Citation for published version:
Jordana-Mitjans, N 2021, 'How to probe GRB jets', *Astronomy & Geophysics*, vol. 62, no. 5, pp. 5.24-5.27.
https://doi.org/10.1093/astrogeo/atab089

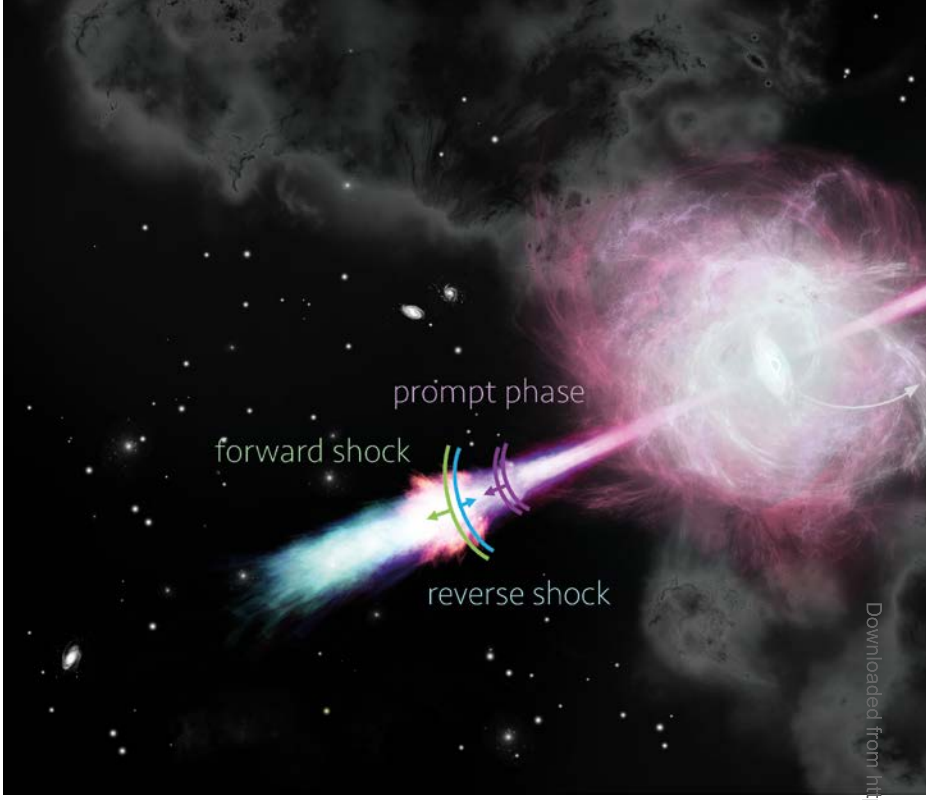
DOI:
10.1093/astrogeo/atab089

Publication date:
2021

Document Version
Publisher's PDF, also known as Version of record

How to probe

Núria Jordana-Mitjans explains how she uses linear polarization to unveil strong magnetic fields in gamma-ray burst outflows.



1 *Artist's impression of a gamma-ray burst outflow, from an equatorial view.* (N Jordana-Mitjans)

Polarization studies of gamma-ray bursts (GRBs) offer a great tool to infer the degree of order – and therefore the structure – of the magnetic field embedded in these relativistic jets. During the first hundreds of seconds after the burst, polarization observations are still sensitive to the jet physics and a variety of polarization signatures are expected for different jet models (unpolarized emission for a baryonic jet and polarized emission for a magnetized jet) and emission components (prompt phase, reverse shock and forward shock), which spectrally and temporally overlap. Here I review the current understanding of the role of magnetic fields in GRB outflows with the state-of-the-art optical polarization measurements at early times.

GRBs were discovered by the military-operated Vela satellites in the late 60s as mysterious gamma-ray flashes of extraterrestrial origin. With the launch of the GRB-dedicated Compton Gamma Ray Observatory (1991–2000) and BeppoSAX (1996–2002) gamma-ray telescopes, GRB sky distribution was mapped as isotropic and they were rapidly associated with extragalactic sources. Additionally, these gamma-ray flashes presented a bimodality in their hardness–duration distribution, which was traced back to two different progenitors.

