Final Report for Spring 2015 Blue Waters Illinois Allocation

I. PROJECT INFORMATION

- Project title: Gravitational and Electromagnetic Signatures of Compact Binary Mergers: General Relativistic Simulations at the Petascale
- Principal investigator: Stuart Shapiro, University of Illinois at Urbana-Champaign
- Co-PIs and collaborators: Vasileios Paschalidis, Princeton University, Ryan Lang, Milton Ruiz, University of Illinois at Urbana-Champaign
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II. EXECUTIVE SUMMARY

It is an extremely exciting time for general relativity and numerical relativity. The LIGO-VIRGO Scientific Collaboration reported the *first* two direct detections of gravitational wave signals, which were produced by the inspiral and merger of binary black hole system. This breakthrough opens a new window to our Universe, as gravitational signals are expected to be generated not only by binary black hole systems, but also by other compact objects. Gravitational waves encode information about physical properties of the sources themselves that cannot be obtained otherwise.

Our research focuses on simulations of plausible relativistic astrophysical scenarios involving compact objects. They are promising sources of detectable gravitational waves and electromagnetic signals. These simulations also provide waveform templates needed for the detection of gravitational waves by the based ground detectors. Besides, other current X-ray space observatories provide additional opportunities for probing the physics of compact objects and advancing the era of "multimessenger" astronomy.

III. DESCRIPTION OF RESEARCH ACTIVITIES AND RESULTS

We have embarked on multi-year projects with the goal of exploring astrophysical scenarios that are particularly promising for the detection of gravitational waves (GWs) and their electromagnetic counterparts. The main thrust is to use our codes to study the inspiral and coalescence of binary black holes (BHBH), binary neutron stars (NSNS) and black hole-neutron star (BHNS) mergers, which are expected to be among the most promising sources of GWs.

In the last past year we have particularly focused in:

Merger of binary neutron stars: After the first two direct detections of GWs from the merger of BHBH systems, it seems to be just a matter of time before GWs from merging NSNS are detected as well, especially since their detection rates are likely to be similar to those of BHBH systems [1, 2]. These systems are also one of the most popular progenitors suggested for the formation of the BH-disk engine associated with sGRBs [3–10]. To demonstrate this possibility, our group has pursued the magnetohydrodynamic NSNS merger scenario in full GR for many years.

General relativistic megnetohydrodynamic (MHD) simulations require the 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 [11], we performed one of the first sets of magnetized NSNS merger simulations [12] and recently the first study to demonstrate explicitly that cooling can accelerate the "delayed" collapse of the transient hypermassive neutron star (HMNS) remnant formed following a NSNS merger [13].

Our recent discovery that BHNS mergers can launch jets if the NS is initially endowed with a dipole magnetic field that extends from the NS interior to its exterior, as is required by current theories of pulsars, [14] motivated the following question:

Can NSNS mergers produce jets in the same way as BHNS systems, or does this mechanism require an initial BH?

We performed preliminary simulations for magnetized NSNS systems with large, but dynamically weak, B-fields, and treated both interior plus exterior and interior-only field configurations. In contrast with the BHNS systems, we found that a jet could be launched in both cases. We found that at ~ 40 ms following the BH formation, magnetic field winding above the remnant BH poles builds up the magnetic field sufficiently to launch a mildly relativistic, collimated outflow—an incipient jet (see Fig. 1). The duration of the accretion and the lifetime of the jet is 0.1 seconds, which is consistent with very short-duration sGRBs. The luminosity was $\sim 10^{51}$ erg/s, also consistent with observed sGRB values. Our simulations are the first self-consistent calculations in full GR that provide theoretical corroboration that mergers of NSNS systems can launch jets and be the central engines that power sGRBs. These simulations are now being summarized in [15]

These results come with a caveat. Although the initial B-field is dynamically weak, it is astrophysically large at the surface. We need to verify the robustness of this out-

