Studies In Theoretical Astrophysics and General Relativity

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1 Executive summary

We have been using the petascale-level infrastructure of Blue Waters to continue our multi-year effort to tackle several large-scale, long-standing, unsolved problems in theoretical astrophysics and numerical relativity. We numerically solve Einstein's gravitational field equations coupled to the equations of relativistic hydrodynamics, magnetohydrodynamics and Maxwell's equations to model compact binaries (e.g. neutron star, black hole and black hole-neutron star binaries), as well as accretion disks, supermassive stars, and other relativistic astrophysical objects. These simulations address fundamental questions dealing with strong-field gravitation, gravitational waves and electromagnetic signatures. We focus on problems that are motivated by current and future observations of gravitational waves by e.g. Advanced LIGO/VIRGO and LISA, and by gamma-ray bursts observed by NASA satellites, such as SWIFT and FERMI. This research is supported by grants from the National Science Foundation (NSF) and the National Aeronautics and Space Agency (NASA).

2 Description of research activities and results

The LIGO-VIRGO Scientific Collaboration has already reported three direct detections of gravitational wave (GW) signals (events GW150914, GW151226 and GW170104), which were produced by the inspiral and merger of binary black hole (BHBH) systems [1–3]. These detections provided spectacular confirmation of general relativity (GR) theory as the fundamental theory of gravitation. This breakthrough opens a new window to our Universe, as GW signals are expected to be generated not only by BHBH systems, but also by binary neutron stars (NSNSs), and binary black hole–neutron stars (BHNSs), among other compact objects (COs). These GWs encode information about physical properties of the sources themselves that cannot be obtained otherwise.

Numerical simulations in full GR are extremely important to understanding the physics of COs and, more generally, the physics of matter under extreme conditions. These simulations also provide waveform templates needed for the detection of GWs by the observatories of GWs such as aLIGO/VIRGO. Several other current space observatories of X-rays and γ-rays, such as CHANDRA, FERMI, NuSTAR, NICER and SWIFT (see eg. [4–7]) provide additional opportunities for probing the physics of COs and advancing the era of "multimessenger" astronomy (MA). To learn from these observations, it is crucial to compare them with predictions from theoretical modeling.

Our research focuses on simulations of plausible relativistic astrophysical scenarios involving COs (see eg. [8–12]). These systems are unique MA systems, as they are promising sources of detectable GWs and electromagnetic (EM) signals, and also, possibly, of neutrinos. Detecting EM signals from promising GW sources will help localize the sources on the sky, resulting in improved parameter estimation via GWs by eliminating degeneracies resulting in imprecise localization [13]. Combining GW and EM observations (the MA approach) offers a unique probe to understanding strong-field gravitation, the physics of COs and cosmology as a whole. However, the identification, detection, and interpretation of such multimessenger signals will crucially depend on theoretical modelling of COs. Our research is therefore extremely timely in light of current and future observational probes.

To study the evolution of COs we use 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. We have used it successfully to tackle a plethora of astrophysical scenarios such as e.g. merger of magnetized NSNSs, the merger of BHNSs and the merger of BHBHs in circumbinary, magnetized disks. This code utilizes state-of-the-art high resolution shock capturing methods to evolve scenarios involving either vacuum or matter spacetimes, with or without B-fields. It utilizes the BSSN formulation of the Einstein field equations [14] with puncture gauge conditions [15]. 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 [16]. In the following section, we outline our recent progress to date.