GRBs that last more than 2 s have a softer, i.e. steeper, spectrum and are associated with the core collapse of massive stars. In contrast, short bursts are harder, with a flatter spectrum, and are related to mergers of an old population of degenerated compact stars (e.g. neutron star binaries). This classification is further supported by the different host-galaxy environments found in both GRB types, the presence of supernovae in long bursts, radioactively powered kilonovae in short bursts, and the joint detection of the short GRB 170817A with the gravitational wave event GW 170817 – the signature of the final stage of a neutron star binary inspiral and coalescence. More recently, the short GRB 200415A was also associated with a giant flare from a magnetar in the Sculptor galaxy.

GRBs are sources of extreme energy ($E = 10^{51}$–10^{54} erg) with material collimated and accelerated to bulk Lorentz factors of $\Gamma > 100$, close to the speed of light. They are produced when the accretion onto a new-born black hole or magnetar powers two highly relativistic jets that burrow through the stellar ejecta and, via internal dissipation mechanisms, emit the characteristic gamma-ray prompt emission. Additionally, a lingering non-thermal emission called the afterglow can be detected seconds to years after the burst at wavelengths across the electromagnetic spectrum. This afterglow emission radiates via the synchrotron mechanism and has its origin in the deceleration of the relativistic ejecta by the circumburst medium in a pair of shocks: a reverse shock that propagates backwards into the jet – powering bright and short-lived emission sensitive to the central engine properties – and a forward shock that travels into the interstellar ambient medium (figure 1). The interplay between these two external shocks leads to a variety of afterglow light curves.

Magnetic fields in GRBs

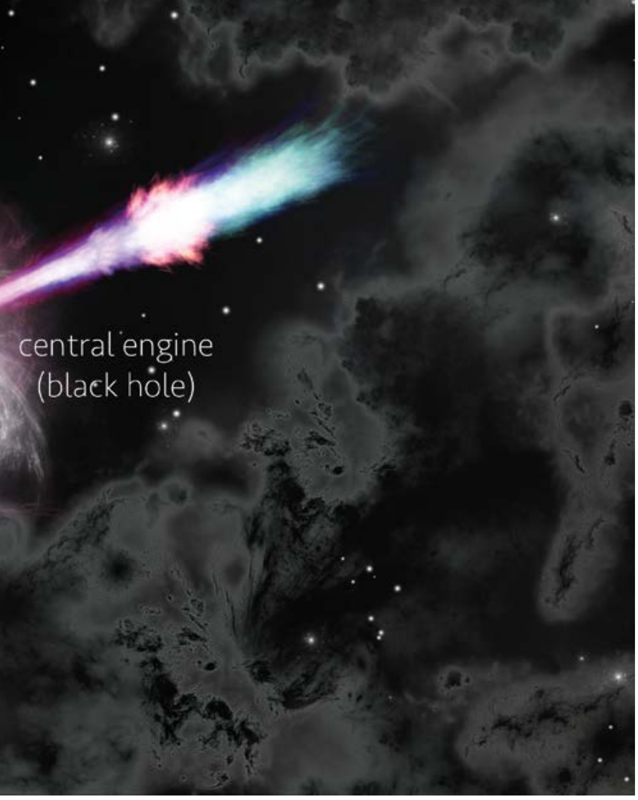
Magnetic fields play an important role in the physics of GRBs by affecting how the jet is launched and in shaping the afterglow emission. Depending on the driving energy of the outflow – if kinetic or magnetic – jets can be launched as baryonic or magnetized. The degree of magnetization of the outflow is usually characterized by σ, which is the ratio of magnetic to kinetic energy flux.

In a matter-dominated jet ($\sigma \ll 1$), neutrino annihilation at the polar regions of the accreting system is believed to form a thermally driven fireball. Therefore, weak tangled magnetic fields are generated locally, in shocks, and do not become dynamically important. Traditionally, this is the standard fireball model that has been the benchmark to understand the dynamics of GRB outflows.

