hard gamma-ray bursts. Simultaneous observation of gravitational waves and gamma rays from these systems is the holy grail of "multi-messenger astronomy." Until now, no self-consistent calculation existed in full general relativity that starts from the compact binary inspiral and demonstrates that jets can be launched after the tidal disruption of the neutron star. We performed ideal magnetohydrodynamic simulations of black hole–neutron star systems in full general relativity and showed, for the first time, that they can indeed launch incipient jets if the neutron star is initially endowed with a dipolar magnetic field extending from its interior well into its exterior.

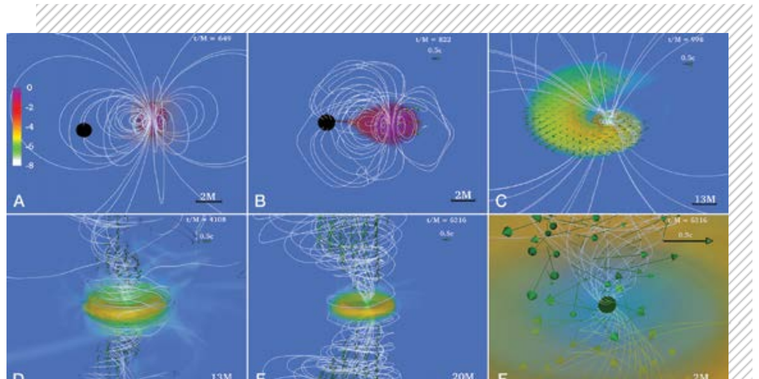

FIGURE 1 (LEFT): Snapshots of the rest-mass density, normalized to its initial maximum value (log scale), at selected times. Arrows indicate plasma velocities and white lines show the magnetic field lines. Panels d-f highlight the system after an incipient jet launched.

INTRODUCTION

On the centennial anniversary of Einstein's theory of general relativity, we are on the verge of directly detecting one of its most remarkable predictions: gravitational waves (GWs). The inspiral and merger of compact binaries—binaries with black hole (BH), neutron star (NS), or white dwarf companions—are among the most promising sources of GWs. Many of these sources likely also generate electromagnetic (EM) radiation counterparts to the GWs. Detecting both GW and EM radiation from the same cosmic source will be a major advance in "multi-messenger astronomy."

Gamma-ray bursts (GRBs) were first discovered in 1967, and theorists have been working to explain them since. The current best model for short bursts (sGRBs), those with duration less than two seconds, is the merger of a NS with a companion NS or BH. These systems are thus excellent candidates for multi-messenger detection. In order to verify the binary–sGRB association and properly interpret the GW and EM signals we will receive, we need to model these systems and simulate their evolution in full general relativity with magnetohydrodynamics (GRMHD). Our work to date has focused on studying the black hole–neutron star (BHNS) case.

METHODS & RESULTS

GRMHD numerical simulations require simultaneous solution of Einstein's equations to determine the gravitational field, the relativistic MHD equations to determine the flow of matter, and Maxwell's equations to determine the magnetic field. Together the equations constitute a large system of highly nonlinear, multidimensional, partial differential equations in space and time.

Using our latest adaptive-mesh refinement GRMHD code (see, e.g., [1]) we performed the first study of merging magnetized BHNS binaries [2,3]. In these simulations, the NS was seeded with strong magnetic fields confined to the NS interior. Many sGRB models require relativistic outflows and magnetic field collimation in the merger remnant, but these features were not observed in these initial simulations. Instead, they showed that interior-only initial magnetic field configurations inevitably led to a final magnetic field in the disk that was almost purely toroidal. Toroidal magnetic fields cannot launch a jet. Accretion of poloidal magnetic flux is necessary to launch and sustain jets from BH accretion disk systems [4].

Real neutron stars are expected to be endowed with dipole magnetic fields that extend from the interior well into the exterior, as required by current theories of pulsars. In addition to being more realistic, this initial magnetic field configuration is also more likely to provide the necessary conditions for launching a relativistic jet. When the magnetic field is allowed to extend into the NS exterior, poloidal magnetic field lines attached to fluid elements thread the BH prior to tidal disruption. Following disruption, while the magnetic field in the disk winds up in a predominantly toroidal pattern, a strong poloidal component is also amplified, threading the low-density debris.

To study this configuration, we performed simulations of a BHNS binary initially on a quasicircular orbit [5]. The binary mass ratio was 3 to 1, the BH had initial spin $a/M = 0.75$, and the NS was modeled as an irrotational, initially unmagnetized polytrope. We evolved the hydrodynamic and metric fields until two orbits formed prior to tidal disruption, at which point the NS was seeded with a dynamically weak dipole magnetic field that extended from the stellar interior well into the exterior (fig. 1, upper left). To ensure reliable evolution of the exterior field and to properly mimic the conditions that likely characterize the exterior magnetosphere, we also imposed a low-density atmosphere such that the NS exterior was described by a constant plasma parameter, defined as the ratio of the gas pressure to the magnetic pressure. We then continued the evolution through the tidal disruption of the NS and subsequent formation of a magnetized accretion disk (fig. 1, upper center and right).

We found that at ~100 ms following the onset of accretion, magnetic field winding above the remnant BH poles built up the magnetic field sufficiently to launch a mildly relativistic, collimated outflow—an incipient jet (fig. 1, bottom row). The duration of the accretion and the lifetime of the jet was ~0.5 seconds, which is consistent with the typical duration of sGRBs. The luminosity was 10^{51} erg/s, also consistent with observed sGRB values. Our simulations were the first self-consistent calculations in full general relativity that provided theoretical corroboration that mergers of BHNS systems can launch jets and be the central engines that power sGRBs.

WHY BLUE WATERS?

By adding OpenMP support to our MPI-based code, scalability on multi-core machines improved greatly. With the Blue Waters interconnect and processors, our hybrid OpenMP/MPI code exhibited 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 30% boost to our code's performance, making Blue Waters uniquely capable for tackling the astrophysical problems we want to address.

Our undergraduate research team also used Blue Waters to make visualizations (e.g., fig. 1) and movies of our simulations with the VisIT software. Recently, we created the first 3D movies using VisIT on Blue Waters, in collaboration with Professor Donna Cox and her group.

PUBLICATIONS

Paschalidis, V., M. Ruiz, and S. L. Shapiro, Relativistic simulations of black hole–neutron star coalescence: the jet emerges. *Astrophys. J.*, 806 (2015), L14, doi:10.1088/2041-8205/806/1/L14.

Etienne, Z. B., et al., Improved moving puncture gauge conditions for compact binary evolutions. *Phys. Rev. D*, 90 (2014), 064032, doi:10.1103/PhysRevD.90.064032.

Gold, R., et al., Accretion disks around binary black holes of unequal mass: GRMHD simulations of postdecoupling and merger. *Phys. Rev. D*, 90 (2014), 104030, doi:10.1103/PhysRevD.90.104030.

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Ruiz, M., V. Paschalidis, and S. L. Shapiro, Pulsar spin-down luminosity: Simulations in general relativity. *Phys. Rev. D*, 89 (2014), 084045, doi:10.1103/PhysRevD.89.084045.