The Properties of Short Gamma-Ray Burst Jets Triggered by Neutron Star Mergers

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Abstract

The most popular model for short gamma-ray bursts (sGRBs) involves the coalescence of binary neutron stars. Because the progenitor is actually hidden from view, we must consider under which circumstances such merging systems are capable of producing a successful sGRB. Soon after coalescence, winds are launched from the merger remnant. In this paper, we use realistic wind profiles derived from global merger simulations in order to investigate the interaction of sGRB jets with these winds using numerical simulations. We analyze the conditions for which these axisymmetric winds permit relativistic jets to break out and produce an sGRB. We find that jets with luminosities comparable to those observed in sGRBs are only successful when their half-opening angles are below \( \approx 20° \). This jet collimation mechanism leads to a simple physical interpretation of the luminosities and opening angles inferred for sGRBs. If wide, low-luminosity jets are observed, they might be indicative of a different progenitor avenue such as the merger of a neutron star with a black hole. We also use the observed durations of sGRB to place constraints on the lifetime of the wind phase, which is determined by the time it takes the jet to break out. In all cases we find that the derived limits argue against completely stable remnants for binary neutron star mergers that produce sGRBs.

Key words: gamma-ray burst: general – hydrodynamics – relativistic processes – stars: neutron – stars: winds, outflows

1. Introduction

Neutron star binary mergers (NSBMs) are sources of gravitational waves, and the most discussed model for short \( \gamma \)-ray bursts (sGRBs; Eichler et al. 1989; Paczynski 1991; Narayan et al. 1992). As the binary coalesces, the resulting object depends on the total merger’s mass. If that mass is less than the maximum mass allowed by rigid rotation (constrained to be at least \( \approx 2 M_\odot \)) by observations of PSR J0348+0432 and PSR J1614–2230; Demorest et al. 2010; Antoniadis et al. 2013), it can result in a supramassive neutron star. Furthermore, if it is greater than that threshold mass, the merger will become a hot, differentially rotating, hyper-massive neutron star (HMNS) surrounded by an accretion disk (e.g., Baiotti et al. 2008). The HMNS can either live stably for a long time, or undergo collapse to a black hole (BH) (Shibata & Taniguchi 2006; Baiotti et al. 2008; Ravi & Lasky 2014).

In the latter case, delayed collapse to a BH and significant mass-loss can occur after sufficient angular momentum transport from the inner to outer regions of the remnant. Several processes can act to transport angular momentum and drive collapse, including gravitational waves, neutrino-driven winds, and magnetic fields (Lee & Ramirez-Ruiz 2007). As the mass is accreted, jets can be launched from the compact object. Details about that process remain unsure, as central engine models often invoke either prompt collapse to a BH (e.g., Murguia-Berthier et al. 2014) or formation of a rapidly spinning, highly magnetized HMNS (e.g., Zhang & Meszaros 2001; Metzger et al. 2008; Rezzolla & Kumar 2015).

In order to discriminate between progenitor scenarios, we need to better understand how the emerging relativistic jet propagates through the surrounding medium (Mochkovitch et al. 1993; Rosswog & Ramirez-Ruiz 2003; Rosswog et al. 2003; Aloy et al. 2005; Aloy & Rezzolla 2006; Rezzolla et al. 2011; Palenzuela et al. 2013; Ruiz et al. 2016). There are many collimation mechanisms (and potential death traps) for relativistic jets (Lee & Ramirez-Ruiz 2007) in an NSBM context, including dynamically ejected material from the tidal tails and various types of baryon-loaded winds produced during the HMNS phase (Hotokezaka et al. 2013b; Nagakura et al. 2014; Perego et al. 2014; Siegel et al. 2014; Duffell et al. 2015; Sekiguchi et al. 2016). In this Letter we explore how the neutrino-driven and magnetically driven winds produced during the HMNS phase shape the jet and determine under which conditions a jet can break out successfully. We use latitudinal density profiles taken from simulations of NSBMs in order to calculate a more realistic circumburst environment.

