Neutron Star Astrophysics at the Crossroads: Magnetars and the Multimessenger Revolution
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HARM3D+NUC: GRMHD, nuclear tables and neutrino leakage

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Abstract. On August 17, 2017, the LIGO/VIRGO collaboration detected the first gravitational wave signal coming from the merger of two neutron stars. This groundbreaking discovery, referred to as GW170817, revealed to us how heavy elements, such as gold and platinum, are synthesized through a mechanism known as rapid neutron capture (r-process). In order to fully understand these signals, we need to simulate the resulting accretion disk around a black hole, and its outflows. This task requires efficient computing codes that include general relativity magnetohydrodynamics (GRMHD), neutrino physics, and a model for matter at high densities. We present the implementation of a tabulated equation of state that takes care of matter at high densities and a neutrino leakage scheme that considers the impact of neutrinos into HARM3D, a GRMHD parallelized code. We also apply the tools to a magnetized torus.

Keywords. stars: neutron, black hole physics, equation of state, nuclear reactions, nucleosynthesis, abundances, neutrinos

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1. Introduction

On August 17, 2017, the LIGO/VIRGO collaboration detected the first gravitational wave signal arising from the merger of two neutron stars (Abbot et al. 2017a), named GW170817. The event was also observed in the electromagnetic spectrum (Abbot et al. 2017b; Murguia-Berthier et al. 2017; Coulter, D. A. *et al.* 2017). This discovery allowed us to understand more about how heavy elements such as platinum and gold are formed through what is known as the rapid neutron capture, or $r-$process (Lippuner, & Roberts 2015).

It is widely believed that in the case of GW170817, the two neutron stars merged and created a hyper-massive, rapidly rotating neutron star surrounded by an accretion disk. After a certain delay time, the hyper-massive neutron star collapsed into a black hole (Nakar 2019; Murguia-Berthier et al. 2021a). The end result is a black hole surrounded by an accretion disk of neutron-rich material (Baiotti et al. 2008).

Magnetic torques arising from the magneto-rotational instability (Balbus & Hawley 1998) transfer angular momentum of the gas in the disk outward and gas falls into the black hole. Because of the loss of potential energy, a powerful wind, known as the MHD-driven wind is launched. This disk has enough temperature and density in order to synthesize $r-$process elements (Siegel & Metzger 2018). In the inner regions of the disk, neutrinos and antineutrinos will be created via the charged $\beta-$process (Narayan et al. 2001). Neutrinos will act as cooling agents which makes the disk more geometrically thin. In the outer regions of the disk, $\alpha-$particles are formed from the free nucleons in the inner regions. This extra energy will heat up material and drive an outflow (Lee et al. 2009).

The problem is that there is a debate on the final abundance of elements and on the final mass of the MHD-driven wind (Siegel & Metzger 2018; Miller et al. 2019), as different simulations give different results. The main challenge is that different physics included in the simulations will severely alter the composition and properties of the wind. In order to simulate the accretion disk that surrounds the black hole, we need general relativity (GR), magnetohydrodynamics (MHD), a realistic treatment of the equation of state that considers the energy released through the $\alpha-$recombination, and a treatment of the neutrino physics. Here we present the addition of a tabulated equation of state and a neutrino leakage scheme in the code HARM3D (Gammie et al. 2003; Noble et al. 2006). We use this code to perform simulations of neutrino cooled accretion disks that simulate the post-merger conditions.

2. Simulations of neutrino cooled accretion disks

HARM3D is a parallelized code that solves the equations of GRMHD (Gammie et al. 2003; Noble et al. 2006). It has been widely used and tested. It has copious analysis tools. It also has the capabilities of having arbitrary grids, reducing numerical dissipation.

We added a way in which to consider a tabulated equation of state and an approximate neutrino transport (leakage scheme) into HARM3D. This new version, called HARM3D+NUC uses equation of state tables that naturally consider the recombination of free nucleons into $\alpha-$particles (Murguia-Berthier et al. 2021b). The new version offers several new routines for converting conserved variables to primitive variables (e.g., Siegel et al. 2018). The primary routine, called the 3d routine, is the fastest, and most accurate but least robust. If it fails, the code uses several backup routines that are more robust, but slower and less accurate. In Murguia-Berthier et al. 2021b, we present different routines as well as tests for the new tabulated equation of state implementation. Additionally, we included a grey neutrino leakage scheme, where we add the cooling and emission terms due to neutrinos as source terms in the energy and number density equations, respectively (Ruffert et al. 1996; Siegel & Metzger 2018). The implementation and tests can be found at Murguia-Berthier et al. 2021b.

We performed simulations using HARM3D+NUC of accretion disks surrounding black holes. We simulate an isentropic torus (Fishbone & Moncrief 1976), emulating the post-merger phase of a binary neutron star merger. We added a poloidal field in the accretion disk that seeds the magneto-rotational instability, which will eventually launch a wind where $r-$process elements are created. The initial parameters used are shown in Table 1.

Figure 1 shows the evolution of the disk after 114ms. As can be seen from the figure, the initial disk remains very neutron rich. This is due to a self-regulating mechanism described in Siegel & Metzger 2018. In this region, the heating due to magnetic torques and the neutrino cooling are balanced, allowing for a neutron rich environment.

The effect of neutrinos can be seen in the disk thickness in Figure 2. In the inner regions of the disk (less than 100km), neutrinos are formed and act as the main cooling agent. The main effect is a geometrically thinning of the disk. Not surprisingly, as more material enters the black hole, and is heated up, more neutrinos are formed. This is clear when

Table 1. Parameters used in the simulation.

