EM counterparts of structured jets from 3D GRMHD simulations

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ABSTRACT
GW170817/GRB170817A has offered unprecedented insight into binary neutron star post-merger systems. Its Prompt and afterglow emission imply the presence of a tightly collimated relativistic jet with a smooth transverse structure. However, it remains unclear whether and how the central engine can produce such structured jets. Here, we utilize 3D GRMHD simulations starting with a black hole surrounded by a magnetized torus with properties typically expected of a post-merger system. We follow the jet, as it is self-consistently launched, from the scale of the compact object out to more than 3 orders of magnitude in distance. We find that this naturally results in a structured jet, which is collimated by the disk wind into a half-opening angle of roughly 10°, its emission can explain features of both the prompt and afterglow emission of GRB170817A for a 30° observing angle. Our work is the first to compute the afterglow, in the context of a binary merger, from a relativistic magnetized jet self-consistently generated by an accreting black hole, with the jet’s transverse structure determined by the accretion physics and not prescribed at any point.

Key words: MHD – radiation mechanisms: non - thermal – methods: numerical – gamma - ray burst: individual:170817A – stars: jets

1 INTRODUCTION

The conjoint detection of the first binary neutron star (NS) merger, GW170817, in both gravitational and electromagnetic waves heralds a new era in multi-messenger astronomy (Abbott et al. 2017a,b). One of the electromagnetic (EM) counterparts associated with this event was a burst of gamma rays detected about 1.7 seconds after the merger and lasted for ~ 0.6 seconds (GRB 170817A) (e.g., Goldstein et al. 2017; Savchenko et al. 2017). This detection provides the most conclusive evidence yet that binary NS mergers are indeed progenitors of short gamma-ray bursts (GRBs) as hypothesized a few decades ago (Blinnikov et al. 1984; Paczynski 1986; Eichler et al. 1989; Narayan et al. 1992). However, this short GRB and its associated afterglow emission exhibit some peculiar characteristics that are unlike any other burst. For example, it was a faint short GRB despite being, by far, the closest detected to date, and its afterglow showed a shallow rise for several months as opposed to typical afterglows that show a decline from the beginning (e.g., Fong et al. 2017; Margutti et al. 2017; Troja et al. 2017).

In standard GRB theory, the EM emission is produced by a highly relativistic jet launched by a compact object, either a NS or a black hole (BH). In the case of short GRBs, this jet is believed to be produced by the remnant of a binary NS or NS-BH merger (for a review see e.g., Lee & Ramirez-Ruiz 2007; Nakar 2007; Metzger & Berger 2012). The brief flash of high energy X-rays and gamma rays typically lasting less than 2 seconds (the ‘prompt’ emission associated with the sGRB) is attributed to an internal mechanism within the jet that is not yet well understood. As the jet propagates through the external, interstellar medium (ISM), it drives a shock that sweeps up and accelerates external particles which in turn radiate predominantly via synchrotron emission (the GRB ‘afterglow’) that can last up to several months. The most widely used jet model when calculating the emission from a GRB jet is a ‘top-hat’ jet, where the jet is a conical outflow and the properties of the jet within this cone (e.g., Lorentz factor and energy) are assumed to be constant. Beyond this cone, the jetted outflow ceases abruptly. In the past, the top-hat jet has been able to reproduce the observed characteristics of GRBs, but it fails to explain both the prompt and afterglow emission of GW170817 (e.g., Granot et al. 2017). The key difference is that due to the gravitational wave trigger and impressive follow-up effort of GW170817, it might be the only known GRB viewed at an angle larger than the jet’s core (i.e. “off-axis”), for which the prompt and afterglow emission has been detected. The emission received by off-axis observers can vary greatly depending on how the jet’s power and Lorentz factor vary as a function of polar angle. Previous studies have suggested that a more realistic model is that of a structured jet, where the Lorentz factor and energy flux vary smoothly within the jet as a function of polar...
angle (e.g., Rossi et al. 2002; Kumar & Granot 2003; Aloy et al.
2005; Janka et al. 2006). Recent works have used structured jet
models to investigate the characteristics and feasibility of detecting
the prompt and afterglow emission from such jets as possible EM
counterparts to GW events (Lamb & Kobayashi 2017; Lazzati et al.
2017; Kathirgamaraju et al. 2018). Now, a year after the detection of
GW170817, the structured jet model has been able to success-
fully reproduce the observed afterglow and can explain some of the
peculiar characteristics related to the prompt emission of the short
GRB, leading to the interpretation that GRB 170817A may have
peculiar characteristics related to the prompt emission of the short

2018; Lazzati & et al. 2018; Margutti et al. 2018; Resmi et al. 2018;