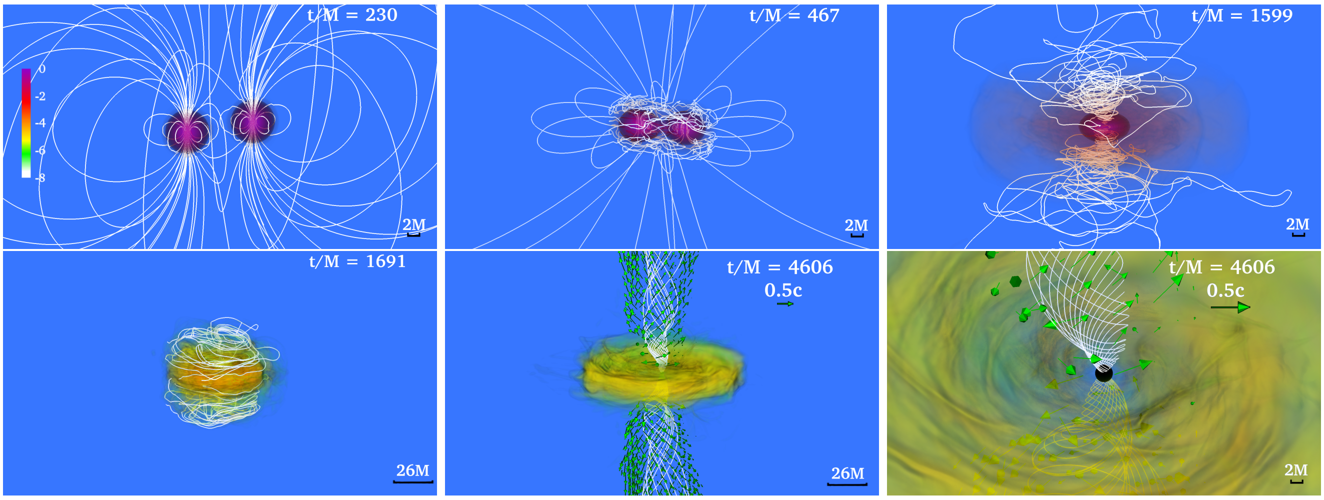

FIG. 1. Snapshots of the rest-mass density, normalized to its initial maximum value (log scale), at selected times before and after merger. Arrows indicate plasma velocities and white lines show the magnetic field lines. Bottom panels highlight the system after an incipient jet is launched. Here $M = 1.47 \times 10^{-2}(M_{\rm NS}/1.625M_{\odot})$ms $= 4.4288(M_{\rm NS}/1.625M_{\odot})$km.

come by using a weaker B-field. Kiuchi et al. [16] has shown that high resolution simulations ($\Delta x \lesssim 40$m) are required to properly capture the magnetic instabilities responsible to boost the initial rms B-field by several orders of magnitude. In the near future, we plan to do a three-stage simulation: At first, we will launch with a resolution of $\Delta x \lesssim 200$ m until merger, then regrid the simulation to $\Delta x \lesssim 40$ m so as to resolve the magnetic instabilities for $t \sim 5$ ms ($t \sim 350$ M), and finally regrid once again to the original resolution.

We will also perform a survey of NSNS systems with different mass-ratios and B-field configurations to study how sensitive jet launching is to system parameters.

Collapse of Supermassive Star: Supermasive BHs with masses between $10^6 M_\odot$ to $10^9 M_\odot$ reside at the center of the most galaxies [17, 18]. They may be the final fate of supermassive stars (SMSs) that undergo gravitational collapse once they evolve to the point of a relativistic radial stability. We started preliminary studies the evolution of radially unstable, uniformly rotating magnetized SMSs modeled as $n = 3$ polytropes (radiation-dominated stars) that undergo collapse to BHs with masses $\gtrsim 10^4 M_\odot$ [19, 20]. They model the formation of SMBHs at high cosmological redshifts, which may explain the appearance of SMBHs and quasars at redshifts of z $\sim$ 7. They also crudely model the collapse of massive Pop III stars to massive BHs, which could power some of the long gamma-ray bursts observed by the FERMI and the SWIFT satellites at redshift z$\sim 6-8$.

