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*Review Article*

# Gamma-Ray Bursts in the Era of Rapid Followup

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We present a status report on the study of gamma-ray bursts (GRBs) in the era of rapid followup using the world's largest robotic optical telescopes—the 2 m Liverpool and Faulkes telescopes. Within the context of key unsolved issues in GRB physics, we describe (1) our innovative software that allows real-time automatic analysis and interpretation of GRB light curves, (2) the novel instrumentation that allows unique types of observations (in particular, early time polarisation measurements), and (3) the key science questions and discoveries to which robotic observations are ideally suited, concluding with a summary of current understanding of GRB physics provided by combining rapid optical observations with simultaneous observations at other wavelengths.

## 1. Introduction

Gamma-Ray Bursts (GRBs) are the most powerful explosions in the Universe and, arguably, represent the most significant new astrophysical phenomenon since the discovery of quasars and pulsars. As their name suggests, GRBs are detected as brief, intense and totally unpredictable flashes of high-energy gamma rays, thought to be produced during the core collapse of massive stars (long-soft bursts, $T_\gamma > 2$ seconds) or the merger of two compact objects such as two neutron stars or a neutron star and a stellar-mass black hole (short-hard bursts, $T_\gamma < 2$ seconds). Although discovered through their $\gamma$-ray emission [1], they are now known to emit nonthermal radiation detectable across the electromagnetic spectrum [2–4]. However, despite their enormous luminosity, their unpredictability and short duration limit rapid, accurate localisation and observability with traditional telescopes. Consequently, new ground and space-based facilities have been developed over the past decade; dedicated satellites optimised for GRB detection and followup, such as Swift [5], are revolutionizing GRB studies by locating ∼100 bursts per year with $\gamma$-ray positions accurate to $\sim 3'$ and X-ray positions accurate to $5''$ within seconds or minutes of the burst. Here we describe the automatic ground-based followup of GRBs with the world's largest robotic optical telescopes that use intelligent software and innovative instruments.

*The Era of Rapid Followup: Predictions and Outcomes.* Before the launch of current satellites such as Swift, Integral, and Fermi, significant progress in understanding GRBs had been made since their discovery, in particular the general $\gamma$ and X-ray properties. The first crucial step in disseminating real-time GRB positions to ground observers was triggered by BATSE on the CGRO [6] through the GRB Coordinates Network (GCN) [7] via internet socket connection (no humans-in-the-loop). This drove development of the first generation of wide-field robotic followup ground-based facilities, such as GROCSE, ROTSE, and LOTIS, culminating with the discovery of the optical flash associated with GRB 990123 [8]. BATSE provided an invaluable catalogue of prompt $\gamma$-ray profiles, whose isotropic sky distribution and inhomogeneous intensity distribution suggested a cosmological origin [6], and BeppoSAX [9] revolutionised the cosmological study of GRBs by providing subarcmin ($\sim 50''$) localisation of X-ray afterglows that enabled late-time (∼hours) optical followup with traditional ground-based telescopes and redshift determinations. Collimation of the ejecta (i.e., jets) was inferred from temporal breaks—steepening—of optical light curves at ∼1 day post burst and

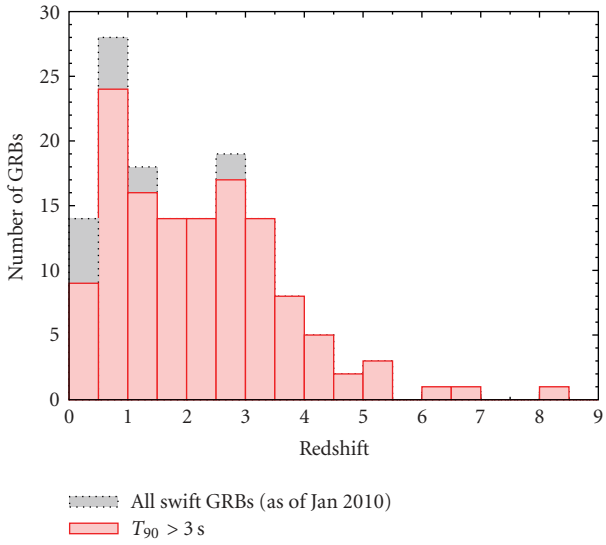



Figure 1: Redshift distribution of *Swift* GRBs detected to-date.

the concept of a universal central engine and the use of GRBs as standardisable cosmological candles was introduced [10, 11].

