The evolution of relativistic jets through the magnetized medium produced by the fusion of two neutron stars

Leonardo García García[1], Diego López-Cámara[1], Davide Lazzati[2]
[1]Astronomy Institute–UNAM [2]Oregon State University

The merger of a BNS system results in the emission of a GW, a highly dense and magnetized medium, and the launch of a collimated relativistic jet which produces a short gamma-ray burst (SGRB). Although the evolution of a jet-SGRB has been studied through different media, the evolution through a magnetized medium is not fully understood. Therefore, to understand the importance of the magnetic field of the medium, we studied the evolution of several SGRB-jets through media with different varying the magnitude and geometry of B using 2.5D RMHD (ideal) numerical simulations. We follow the evolution of jets-SGRB with $L_j = 2\times10^{50}$ erg s^{-1} and an opening angle $\theta_j = 10°$ through a medium with different distributions and magnitudes of B.

Introduction

- SGRBs: short non-repeating flashes of γ-rays with $T_{90} = 10^{-1} - 2$ s (Nakar, 2007; Berger, 2013), $L_{iso} \sim 10^{47} - 10^{53}$ erg s^{-1} (Hamidani, 2019) and $\theta_j \cong 5^{\circ} - 25^{\circ}$ (Fong et al., 2015).
- The jet, launched from a CO formed by the merger of a BNS, evolves through the post-merger medium which has a mass of $M_m = 10^{-3} - 10^{-2}\ M_{\odot}$ (Tanaka et. al 2017) and $B_m = 10^{12} - 10^{16}$ G (Ciolfi et al. 2017).
- The ρ_m effects on the jet have been studied (Lazzati et al., 2017, 2018; Murguia-Berthier et al., 2017), magnetic jets have been studied (Bromberg et al., 2018 Gottlieb et al. 2020; Nathaniel et al. 2020), but the role of the B_m on the jet is still to be fully understood.
- In this study we explore the effect of a highly magnetized medium with different geometries of B in the evolution of a relativistic and collimated jet.

Methodology

- 2.5D RMHD (ideal) simulations performed using the PLUTO code (Mignone et. al 2007, 2012).
- Initial condition based on Ciolfi et al. (2017) (see Figure 1)
- Ideal gas EOS P_m, $\beta = \frac{P_B}{P_g}$ = cte, poloidal or poloidal + toroidal B
- We performed 10 simulations with the configurations of B and 1 with $B_m = 0$ which serves as control simulation (Figure 2).