These simulations are now being summarized in a paper in preparation and show that SMSs indeed can be the progenitors of supermasive BH. We have also observed that these kind of stars launch jets (see Fig. 2).

Why Blue Waters: By adding OpenMP support to our MPI-based code, scalability on multi-core 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 codes 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 (see Figures 1-2) and movies of our simulations with the VisIT software. Recently, we recently created the first 3D movies using VisIT on BW, in collaboration with Professor Donna Cox and her group.

IV. LIST OF PUBLICATIONS, DATA SETS ASSOCIATED WITH THIS WORK

1. L. Sun, V. Paschalidis, M. Ruiz and S. Shapiro. Magnetorotatioal Collapse of Supermassive Stars: Black Hole Formation and Jets.
(in preparation).

2. M. Ruiz, V. Paschalidis, and S. Shapiro. Binary neutron star mergers as engines of short gamma-ray bursts: delayed vs. prompt collapse.
(in preparation)

3. M. Ruiz, R. N. Lang, V. Paschalidis and S. Shapiro..
Binary neutron star mergers: a jet engine for short gamma-ray bursts.
ApJ, 824, L6, 2016.

4. V. Paschalidis, M. Ruiz, and S. Shapiro. Relativistic simulations of black holeneutron star coalescence: the jet emerges.
ApJ, 806, L14, 2015.

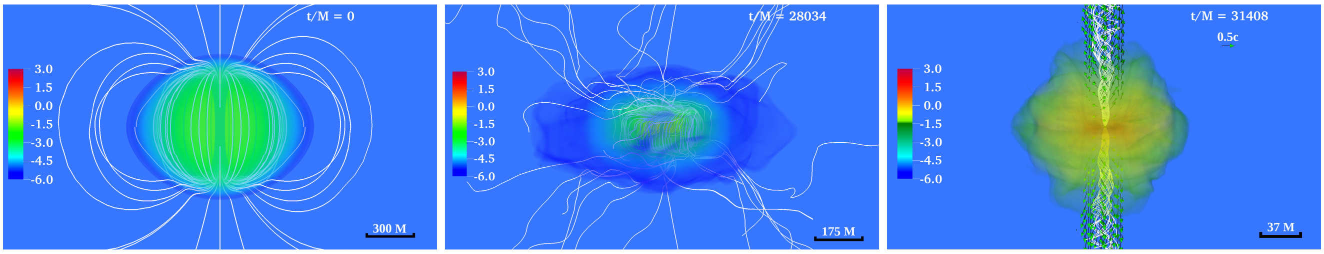

FIG. 2. Snapshots of the rest-mass density, normalized to its initial maximum value (log scale), at selected times before and after merger. Arrows indicate plasma velocities and white lines show the magnetic field lines. Right panel highlight the system after an incipient jet is launched. We found that a typical value of the rest-mass density in the disk at the end of the simulation is $\rho_0 \approx 6000(M/10^4 M_\odot)\,\mathrm{g\,cm}^{-1}$.

5. Etienne, Z. B., Y. T. Liu, and S. Shapiro. Relativistic magnetohydrodynamics in dynamical spacetimes: A new AMR implementation.
Phys. Rev. D, 82 (2010), 084031.

6. Etienne, Z. B., Y. T. Liu, V. Paschalidis, and S. Shapiro. General relativistic simulations of black holeneutron star mergers: Effects of magnetic fields.
Phys. Rev. D, 85 (2012), 064029.

7. Etienne, Z. B., V. Paschalidis, and S. Shapiro. General relativistic simulations of black holeneutron star mergers: Effects of tilted magnetic fields.
Phys. Rev. D, 86 (2012), 084026.

8. To view some of our visualizations visit: `http://tinyurl.com/shapiromovies`

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