2.1 Binary Black Holes in Circumbinary Disks

We have made significant progress on this problem with our simulations of equal-mass BHBH mergers in the presence of unmagnetized or magnetized gas. We simulated binaries immersed both in a homogeneous gas cloud (the "binary Bondi problem") [17], as well as in a gaseous disk [18]. We have calculated the mass accretion rate and EM luminosity due to thermal bremsstrahlung and synchrotron emission, and studied their dependence on the binary separation and the equation of state (EOS). We showed that shock heating plays a major role in determining the amount of EM energy radiated, especially at merger. In the disk accretion case, there is a decline in the accretion rate and luminosity throughout the merger once the disk and binary "decouple", as the binary torques responsible for stripping gas from the inner disk are reduced. In our preliminary GRMHD studies of magnetized accretion disks around equal-mass and unequal-mass BHBHs [9, 19, 20] we find that MRI induces MHD turbulence. The effective viscosity associated with MHD turbulence leads to accretions streams onto the two BHs, even when a partial hollow in the disk is present. We find that the binary torques balance viscous torques prior to the final inspiral, leading to a quasi-equilibrium state. We find relativistic outflows (jets) and an outward Poynting flux, both prior and following binary merger, indicating that these systems are promising sources of EM signals. The accretion rate and Poynting flux have characteristic time evolutions during the inspiral and merger of the BHs, while there is a prompt EM luminosity enhancement following merger ("aftermath" EM radiation) due to shock heating and increased accretion onto the spinning BH remnant.

During the last few years we advanced our studies of magnetized accretion onto binary BHBHs in several aspects:

1. We studied the influence of the binary mass ratio [19] on the quasistationary state that the disk achieves during the predecoupling epoch, finding that the accretion rate, and hence the expected emergent radiation depends on the mass ratio, although it still remains comparable to the accretion rate onto a single BH with the same total mass as the binary.

2. We studied the effects of the mass ratio during the post-decoupling and merger phases [20]. These simulations showed that the density lump at the disk inner edge diminishes as the mass ratio decrease. They also made the important prediction that even a past merger event could be identified based on studies of jet morphology.

3. We constructed a simple (orbit-average) 1+1-dimensional GR-hybrid model for geometrically thin disks around binary black holes [21] and a similar simple Newtonian model for the "afterglow" radiation [22].

4. We studied the evolution of stellar mass *non-spinning* BHs consistent with those detected by GW150914, in a magnetized accretion disk. We compared the EM signature with the sGRB detection by the FERMI satellite. We considered two cases by varying the disk scale-height. Our simulations suggest that if the association of the sGRB and the GW150914 event is real then the disk lifetime must be at least a factor ~ 100 longer than the observed sGRB lifetime, which is puzzling. These last results (see Fig. 1) are now being summarized in a paper in preparation [23].

2.2 Neutron Stars Binaries

We performed our first set of magnetized NSNS merger calculations in [24]. We find that NSNS mergers with interior B-fields can lead either to the formation of hypermassive neutron stars (HMNSs) and delayed collapse to BH, or promptly to a BH, depending on the masses of the stars. Our results are consistent with those reported in [25]. We also find that B-fields can have a substantial influence on the dynamics of the remnants and the gravitational waveforms after merger. In addition, we investigated the importance of cooling in triggering the collapse of an HMNS formed following the merger of a NSNS [11]. We showed that thermal

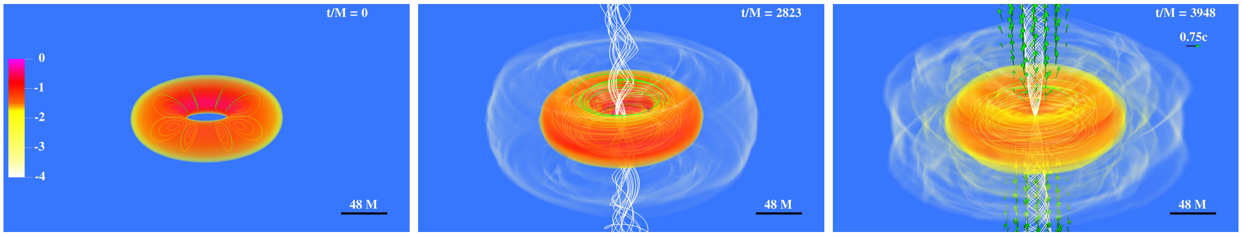

Figure 1: Snapshots of the rest-mass density, normalized to its initial maximum value (log scale), at selected times for the thick disk case. Arrows indicate plasma velocities and lines show the B-field structure. White field lines emanate from the BH horizon.

pressure contributes significantly to the support of the HMNS against collapse and, for the first time, that thermal cooling accelerates its "delayed" collapse.