Initial condition

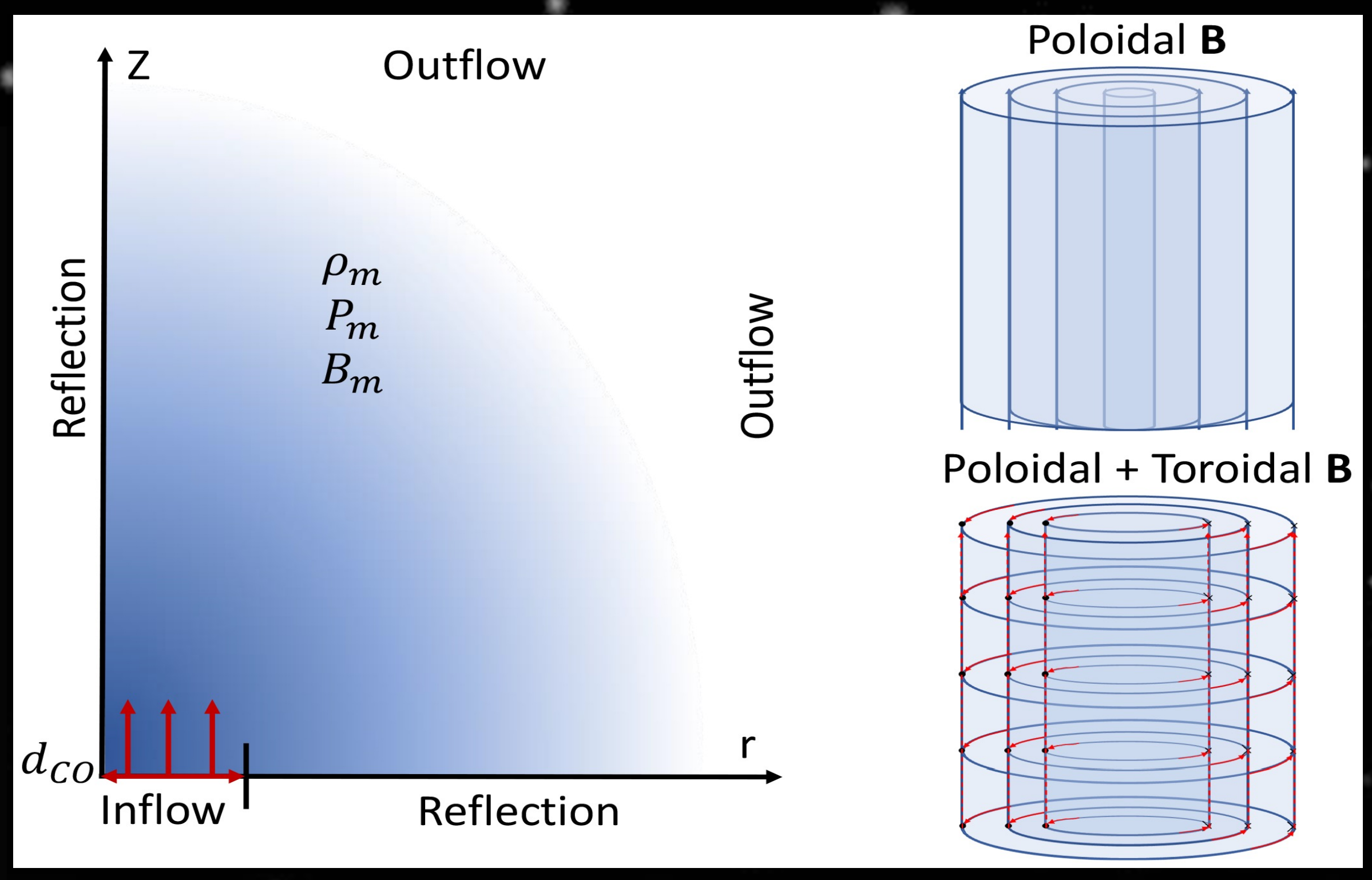

Figure 1. Scheme of the initial condition. The left panel presents a medium with a ρ_m, P_m and B_m in which a jet evolves. The jet is launched on a distance d_{CO} from the compact object with an opening angle θ_j. The upper right figure shows the poloidal magnetic field distribution. Bottom right panel presents a poloidal plus toroidal magnetic field distribution.

Medium

- $\rho_m = \rho \propto R^{-3}$
- $P_m = P_g \propto P_B$
- $P_B \propto R^{-2}$
- $\beta = cte$

Jets

- $L_j = 2X10^{50}\ erg\ s^{-1}$
- $\Gamma_{j,0} = 2.0$
- $\theta = 10°$
- $d_{CO} = 1x10^7$ cm

