PROPAGATION OF A REALISTIC MAGNETAR JET THROUGH BINARY NEUTRON STAR MERGER ENVIRONMENT AND IMPLICATIONS FOR SHORT GAMMA-RAY BURSTS

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ABSTRACT

The origin of short gamma-ray bursts (sGRBs) is associated with outflows powered by the remnant of a binary neutron star merger. This remnant can be either a black hole or a highly magnetized, fastly spinning neutron star, also known as a magnetar. Here, we present the results of two relativistic magnetohydrodynamical (RMHD) simulations aimed at investigating the large-scale dynamics and propagation of magnetar collimated outflows through the environment surrounding the remnant. The first simulation evolves a realistic jet by injecting external simulation data, while the second evolves an analytical model jet with similar properties for comparison. We find that both outflows remain collimated and successfully emerge through the environment. However, they fail to attain relativistic velocities and only reach a mean maximum speed of $\sim 0.7c$ for the realistic jet, and $\sim 0.6c$ for the analytical jet. We also find that the realistic jet has a much more complex structure. The lack of highly relativistic speeds, that makes these jets unsuitable as short GRB sources, appears to be due to the specific injected properties and not general to all possible magnetar outflows.

1. INTRODUCTION

The merger of binary neutron stars (BNS) leads to the formation of another compact object. Its final nature will depend on factors such as the remnant’s mass and its ability – or lack thereof – to support itself against its own gravity as it spins down and cools off (see Radice et al. 2020 for a recent review of BNS mergers). The most massive remnants will immediately collapse into a black hole, while the less massive ones will be neutron stars. This latter case may be further subdivided into unstable hypermassive (HMNS) or supramassive neutron stars (Baumgarte et al. 2000; Cook et al. 1992, 1994) – both of which will invariably undergo gravitational collapse into a black hole – and a stable neutron star.

These events are also among the most luminous in the universe (Abbott et al. 2017a). They have been long hypothesized to be the origin of short gamma-ray bursts (sGRBs; Eichler et al. 1989; Narayan et al. 1992), and play a fundamental role in the origin of kilonovae (KN) and the formation of heavy elements – see e.g. Metzger (2019) for a review.

The prompt gamma-ray emission of GRBs is primarily attributed to two mechanisms. The first of these is internal shocks between shells within relativistic jets powered by the central engine (Narayan et al. 1992; Paczynski & Xu 1994; Rees & Meszaros 1994), while the second is external shocks between the leading shells and the surrounding interstellar medium (Meszaros & Rees 1992; Rees & Meszaros 1992; Katz 1994). Additionally, both mechanisms might be necessary to explain some observations (Piran & Sari 1998). Nevertheless, in order to power such jets, a compact object such as a black hole or a neutron star is required, along with strong magnetic fields.

The multimessenger observation of GW170817 and its electromagnetic counterparts (Abbott et al. 2017a,b) confirmed many of the predictions highlighted above, and placed significant constraints on other hypotheses. Yet, there still remain a few unanswered questions, in particular regarding the origin and engine powering the associated gamma-ray burst GRB 170817A, which was first detected 1.7 seconds after the initial gravitational wave detection (Abbott et al. 2017a).

Follow-up observations of the KN associated to GW170817 highlighted tensions with simulation results with respect to the amount of KN ejecta and its velocity. Moreover, in order to explain the observations, existing models often require additional constraints related to the NS remnant’s lifetime, radius, and accretion disk mass (e.g. Bauswein et al. 2013; Hotokezaka et al. 2013; Fahlman & Fernández 2018). Based on this, Metzger et al. (2018) proposed that this tension can be alleviated if the engine powering GRB 170817A is a rapidly spinning, strongly magnetized HMNS remnant with a lifetime of $t \sim 0.1 – 1s$. 

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Multiple groups have explored the feasibility of a magnetar engine for sGRBs, but again a successful case is highly dependent on factors such as the remnant’s lifetime, and neutrino effects. For instance, Ruiz et al. (2016) found that a jet was produced only after the HMNS had further collapsed into a black hole, while stable magnetars were hampered by baryon pollution at polar regions (Ciolfi et al. 2017, 2019; Ciolfi 2020), which in turn prevented the formation of jets and could not be taken care of in the absence of neutrino effects in those simulations.