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The initial setup consists of 3 solar mass ($M_\odot$) BH wih spin 0.8,
and having a magnetic field prescribed by the vector potential $A_\phi = r^2 \rho^2$ and having a
maximum field strength of $4 \times 10^{14}$ G, where $r$ is the radius in spheri-
cal coordinates and $\rho$ is density. The top panel of Fig. 1 shows a
contour plot of the density and magnetic field of the initial setup.
Regions outside the BH and torus are set to the floor density, which
initially drops off with radius as $\propto r^{-2}$, therefore density contribu-
tions from the post-merger and dynamical ejecta are not considered
in this setup (e.g., Hotokezaka et al. 2013; Sekiguchi et al. 2016).
Following the onset of accretion, a jet is launched $\sim 10^{-3}$ ms after
the start of the simulation and $\sim 90\%$ of the jet (in energy) is ejected
within the first $\sim 1.5$ seconds, which is consistent with the duration of
the prompt phase of GRB170817A. The bottom panel of Fig.
1 shows a contour plot of the density and magnetic field at $\sim 50$
ms.
The polar, under-dense region consists of the jet which is sur-
rounded by the denser disk winds that initially collimate the jet. By
the time the jet reaches a length-scale of $\sim 1000 r_g$ ($r_g = GM/c^2$ is
the gravitational radius of a BH with mass $M_\odot$), it propagates out
of the confining winds and becomes conical, travelling radially out-
wards. The simulation is able to accurately track the jet starting
from its launching region near the compact object, up to a distance
of a few $\sim 1000 r_g$.

3 RESULTS
3.1 Jet structure from simulations
In order to calculate the observed emission from the jet we first
need to extract its structure from the simulations. The required
quantities are the Lorentz factor and energy per solid angle of the
jet as a function of the polar angle $\theta$, the energy here includes the
electromagnetic, thermal and kinetic energy (without rest mass).
Current 3D GRMHD simulations are unable to follow the jet to
the scales where the prompt emission and afterglow emission take
place (beyond $\sim 10^6 r_g$). We are therefore only able to extract the
quantities up to the distance where the simulations are still accu-
rate ($\sim 2000 r_g$), and this structure is plotted in Fig. 2. The dashed
line in Fig. 2 shows the normalized energy per solid angle (dE/dΩ)
of the jet versus polar angle $\theta$, obtained by summing the energy
flux over time at a fixed radius of $\sim 2000 r_g$ and averaging over azi-
munthal angle $\phi$. The jet is dominated by electromagnetic and
kinetic energy with a small thermal component. This distribution
roughly follows a power law decline $\propto \theta^{-3.5}$ between $5 - 15^\circ$, the
total energy of one jet is $\sim 10^{51}$ erg. The next quantity we require
is the Lorentz factor distribution of the jet, however the jet may not
have undergone complete acceleration at the distances mentioned
above. Therefore we find the ratio of the total energy flux to mass
flux ($\mu$), which determines the maximum achievable Lorentz fac-
tor in MHD jets, and use $\mu$ as an estimate for the terminal Lorentz
factor of the jet. We calculate the energy-flux–weighted $\mu$ averaged
over time and $\phi$ at a fixed radius of $\sim 2000 r_g$, as a reliable estimate
for the terminal Lorentz factor ($\Gamma_0$) of the jet as follows

$$\Gamma_0 = \frac{\int \mu T_\phi d\phi dt}{\int T_\phi d\phi dt},$$

where $T_\phi$ is the component of the electromagnetic stress-energy
tensor containing the radial energy flux (electromagnetic, thermal
and kinetic energy with the rest mass energy subtracted). The solid
line in Fig. 2 shows the jet Lorentz factor as a function of $\theta$; it
remains roughly constant at the value of $\sim 100$ up to $\sim 10^\circ$ and
then declines rapidly as a power law $\propto \theta^{-11}$ to $\sim 1$ at $15^\circ$. In
the next subsections, we will use the jet structure in Fig. 2 to calculate
the observed emission in both the prompt and afterglow phases.

1 These simulations were run before GW170817 was detected, thus it does
not use the properties inferred from observations of this event.
2 Available at https://github.com/atchekho/harmpi
3.2 Prompt emission profile

