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Afterglow linear polarization signatures from shallow GRB jets

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When a gamma-ray burst (GRB) occurs inside thick merger ejecta or deep within a star, the newly created jets must drill their way through the confining media before breaking out and emitting their energy. The interaction with the medium leads to the formation of a non-relativistic cocoon around the jet and an interface separating the two components. Once the jet breaks out, the interface material accelerates and forms a mildly relativistic sheath around the jet, which can radiate over a wide range of angles. Recent studies have shown that the interface can hold a substantial amount of energy, which can alter the observed light during the prompt and afterglow phase, thus reveling information on both the jet and medium properties prior to the jet breakout. In this work I will present a method to probe the jet structure and its interface by modeling the afterglow light, focusing on its linear polarization. The temporal evolution of the polarization signature is highly sensitive to the emission region geometry, and when modelled carefully, can give robust observational features of jets with varying structures.

High Energy Phenomena in Relativistic Outflows VIII (HEPROVIII)
23-26 October, 2023
Paris, France

[*] Speaker

PoS(HEPROVIII)021

1. Introduction

Gamma-ray bursts (GRBs) are extreme events placed at cosmological distances [1], identified by γ-ray pulses that can last fractions of a second to hundreds of them [2]. The energies released in GRBs are associated with the formation of compact objects [3, 4] that can launch relativistic jets following accretion combined with electromagnetic processes [5]. GRBs have two main observational phases:

1. The prompt γ-ray emission that occurs due to internal energy dissipation mechanisms within the jet [6, 7].
2. When the relativistic jet interacts with the cold ambient medium, it drives a relativistic shock into it. This shock accelerates charged particles to relativistic energies which allows them to emit synchrotron radiation under the influence of shock-generated magnetic fields. The multi-wavelength emission is named the afterglow [8, 9].

GRB jets can be launched within either stellar envelopes or merger ejecta and in order to break out, they must drill through the medium that confines them. As the jets do so, they deposit energy into the confining medium, forming an extended angular structure that proceeds to break out along with the jet. When analysing these jet structures, seen in numerical simulations, an angular power-law jet structure emerges with a highly relativistic core, followed by a mildly relativistic extended structure that declines like a power-law in angle for both the Lorentz factor and energy [10, 11]. The GRB jet cannot be probed observationally before it breaks out of the confining medium and therefore, the only way to study the processes it underwent during this time is through understanding its structure.

GRB 221009A, dubbed as the brightest observed of all times (BOAT), was an extremely energetic burst with intrinsic energies of $10^{54} - 10^{55}$ ergs [12–14] and prompt emission lasting 600 seconds [15]. Redshift measurements placed this GRB at $z = 0.151$ [12, 16], producing a luminosity distance of ~ 720 Mpc [14]. The combination of these two parameters allowed detailed observations of the multi-wavelength afterglow. The first 100 days of the afterglow light curves seem to be devoid of a classical jet break during which the temporal power-law index of the light curve dips below -2, indicating a very large jet opening angle according to the top-hat jet model [14]. This poses an energy crisis for classical GRB progenitor models [17].

A solution to this problem is given by assuming the jet has a power-law structure, as seen in simulations. This structure features a uniform energy and initial Lorentz factor within the jet core $\theta < \theta_c$ and a declining power-law behaviour at angles $\theta > \theta_c$ with $E, \Gamma_0 \propto \theta^{-a,-b}$ respectively. When the energy in the jet wings is comparable to the energy in the jet core, the structure is defined as a "shallow jet" [11]. In the lower panel of Fig. 1, I present the light curve fits two groups produced using configurations of the shallow jet model to the X-ray (blue) and optical (red) afterglow of GRB 221009A [14, 18]. However, using the light curve alone fit alone does not allow to discriminate observationally between the structures.