Mösta et al. (2020), hereafter M20, performed a series of high-resolution simulations of NS merger remnants with a nuclear equation of state, neutrino cooling and heating, while adding strong magnetic fields similar to those in magnetars. Due to the high-resolution being able to resolve MRI, M20 found that the strong magnetic fields in the HMNS were capable of launching jets when neutrino effects were included, in particular neutrino cooling which reduced baryon pollution around the poles and allowed the jets to reach Lorentz factors of 2–5, depending on the simulation.

Here, we evolve the outflowing material from M20 for another order of magnitude in distance, and compare those features to those of an analytical jet simulation with similar initial conditions. We find that the outflowing material reaches mean velocities of $\lesssim 0.7c$ in the realistic jet, and about $0.6c$ in the analytical jet. Within the cocoon, we found velocities of $\lesssim 0.5c$ in both simulations. Overall, although both jets remained collimated and achieved moderate to high velocities, we found that they are most likely unable to power sGRBs. However, this does not necessarily imply that magnetars are, as a whole, unsuitable sources of sGRBs, because full neutrino transport has not been included and the ejected material may be less baryon-rich if neutrino pair-annihilation is taken into consideration (Fujibayashi et al. 2017).

In this paper, we describe our simulations in Section 2. The main results are presented in Section 3, and they are further discussed in Section 4. We present our conclusions in Section 5.

2. SIMULATIONS: SETUP AND OVERVIEW

We ran two 3D RMHD simulations with PLUTO 4.4 (Mignone et al. 2007). Our integration setup consists of a second order Runge-Kutta time-stepping, an HLLC Riemann solver, and piecewise parabolic reconstruction. We assumed an ideal gas equation of state for the background gas and enforced $\nabla \cdot \mathbf{B} = 0$ through divergence cleaning.

The first of our simulations, which we will constantly refer as having a “realistic jet”, is evolved with periodic injections of outflowing material from a general relativistic MHD simulation of a newly formed magnetar (M20, see Section 2.1 for more details) mapped into our grid, as explained in Section 2.2. The second simulation is described in Section 2.3 and consists of an analytical jet injected at and around the grid origin.

In both cases, we adopt a set of background initial conditions consisting of background gas with ambient density $\rho_0 = 10^{-4} \text{ g/cm}^3$ and ambient pressure $p_0 = 6 \times 10^{-7}$ in units of $c^2$. We also added a semi-spherical material at rest with radially decreasing density and pressure according to a Gaussian profile,

$$\rho(r) = \rho_i \exp(-r^2/r_s^2),$$

where $r_s = 3.8 \times 10^8$ cm, $\rho_i$ is the density of a mass of $2 \times 10^{30}$ g within a sphere of radius $r_s$, and $p(r) = 10^3 \rho(r)$.

For both our simulations, we adopted a Cartesian grid extending for $8 \times 10^8$ cm in the $x$– and $y$–, and $1.4 \times 10^9$ cm in the $z$-direction.

2.1. Input data

The data mapped into our realistic jet simulation is described in detail in M20. It originated from an ideal GRMHD simulation with an adaptive mesh with the open-source Einstein Toolkit (Babiuc-Hamilton et al. 2019; Löffler et al. 2012; Schnetter et al. 2004) module GRHydro (Mösta et al. 2013). Initial data in that simulation was mapped from a GRHD binary neutron star (BNS) merger simulation with WhiskyTHC (Radice & Rezzolla 2012) 17 ms after the BNS merger.