The possibility for great advances with the launch of Swift was fully recognised. Optical counterparts were expected to be found for all GRBs with many GRBs expected to exhibit bright optical flashes from reverse shock emission at early-times, similar to GRB 990123 [8]. An increase in the number of GRBs detected would lead to many jet breaks being identified, short GRBs would be easily observed and understood, and identification of GRBs at very high redshift would be routine. Instead, 50% of GRBs remain optically dark, despite deep, rapid followup [12–15]; there is a dearth of bright reverse-shock optical emission [16]; light curves are complex in all bands with a variety of chromatic and achromatic breaks and flares observed (e.g., [17–23]). Jet breaks have proven elusive, short bursts remain technically challenging [24], and only 3 GRBs have been identified to lie a $z > 6$ (Figure 1) [25–28].

## 2. Robotic Followup and Intelligent Autonomy

The field of GRB research is the most rapidly evolving topic in modern day astrophysics—driven primarily by technological innovation in both hardware and software; most notable is the need for rapid, intelligent, and fully autonomous followup. Within the context of robotic telescopes devoted to searching for optical counterparts to GRBs (e.g., [29–36]), the Liverpool Telescope (LT) offers a unique combination of sensitivity, speed, instrument choice, and real-time reduction pipeline with complexity and flexibility. The LT, owned and operated by Liverpool John Moores University (LJMU), has a 2 m diameter mirror, altitude-azimuth design, final focal ratio f/10, a comprehensive suite of instruments, and a fully robotic control system. As shown in Figure 2, it is sited at the Observatorio del Roque de los Muchachos in La Palma. Optimised for robotic followup of transient sources, the LT was designed to have a fully open enclosure, robustness to wind gusts, and a fast slew rate of 2°/s; currently as the fastest telescope for its size, it observes GRBs within 1–3 minutes of receipt of a satellite alert. Although smaller robotic telescopes slew more quickly, the LT is more sensitive to fainter bursts at early-time. Most importantly, the LT can perform unique early-time polarisation measurements (see Section 4).

Table 1: Current instrumentation on the Liverpool and Faulkes telescopes and associated GRB science goals; upcoming instrumentation is shown in italics.

| Instrumentation | Science goals |
|---|---|
| Optical Camera (FoV ~ 5′) (BVRi′z′) (LT/FTN/FTS) | (i) Early multicolour light curves<br>(ii) Shock physics/ISM studies<br>(iii) Later-time light curves/jet breaks<br>(iv) GRB-supernova connection |
| RINGO2 polarimeter (FoV ~ 4′) (LT only) | (i) Early-time polarisation studies 1% polarisation at $r' < 17$ mag in 1 minute<br>(ii) Fundamental tests of magnetization |
| SupIRCam Infrared Camera (FoV ~ 1′) (LT only) | (i) High-$z$ "naked" bursts<br>(ii) Low-$z$ "obscured" bursts |
| FRODOSpec IFU (FoV ~ 11″) (LT only) | (i) Early evolution of circumburst medium |
| STILT (FoV 1°/20°/180°) (LT only) | (i) Bright bursts/neutrino counterparts |
| *IO—wide-field optical/IR imager (LT-2010)* | (i) Deep, simultaneous optical/IR light curves over 2° FoV |

The LT has five instrument ports: four folded and one straight-through, selected automatically within 30 seconds by a deployable rotating mirror in the Acquisition and Guidance (AG) box. Table 1 describes the instruments available and the related GRB science goals. All GRB followups with the LT begin with RINGO polarimetry exposures before continuing with a sequence of 10-s $R$-band exposures that are used to automatically identify an optical counterpart, determine its characteristics, and conduct subsequent optimized followup observations with the most appropriate instrument. Guidorzi et al. [36] describe the intelligent software logic—LT-TRAP—developed to perform the real time analysis and followup. Automatic multicolour light curves of optical transients brighter than $R \sim 19$ mag are produced in real-time; transients brighter than $R \sim 15$ mag trigger additional RINGO polarisation observations before continuing with multicolour imaging. Faint OTs or nondetections trigger deep exposures in red filters. The 2 m Faulkes telescopes[1], clones of the LT, provide additional sky coverage, operate the same intelligent LT-TRAP software—apart from small differences due to the different instruments mounted on each facility—and concentrate on multicolour optical imaging (Figure 2 and Table 1). Figure 3 displays the flow chart of the LT-TRAP.