In contrast, the magnetic-dominated jet model ($\sigma \gg 1$) claims that a large-scale magnetic field is powerful enough to extract the rotational energy from the central engine (or the accretion disc) and efficiently accelerate the material. Consequently, the detection (or non-detection) of this large-scale magnetic field remnant is crucial in order to support (or discard) the magnetized jet model.

A likely scenario is that GRB outflows are launched with both hot-baryonic and cold-magnetic components. The degree of magnetization (σ) at the different stages of the jet will have consequences for the prompt and the afterglow emission. If the outflow is matter-dominated at the prompt radius ($\sigma \lesssim 1$), the prompt emission is likely to come from internal shocks from shells ejected at different velocities – i.e. via kinetic energy dissipation mechanisms. If the outflow is strongly magnetized at the prompt emission radius ($\sigma \gtrsim 1$), magnetic dissipation mechanisms such as reconnection can take place, altering the magnetic field topology.

GRB jets could be magnetized when launched, but be already weakly or mildly magnetized at the prompt emission radius (radiating via internal shocks) and at the afterglow external shock. In this scenario, the magnetic fields ejected from the central engine would not play an



GRB jets

important role in dynamically driving the system, but can still affect the interaction between the outflow and the ambient medium – i.e. the strength of the reverse shock. The brightness of the reverse shock will increase with the outflow magnetization – reaching maximum brightness at $\sigma \sim 0.1$–1. For higher values of σ, the reverse shock will become progressively weaker to the extent that the magnetic pressure is likely to suppress its formation. If the jet is still highly magnetized at the prompt emission radius and reconnection mechanisms take place, the subsequent jet dynamics and early afterglow emission could still be affected by the primordial magnetic fields.

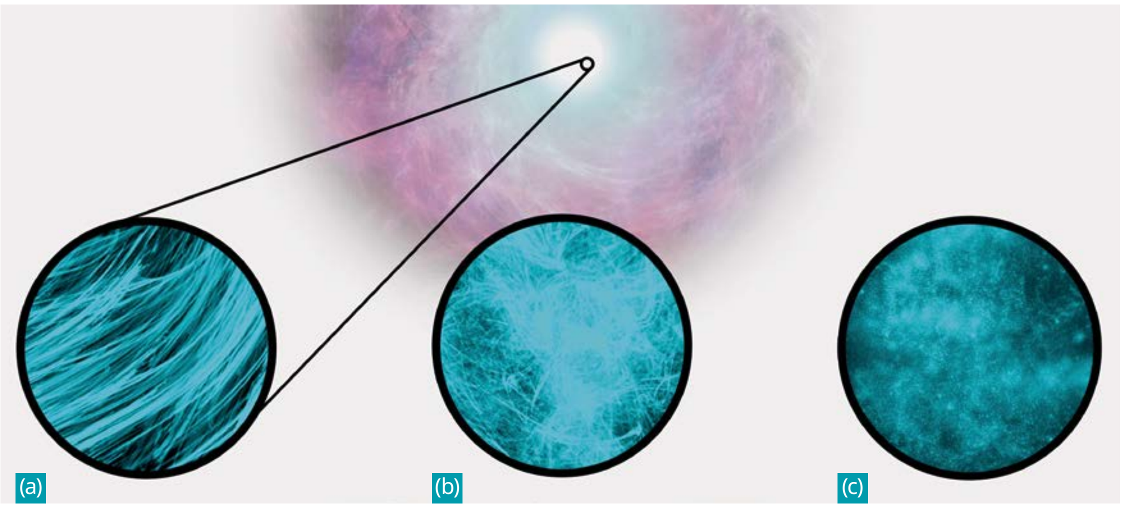
Expected polarization signatures at early times

GRBs are collimated outflows and, because of the relativistic beaming effect, we can only see a small angular region of the actual size of the jet; that is $\theta_v(t)=1/\Gamma(t)<\theta_j$ where θ_j is the jet opening angle. During the afterglow, the size of the visible emitting region increases with time as the outflow decelerates. In this scenario, the polarization of light provides a unique tool to study the magnetic field topology and the angular geometry of these extragalactic jets on length scales much smaller than what imaging can probe. Furthermore, it gives an extra dimension of information on the jet physics and emission mechanisms, which can eventually help to break the temporal and spectral degeneracy of the different emission components (prompt, reverse shock and forward shock). While the mechanism for the prompt emission is still under debate, the afterglow emission is widely proven to be synchrotron – which is intrinsically linearly polarized to $P=70\%$.