The simulation in M20 employs the equation of state of Lattimer & Douglas Swesty (1991), with $K_0 = 220$ MeV, along with the neutrino leakage and heating approximations of O’Connor & Ott (2010); Ott et al. (2012). It tracks electron neutrinos, electron antineutrinos and heavy–lepton neutrinos, the latter being treated as a single species. Neutrino cooling is implemented by approximating energy-averaged neutrino optical depths followed by local estimates of energy and lepton loss rates, while neutrino heating is approximated using a prescription for the neutrino heating rate. It depends on the neutrino luminosity as predicted by the neutrino leakage approximation along radial rays, as well as the electron mass, the neutron mass, the speed of light, the rest mass density, the neutron (proton) mass fraction for electron neutrinos (antineutrinos), the mean-squared energy of the neutrinos, and the mean inverse flux factor. The explicit prescription and details can be found in M20. Finally, the mapped GRHD BNS remnant is endowed with an ad hoc parameterized electric field described through the vector potential with $A_x = A_\theta = 0$ and $A_\phi = B_0 r_\phi^2 (r_\phi^2 + r^2)^{-1} r \sin \theta$. The parameters $B_0$ and $r_0$ control the overall strength and the falloff of the magnetic field, respectively. In M20 the numerical evolution was carried out, at three different resolutions, with values $B_0 = 10^{15}$ G, to have magnetar-level magnetic field strengths, and $r_0 = 20$ km, to keep the magnetic field nearly constant within the HMNS. Additionally, to prevent violations of the divergence-free constraint of the magnetic field, $\nabla \cdot \mathbf{B} = 0$, a
constrained transport scheme is employed. In this work, we map the first level of lowest resolution simulation B15-low from M20 onto our grid as described below, in Sec. 2.2.

2.2. Data injection

Our Cartesian grid for this simulation was constructed as follows. We kept a $237 \times 237 \times 237$ box at the origin of our simulation, in which the jet was injected. This corresponds to a cube of $\sim 420$ km in each direction. This was chosen to match the 237 cells in the $xy$-plane in the original simulation (within their first level of AMR), and preserve the original jet as best as possible without too many interpolations into grids with drastically different sizes, which could lead to inaccuracies in the data as it was injected. Within this box, all the cells have the same size as in the original simulation (again, within one level of AMR), 1.77 km. We then proceeded to extend this original box along the $x$- and $y$-directions logarithmically, with 100 cells on either side. Finally, we extended the $z$-direction by adding 600 cells in a logarithmic grid. In total our grid has 437 cells in the $x$- and $y$- directions, and 837 cells in the $z$-direction.

The snapshots are extracted from M20 at 0.15 ms intervals during the (quasi) steady-state operation of the jet which lasts about 5 ms. For reference, in M20, the HMNS is evolved roughly 23 ms before collapsing to a black hole. In our current simulation, we inject these snapshots at the same rate as they were extracted, 0.15 ms, keeping the time interval fixed. Once all the snapshots are injected we restart the procedure until the end of the simulation; effectively cycling over the available snapshots and treating the injection process as a loop. Given that we are looping over the (quasi) steady-state operation of M20 simulations, this scheme provides a reasonable approximation for a long-lived jet. The total evolution time is $\sim 67$ ms (i.e. around 13 completed injection cycles), thus any specific features arising from jet launching or the eventual collapse of the HMNS will not be reproduced here.

Figure 1 shows a few physical quantities of interest – both background and injected – in the equatorial plane for $z = 0$, at the start of the simulation. The four panels show (a) the gas density $\rho$, (b) the gas pressure $p$, (c) the velocity $v_z$ along the $z$-direction, and (d) the plasma $\beta$. The central material corresponds to the data mapped from M20 into our grid. Data mapping occurred within a circle of radius $0.21 \times 10^8$ cm – this length was chosen because it corresponds to the first level of grid refinement in M20. Decreasing radially in the $xy$-plane are the extra density and pressure representing stellar material. Along the positive $x$- and $y$-directions as we transition from the injection region towards the rest of the simulation domain, there are two small bulging features on all panels. These are numerical in nature and likely occurred during data interpolation. They do not seem to affect the evolution of our simulation.

Upon looking at the panels in Figure 1, we can also note a hollow geometry in the jet. Its central axis is characterized by lower densities compared to the rest of the material as we move away from this axis (evidently discarding the low-density region outside of the injection area). This lower density along the jet’s axis is accompanied by higher pressure – which remains relatively constant within the injected area – and low $\beta$, an indication of high magnetization.