2. Linear polarization in GRB afterglows

In this work I aim to construct a numerical tool that, when given an afterglow model and jet structure, is able to produce multi-wavelength afterglow light curves and corresponding polarization

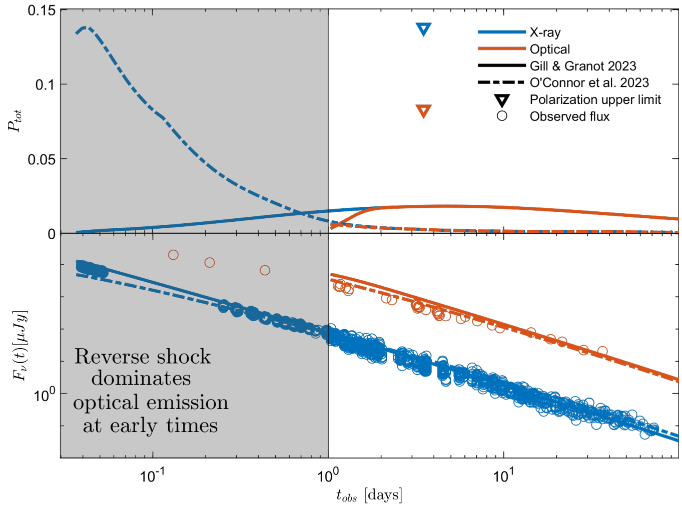

Figure 1: Upper panel: Temporal evolution of the polarization degree for two suggested shallow jet structures for GRB 221009A: [18] in solid lines and [14] in dash-dotted lines. The curves are computed in two bands: X-ray (blue) and optical (red) where the upper limits on linear polarization [19] in both bands is presented with triangles in corresponding colors. The structure of the magnetic field is taken to be random on the plane of the emitting region. Both proposed models agree with the upper limits on polarization taken at 3.5 days in both bands. Lower panel: X-ray (blue) and optical (red) light curves for two of the proposed models for the structure of the jet of GRB 221009A: [18] in solid lines and [14] in dash-dotted lines. Both forward shock models fit the observed data [14, 18].

curves from the forward shock. Since linear polarization is an observational quantity extremely sensitive to system geometry, a correct interpretation of it can allow us to deduce the jet structure. I start out by looking at two geometrical setups, set by the ratio between the viewing angle $\theta_{\rm obs}$ and the jet core opening angle θ_c. For all the geometrical setups considered in this section, I assume a purely random magnetic field structure, confined to the face of the shock, and a uniform initial Lorentz factor distribution with $b = 0$. The observed frequency in this section lies in the optical regime with $\nu_{\rm obs} = 10^{15}$ Hz.

2.1 On-axis jets ($\theta_{\rm obs} < \theta_c$)

I start by exploring the polarization signatures from structured on-axis jets that are observed from within their core opening angle with $\theta_{\rm obs} < \theta_c$. In this sub-section I focus on structures featuring a sharp transition between the uniform jet core, that dominates the emission at all times, and the power-law wings in order to emphasise the interplay between the two components. In Fig. 2, I set the viewing angle to be constant at a value of $\theta_{\rm obs} = 0.7\theta_c$ and vary the jet structure from top-hat jet (blue) to shallower structures in energy with $a \in \{2, 1, 0.5\}$ (red, purple and yellow respectively). The temporal evolution of the polarization degree is presented in the upper plot and the observed light curve can be seen in the lower plot. The polarization signature is similar for both top-hat and shallow jet structures, with two polarization peaks at opposing signs which correspond to perpendicular polarization vector inclinations. The first polarization peak occurs when parts of the ring-shaped polarized emission from the uniform core weaken beyond it due to the power-law jet extended structure (or disappears altogether for top-hat jets). This leads to cancellation of