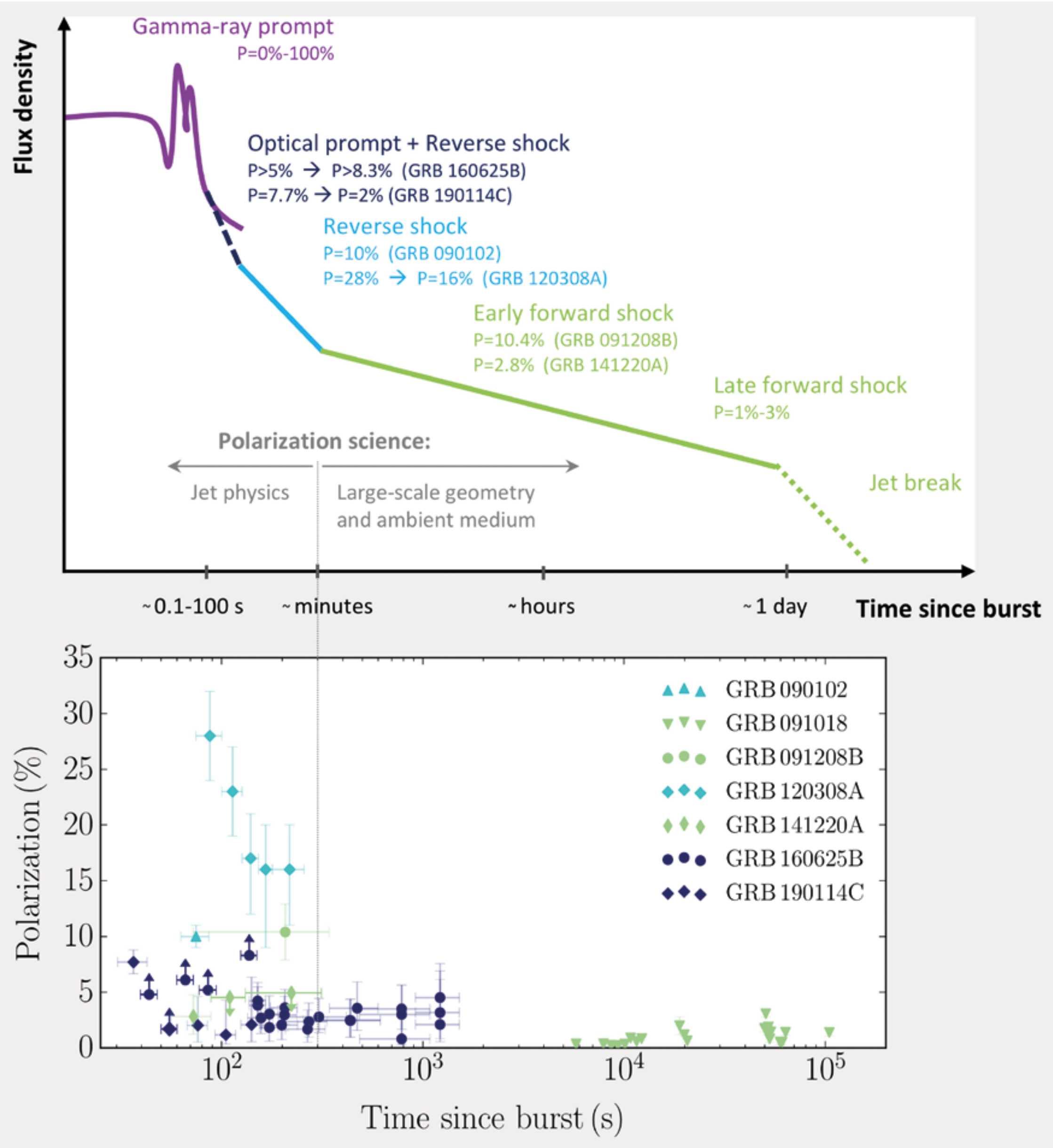
> *"The polarization of light is a unique tool to study the magnetic field and angular geometry of the jets"*

