Off-axis Short GRBs from structured jets associated with Gravitational Wave events

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Introduction

Binary Neutron star (NS) mergers are the most promising source of Gravitational waves (GWs) and associated electromagnetic (EM) counterparts. These mergers are believed to launch relativistic jets that lead to short Gamma ray Bursts (sGRBs). Due to relativistic effects, the prompt emission from sGRBs are strongly beamed along the direction of motion of the jet. As a result, the rate of detecting a sGRB from these mergers is estimated at 0.1 per year [1]. However, these low rates are based on simplistic models for the jet. Where the jet is assumed to be conical with some opening angle θ_j, has constant properties that don't depend on angle (e.g., Lorentz factor and jet power), and the jet abruptly disappears for angles larger than θ_j, this is called a 'top hat' jet model.

In this work [2], we investigate the emission profile of sGRBs using a more realistic jet model, whose properties vary smoothly with angle, we call this a 'structured' jet. We obtain the jet structure (i.e, the angular dependance of the jet properties) using relativistic magneto-hydrodynamic (MHD) simulations. From theory and simulations, the jet is expected to have a very bright, fast core at small polar angles (a luminous core) and the speed and brightness of the jet drops off at wider angles, resulting in a slower, fainter extended lateral structure, see Fig. 1 for a cartoon of the jet.

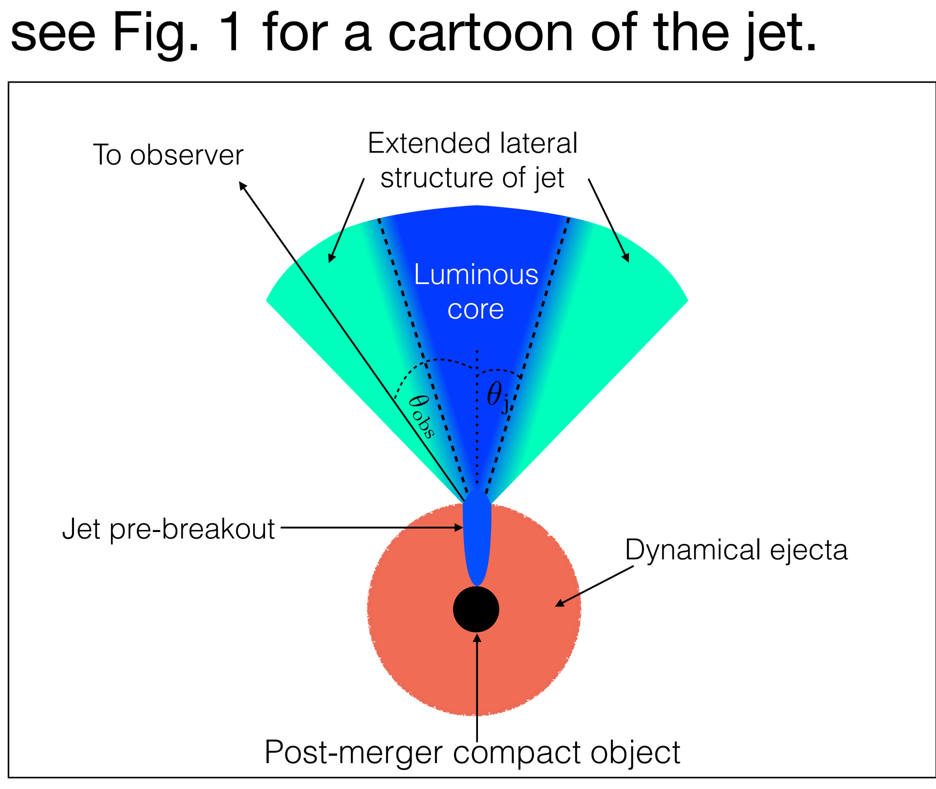

Fig.1 A cartoon of a sGRB jet. Once the jet breaks out of its collimating medium it develops a lateral structure.