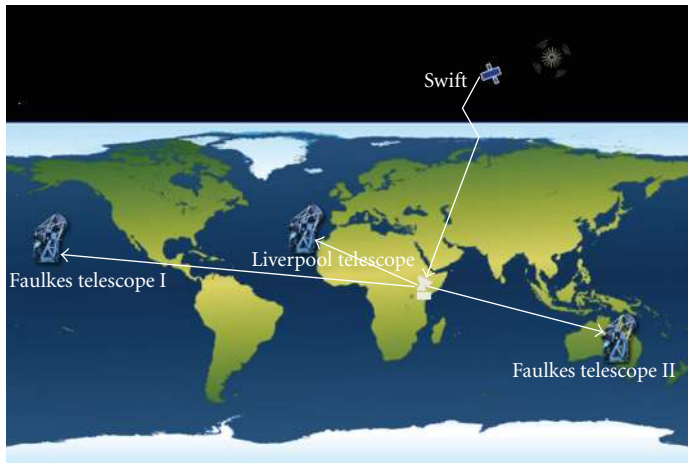



Figure 2: The locations of the 2 m robotic Liverpool Telescope and its clones the Faulkes telescopes. GRB triggers from satellites drive prompt automatic followup.

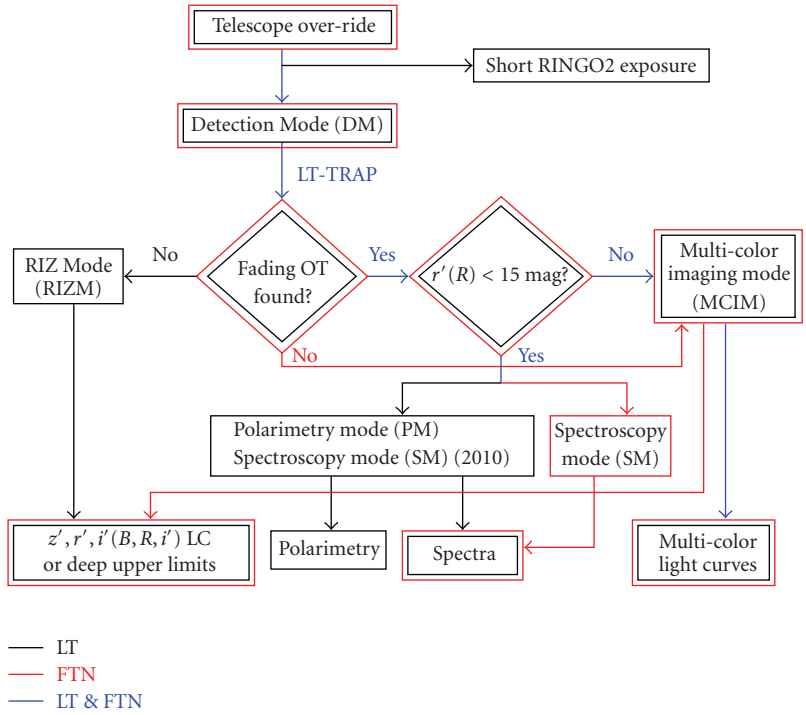



Figure 3: Flow chart of the robotic GRB pipeline currently running on the Liverpool and Faulkes Telescopes (adapted from [36]).