During the last few years we advanced our study of binary neutron stars in the three scenarios:

1. We studied the development and saturation of the $m = 1$ one-armed spiral instability in an unmagnetized simulation of merging binary neutron stars [26–28]. We focused on the case of a dynamical capture merger where the stars have a small spin, as may arise in globular clusters. We found that this instability develops when post-merger fluid vortices lead to the generation of a toroidal remnant. The instability quickly saturates on a timescale of $\sim$ 10ms. Gravitational waves emitted by the $m = 1$ instability have a peak frequency around $1 - 2$ kHz and, if detected, could be used to constrain the equation of state of neutron stars. In a recent paper [28], we provide estimates of the properties of dynamical ejecta, as well as the accompanying kilonovae signatures.

2. Motivated by our recent discovery that BHNSs can launch jets if the neutron star is initially endowed with a dipole B-field that extends from the NS interior to its exterior, we simulated magnetized NSNS systems with a dynamically weak initial B-field [29]. We found that, in contrast with the BHNS systems, the NSNS systems launch jets both for interior-only and for interior plus exterior dipole magnetic field configurations. These binaries thus could also be the central engines that power sGRBs. The key ingredient for generating a jet was found to be the ability of the transient remnant HMNS to amplify the magnetic field prior to its delayed collapse to a BH. These results spark our urgent need to probe new configurations to corroborate the robustness of this outcome and to establish more firmly NSNSs as candidates for sGRB engines.

3. We studied magnetized NSNS mergers that undergo prompt collapse. We found that the absence of a hypermassive NS epoch does not allow the magnetic energy to reach equipartition and force-free levels, preventing the formation of either a B-field collimation or a jet. Our simulations suggest that GWs from merging NSNSs may be accompanied by sGRBs in the case of delayed collapse but not in the case of prompt collapse. The absence or presence of a counterpart sGRB following merger will shed light on the EOS and potentially on the compaction of the stars. These results are now being summarized in a paper in preparation [30].

2.3 Secular evolution and Collapse of Rotating Stars

2.3.1 Collapse of Supermassive Stars: Black Hole Formation and Jets

We have recently performed GRMHD simultions on SMSs collapse by evolving uniformly rotating $\Gamma = 4/3$ polytropes that are marginally unstable (see Fig. 2). They model the direct collapse of supermassive stars (SMSs) to seed BHs that can become supermassive BHs, as well as the collapse of massive Pop III stars, which could power long gamma-ray bursts (GRBs). Our preliminary results show that the stars collapse to a massive and highly spinning BH remnant surrounded by a hot, magnetized torus. By $t \approx 2000(M/10^6 M_\odot)$s following the GW peak amplitude, an incipient jet is launched. The disk lifetime and the outgoing Poynting luminosity are consistent with those expected from the Blandford–Znajek process. If $\sim 1\%$ of the luminosity is converted into gamma-rays, then *Swift* could potentially detect these events at large redshifts [31].