Simulating the Jet

We run relativistic MHD simulations using the HARM code [3]. The initial conditions and numerical scheme of these simulations are adapted to the physical setup relevant to this work [2,4]. We initiate the jets via the rotation of the central magnetized compact object. The jets are therefore launched magnetically dominated. By adjusting the density of the gas in the injection radius, the jet is launched with magnetization $\mu=2p_0/(\rho_0 c^2)\approx 25$, where p_0 is the magnetic pressure and ρ_0 is the density at the base of the jet. The initial magnetization μ determines maximum Lorentz factor of the jet. Very close to the compact object, we set a high density in order to mimic the presence of the dynamical ejecta.

Fig. 2 shows a density and Lorentz factor contour plot at a snapshot in time. Initially, the jet is collimated by the dynamical ejecta. Once the jet breaks out of the ejecta it, undergoes a rarefaction and further acceleration and develops a lateral structure.

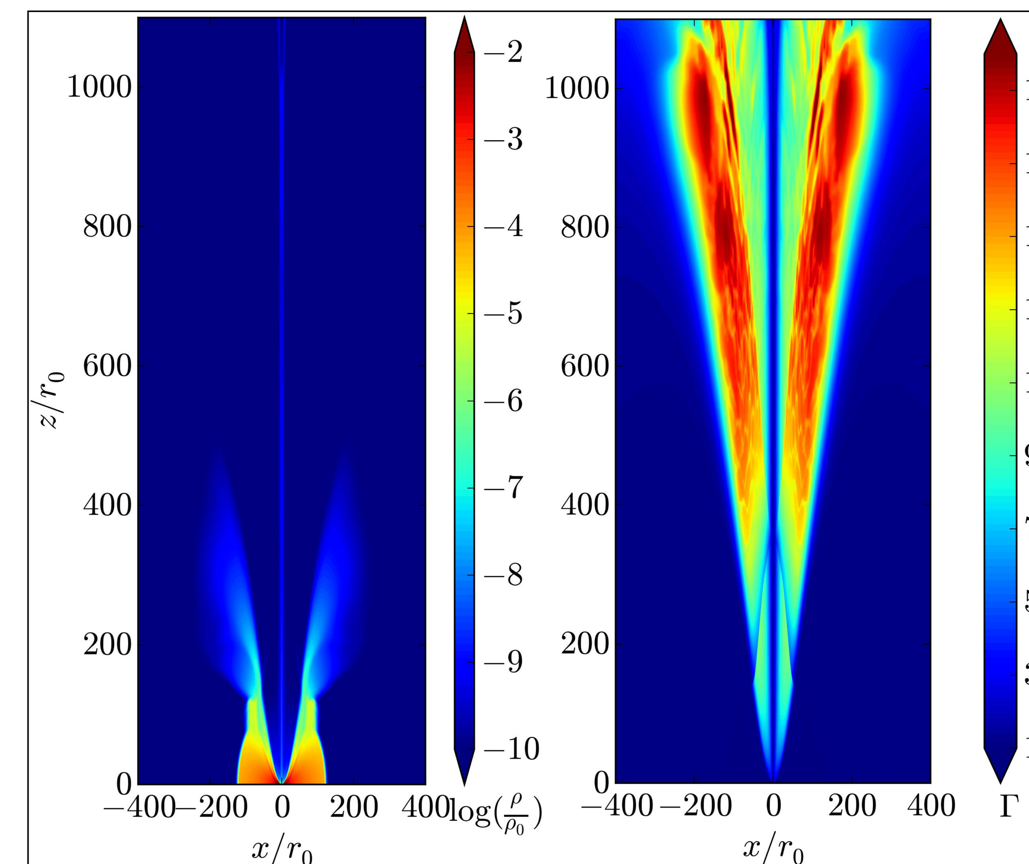

Fig. 2 Numerical simulation of a jet that is collimated by and breaks out from the dynamical ejecta. We show 2D cuts of density (left-hand panel) and Lorentz factor (right-hand panel), where r0 stands for a few times the radius of the central compact object.