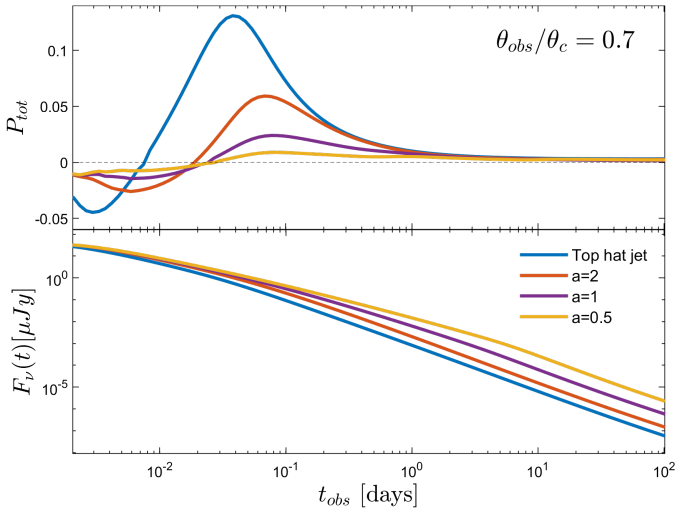

Figure 2: Observed polarization degree (upper panel) and flux (lower panel) as function of time for the power-law jet model at observer frequency $\nu_{\rm obs} = 10^{15}$ Hz with a flat distribution of initial Lorentz factor ($b = 0$) and a random magnetic field structure, confined to the face of the shock. The various values of a represent differing slopes for the power-law jet wings and the observer is located at $\theta_{\rm obs} = 0.7\theta_c$. The signs of the polarization degree represent opposing directions of it.

the horizontally polarized component and a consequent rise in the vertically polarized one (for a visualisation of this effect, we refer the reader to [20, 21]). The direction of the polarization vector rotates by 90° as the polarization degree crosses zero, when approximately half of the polarized ring weakens beyond the jet core. The second polarization peak is associated with a jet break in the light curve and occurs when the vertically polarized region disappears, leaving mostly horizontally polarized emission. Structures containing more energy in their power-law wings (lower values of a) correspond to lower observed polarization degrees, as the setup is more symmetrical around the line of sight. These predictions may describe observed polarization degrees of optical GRB afterglows that mostly remain below 10% [22–24].

2.2 Off-axis jets ($\theta_{\rm obs} > \theta_c$)

In this subsection I consider off-axis jets, observed from viewing angles lying outside of their core opening angle with $\theta_{\rm obs} > \theta_c$. The power-law structure analysed in this sub-section has a smooth transition between the uniform core and the power-law jet wings to allow a smooth transition from the early time wing-dominated emission to the late time core-dominated emission. In Fig. 3 the off-axis viewing angle is set to $\theta_{\rm obs} = 5\theta_c$ while the jet structure varies between top-hat jet (blue) and shallower structures in energy with $a \in \{2, 1, 0.5\}$ (red, purple and yellow respectively). The direction of the polarization remains constant throughout the temporal evolution of it (upper panel) due to symmetry considerations and the polarization degree features a single peak that becomes lower with decreasing values of a. The polarization peak occurs at similar times for all jet structures, associating it with the time the observer starts to see radiation from the jet core. A slight break in the light curve can be seen around the same time the polarization curve peaks, strengthening this conclusion (lower panel). Another way to lower the polarization degree is by viewing the system from an angle closer to the jet symmetry axis. This idea is explored in

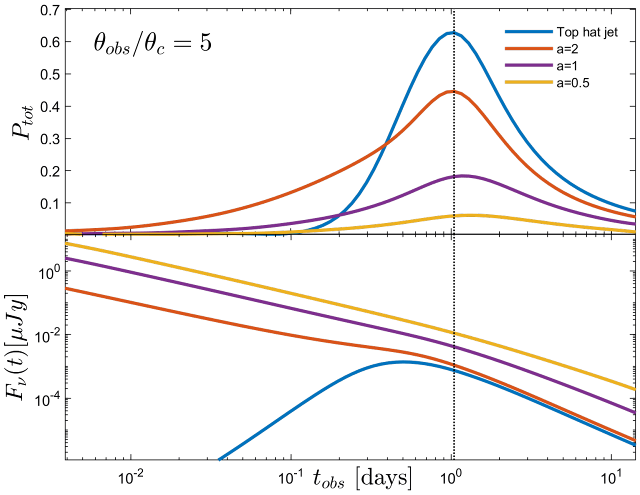

Figure 3: Observed polarization degree (upper panel) and flux (lower panel) at observer frequency $\nu_{\rm obs} = 10^{15} Hz$ with a flat distribution of initial Lorentz factor ($b = 0$) and a random magnetic field structure confined to the face of the shock. The direction of the polarization vector remains constant throughout the temporal evolution. I set the viewing angle to be constant for an off-axis jet with $\theta_{\rm obs} = 5\theta_c$ with varying values of a. The polarization degree reduces with a and its peak coincides with a break in the light curve.