The long-lasting forward shock emission is powered by shocked ambient medium, with tangled magnetic fields locally produced in shocks (figure 2c) and amplified by e.g. a two-stream magnetic instability (Weibel instability). Note that a magnetic field amplification mechanism is needed to increase orders of magnitude the magnetic energy density of the interstellar medium to the levels we measure when modelling GRB afterglows. Therefore, the forward shock emission is insensitive to the magnetic field structure of the original ejecta and the magnetic field coherent length scales are much smaller than the observing region. Synchrotron intrinsic polarization is averaged out and we expect unpolarized emission from forward shocks.

In contrast, the fast-fading emission from the prompt and reverse shock is still sensitive to the properties of the central engine ejecta and measuring its polarization allows discriminating between competing jet models. In a baryonic jet ($\sigma \ll 1$), tangled magnetic fields are locally generated in shocks and the prompt and reverse shock emission is unpolarized (figure 2c). In a magnetized jet ($\sigma>1$), the large-scale magnetic fields ejected from the central black hole are frozen in the expanding ejecta (figure 2a). For mild magnetization regimes, both the prompt and reverse shock emission are expected to be highly polarized – with the maximum synchrotron polarization reduced to $P=50\%$ due to relativistic aberration effects (i.e. the rotation of the polarization vectors). Additionally, the magnetic fields could become slightly distorted during the internal shocks at the prompt phase, but we still expect large polarization because only a small area of the jet is observed as a result of relativistic beaming. In the case of a highly magnetized jet, reconnection mechanisms are thought to power the



2 *Magnetic field structures expected in GRBs outflows.* (a) *Large-scale ordered magnetic fields (P = 50% polarized).* (b) *Distorted ordered magnetic fields or overlapping emission components with distinct magnetic field properties (P < 50%).* (c) *Tangled magnetic fields (P = 0%).* (N Jordana-Mitjans)



3 *Temporal evolution of the different emission components and the relevant measurements of polarization at the GRB rest-frame. The colour map corresponds to forward shock-dominated emission (green), reverse shock (light blue) or reverse shock emission with contribution from prompt photons (dark blue). Note that polarization measurements up to a few minutes post-burst can be used to infer the jet physics and that late-time observations give information about the jet geometry and host galaxy dust properties.* (Adapted from Mundell *et al.* 2013. Data from Steele *et al.* 2009, Wiersema *et al.* 2012, Uehara *et al.* 2012, Mundell *et al.* 2013, Troja *et al.* 2017, Jordana-Mitjans *et al.* 2020, 2021)

prompt emission and are likely to distort the order in the magnetic fields (figure 2b).

Depending on the degree of magnetization of the outflow (σ) at the emission site, the different magnetic field structures will imprint a characteristic signal in the polarization degree and angle. Consequently, multiband early-time polarization measurements of GRBs are crucial for diagnosing the outflow composition and discriminating among competing jet models.

Polarization with rapid follow-up technology

While the afterglow emission from these extragalactic jets is faint in comparison to other sources in our galaxy, their characteristic gamma-ray prompt emission briefly outshines any source of gamma-rays in the universe. Consequently, we use gamma-ray satellite observatories to localize GRBs and real-time triggers to follow them up with ground-based telescopes.

Initial polarization studies with large telescopes in the 90s found few degrees of polarization hours to days after the burst during the long decay of the forward shock – when all candidate components of polarized emission have long subsided. Therefore, to distinguish between jet models and ultimately determine the power source of these energetic explosions, we needed polarimeters on fully autonomous telescopes to catch the fast-fading emission of the prompt and reverse shock (figure 3). Consequently, measurements of the early afterglow – seconds to minutes after the gamma-ray flash – became the domain of small and intermediate-sized robotic telescopes with rapid follow-up capabilities that do not need human intervention to start observations.