Results

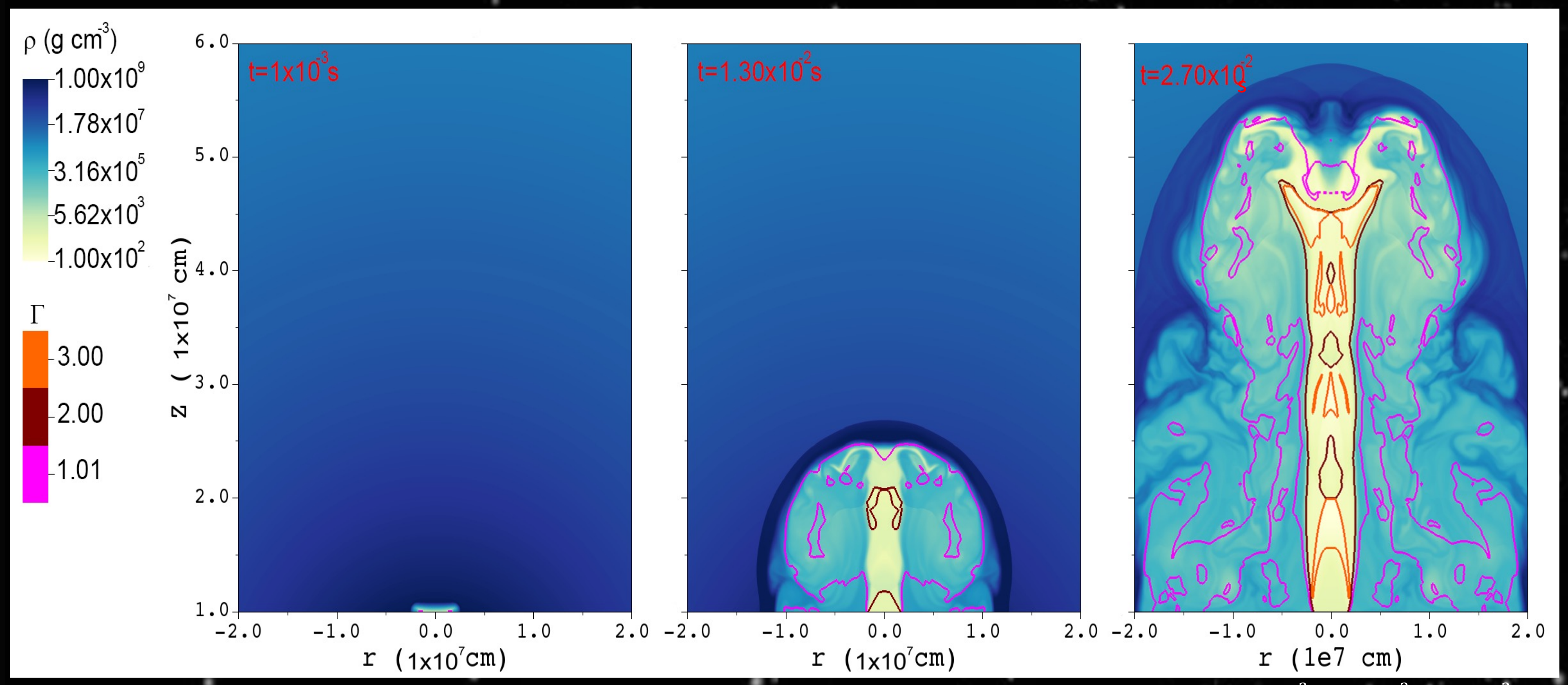

Figure 2. Density maps of a relativistic jet drilling through a dense and non- magnetized media. Three characteristic times are shown ($t = 10^{-3}, 1.3\times10^{-2}, 2.7\times10^{-2}$ s). Lorentz factor isocontours are presented in pink ($\Gamma = 1.01$), carmin ($\Gamma = 2.0$), and orange ($\Gamma = 3.0$).

- Figure 2 shows the evolution of a relativistic jet in a non magnetized medium. This simulation is used as a control case.
- $d(\beta_P = 100)$ t differs 0.10 % from the control case with slight differences in the cocoon and jet core.
- For the case of $\beta_P = 100$, the distance traveled by the jet differs 0.10 % from the control case with slight differences in the cocoon and jet core.
- β_P =0.1 the jet reaches the larger distance: 1.034 $d_{Control}$