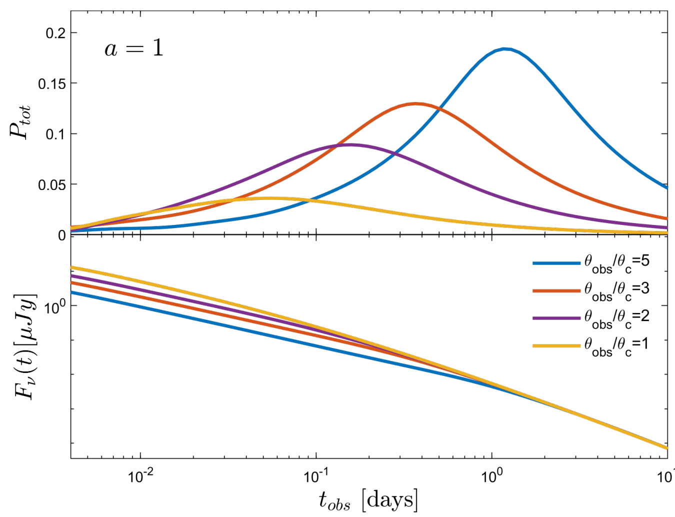

Figure 4: Observed polarization degree (upper panel) and flux (lower panel) at observer frequency $\nu_{\rm obs} = 10^{15} Hz$ with a flat distribution of initial Lorentz factor ($b = 0$) and a random magnetic field structure confined to the face of the shock. The direction of the polarization vector remains constant throughout the temporal evolution. The structure of the jet is held constant with $a = 1$ and the off-axis viewing angle is changed. As the observer approaches the jet axis with reducing values of $\theta_{\rm obs}$, the polarization peak becomes lower and occurs at earlier times.

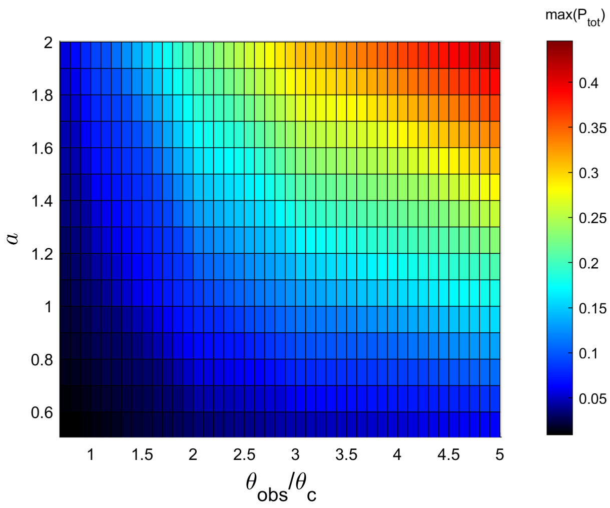

Figure 5: 2D visualization of the maximal polarization degree for various combinations of $\theta_{\rm obs}$ and a produced with interpolation over the results in Figs. 2,3 and 4. The polarization peak becomes higher as the the degree of asymmetry in the system increases.

Fig. 4 by setting a constant structure with $a = 1$ and modeling the polarization and light curves for different jet off-axis viewing angles. The peak polarization degree declines with the value of $\frac{\theta_{\rm obs}}{\theta_c}$, marking polarization as a tracer for asymmetry in the physical system. The polarization peak time also decreases with this ratio due to the angular proximity to the core that allows radiation from it to reach the observer at earlier times.