The Letter is structured as follows. Section 2 gives a description of the wind’s properties derived from global NSBM simulations and investigates how they can potentially alter the jet’s properties. Section 3 describes the numerical methods used and presents a description of the jet’s interaction, thought to be produced after the collapse to a BH, with the previously ejected wind material. Finally, in Section 4 we discuss the results obtained and compare them with observations of sGRBs.
2. Jet Advancement and Collimation

The environment’s properties could hamper the jet’s advancement. The jet should be able to break free from the baryon-loaded wind if the velocity of the jet’s head is larger than that of the wind’s material. By balancing momentum fluxes at the jet’s working surface, we obtain (e.g., Begelman & Cioffi 1989; Bromberg et al. 2011)

$$\beta_h = \frac{\beta_j + \beta_h \langle L \rangle^{-1/2}}{1 + \langle L \rangle^{-1/2}}$$

for $\beta_h > \beta_w$, where $\beta_h$ and $\beta_j$ represent the velocities of the jet’s head and the shocked material, respectively, and

$$\langle L \rangle = \frac{\rho_j \Gamma_j^2 h_j \Gamma_j^2}{\rho_w \Gamma_w^2},$$

where $h_j$ is the specific jet’s enthalpy, $\Gamma_j$ is the initial jet’s Lorentz factor, $\beta_j$ and $\rho_w$ are the jet’s and wind’s densities, respectively, $L$ is the jet’s critical parameter that determines the evolution (Bromberg et al. 2011); collimation can be attained if:

$$L < \Theta_j^{-4/3},$$

where $\Theta_j$ is the jet’s half-opening angle. For a jet with axial symmetry, its structure can be described by the angular distribution of its luminosity content per unit solid angle, $L_{\Theta}$ ($\Theta$). For this discussion, we shall assume the jet is uniform, where $L_{\Theta}$ and $\Gamma_j$ are constant within $\Theta_j$ and sharply decreasing at larger polar angles. Thus, $L_{\Theta}$ is the isotropic equivalent luminosity as derived, for example, from a fraction of the $\gamma$-ray luminosity. The complex nature of the HMNS close to critical rotation leaves open the possibility of the jet interacting with a non-spherical mass distribution: $\rho_w(\Theta)$. As we show in Section 2.1, the jet is likely to encounter a slower and denser wind confined to the equatorial plane. To compute the exact latitudinal dependence of the wind properties of HMNS we require global simulations that reproduce, as realistically as possible, the conditions expected in NSBMs.

2.1. Constraints Derived from Neutrino-driven and Magnetically driven Winds

Considering the spectral frequencies of the gravitational wave signal of a NSBM (Rezzolla & Takami 2016), we can determine a dynamical timescale associated with the HMNS’s rotation: $t_{\text{dyn}} \approx 1$ ms. Given the various stabilizing mechanisms, the HMNS is likely to survive for a timescale longer than $t_{\text{dyn}}$. Thermal support in the HMNS is governed by neutrino diffusion where the cooling time is (Perego et al. 2014)

$$t_c \approx 1.88 \left( \frac{R_{\text{ns}}}{25 \text{ km}} \right)^2 \left( \frac{\rho_{\text{ns}}}{10^{14} \text{ g cm}^{-3}} \right) \left( \frac{k_B T_{\text{ns}}}{15 \text{ MeV}} \right)^2 \text{s}. \quad (4)$$

Stabilization of HMNS due to differential rotation is expected to last for many $t_{\text{dyn}}$ and is presumed to be halted by some dissipative mechanism, like viscosity, gravitational radiation, magnetic amplification, and/or magnetic braking (Price & Rosswog 2006; Baiotti et al. 2008; Giacomazzo et al. 2011; Siegel et al. 2013; Kiuchi et al. 2014, 2015). The characteristic timescale for magnetic braking of differential rotation by toroidal Alfven waves is estimated to be of the order of $R/v_A$ (Shapiro 2000):

$$t_A \approx 0.17 \left( \frac{R_{\text{ns}}}{25 \text{ km}} \right)^{-1/2} \left( \frac{B}{10^{15} \text{ G}} \right)^{-1/2} \left( \frac{M_{\text{ns}}}{3 M_\odot} \right)^{1/2} \text{s}, \quad (5)$$

where differential rotation has been assumed here to convert a fraction of the kinetic energy in differential motion in the (initially weakly magnetized) HMNS into magnetic field energy (e.g., Siegel et al. 2014). These angular momentum transport processes push the HMNS to uniform rotation, which could lead to a collapse to a BH on a timescale $\ll t_r$, if the excess mass cannot be supported (Fryer et al. 2015; Lawrence et al. 2015).