Parameter	**Value**
Disk radius of maximum pressure	$9r_{\rm g}$
Disk inner radius	$4r_{\rm g}$
Mass of disk	$0.03M_\odot$
Y_e in the disk	0.1
Specific entropy in the disk	7 $k_{\rm b}$/baryon
$(P_{\rm gas}/P_{\rm mag})$	100
BH spin	0.9375
BH mass	$3M_\odot$
Specific enthalpy at boundary	0.9977 [code units]
Temperature at radius of maximum pressure	4.4 MeV

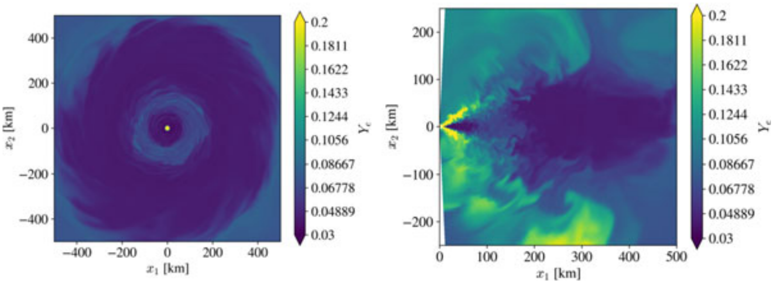

Figure 1. Electron fraction of a magnetized torus including the impact of neutrinos at 114ms. Shown is an equatorial cut (*left* panel) and a meridional cut (*right* panel).

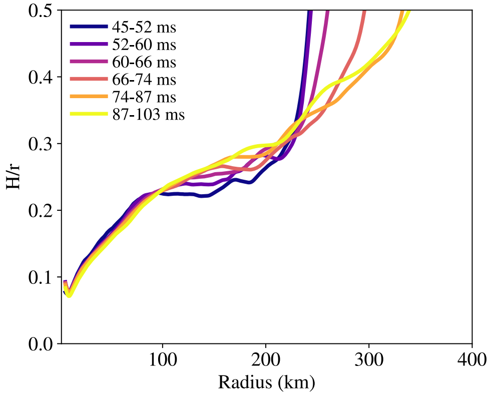

Figure 2. Geometrical thickness (H/r) of the disk, as a function of radius. We show the averaged thickness between the times indicated in the legend.

comparing the *left* panel of Figure 3 and Figure 4, as the neutrino luminosity follows the mass accretion rate.

At larger radius (larger than 100km), there are no neutrinos, but the free nucleons recombine into $\alpha-$particles. The release in binding energy effectively increases the enthalpy, unbinds material and drives a wind. This can clearly be seen in the *right* panel of figure 3, where we show the mass accretion rate at different times as a function of radius. At larger radius, the mass accretion becomes negative, which symbolizes an outflow.

For the future, we will use the new code HARM3D+NUC to perform several long-term evolution simulations of binary neutron star mergers. We will start as the neutron stars merge and evolve the subsequent outflow, where we expect heavy elements to be created.

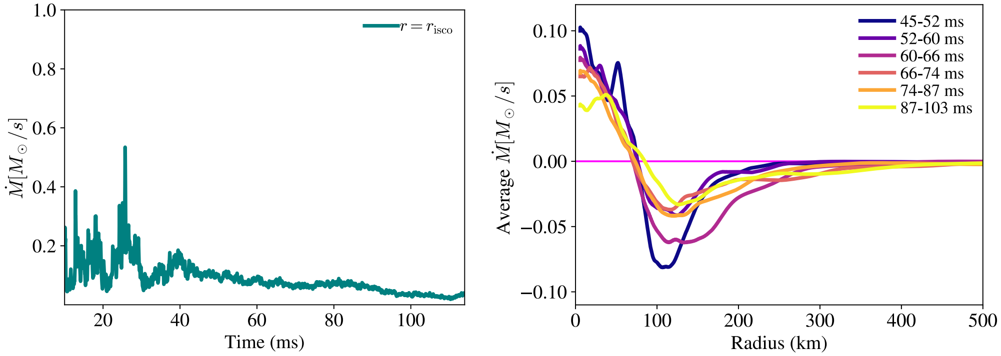

Figure 3. *Left* panel: Mass accretion rate onto the innermost stable circular orbit (ISCO) of the black hole as a function of time. *Right* panel: Average mass accretion rate as a function of radius. We indicate the average mass accretion rate between different times in the legend.

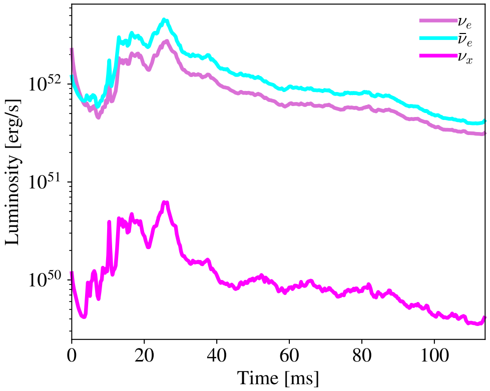

Figure 4. Luminosity due to the different neutrino species as a function of time.

The plan is to use different codes and methods for the different phases of the merger. We will construct the initial data with a modified version of LORENE (Gourgoulhon et al. 2016). After, we will evolve the binaries until they eventually merge and form a black hole with an accretion disk. This will be done with two GRMHD codes with dynamical metrics: IllinoisGRMHD and Spritz (Etienne et al. 2015; Cipolletta et al. 2020). Then we will interpolate the primitives and numerical grid into HARM3D using the methods developed in Lopez Armengol et al. (2021), where we will evolve the post-merger evolution. Finally, we will use Skynet (Lippuner & Roberts 2017) to evaluate the final abundances of heavy elements created, and study the outflow.

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