Interpolation is applied to the peak polarization results presented in this section, within the $\theta_{\rm obs}$-a parameter space, in order to map out how the polarization changes when the geometry is shifted. This is visualized in Fig. 5 where the x-axis stands for the normalized viewing angle and the y-axis stands for the slope of the jet wing power-law in energy. The color bar marks the peak polarization degree for each parameter combination. A rise in polarization is correlated with geometrical asymmetry in the system which can be manifested through a large viewing angle ($\theta_{\rm obs}$), a steeper structure in energy within the jet wings (larger values of a) or both.

3. GRB 221009A

An upper limit of 13.8% (8.3%) was placed on the X-ray (optical) polarization at 3.5 days post-burst for the afterglow of GRB 221009A [19]. After constructing a numerical tool that produces polarization curves when given an afterglow model and a jet structure, it is employed on the shallow jet models suggested for GRB 221009A by [14, 18]. In Fig. 1 I present the temporal evolution of the linear polarization in the upper plot and the observed flux in the lower plot. The [18] model is presented in solid lines and the [14] model is shown in dash-dotted lines. The X-ray band is shown in blue and optical band is colored red. Triangles and circles stand for upper limits on the linear polarization and observed flux respectively. The two suggested jet structures agree with the upper limits placed at 3.5 days. In this case, linear polarization probably cannot distinguish between the two suggested jet structures. However, at times < 1 day there is a noticeable difference in the polarization curves of the two models while the light curves remain similar at those times. Had polarization been measured at earlier times in the X-ray band, the structure of the jet could have been better constrained.

4. Conclusions

In this work I aim to construct a numerical tool that produces polarization and light curves for different jet structures and afterglow models. While several jet models can reproduce the same observed light curve, their polarization may give differing predictions. This makes linear polarization a powerful observational quantity that can help uncover the processes the GRB jet underwent before breaking out of its confining medium, which cannot be probed otherwise. Adding energy to the jet structure beyond its core opening angle lowers the observed polarization degree which may help explaining low observed polarization degrees in GRB optical afterglows. A correlation between the polarization peak and break in the light curve is established for both on- and off-axis jets and used to visualize polarization as a tracer of asymmetry in the physical system. Finally, this tool is employed on the observed flux and polarization upper limits of GRB 221009A. While the observed polarization at 3.5 days post-burst cannot distinguish between the two jet structures explored in this work, a faster Imaging X-Ray Polarimetry Explorer (IXPE) response time might have allowed to do so.

References

[1] C.A. Meegan, G.J. Fishman, R.B. Wilson, W.S. Paciesas, G.N. Pendleton, J.M. Horack et al., *Spatial distribution of γ-ray bursts observed by BATSE*, **355** (1992) 143.

[2] C. Kouveliotou, C.A. Meegan, G.J. Fishman, N.P. Bhat, M.S. Briggs, T.M. Koshut et al., *Identification of Two Classes of Gamma-Ray Bursts*, **413** (1993) L101.

[3] D. Eichler, M. Livio, T. Piran and D.N. Schramm, *Nucleosynthesis, neutrino bursts and γ-rays from coalescing neutron stars*, **340** (1989) 126.

[4] A.I. MacFadyen and S.E. Woosley, *Collapsars: Gamma-Ray Bursts and Explosions in "Failed Supernovae"*, *The Astrophysical Journal* **524** (1999) 262.

[5] R.D. Blandford and R.L. Znajek, *Electromagnetic extraction of energy from Kerr black holes*, *Monthly Notices of the Royal Astronomical Society* **179** (1977) 433.

[6] E.E. Fenimore, C.D. Madras and S. Nayakshin, *Expanding Relativistic Shells and Gamma-Ray Burst Temporal Structure*, **473** (1996) 998 [astro-ph/9607163].

[7] R. Sari, T. Piran and R. Narayan, *Spectra and Light Curves of Gamma-Ray Burst Afterglows*, 9712005.

[8] B. Paczynski and J.E. Rhoads, *Radio Transients from Gamma-Ray Bursters*, *Astrophysical Journal Letters* **418** (1993) L5 [astro-ph/9307024].