2.3. Analytical jet

The background initial conditions used in this simulation are the same that were used in the realistic jet simulation. Our grid for this simulation differs slightly from that; here we have a total of 440 cells in the $x$- and $y$-directions, with 200 of these concentrated within a radius $r_0$ in the $xy$-plane, taken to be the initial radius of the domain in which we injected our data in the previous simulation. Finally, there are 600 cells in the $z$-direction. Our prescription for the jet follows closely that of Mignone et al. (2009, 2013); Gottlieb et al. (2020), with a few modifications aimed at matching as much as possible the values of quantities in this simulation to those of our data-injected simulation. Within $r_0$, we assume a density $\rho_0$, which is taken to be the mean density in the injection domain of M20, and is then radially smoothed out as
we multiply the density along the $xy$-plane by the profile
\[ \frac{1}{\cosh(r/a)^8}, \tag{2} \]
where $a = r_0/2$ and $r = \sqrt{x^2 + y^2}$. Within the jet, the purely toroidal magnetic field is given by $B_\phi(r) = \gamma b_\phi(r)$, where
\[ b_\phi = \begin{cases} \frac{b_m r}{a}, & \text{if } r \leq a \\ \frac{b_m a}{r}, & \text{if } a < r < r_0, \end{cases} \tag{3} \]
and $b_m = \sqrt{-4p_0\sigma_\phi/[\sigma^2(2\sigma_\phi-1+4\log a)]}$. Here, $\sigma_\phi = 1$ is the toroidal magnetization parameter and $p_0$ was taken from the data-injected simulation, being the mean pressure within the injected domain. Finally, the pressure inside the jet, $p_j$, is given by
\[ p_j(r) = p_0 + b_m^4 [1 - \min(r^2/a^2, 1)], \tag{4} \]
which is also multiplied by Eq. 2. The jet’s initial velocity is $v_j \sim 0.4c$.

3. RESULTS

3.1. Realistic jet

The four panels in Figure 2 display, left to right, the gas density, pressure, velocity in the $z$-direction, and the ratio between gas and magnetic pressure $\beta = p/g$, with $p_0$ taken from the data-injected simulation, being the mean pressure within the injected domain. Finally, the pressure inside the jet, $p_j$, is given by
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The analytical jet shows a qualitatively similar behavior on many aspects, when compared to the realistic jet. As seen on Figure 3, which is analogous to Figure 2, the presence of a shock is visible around $8 \times 10^8$ cm, although this is a very symmetric shock, with an X-shaped propagation, and the jet retains its overall form for the entire duration of the simulation, i.e., we found no significant pinching occurring along the jet. Having said this, we do notice a decrease in density and pressure along with an increase in velocity at $z \sim 8.2 \times 10^8$ cm, which is similar to the behavior of the realistic jet.

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As suggested by the plasma-$\beta$, the analytical jet appears to be far more collimated than the realistic jet. This could be due to our choice of the toroidal magnetization parameter $\sigma_\phi$, which was initialized at $\sigma_\phi = 1$. Overall, the jet retains a nearly axis-symmetrical structure throughout the entire simulation, and we found no signs pointing towards a change in that structure.

Furthermore, compared to the realistic jet, we see that the central axis of the analytical jet has a very clear high-$\beta$ region. Although the magnetic fields are comparable in both simulations, there is a striking difference in the pressure, as can be seen on the second panel of Figures 2 and 3, which accounts for this difference.

4. DISCUSSION

4.1. Jet velocities and short GRBs

The similarities in density and pressure between the two simulations are not unexpected, considering that our analytical jet had its initial values for these quantities chosen so that they would be similar to those in the realistic jet simulation. In order to better track and visualize these features, we traced the profiles of a few quantities, namely the density, pressure and velocity, along the jet. We did this by locating the jet axis – taking into account its tilt – and then taking the mean values of these quantities within a certain distance of the jet’s
Figure 2. Meridional slice, $xz$-plane, of the density $\rho$, pressure $p$, velocity in the $z$-direction $v_z$ and plasma $\beta$, respectively from left to right, in the realistic jet at a late time in the simulation.

Figure 3. Meridional slice, $xz$-plane, of the density $\rho$, pressure $p$, velocity in the $z$-direction $v_z$ and plasma $\beta$, respectively from left to right, at a late time in the simulation, for the analytical jet initial data.
central axis. The profiles are shown in Figure 4. Top to bottom, they are the mean density, pressure and velocity along the portion of the outflows described above.

The features that we have qualitatively discussed before are better seen here. The shocks in the realistic jet do not appear to be very well-defined in Figure 4, but this is simply because the shocks in this jet are “pointy” (see Figure 2), marking the boundary between shocked and unshocked jet, and taking the average values of quantities within a small distance from the jet axis makes the shocks appear less obvious in Figure 4.