Using the jet structure in section 3.1 we can calculate a luminosity profile for the prompt emission; the total prompt luminosity an observer can expect to receive versus observing angle. Following the calculations done in Kathirgamaraju et al. (2018), we estimate the prompt emission luminosity as a function of the observing angle, \( \theta_{\text{obs}} \), which is the angle between the jet axis and the line of sight towards the observer. We assume a fixed fraction of the energy is radiated instantaneously and isotropically in the co-moving frame of the jet, and transform it to the observer frame (addressing dissipation mechanisms for the prompt emission is beyond the scope of this work). Fig. 3 compares the prompt emission profile of observed luminosity \( L_{\text{obs}} \) (normalized to the peak luminosity \( L_{\text{peak}} \)) versus observing angle \( \theta_{\text{obs}} \) for our simulated structured jet and a top-hat jet. We adopt a structured jet profile from the simulation, using the energy and Lorentz factor distributions in Fig. 2, and only take into account material with Lorentz factor \( \gtrsim 3 \) (corresponding to \( \theta \lesssim 13^\circ \)) as implied by observations and constrained by the fact that slower components might initially be too optically thick to contribute to the prompt phase of GRB 170817A (Burgess & et al. 2017; Margutti et al. 2017). The top-hat jet has half opening angle \( 13^\circ \) and a constant initial Lorentz factor of 100 which roughly correspond to the extent and maximum Lorentz factor of our structured jet, respectively. The total energy of the top-hat jet is set to be equal to that of the structured jet, thus enabling a fairer comparison. If the count rate of a typical sGRB is scaled to within the LIGO detectability distance (\( \sim 200 \) Mpc at design sensitivity; Martynov et al. 2016), it would be an extremely bright source of \( \sim 10^6 \) counts/s (e.g., Fong et al. 2015), and since these typical short GRBs are viewed on axis, we can translate the normalized \( L_{\text{obs}} \) profile in Fig. 3 to a count rate by scaling the peak of this profile to \( 10^6 \). The required count rate for a robust detection of short GRB that is coincident with a LIGO trigger is estimated to be \( \sim 10^3 \) counts/s (Connaughton et al. 2016), which correspond to \( L_{\text{obs}}/L_{\text{peak}} \sim 10^{-3} \). This limit is indicated by the horizontal dashed line in Fig. 3, and it gives us a robust detectability limit for a short GRB with an associated GW trigger from LIGO.

3.3 Afterglow emission

The afterglow is calculated using the standard synchrotron emission techniques from forward shocks in an external medium of uniform density (e.g., Sari et al. 1998). Jet spreading is taken into account following Duffell & Laskar (2018), who utilize simulations to derive analytic expressions for the dynamics of a spreading jet. Although these expression were derived for a top-hat jet, they are still applicable to the core of our structured jet (\( \lesssim 5^\circ \)), where the energy and Lorentz factor do not change by more than a factor \( \sim 2 \). In order to calculate the afterglow we first need the initial structure of the blast wave, which is obtained from the Lorentz factor and energy profile of our simulated jet in Fig. 2. The synchrotron emission is obtained semi-analytically by dividing up the blast wave into \( 10^4 \) patches (100 uniform segments along the \( \theta \) and \( \phi \) directions), calculating the synchrotron emission associated with the forward shock of each patch, and then summing the emission from all patches to obtain the total afterglow emission. We assume each patch coasts at its initial Lorentz factor (\( \Gamma_0 \), shown in Fig. 2) until the energy in the swept up, shocked medium is comparable to the initial energy of the patch, after which each patch decelerates as \( \Gamma \propto E^{1/2}R^{-3/2} \).
where \(E, R\) are the kinetic energy and spherical radius of the blast wave respectively and \(\beta = \beta(\theta); \Gamma = \Gamma(\theta)\) are the 3-velocity and Lorentz factor of the blast wave respectively during the deceleration phase. The dependence of \(\Gamma \beta R\) on \(R\) will steepen when the jet begins to spread and its observable implications will be discussed in Sec. 4. We assume the synchrotron emission from each patch is radiated isotropically in the rest frame of the emitting region, and then transform this to the observer frame. The total afterglow emission is obtained by summing over all patches, covering the entire solid angle of the jet, and taking into account differences in the photon arrival time, \(T_{\text{obs}} \approx \int \frac{d\Omega}{4\pi} (1 - \beta \cos \alpha)\), where \(T_{\text{obs}}\) is the time in the observer frame, \(\alpha\) is the angle between velocity vector of a patch of the jet and its line of sight towards the observer, \(\beta\) is the velocity of the patch of the jet and \(c\) is the speed of light.