Results

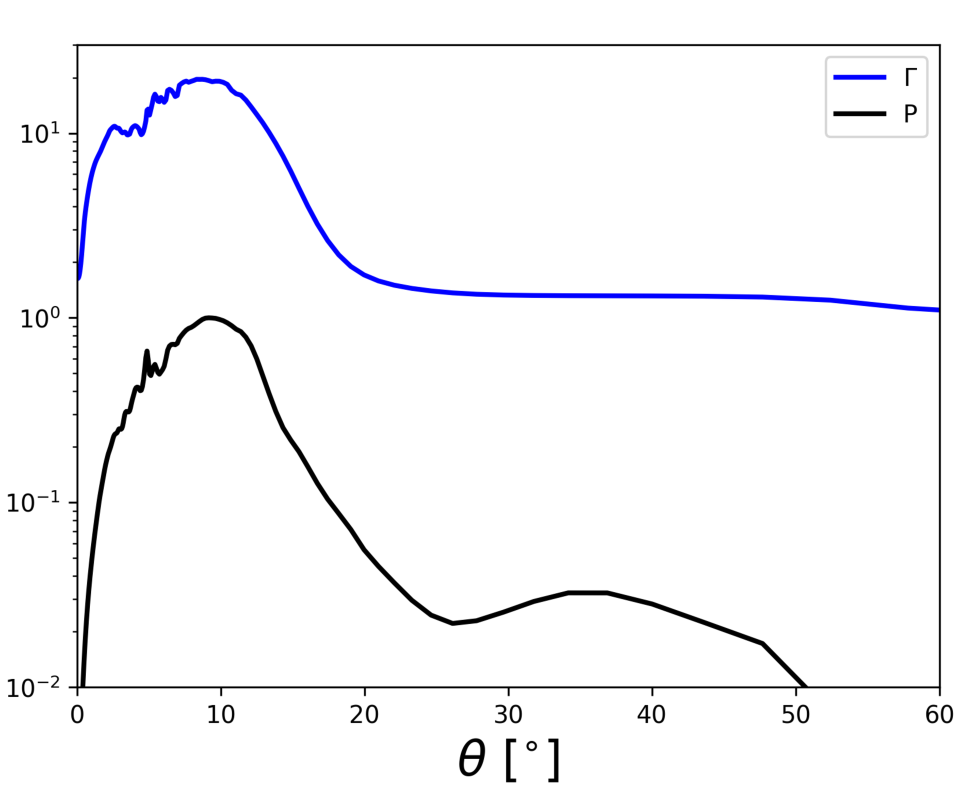

Fig. 3 Jet power per solid angle (black) normalized to peak and Lorentz factor (blue) as a function of polar angle θ. These are extracted from the simulations along a fixed radius of the jet.

Assuming a fixed fraction of the power shown in Fig. 3 is radiated instantaneously and isotropically in the comoving frame

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we calculate the observed luminosity for the structured jet, this is shown in Fig. 4 (blue line)