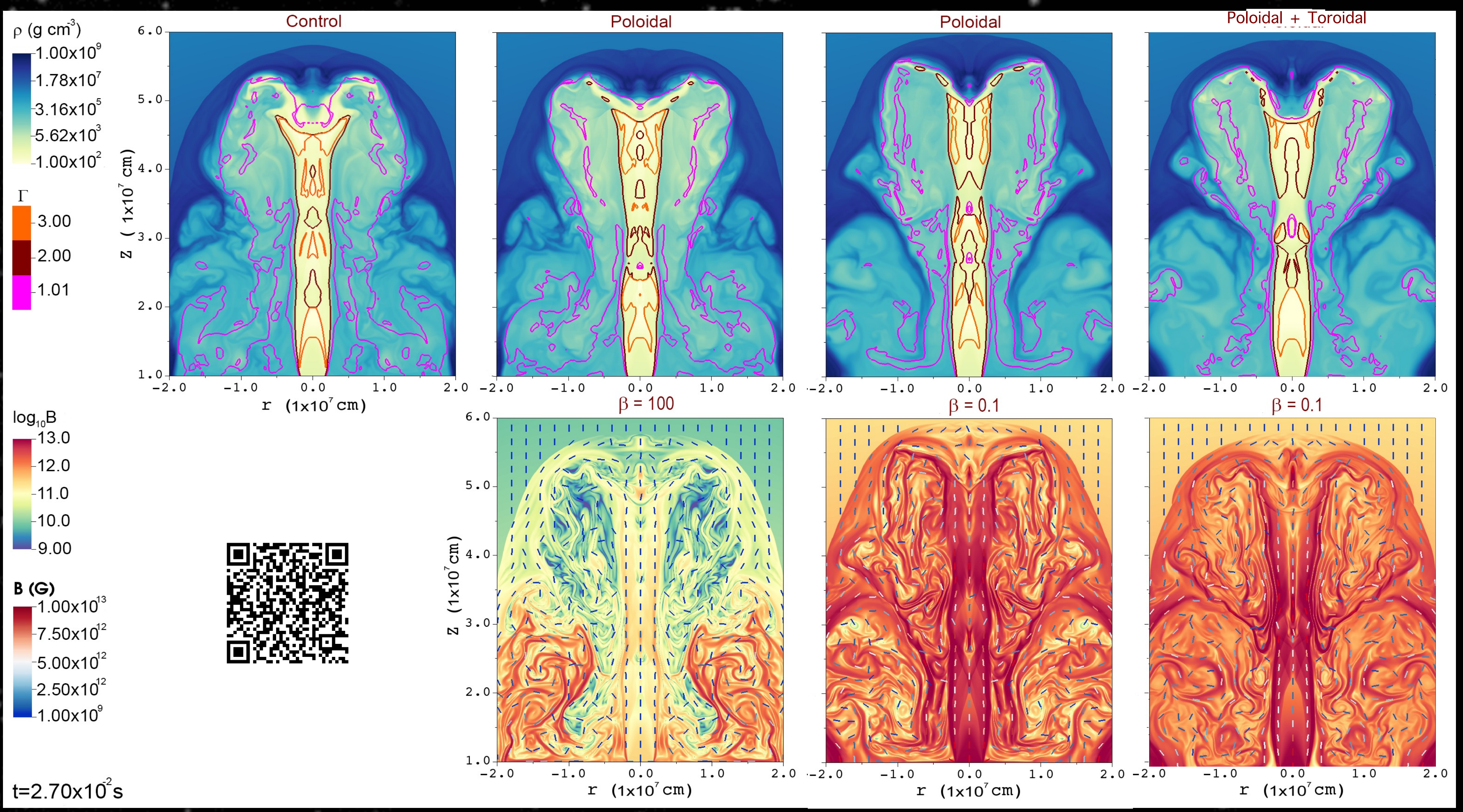

Figure 3. Comparison of the outcome for different simulations at $t = 2.7\times10^{-2}$ s. The upper panels present the density map and Lorentz factor isocontours, whereas the lower panels show the $log_{10}$of B and the magnetic field lines.

- Figure 3 shows the final output for the control and magnetized cases, also de magnetic field map is presented.
- The magnetic field is larger in the jet core and the turbulent zones of the cocoon
- $d \propto \beta^{-1} \propto B^2$.
- $d(\beta_P + \beta_T) < d(\beta_P)$