With the first-generation RINGO optical polarimeter at the largest fully robotic telescope, the 2 m Liverpool Telescope, Mundell *et al.* (2007) measured $P<8\%$ during the broad deceleration peak of the afterglow, at 3.3 min after GRB 060418. This first early-time polarization result was consistent with two interpretations: no large-scale magnetic fields in the fireball (baryonic jet) or strong magnetic fields that suppressed the reverse shock (highly magnetized jet).

Later on, the polarization measurement of $P=10\%$ during the GRB 090102 bright reverse shock was the first evidence of large-scale ordered magnetic fields in the outflow and proved that they can persist at great distances from the central source, up to the external shock radius (Steele *et al.* 2009). On this line, GRB 120308A time-resolved polarization measurements displayed a steady decay from $P=28\%$ to $P=16\%$ with constant polarization angle during a reverse-forward shock interplay (figure 3), implying an increase of unpolarized forward photons in the overall polarized emission received (Mundell *et al.* 2013). Additionally, GRB 110205A and GRB 101112A afterglows also displayed a reverse shock signature; Steele *et al.* (2017) measured significant polarized emission and further validated the existence of large-scale ordered magnetic fields.

> *"Multiband polarization measurements of GRBs are crucial to diagnose outflow composition"*

Lower limits on polarization were measured with the 0.4m MASTER II instrument during the long gamma-ray prompt emission of GRB160625B (Troja *et al.* 2017). The fading optical emission in between the gamma-ray pulses was interpreted as reverse shock and presented a significant increase of polarization from $P>5.2\%$ to $P>8.3\%$ cotemporal with a gamma-ray pulse – implying that polarized prompt photons contributed in the optical band. Additionally, the polarization lower limits were quite low for a reverse shock, which led to speculation about possible distorting mechanisms during the gamma-ray prompt emission, such as magnetic reconnection.

Overall, current modelling of the early GRB afterglow suggests mildly magnetized jets at the deceleration radius, with magnetization degrees $\sigma=0.1$–1, which is consistent with bright reverse shocks and large-scale ordered magnetic fields in the fireball. In this scenario, prompt emission is understood in terms of internal shocks and we expect high polarization for both prompt and reverse shock emission (see relevant measurements in figure 3).

Coherent length scale of magnetic fields

Pioneering observations of polarization in GRBs measured $P=1$–3% in the hours to days after the burst. These low polarization levels in forward shocks were usually attributed to dust in the GRB line-of-sight – from the Milky Way and the host galaxy – or as arising from asymmetries in the emitting region. For example, if the tangled magnetic fields are anisotropic in the shock direction, we would measure significant polarization when we notice the edge of the jet at the so-called light curve jet break (figure 3 upper panel) – usually at ~1 day post-burst when the emitting region size becomes of the order of the jet opening angle, $\theta_v(t)=1/\Gamma(t)\sim\theta_j$. Furthermore, different polarization signatures are expected depending on the jet angular geometry.

However, the intrinsic polarization of forward shocks at early times is still an open debate. While theory predicts unpolarized emission in forward shocks with magnetic length scales much smaller than the emitting region, Uehara *et al.* (2012) measured significant polarization $P=10.4\%$ in GRB091208B forward shock at 2.5–11.8 minutes after the burst and favoured the patches model. In this phenomenological model, the emitting region contains macroscopic magnetic domains – patches – with ordered magnetic fields and local polarization $P=50\%$. However, the orientation of the magnetic field is random from one domain to another and the polarization averages out when we include several patches – easily reproducing the polarization levels observed in GRB091208B. As the outflow decelerates, the visible emitting region increases and more randomly oriented magnetic domains are visible over time, producing a decrease of the polarization. Consequently, the GRB091208B measurement would still agree with the $P=1$–3% polarization measured in late-time forward shocks. Physically, this model proposes that the amplification mechanism of the magnetic field at the shock front leads to the formation of large magnetic domains.

