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Advancing Computational Methods to Understand the Dynamics of Ejection, Accretion, Winds, and Jets in Binary Neutron Star Mergers

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Abstract. We introduce the HandOff, a set of computational tools to transfer general relativistic magnetohydrodynamic and spacetime data from the numerical code IllinoisGRMHD to Harm3d. While the former simulates binary neutron star (BNS) mergers in full dynamical General Relativity, the latter specializes in modeling accretion disks around black holes (BH) over long timescales. The HandOff, then, enables us to transfer the outcome of BNS mergers after BH formation from IllinoisGRMHD to Harm3d and to evolve the post-merger system efficiently over long timescales. We show our latest results in this respect, for matter modeled as a magnetized ideal-fluid, and discuss our future plans which involve incorporating advanced equations of state and neutrino physics into BNS simulations using the HandOff approach.

Keywords. stars: neutron, (magnetohydrodynamics:) MHD, black hole physics, accretion, accretion disks

1. Introduction

Numerical simulations are key to understanding the dynamics of binary neutron star (BNS) mergers and to link astronomical observations to the physical properties of the system. However, these simulations are highly challenging, as they must include Numerical Relativity (NR) for the evolution of the spacetime metric, General-Relativistic Magnetohydrodynamics (GRMHD) for the evolution of matter fields, realistic equations of state (EoS) as tabulated from nuclear interactions, and consistent emission, absorption and transport of neutrinos. Furthermore, the heterogeneous geometry of the system and the different resolution requirements at each stage of the merger and post-merger prevent the performance of a self-consistent and long-term simulation within a single numerical code. In particular, numerical codes that take NR into account usually make use of Cartesian coordinates in a hierarchy of inset boxes with different resolutions (Adaptive Mesh Refinement, AMR) and adopt a finest resolution of ∼200m. This grid is suboptimal to evolve the post-merger accretion disk as the plasma flows obliquely across coordinate lines and numerical errors dissipate angular momentum from the disk. Also, the resolution of this grid is insufficient to resolve the length-scales of the relevant mechanisms in the post-merger, as the magneto-rotational instability (Kiuchi, et al. 2018).

In this context, we present the HandOff, a set of computational routines designed to translate the state of a BNS post-merger from the code IllinoisGRMHD (Etienne et al. 2015) that uses Cartesian coordinates with AMR to simulate the BNS merger, to Harm3d (Noble et al. 2009; Murguia-Berthier, et al. 2021) that adopts a grid adapted to the

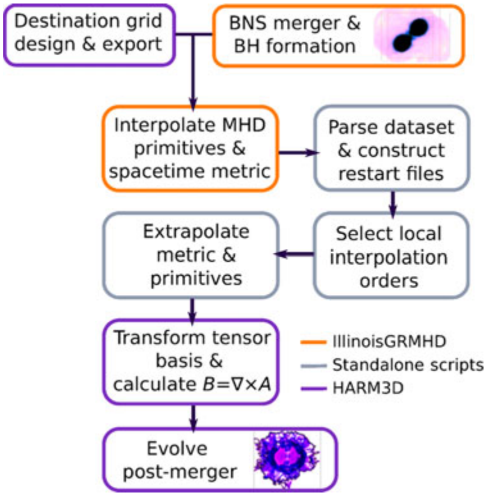

Figure 1. Steps in the HandOff process. The colors of the borders shows the code responsible for each step, with orange for IllinoisGRMHD, grey for standalone scripts, and purple for Harm3d.

requirements of the post-merger after BH formation. In particular, this grid is based on spherical-like coordinates for better conservation of angular momentum, it has higher resolution in the polar coordinate towards the equator if close to the BH, to resolve the disk, but higher resolution towards the polar axis if farther away, to resolve the jet-cocoon system (see Fig. 3, right). Also, its outer boundary is far enough ($\sim 10^5$km) to include the region of the jet breakout in the domain. The details of this numerical grid, along with a detailed description of the HandOff package, is presented in Lopez Armengol, et al. (2021).

Our manuscript is organized as follows. In Section 2 we briefly describe the methods of the HandOff package. Then, in Section 3, we present our latest results on transitioning a BNS post-merger from IllinoisGRMHD to Harm3d. Finally, in Section 4 we discuss our main conclusions and future work.

2. The HandOff Package

Both codes IllinoisGRMHD (Etienne et al. 2015) and Harm3d (Noble et al. 2009; Murguia-Berthier, et al. 2021) evolve the equations of motion of GRMHD in the limit of infinite conductivity. IllinoisGRMHD also can evolve the spacetime metric as it couples to such GRMHD fields. The main objective of the HandOff package is to transition a simulation between these two codes for the case of a static spacetime. Below we describe briefly the steps required for this process. For a detailed description of the codes involved, see Lopez Armengol, et al. (2021).

In Fig. 1 we show a scheme of the workflow around the HandOff. First, by making use of Cartesian coordinates with AMR, we perform a BNS merger simulation until BH formation with IllinoisGRMHD. At the same time, we design the destination grid that we will use to continue the post-merger evolution in Harm3d and we export the coordinates of the centers, lower faces, and lower corners of each numerical cell. Once the spacetime geometry has stabilized to that of a rotating BH, we proceed to interpolate the GRMHD primitives and spacetime metric of the post-merger onto the destination grid. We select results from lower or higher orders of interpolation, depending on the local smoothness of each grid function. Usually, the destination domain will be larger than the domain utilized for the merger so we extrapolate the primitives and spacetime metric to populate the