During the HMNS phase, these various dissipation and transport mechanisms give rise to significant mass-loss. Because of the density and velocity structure in the HMNS, the mass-loss is expected to be anisotropic (e.g., Rosswog & Ramirez-Ruiz 2003). The result is a remnant wind that originated in the presence of the HMNS. The numerical tools needed to study this problem have not been available until recently. Here we make use of the results of two global simulations of NSBMs aimed at, as realistically as possible, quantifying the properties of neutrino-driven (Perego et al. 2014) and magnetically driven (Siegel et al. 2014) winds from HMNS, respectively.

The angular dependencies of the winds are derived by fitting the latitudinal ram pressure profile at the end of the simulation in Perego et al. (2014), and the random configuration of Siegel et al. (2014). The latitudinal ram pressure profile is evaluated close to the edge of the remnant, where the maximum ram pressure is attained. By assuming that the conditions at the end of the simulation are representative of the steady state of the wind, the corresponding density profile $\rho_w = \rho_w(\Theta, \Theta_j)$ can be calculated, taking the wind’s velocity to be close to the escape velocity of the merger ($\beta_w \approx 0.3$ in both cases). Then, we estimate the minimum $L_{\Theta}$ needed for a uniform sGRB jet to break free from the wind, which we assume needs $\beta_h > 2 \beta_w$ (and $t_w \sim t_{\text{sgrb}}$) at all angles. If we assume that the velocity of the jet’s head is limited by its expansion along the highest density region within $\Theta_j$, we can use Equation (1) with $\rho_w = \rho_w(\Theta_j, \Theta_j)$.

The resulting constraints are plotted in the top panel of Figure 1. For comparison, the distributions of isotropic equivalent $\gamma$-ray luminosities $\langle L_{\gamma,\text{iso}} = E_{\gamma,\text{iso}}/\theta_0 \rangle$ and half-opening angles from Fong et al. (2015, 2016a) and Troja et al. (2016) are also plotted. We note that the ensuing collimation will change $\beta_h$ from the simple analytical estimate presented here. Our simulations show that $\beta_h$ differs for this simple estimate by up to 30%. It is notable that the constraints derived from both sets of global simulations are rather similar and they are in agreement with observations, suggesting that the properties of sGRB jets are likely shaped by the wind’s character.

We can also derive a limit on the wind injection’s duration $t_w$, which is determined by the time it takes the HMNS to collapse to a BH. The velocity of the jet’s head is subrelativistic while traversing the wind. Thus, if the central engine stops the energy input in the jet’s head before it breaks free, the head will stay subrelativistic and there will be no emission. The sGRB is successful if:

$$t_w \leq t_{\text{sgrb}} \frac{\beta_h - \beta_w}{\beta_w}, \quad (6)$$
where $t_{\text{grb}}$ is the event’s duration. If Equation (6) is satisfied, the jet will be able to produce an sGRB lasting $\approx t_{\text{grb}}$. Figure 2 shows the limits on $t_w$ for the same sample as Figure 1, derived by assuming that such jets need to successfully break free from the HMNS wind. In all cases, the required limits are $\lesssim t_f$ (Equation (4)), which argues against the complete stabilization of the HMNS and suggests that the collapse to a BH occurs on a timescale $\approx t_A \gg t_{\text{dyn}}$ (see, e.g., Murguia-Berthier et al. 2014).

3. Numerical Study

We performed 2D numerical simulations to quantify how the interaction of the wind, ejected during the HMNS phase, modifies the propagation of a relativistic jet, assumed to be produced after the collapse to a BH. The simulations were performed using the Mezcal special relativistic hydrodynamic code. It uses adaptive mesh refinement in order to resolve the flows. A description can be found in De Colle et al. (2012) along with tests.

The simulation setup follows that implemented by Murguia-Berthier et al. (2014). It begins with the injection of a slow ($\beta_w = 0.3$), dense wind lasting for $t_w$. After $t_w$, the wind’s density is decreased as $r^{-5/3}$ (e.g., Lee & Ramirez-Ruiz 2007) and a jet is introduced. The jet should retain its structure before it decelerates, thus it is uniform and characterized by its luminosity ($L_{\text{si}}$), half-opening angle ($\theta_j$), Lorentz factor ($\Gamma_j = 10$), and duration ($t_j$). We relax the assumption in Murguia-Berthier et al. (2014) of a uniform wind and explore the interaction with a non-spherical distribution: $\rho_w(\theta)$, calculated using the same dependence as Figure 1. A denser wind will likely impede the jet’s advancement.