Figure 4 shows afterglow light curves from our simulated structured jet and observed data points of GRB170817A afterglow for comparison. We neglect the counter-jet because its afterglow will be too faint to be detected. The parameters used to calculate the light curves in Fig. 4 are \(E_j = 5 \times 10^{50}\) erg, \(n \approx 0.05\) cm\(^{-3}\), \(\epsilon_e \approx 0.01\), \(\epsilon_B = 10^{-4}\), \(p = 2.17\), \(\theta_{\text{obs}} = 30^\circ\), where \(E_j\) is the true energy of the jet (without rest mass energy), \(\epsilon_e, \epsilon_B\) are the fractions of the total energy in the shocked electrons and magnetic fields respectively, \(n\) is the number density of the uniform external medium and \(p\) is the power law slope of the distribution of shocked electrons. In reality, the value of \(E_j\) depends on the radiative efficiency of the prompt emission. From observations, this efficiency varies between a few percent to more than 90% (Fong et al. 2015), therefore we will assume a median value of 50% efficiency, which means \(E_j \approx 5 \times 10^{50}\) erg (half the value of the jet energy obtained from our simulations). The shallow rise in the afterglow (between \(\sim 20 - 200\) days) occurs as the entirety of the jet becomes visible to off-axis observers. In our modelling, the slope of this rise (in a uniformly dense external medium) depends only upon the jet structure and observing angle. Since the jet structure is fixed from our simulations, we vary the observing angle and find that \(\theta_{\text{obs}} \approx 30^\circ\) produces a rise that matches the observations. The value of \(p\) is inferred from observations (Margutti et al. 2018) and rest of the parameters are adjusted to match the peak time and flux. These parameters are largely consistent with other works which model the afterglow (e.g., Lazzati & et al. 2018; Troja et al. 2018). Admittedly, the prompt radiative efficiency (and therefore \(E_j\)) can vary by a factor \(-2\), which would require a change in the external density and microphysical parameters by a similar factor. However, these changes will not affect the slope of the rise in the afterglow. We find that the observed frequency lies between the minimum and the cooling frequencies, in agreement with observations (Margutti et al. 2018).

4 DISCUSSION AND CONCLUSIONS

Determining how the power and Lorentz factor of a jet are distributed as a function of angle is a multi-scale endeavor. The simulations and analysis carried out in this work start at the central engine, where a jet is self consistently launched, and follows the jet out to larger distances as it collimates, accelerates and interacts with surrounding disk winds. The result is a more realistic description of the transverse jet structure that naturally produces an emission profile consistent with both the prompt and afterglow EM counterparts of GW170817. One aspect not considered here is interactions with the post-merger and dynamical ejecta that can take place at larger scales: in some extreme cases, this may even choke the jet and prevent it from breaking out (e.g., Gottlieb et al. 2018). However, it is likely that jet interactions with the ejecta will result in more energetic outflows at wider angles (e.g., Nagakura et al. 2014; Duffell et al. 2015; Murguia-Berthier et al. 2017; Bromberg et al. 2018; Duffell et al. 2018), that can potentially brighten the emission for off-axis observers at earlier times. This could be a reason why the first X-ray point at \(\sim 10\) days in Fig. 4 is brighter than the afterglow model of our structured jet.

As seen in Fig. 2, the transverse jet structure in Lorentz factor remains approximately constant over most of the jet core before sharply declining at larger angles. In contrast, the energy per solid angle shows a much shallower decline for the majority of the jet’s transverse extent. However, \(\sim 90\%\) of the jet’s energy is concentrated within a polar angle of \(10^\circ\), indicating a narrow, energetic jet core in agreement with afterglow fits and the observa-
tions (e.g., Margutti et al. 2018; Mooley et al. 2018; Troja et al. 2018). The prompt and afterglow emission calculated using this structure obtained from our simulations match the observed data of GRB170817A well. The prompt emission profile in Fig. 3 shows that for an event within the LIGO detectability volume, the count rate due to the prompt emission at an observing angle of ~ 20° is the order of ~ 10^3 – 10^4 counts/s (Sec. 3.2). These values match the data obtained and inferred from GRB170817A (e.g., Abbott et al. 2017b; Finstad et al. 2018). In comparison, producing a similar result for the prompt emission with a top-hat jet would require θ ≥ 20° (which is also the case for the afterglow; Lazzati & et al. 2018), this is not supported by observations of GRB170817A. As mentioned previously (e.g., Salafia et al. 2015; Kathirgamaraju et al. 2018), the prompt emission profile for a structured jet has a much shallower drop off for larger observing angles compared to the emission profile of a uniform top-hat jet. Tied with a coincident LIGO trigger, this enables the detection of the prompt emission for substantially misaligned observers, making this signal a more feasible EM counterpart than previously thought. Indeed, Fig. 3 indicates the prompt emission would be detectable, with the aid of a coincident LIGO trigger, up to an observing angle of ~ 20° off-axis for a source at the edge of the LIGO detectability volume (~ 200 Mpc), and up to ~ 30° for events like GW170817 that are much closer. Let us assume the prompt emission of all short GRBs, from GW events detected by LIGO, are detectable up to a viewing angle of 20°. Then by integrating the detection probability of GW events (Schutz 2011) from an inclination angle of 0° to 20°, we find that a fraction of ~ 0.2 GW events (out of all that produce short GRBs) will have a detectable prompt emission. However this fraction could change appreciably for different jet structures (e.g., Beniamini et al. 2018).

The afterglow light curves from our structured jet reproduce the observed rise, peak and decline of GRB170817A. The core of the jet begins to spread after it decelerates, which will steepen the observed rise strongly constrains the viewing angle to be close to 30°, since larger (smaller) viewing angles will produce a steeper (shallower) rise in the afterglow.

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