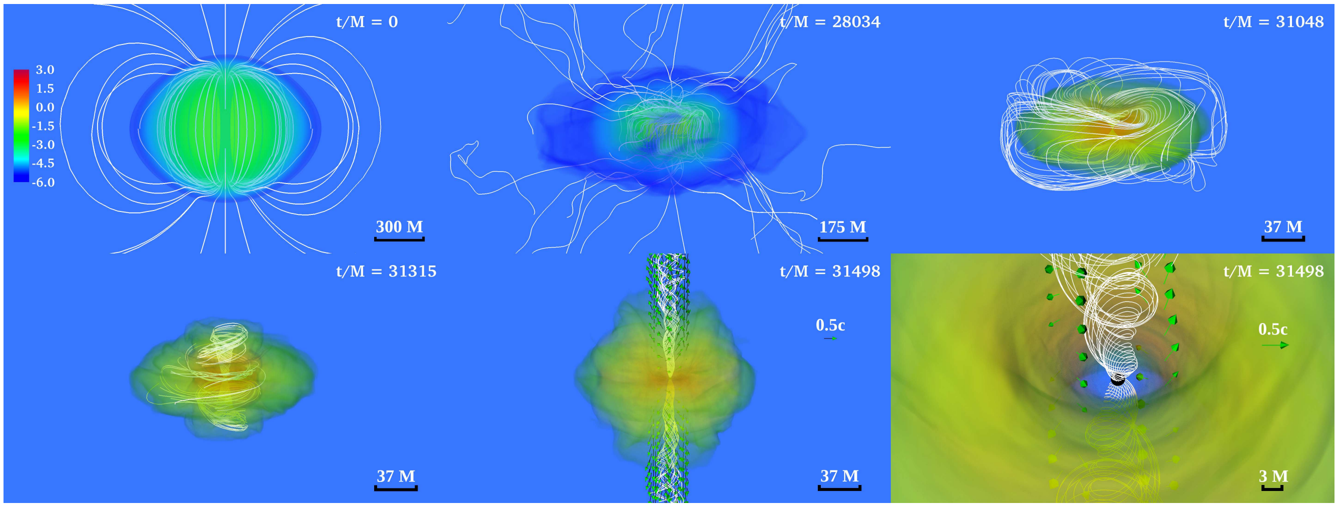

Figure 2: Volume rendering of the rest-mass density normalized to its initial maximum value (log scale) at selected times. Arrows show plasma velocities and white lines show the magnetic field lines. Bottom panels highlight the system during and after an incipient jet is launched.

2.3.2 Secular Evolution of Newly Discovered Stable Triaxial NSs

A single NS can become an emitter of GWs as long as it has a non-spherical time changing quadrupole moment. The lack of symmetry can arise in various scenarios that include binary NS mergers, which are themselves prime candidates for the production of GWs, and in gravitational stellar collapse where the bouncing core can be rotating fast enough so that non-axisymmetric instabilities set in and deform the star into an ellipsoid.

The *ab initio* computation of such non-axisymmetric objects presents a number of challenges. First, these objects are not stationary equilibria, since they emit GWs, and therefore an approximate scheme has to be applied in order to find quasi-stationary solutions. Second, such models are known to exist only for stiff equations of state (EOS). If we assume a polytropic law, then the polytropic index Γ needs to be larger than 2.24 in the Newtonian limit. For softer EOS mass shedding appears at lower angular velocity than the one needed to reach the triaxial state. General relativity increases the critical value of the polytropic index by a small amount. Third, uniformly rotating, non-axisymmetric solutions exist only for high spin rates, i.e. when $T/|W|$ is larger than 0.14 in the Newtonian case.

In a previous work [32] we computed for the first time triaxial *supramassive* NSs (uniformly rotating models with rest-mass higher than the maximum rest-mass of a non-rotating star, but lower than the maximum rest-mass when allowing for maximal uniform rotation), by using a piecewise polytropic EOS. In the preliminary work [33] we performed the first evolutions of such stars and investigated their stability and GW content.

We were able to follow the evolution of these objects for more than twenty rotation periods, proving that they are *dynamically stable*. After an initial short period of time where junk radiation in the initial data propagates away, the NS evolves along quasi-equilibrium states that satisfy the first law, $dM = \Omega dJ$. Along this trajectory the orbital angular velocity remains constant inside the NS, whose triaxial shape evolves toward axisymmetry. During this period the GW amplitude decreases significantly, especially in the highly compact models. Also we showed that the peak GW amplitude is approximately one tenth of that of binary neutron stars.

3 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 30making 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 (e.g., Fig. 1 and Fig. 2) and movies of our simulations with the VisIT software.

4 List of publications, data sets associated with this work

- Sun, L et al. Magnetorotational Collapse of Supermassive Stars: Black Hole Formation, Gravitational Waves and Jets. ArXiv:1704.04502 (Accepted for publication in Phys. Rev. D).
- Shapiro S.L.. Black holes, disks and jets following binary mergers and stellar collapse: The narrow range of EM luminosities and accretion rates. Phys. Rev. D 95, (2017) 101303.
- Tsokaros, A. et al. Gravitational wave content and stability of uniformly, rotating, triaxial neutron stars in general relativity. Phys. Rev. D 95, (2017) 124057.
- Khan, A. et al. Black hole binaries in an accretion disk: LIGO-FERMI simulations. In preparation (2017).
- Ruiz, M. et al. GRMHD simulations of neutron star mergers resulting in prompt collapse: jets and fast radio bursts. In preparation (2017).

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