Initially, the jet is unable to move the wind material at a speed comparable to its own and thus is decelerated to a Lorentz factor $\Gamma_j < \tilde{\Gamma}_j$. Most of the excess energy is accumulated within a cocoon that engulfs the jet (Ramirez-Ruiz et al. 2002). If the jet produced by the accretion onto the newly formed BH maintains its luminosity for longer than it takes the jet’s head to reach the edge of the wind, a successful sGRB will be produced (as in the case depicted in the top panel of Figure 3). If the jet activity terminates beforehand, the jet will be choked (bottom panel of Figure 3).

The angular properties of the wind also have an important effect on the jet. Figure 4 shows the structure of jets varying $\theta_j$. For narrow jets, the outer edge of the wind is reached in a crossing time that may matter little when compared to $t_f$. Nonetheless, wider jets have to traverse higher density regions and they may be unable to breakthrough despite having the same $L_{\text{si}}$. An initially wide jet could advance much faster along the rotation axis and may eventually escape along the direction of least resistance, getting further collimated before emerging. Figure 5 shows the relativistic energy per solid angle for configurations shown in Figure 4. Only narrow jets are able to successfully emerge from the wind region, and in some cases experience significant collimation.

We can conclude that the properties surrounding an HMNS at the time of the collapse to a BH occurs have a decisive effect on the propagation and jet’s angular structure. Whether a sGRB will be observed depends not only on the power and the jet’s duration but also on its initial angular structure, and patchiness of the wind. Thus, the detection of a successful sGRB and its parameters provides a clear test of the neutron star merger model and the precise measurement of the duration, luminosity, and jet’s half-opening angle may help constrain the dimensions and mass distribution of the HMNS region.

4. Discussion

Soon after the coalescence of two neutron stars, dense mass outflows are generated within the HMNS. The resulting wind can hamper the advancement of a relativistic jet, potentially
leading to a failed SGRB. To break free from the wind, we need two conditions. First, the velocity of the jet’s head has to be greater than that of the wind. For the realistic wind profiles analyzed here, we find that this constraint can be fulfilled if the jet’s power exceeds some particular limit that increases with increasing opening angle. When compared to the observed distributions of isotropic equivalent $\gamma$-ray luminosities and half-opening angles

**Figure 3.** Temporal evolution of a jet propagating through a realistic wind. Top: The jet has $L_\Omega = 10^{51}$ erg s$^{-1}$, $\Gamma_j = 10$, $t_j = 0.5$ s, and $\theta_j = 10^\circ$. For the wind: $t_w = 0.5$ s. Bottom: the jet has $L_\Omega = 10^{59}$ erg s$^{-1}$, $\Gamma_j = 10$, $t_j = 0.5$ s, and $\theta_j = 10^\circ$; for the wind: $t_w = 1$ s. Shown are $\log \rho$ and $\Gamma$ contours at different times. $[\rho_{\min}, \rho_{\max}] = [7.6 \times 10^{-7}, 1386.3]$ g cm$^{-3}$, $[\Gamma_{\min}, \Gamma_{\max}] = [8.0, 10.0]$. A $3 \times 10^{10}$ cm scale bar is shown. Calculations were done in 2D spherical coordinates using an adaptive grid of size $l_r = 6 \times 10^{10}$ cm, $l_\theta = \pi$, with 100 $\times$ 40 initial cells, and five levels of refinement (maximum resolution of 3.75 $\times$ 10$^7$ cm).

**Figure 4.** Top: the structure of jets interacting with a wind. The jet has $L_\Omega = 10^{51}$ erg s$^{-1}$, $\Gamma_j = 10$, $t_j = 0.5$ s, and varying $\theta_j$. For the wind: $t_w = 0.5$ s. Shown are $\log \rho$ and $\Gamma$ contours at $t = 2.25$ s. $[\rho_{\min}, \rho_{\max}] = [7.6 \times 10^{-7}, 1386.3]$ g cm$^{-3}$, $[\Gamma_{\min}, \Gamma_{\max}] = [8.0, 10.0]$. The setup is the same as in Figure 3. Bottom: spacetime diagram for the jet’s head. Plotted with symbols are the position jet’s head at different angles ($\theta = 0^\circ$ and $\theta = 20^\circ$) for the simulations with $\theta_j = 10^\circ$ and $\theta_j = 40^\circ$ shown above. $t = 0s$ corresponds to $t_w$. Analytical estimates for $\beta_h$ at those specific angles are also plotted. The trajectory at $20^\circ$ ends as the jet is choked.