## 3. Characteristics of Multiwavelength Light Curves

A major breakthrough provided by Swift was the discovery of complex light curves at X-ray energies that led to introduction of the so-called canonical light curve [37, 38], characterized by four decay segments: (1) an "early steep decay" with power-law decay indices ~3 or even steeper; (2) a "shallow or flat decay" with a typical index around 0.5; (3) a normal decay, with indices around 1.2; and (4) finally, the late steep decay with typical values around 2. In ~50% of cases, flares are also superimposed [20, 21]. Some complexity is attributed to on-going central engine activity producing different emission components that originate from spatially distinct regions but that are temporally coincident, but alternative explanations invoking an external origin have also been suggested [39, 40]. Unlike other high-energy phenomena such as Active Galactic Nuclei, GRBs will remain spatially unresolved with current and future instrumentation. Model-dependent temporal properties therefore provide a powerful, indirect probe of the expanding fireball and its interaction with the surrounding medium. Polarisation measurements provide a *direct* probe.

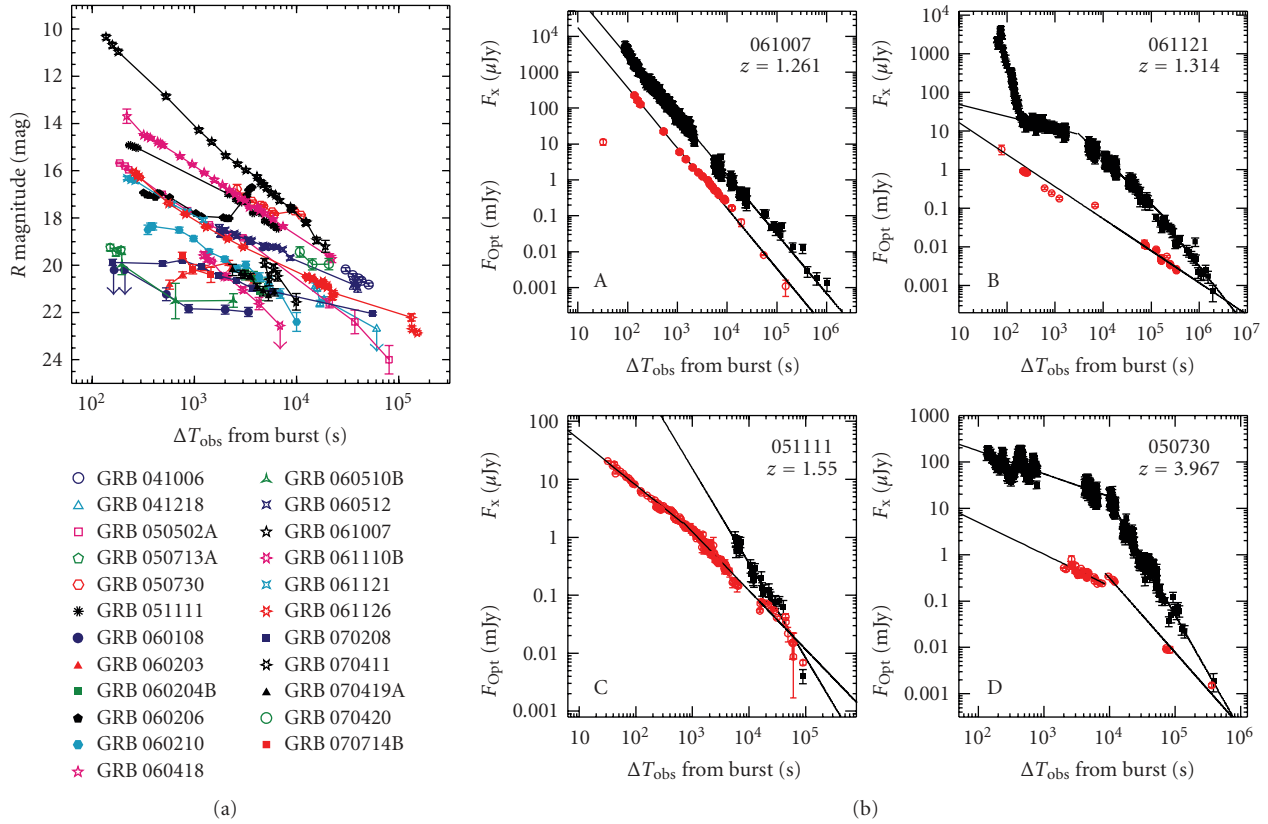



FIGURE 4: (a) Selection of early-time optical light curves from the Liverpool and Faulkes telescopes. (b) Examples of X-ray (black) and optical (red) light curve comparisons leading to classification scheme using synchrotron model breaks [12].