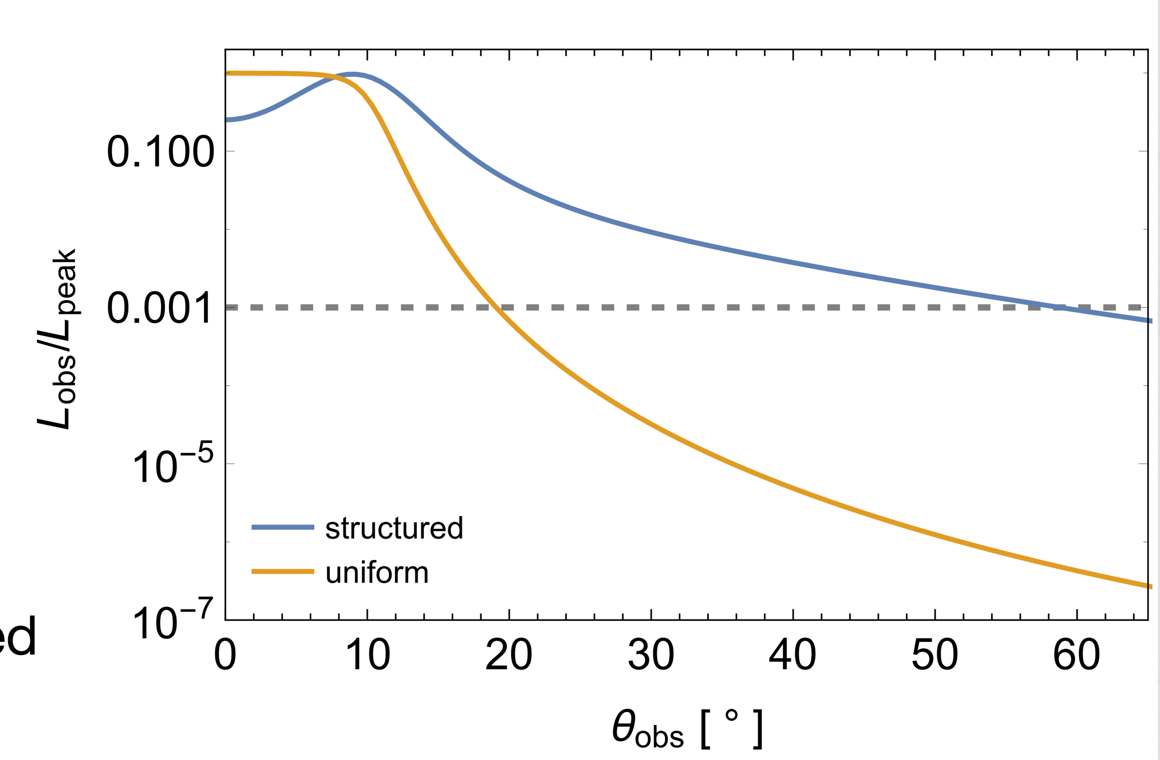

Fig. 4 Observed (radiated) prompt emission as a function of observer angle, for two jet models. In blue, the structured jet obtained from our simulations, in orange, a 'top hat' jet model with θ_j=10°, Γ=20. The dashed gray line indicates a sGRB sensitivity limit for the *Fermi* detector, in the presence of a GW trigger from LIGO [5] .

From Fig. 4, it is evident that the prompt emission from a structured jet is detectable for a much larger range of observing angles, with the aid of a coincident LIGO trigger. Consequently, the rates of detecting a sGRB associated with a binary NS merger can be higher. Making the prompt emission a promising EM counterpart.

Conclusions and First Detection

By investigating the prompt emission profile of a structured sGRB jet, we conclude that the prospects of detecting a sGRB as an EM counterpart associated with a LIGO trigger is very favorable. We estimate a detection rate of ~ a few per year, as opposed to 1 per decade as previously thought. Even though the sGRB signal from an off-axis structured jet may be faint, it may still make for a significant detection with the aid of the temporal coincidence of a GW trigger from LIGO.

The first ever detection of a binary NS merger was announced on Oct 2017. Around 2 sec after the merger, a sGRB was detected by the *Fermi* satellite. However, this sGRB was the faintest one ever observed, despite it being the closest. The combined estimates from LIGO and EM detections suggests that this event was viewed off-axis. These observations are consistent with our model for a sGRB from an off-axis, structured jet.

References

[1] Wanderman D., Piran T., 2015, MNRAS, 448, 3026
[2] Kathirgamaraju A., Barniol Duran R., Giannios D., 2017 MNRAS: *Letters*, slx175
[3] Gammie C. F., McKinney J. C., To´th G., 2003, ApJ, 589, 444
[4] Barniol Duran R., Tchekhovskoy A., Giannios D., 2017, MNRAS, 469, 4957
[5] Connaughton V. et al., 2016, ApJ, 826, L6

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