The appearance of GRBs is associated with multiple factors. Crucial, though, are high speeds in the jet, while moderate to high speeds in the cocoon could also lead to sGRBs (Gottlieb et al. 2018). Since our engine powering the realistic jet is a neutron star before its collapse into a black hole, there are a few additional factors that affect the jet’s properties that were taken into account in M20. For instance, neutrino cooling reduces baryon pollution in the polar regions, which in turn allows for the launch of faster jets. However, the main question still remains whether the jets are fast enough.

The velocities shown in Figure 4 are mean values within a small radius from the jet’s central axis. We see that the jet reaches mean velocities of up to $\sim 0.71c$ in the realistic jet simulation, and $\lesssim 0.6c$ in the analytical jet. These correspond to Lorentz factors of $\Gamma \lesssim 1.45$, i.e., both jets only achieve moderate velocities, which suggests they are unsuitable as sGRB sources.

We note that, in M20, Lorentz factors of $\sim 2$ were found in the jet. Still, it is possible that those speeds were not maintained up to the moment of injection into our simulation, and the difference between those Lorentz factors and the ones we have here are not significant. Moreover, we can also estimate the Lorentz factor that could be achieved by our jet by using $\Gamma_{\text{max}} = \Gamma_{\text{inj}}(1 + 4p/\rho)$. Our values of $\rho$, $p$ (see for example Fig. 4) or $\beta$ (Fig. 1) do not suggest that such an increase would be substantial. Even if all magnetic energy could be used to power the jet, we would still obtain $\Gamma_{\text{max}} < 5$ for the values of $\Gamma$, density and pressure encountered along the jet.

With this in mind, however, we note that if a long-lived jet would be able to maintain its hollow nature, with comparatively low density and high pressure within its central axis, it could achieve higher Lorentz factors and therefore be a viable source of sGRBs. Furthermore, the analytical jet is limited by the way the initial quantities are prescribed, which is not the same as in the realistic jet. Even though both jets evolve differently, the initial velocity conditions are not conducive to reaching high Lorentz factors. Further propagation over at least another order of magnitude in distance where the background density drops significantly could, however, clarify the behavior of the jet and in particular its terminal speed.

With a hybrid approach, Pavan et al. (2021) evolved a top-hat jet within a realistic binary neutron star merger background, similar to Lazzati et al. (2021), and showed that the jet achieves a terminal Lorentz factor of $\sim 40$. Furthermore, Gottlieb et al. (2022) showed that a self-consistent jet launched upon a collapsar reached Lorentz factors of $\lesssim 30$ at distances of $10^{12}$ cm; comparatively, they propagate the jet 3 orders of magnitude more than in our evolution.

Gottlieb et al. (2018) presented a model in which a cocoon shock breakout could power GRB 170817A, provided the material in the cocoon achieved moderate to high velocities, $v \gtrsim 0.6\sim 0.8c$. The total ejected mass in M20 is around $1.1 \times 10^{-3} M_\odot$, and with the exception of the jet, none of the ejecta achieved velocities above $0.5c$. Upon propagating that jet, we found that the cocoon material still falls short of achieving velocities above $0.5c$. We found the same for the analytical jet. This further suggests that neither jet studied here is likely to lead to sGRBs in this scenario.
The approximate neutrino leakage scheme, employed in M20, captures the overall neutrino energetics up to a factor of a few when compared to a full transport scheme in core-collapse supernovae simulations. The dependence on the energy, the deposition of momentum and neutrino pair-annihilation are not included and are possibly important in the jet formation process and the outflow properties. The approximate neutrino leakage scheme used in M20, thus, introduces some uncertainties and can be a potential source of errors.

Finally, it should be noted that the analytical simulation makes no direct assumptions regarding factors such as the neutron star EOS, neutrino effects or baryon pollution, all of which contribute to the NS lifetime, jet launching capabilities and jet velocity. Yet, the fact that both jets attained similar, moderate velocities, suggests that simply assuming a low/moderate initial velocity for the jet in the analytical simulation – which in a realistic case would be due to the aforementioned factors – partially makes up for the lack of explicit neutrino effects in this simulation. Nonetheless, the lack of relativistic speeds along the jets, or moderate-to-high speeds in the cocoon, makes them unlikely to produce sGRBs.