In the recent paper Jordana-Mitjans *et al.* (2021), we report the early-time observations from GRB141220A forward shock. This afterglow has temporal and spectral properties typical of late-time forward shocks, but starting as early as 1.4 minutes post-burst. Additionally, our polarimetric observations at 2.2–3.4 minutes post-burst are earlier than GRB091208B measurement (figure 3), which acts as a microscope to probe smaller emitting regions. If the length scale of the magnetic field was the same as in GRB091208B, we would expect $P=20\%$ polarization for GRB141220A at the time of observations. Instead, we measure $P=2.8\%$ in GRB141220A, which agrees with theoretical predictions and other forward shock measurements minutes to days after the burst. Consequently, GRB091208B polarization measurements support a more stable underlying polarized component and ordered large-scale magnetic fields in the fireball.

Prompt polarization observations

Recent MASTER II and RINGO3 Liverpool Telescope observations of the first GRB detected at very high energies (in the TeV domain) reported remarkably low polarization for GRB190114C just after the end of the gamma-ray flash ($P=7.7\%$), a sharp drop of polarization one minute later ($P=2\%$) and constant levels during the following half an hour (Jordana-Mitjans *et al.* 2020; see figure 3).

We find that the $P=2\%$ polarization is probably from differential dust absorption in the line of sight – mainly due to the highly obscured environment in which the GRB was formed – which means that the intrinsic polarization of the jet is very small. The temporal and spectral modelling of GRB190114C emission indicates a clear interplay between the reverse and forward shock and more magnetization in the reverse shock, which suggests the existence of primordial large-scale magnetic fields. Overall, our polarimetric observations reveal that the magnetic field in the ejecta was mostly randomly oriented in space, which does not agree with what we expect from previous measurements of polarized reverse shocks.

Therefore, why was the polarization from the reverse shock so low in GRB190114C? We propose that the large-scale magnetic fields catastrophically collapsed during the first tens of seconds of the gamma-ray flash via magnetic reconnection mechanisms and that the $P=7.7\%$ measurement is a relic from this emission. In contrast to previous polarization measurements, these findings suggest that at least some energetic GRBs can be launched highly magnetized and that magnetic dissipation mechanisms can power the bright gamma-ray prompt emission. Also, it pins down timescales and distances for which large-scale magnetic fields survive in astrophysical jets and challenges the current models for the production of GRBs.

Looking forward

After 15 years of progress in early-time polarization studies of GRB afterglows, we can confidently confirm the presence of large-scale ordered magnetic fields in a subset of bright afterglows, suggesting that the magnetic field ejected from the central source does indeed play a role in the jet launching. We have not measured the maximum polarization allowed by theory in reverse shocks ($P=50\%$) and polarization observations indicate that highly polarized emission at $P=28\%$ level is not common (GRB120308A; Mundell *et al.* 2013). Therefore, mechanisms that can change the magnetic field topology might play an important role at the early stages of GRB jets.

Great advances will be made in constraining GRBs jet models when we start to accumulate a large polarimetric dataset of measurements at early times and we sample most of the GRB population, at lower luminosities – which needs faster target acquisition and an increase in the sensitivity of polarimeters. Furthermore, other TeV GRBs have now been discovered – something we did not expect before the Cherenkov Telescope Array (CTA). With the start of the CTA era, we will be able to track the earliest stages of the magnetic field and its evolution in the most energetic systems. Consequently, we will need new polarization technology to optimize the follow up with CTA as well as other multimessenger triggers such as gravitational waves or, possibly, neutrinos. ●

> *"We can confirm the presence of large-scale ordered magnetic fields in a subset of bright afterglows"*

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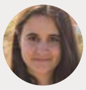

Núria Jordana-Mitjans is a PhD student at the University of Bath, UK, and holder of the Sherwin scholarship. This article is based on her winning entry to the 2020 RAS Early Career Network Poster Competition

ACKNOWLEDGEMENTS

The author would like to acknowledge collaborators CG Mundell, S Kobayashi, RJ Smith, C Guidorzi, A Gomboc, M Marongiu, IA Steele and M Shrestha

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