At optical wavelengths, a variety of light curve properties are expected depending on the relative contributions of emission from reverse and forward shocks, the presence of additional energy injection by a long-lived central engine, and the time of the observations with respect to the initial burst.

Melandri et al. [12] classified a sample of 63 bursts via their optical and X-ray light curves. 50% of the sample remained optically "dark" despite rapid, deep observations through red filters. Optical counterparts ranged in brightness from $R \sim 10$ mag to $\sim$22 mag in the first minutes after the burst and showed a range of decay behaviours (Figure 4). Flares, although less common in the optical than X-ray band, were present and in some cases (e.g., GRB 060206) showed direct evidence of significant energy injection [41–44].

By comparing optical and X-ray light curves observed from $t = 100$ seconds to $\sim 10^6$ seconds post burst, Melandri et al. [12] introduced a coherent classification of optical/X-ray light curves under the framework of the standard fireball model and synchrotron theory, using the presence or absence of temporal breaks in each band (Figure 4); the temporal location and evolution of chromatic and achromatic breaks depend on typical synchrotron and cooling frequencies with respect to the observing bands. Simply, class A shows no break in optical or X-ray bands because $\nu_c$ lies above or between the two bands; class B shows a break in the X-ray but not in the optical band as $\nu_c$ passes through the X-ray band; class C shows a break in the optical but not the X-ray band due to $\nu_c$ passing through the optical band; class D has breaks in both bands as energy injection stops or a jet break occurs. 60% of optically detected bursts were explained with the forward shock model, while the remainder required energy injection and/or an ambient density gradient. GRB 070419A required a long-lived central engine ($\sim$250 seconds in $\gamma$ and X-rays), a finely tuned energy injection rate and an abrupt cessation of injection (Figure 5).

*3.1. Long-Lived Central Engines Explain Bright and Dark Bursts.* Large robotic telescopes such as the LT provide deep upper limits at early-times (e.g., $R < 22$ mag), thereby ruling out slow followup as a reason for nondetection of optical afterglows. Observing with red filters, the LT and FTs can identify GRBs at $z < 4$ within the first few minutes after the burst via $R$-band photometric dropouts; a deep, early upper limit in $R$-band plus an $i'$-band detection quickly identified GRB 060927 as a moderately high-redshift source ($z = 5.467$) [46, 47]. Whilst a small fraction of optically undetected GRBs may lie at very high redshift so have their rest frame emission redshifted out of optical observing bands (e.g., GRB 090423 at $z = 8.1$ [27, 28]), others require a physical explanation for their darkness. Some may be explained by a relatively flat optical-to-X-ray spectral index and modest dust extinction (e.g., GRB 060108 [48]; for typical extinction values, see, e.g., [49, 50]). The underlying physical mechanism may be energy