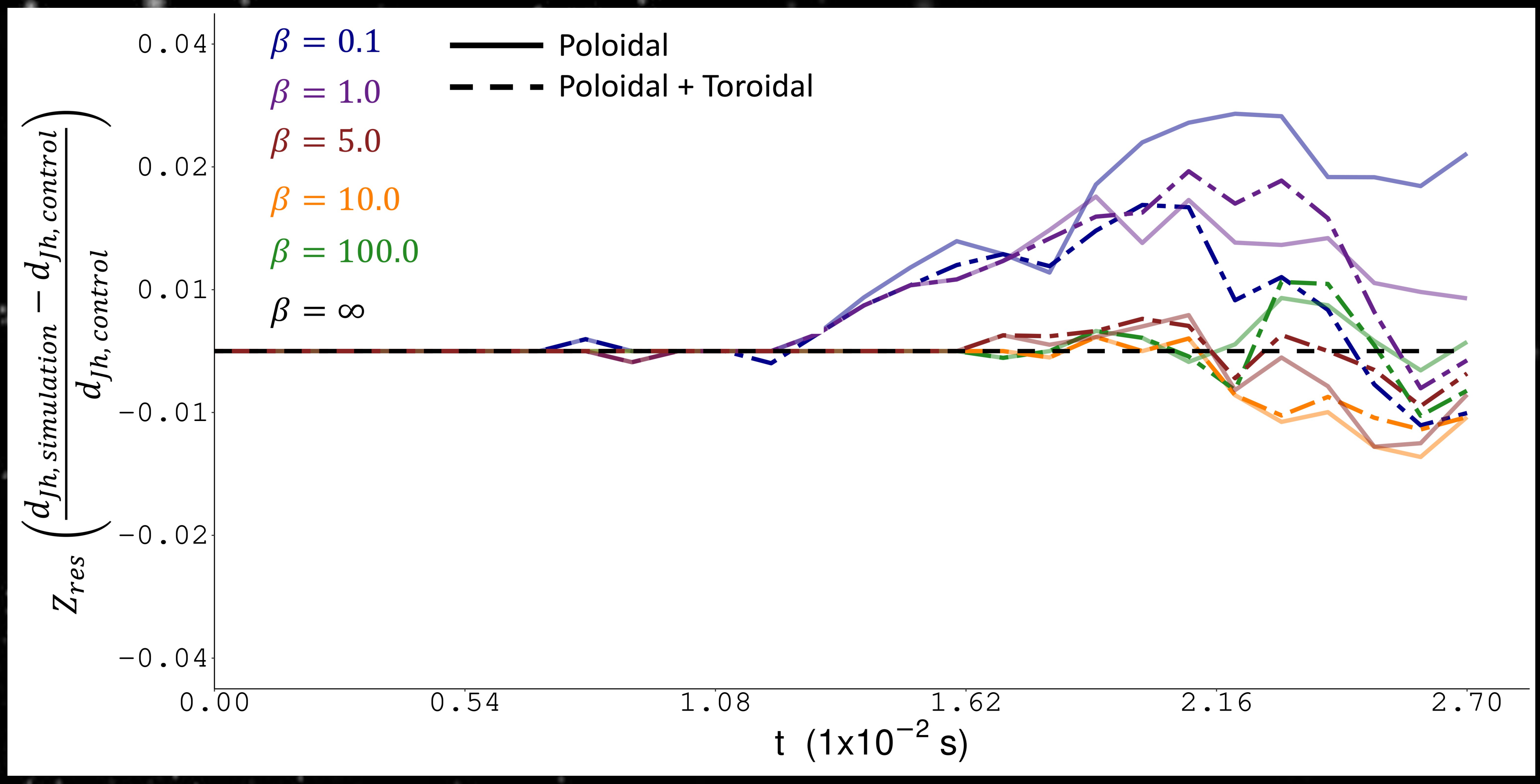

Figure 4. Residuals for the traveled distance by the jets. Solid lines are for models with a poloidal component, dashed lines are for the models with poloidal plus toroidal component.

- Figure 4 presents the residuals for the distance traveled by jet.
- $d(\beta_P + \beta_T) = 0.001 - 0.008\ d_{Control}$
- $d(\beta_P \leq 5) \approx d_{Control}$
- $d(\beta_P = 0.1,1) = 1.007 - 1.034\ d_{Control}$

Conclusions and Future work

- The magnetic field modifies the structure of the jet:
  - Highly magnetized simulations with B_P boosted the jet
  - Highly magnetized simulations with $B_P + B_T$ delays the jet evolution.
- The geometry of the jet its an important factor for the jet evolution.
- In future studies, we will modify the parameter space to find where the magnetic field of the media shows larger effects.

Bibliography

Bromberg, O., Tchekhovskoy, A., Gottlieb, O., et al. 2018, MNRAS, 475, 2971
Ciolfi, R., Kastaun, W., Giacomazzo, B., et al. 2017, Physical Review D 95, 063016
Fong, W., Berger, E., Margutti, R., & Zauderer, B. A. 2015, ApJ 815, 102
Hamidani, H., Kiuchi, K., & Ioka, K. 2020, MNRAS 491, 3192
Lazzati, D., López-Cámara, D., Cantiello, M., et al. 2017, ApJL 848, L6
Lazzati, D., Perna, R., Morsony, B.~J., et al. 2018, Physical Review Letters, 120, 241103
Mignone, A., Zanni, C., Tzeferacos, P., et al. 2012, Astrophysical Journal, Supplement 198, 7
Mignone, A., Bodo, G., Massaglia, S., et al. 2007,Astrophysical Journal, Supplement 170, 228
Murguia-Berthier, A., Ramirez-Ruiz, E., Montes, G., et al. 2017, Astrophysical Journal, Letters, 835, L34
Nakar, E. 2007, Physics Reports, 442, 166
Nathanail, A., Gill, R., Porth, O., et al. 2020, MNRAS, 495, 3780
Tanaka, M., Utsumi, Y., Mazzali, P. A., et al. 2017, Publications of the ASJ, 69, 102r