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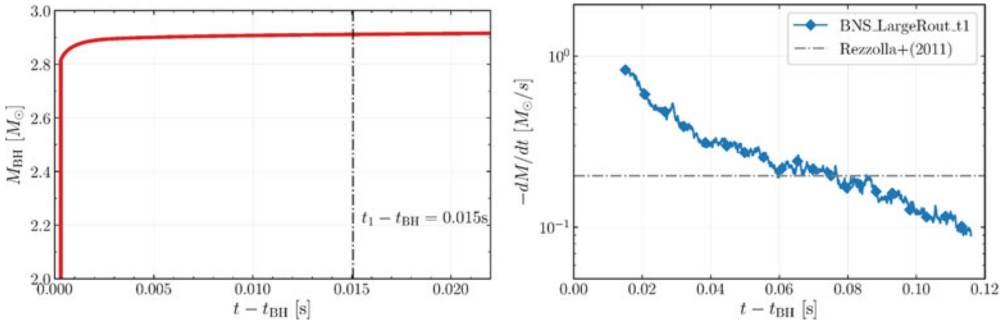

Figure 2. *Left:* Mass of the BH remnant as a function of time. At time $t = t_1$, when the mass of the BH has equilibrated, we apply the HandOff and transition the post-merger to Harm3d. *Right:* Accretion rate at the BH horizon as a function of time for the simulation BNS_LargeRout_t1, after the HandOff transition. The *grey, dashed-dotted* line represent the reference value from the literature.

complementary cells. We transform the tensor basis from Cartesian coordinates to the coordinate system of the destination grid, calculate the magnetic field from the curl of the magnetic vector potential, and continue the postmerger evolution with the usual methods of Harm3d.

3. Results

We evolve a BNS merger with IllinoisGRMHD and apply the HandOff to continue the postmerger evolution in Harm3d. The ID for the BNS is similar to that of Rezzolla et al. (2011): Two NSs in a circular orbit, separated by ~45km, each with a gravitational mass of $1.5M_\odot$ and an equatorial radius of 13.6km. We initialize two poloidal magnetic fields, confined in each star, with a maximum strength of $\sim 10^{15}$G. We use a Cartesian-AMR grid centered in the center of mass of the system, with outer boundaries at ~5700km, and 7 refinement boundaries with a finest resolution of ~180m. We model the fluid as an ideal gas, with adiabatic index $\Gamma = 2$. The NSs merge after ~8ms (~3 orbits) and a HMNS forms but, at $t = t_{\rm BH} = 0.017$ms, it collapses to a BH with mass $2.911M_\odot$ and specific angular momentum 0.82. At $t = t_{\rm BH}$ we add two refinement levels centered at the BH, yielding a finest resolution after merger of ~50m.

In Fig. 2 (*left*) we plot the mass of the BH as a function of time, and notice that, at $t = t_1 = 0.032s$, it is already in a converging regime. We apply the HandOff at such time and proceed to continue the evolution in Harm3d by assuming the spacetime is static thereafter. In Fig. 3 we plot the rest mass density ρ of the post-merger in the $x - z$ plane at $t = t_1$ in IllinoisGRMHD (*left*) and in Harm3d after the HandOff procedure (*right*). We notice the plots of ρ are indistinguishable between the two codes, demonstrating the high fidelity of the HandOff. We evolve the post-merger for ~100ms in Harm3d and reproduce the expected results from the literature. For instance, in Fig. 2 (*right*) we plot the accretion rate at the event horizon to show it devoids unphysical transients and that it approximates the reference value from the literature. We denote this simulaton BNS_LargeRout_t1.

4. Concluding Remarks

We introduced the HandOff, a computational package to translate a GRMHD simulation between two numerical codes, IllinoisGRMHD and Harm3d. The HandOff is particularly interesting to transition the outcomes of BNS or BH-NS mergers and perform long-term, highly accurate and coordinate-optimized simulations of the post-merger.

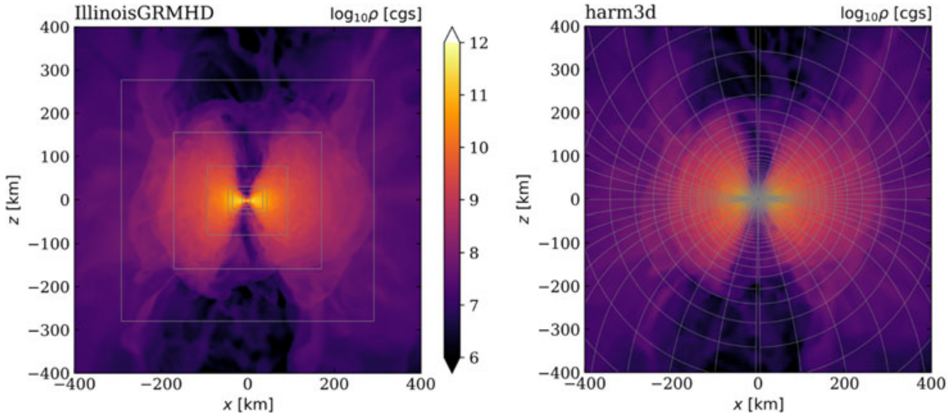

Figure 3. Baryonic density ρ in the $x - z$ plane of the BNS post-merger, before (*left*) and after (*right*) the HandOff procedure, in IllinoisGRMHD and Harm3d, respectively. The grey lines in the plot for IllinoisGRMHD represent the AMR boundaries and, in the plot for Harm3d, they represent 1 every 10 grid-lines of the destination grid.

We showed an application of the HandOff for a BNS post-merger where matter was modeled as an ideal fluid with adiabatic index $\Gamma = 2$. Future work will focus on improving our models for the matter fields, adopting finite-temperature and tabulated EoS, taking neutrino effects into account, and extending the HandOff to transition these realistic simulations to the modern code Harm3d+NUC (Murguia-Berthier, et al. 2021).

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