**Figure 5.** The distribution of relativistic energy ($\Gamma \geq 8$) per solid angle averaged in radius for the jets in Figure 4, for varying initial jet half-opening angle $\theta_j$. 
(Fong et al. 2015, 2016a; Troja et al. 2016), the required constraints are in agreement with observations (Figure 1), giving credence to the idea that the properties of sGRB jets are likely shaped by their interaction with the HMNS wind.

Second, the jet’s head needs to emerge from the wind’s outer boundary before the central engine ceases to operate. This requirement allows us to derive a limit on the duration of the wind injection phase, which is determined by the lifetime of the HMNS. Figure 2 shows the strict constraints on the time of collapse derived using the durations of sGRBs. In all instances, the required times of collapse are larger than the dynamical timescale of the HMNS but are significantly shorter than the cooling timescale of the remnant. This naturally argues against the complete stabilization of the HMNS and suggests that the collapse to a BH occurs promptly (Murguia-Berthier et al. 2014), which in turn can be used to constrain the equation of state of nuclear matter (Fryer et al. 2015; Lawrence et al. 2015). Because even a minuscule mass fraction of baryons polluting the sGRB jet severely limits the maximum attainable Lorentz factor, we argue that jet triggering has to be delayed until after BH collapse.

In this paper, we use realistic latitudinal wind profiles arising from global simulations reproducing the conditions of NSBMs (Perego et al. 2014; Siegel et al. 2014) to show that the HMNS experiences non-spherical mass-loss, and present a detailed numerical study of the propagation of relativistic jets in such environments. Many previous studies have addressed the role of external collimation (Rosswog & Ramirez-Ruiz 2003; Hotokezaka et al. 2013b; Nagakura et al. 2014; Perego et al. 2014; Siegel et al. 2014), using, for example, simple external medium solutions such as spherical (Bromberg et al. 2011) and oblate (Duffell et al. 2015) wind profiles. Here we find that jets with $\theta_j = 40^\circ$ are prone to be choked, whereas narrower jets of similar isotropic luminosity can emerge. We also find that in some limiting cases, wider jets might be able to break out of the wind region and emerge as more collimated outflows.

The resulting sGRB depends on the HMNS’s properties, especially the wind’s latitudinal structure. Thus, we cannot be too specific about the initial jet’s structure when triggered. For example, neutrino pair annihilation is expected to produce jets with $\theta_j \approx 30^\circ$ (Rosswog & Ramirez-Ruiz 2002), which also matches the half-opening angle of the magnetic-jet structure in NSBMs (Rezzolla et al. 2011), but these are likely to be further modified by the interaction with the surrounding environment. It also implies that low-luminosity wider jets can be constraining on the properties of their progenitor. The surrounding environment is expected to be less dense in the case of NS–BH progenitors. In such systems, the constraints on the properties needed for a successful event are not as stringent as in the case of NSBMs (Lee et al. 2004; Rosswog 2005; Just et al. 2016). The luminosity and opening angle of an sGRB would then provide a natural test to distinguish between different merger channels. We claim that this is the case for GRB 050724 (Grupe et al. 2006), in which a low-luminosity, wide jet event was observed. Fong et al. (2016b) rules a long-lived progenitor for the sGRB. Given its properties, we speculate it was likely produced by a NS–BH merger that promptly collapsed to a BH. Rosswog (2005) and Just et al. (2016) argue that low-luminosity events could be caused by neutrino pair annihilation or magnetized outflows in those types of mergers, respectively.

The task of finding useful progenitor diagnostics is simplified if the pre-burst evolution leads to an enhanced wind medium in the jet’s vicinity. The total luminosity and opening angles observed from sGRBs are diverse. One appealing aspect of NSBM’s progenitors is that the interaction with the winds of HMNS can probably explain this diversity.

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