[9] R. Sari, T. Piran and R. Narayan, *Spectra and Light Curves of Gamma-Ray Burst Afterglows*, *The Astrophysical Journal* **497** (1998) L17 [9712005].

[10] O. Gottlieb, E. Nakar and O. Bromberg, *The structure of hydrodynamic γ-ray burst jets*, **500** (2021) 3511 [2006.02466].

[11] P. Beniamini, R. Gill and J. Granot, *Robust features of off-axis gamma-ray burst afterglow light curves*, *Monthly Notices of the Royal Astronomical Society* **515** (2022) 555 [https://academic.oup.com/mnras/article-pdf/515/1/555/44927080/stac1821.pdf].

[12] A. de Ugarte Postigo, L. Izzo, G. Pugliese, D. Xu, B. Schneider, J.P.U. Fynbo et al., *GRB 221009A: Redshift from X-shooter/VLT*, *GRB Coordinates Network* **32648** (2022) 1.

[13] E. Burns, D. Svinkin, E. Fenimore, D.A. Kann, J.F. Agüí Fernández, D. Frederiks et al., *GRB 221009A: The Boat*, **946** (2023) L31 [2302.14037].

[14] B. O'Connor, E. Troja, G. Ryan, P. Beniamini, H. van Eerten, J. Granot et al., *A structured jet explains the extreme GRB 221009A*, *Science Advances* **9** (2023) eadi1405 [2302.07906].

[15] S. Lesage, P. Veres, M.S. Briggs, A. Goldstein, D. Kocevski, E. Burns et al., *Fermi-GBM Discovery of GRB 221009A: An Extraordinarily Bright GRB from Onset to Afterglow*, **952** (2023) L42 [2303.14172].

[16] D.B. Malesani, A.J. Levan, L. Izzo, A. de Ugarte Postigo, G. Ghirlanda, K.E. Heintz et al., *The brightest GRB ever detected: GRB 221009A as a highly luminous event at $z = 0.151$*, *arXiv e-prints* (2023) arXiv:2302.07891 [2302.07891].

[17] T. Piran, *Gamma-ray bursts and the fireball model*, **314** (1999) 575 [astro-ph/9810256].

[18] R. Gill and J. Granot, *GRB 221009A afterglow from a shallow angular structured jet*, **524** (2023) L78 [2304.14331].

[19] M. Negro, N. Di Lalla, N. Omodei, P. Veres, S. Silvestri, A. Manfreda et al., *The IXPE View of GRB 221009A*, **946** (2023) L21 [2301.01798].

[20] R. Sari, *Linear Polarization and Proper Motion in The Afterglow of Beamed GRBs*, *The Astrophysical Journal* **524** (1999) L43 [9906503].

[21] G. Birenbaum and O. Bromberg, *Modelling the linear polarization of GRB afterglows across the electromagnetic spectrum*, *Monthly Notices of the Royal Astronomical Society, Volume 506, Issue 3, pp.4275-4288* **506** (2021) 4275.

[22] R.A.M.J. Wijers, P.M. Vreeswijk, T.J. Galama, E. Rol, J. van Paradijs, C. Kouveliotou et al., *Detection of Polarization in the Afterglow of GRB 990510 with the ESO Very Large Telescope*, **523** (1999) L33 [astro-ph/9906346].

[23] S. Covino, G. Ghisellini, D. Lazzati and D. Malesani, *Polarization of Gamma-Ray Burst Optical and Near-Infrared Afterglows*, in *Gamma-Ray Bursts in the Afterglow Era*, M. Feroci, F. Frontera, N. Masetti and L. Piro, eds., vol. 312 of *Astronomical Society of the Pacific Conference Series*, p. 169, June, 2004, DOI [astro-ph/0301608].

[24] N. Mandarakas, D. Blinov, D.R. Aguilera-Dena, S. Romanopoulos, V. Pavlidou, K. Tassis et al., *GRB 210619B optical afterglow polarization*, **670** (2023) A144 [2208.13821].