4.2. Magnetic field structure

The plots of $\beta$ in Figures 2 and 3 suggest a very noticeable difference in the magnetic field structure of the two jets that we evolved. At first, this is somewhat expected, given the circumstances in which both simulations were started: the realistic jet is an evolution of data that had already been already subjected to previous magnetic field evolution, while the analytical jet was injected with a magnetic field profile given by Eq. 3.

We show in Figure 5 a contour plot of the $z$-component of the jet velocity along with the magnetic field lines. In M20 the purely-poloidal magnetic field initial configuration develops a strong toroidal component during the evolution. The field lines, in this case, retain their helical configuration even after propagating them into large distances.

The magnetic field of the analytical jet is shown in Figure 6, which is analogous to Figure 5. It was initialized here with a purely toroidal component (see Eq. 3), and acquires a poloidal component as the jet propagates. Still, the ratio between its poloidal and toroidal components is smaller in this jet than in the realistic jet by at least a factor of 2, leading to field lines with a compressed helical shape. From a numerical point of view, this only means that we had to increase significantly the amount of integration steps in order to obtain the field lines shown in Figure 6.

5. CONCLUSIONS

The main aim of this work is to show the first steps towards a fully consistent end-to-end description of the BNS merger remnant as well as the jet launching and propagation. We use a realistic self-consistent jet, extracted from the GRMHD evolution of a highly-magnetized BNS merger remnant, to construct a mock long-lived steady-state jet. We employ this steady-state jet as initial data to address the problem of sGRB propagation through a BNS merger environment. Additionally, as a baseline, we evolve an analytically prescribed jet in the same BNS merger environment. We assess, for both cases, their ability to power short GRBs.

We find that both jets remain collimated and achieve moderate velocities, $v \sim 0.6 - 0.7c$ (Lorentz factors of $\sim 1.15 - 1.4$), with cocoon speeds of $\lesssim 0.5c$. Both of these velocities are lower than what is expected for these jets to lead to sGRBs.

We remark that the material that was injected in the realistic jet simulation – the steady-state jet in M20 – spans a total of 5$ms$. Once this material was injected, we restarted this procedure until the end of this simulation, for a total of $\sim 67ms$. This means that any features in the jet that would appear after the HMNS collapsed into a BH could not be reproduced here. Furthermore, this specific initial data leads to slower initial
velocities for the realistic jet and, while they do increase upon propagation the jet, it does not reach a high-enough Lorentz factor to be readily considered suitable for sGRB emission. This is a caveat of our simulations. However, we are moving towards the propagation of a self-consistent long-lived jet, without the need of modifying the initial data, and plan on addressing this in the future.

For this work, we chose not to evolve the jet to distances far beyond $10^9$ cm because this would require us to keep injecting more material through this looped process, which if continued could lead to a mismatch in the jet features when compared to what we would obtain if we had injected a longer-lived jet. Additionally, given our discussion in Sec. 4.1, our jets are very unlikely to reach high terminal velocities. Finally, further evolving our jets would demand higher computational power to maintain a reasonable resolution. Part of this is due to our choice to maintain a very high resolution at the injection cube in order to avoid further inaccuracies upon data interpolation. In a future development, we will make use of adaptive mesh methods that should enable us to extend the grid to longer distances in the $z$-direction without sacrificing computational efficiency, thus allowing us to study further features of the jets.

In M20, the high resolution simulation – which was not used here – reaches a maximal Lorentz factor of $\sim 5$, which is a lower estimate given that full neutrino transport was not included. Similarly, the inclusion of neutrino pair-annihilation can boost the jet’s Lorentz factor to the relativistic sGRB regime. Neutrino effects and resolving MRI-driven turbulence play a fundamental role in jet emission in the GRMHD evolution of the remnant, and in turn have a significant impact when using that evolution as initial data for the propagation of the jet, thus developing high-enough speeds to make them suitable candidates for sGRB emission. This HMNS remnant, however, is still short-lived in comparison to a lifetime of 100 ms or more needed. If the BNS merger leads to a long-lived remnant, however, which is evolved with a full neutrino treatment and the appropriate resolving of the MRI-driven turbulence, the jet will have a longer steady-state operation and will be able to develop higher terminal Lorentz factors. Using this scenario as initial data, without the ad hoc looping over the injected jet, to propagate the jet to longer distances will result in sufficiently large relativistic velocities and make magnetars formed in BNS merger suitable sGRB engines.

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