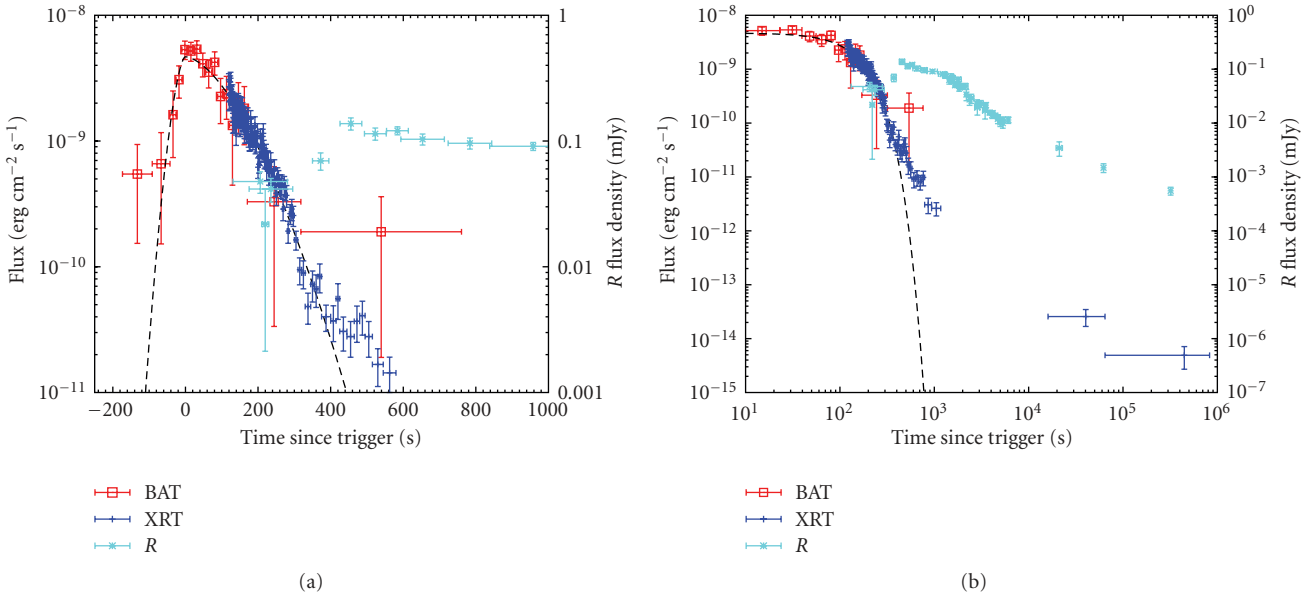



FIGURE 5: $\gamma$-ray, X-ray, and optical light curves of GRB 070419A. (a) Early-time light curves plotted on linear-log scale. (b) Later time evolution included and shown on log-log scale (see Melandri et al. [45]).

injection; as discussed above, a long-lived central engine is required to explain the properties of bright bursts but such a model may also provide a self-consistent explanation for dark bursts at intermediate redshift ($z < 6$). Enhanced X-ray emission in the early-time X-ray afterglow due to late-time central engine activity would make the bursts brighter than expected in the X-ray band compared to the optical band [12].

## 4. Magnetized Fireballs?

The production of synchrotron radiation requires the presence of a magnetic field but the degree of magnetization and the configuration of the magnetic fields remain a matter of debate (e.g, [51–53]). Determination of the magnetic field properties is key to understanding the driving mechanism of the explosion, namely, whether the ultrarelativistic ejecta are dominated by kinetic (baryonic) or magnetic (Poynting flux) energy. The ratio of magnetic and kinetic energy flux, $\sigma$, is used to express the magnetization (e.g., [54]) and is large if the magnetic field originates at the central engine and is advected outwards with the relativistic flow (Poynting flux jet). For a baryonic jet, $\sigma \ll 1$ and magnetic fields are assumed to be produced locally in the shock. Magnetization may be inferred from optical light curves, given a variety of assumptions, or determined directly from measurements of the degree of polarisation of the optical afterglow. In both cases, observations at the earliest possible time after the burst—when the magnetic properties of the expanding fireball are still encoded in the emission—are essential to address these issues.

*Indirect Observational Tests—Light Curve Evolution.* In the standard fireball model (see [55–59] for reviews) a shell of the relativistically expanding fireball collides with the circumburst medium to produce an external shock that results in the long-lived afterglow emission detectable from X-ray to optical, IR, or sometimes radio frequencies. A reverse shock propagating backwards through the shell may, in some circumstances, produce short-lived but bright optical emission—the so-called optical flash. Figure 6 shows three possible optical light curves with the relative contributions from the reverse and forward shocks identified. The strength of the reverse shock depends on magnetization and whether the typical frequency is close to the optical band [52, 54].

The dearth of reverse-shock optical flashes from Swift GRBs may be explained in the standard model via weak, nonrelativistic reverse shocks and a typical frequency far below the optical band at early-time; the bright optical counterpart to GRB 061007 (Figure 7) illustrates this with its light curve comprising forward shock emission only and the typical frequency of the reverse shock emission being shown to lie in the radio band as early as 137 seconds after the burst [60]. Alternatively, some optical flashes may be suppressed by strong magnetization.

*Direct Observational Tests—Polarisation.* Synchrotron radiation is intrinsically highly polarised; specific properties of the emitting region may reduce the observed degree of polarisation, (e.g., [63–71]), so detection of significant polarisation at early-time provides a direct signature of large-scale ordered magnetic fields in the expanding fireball [72]. Claims of high levels of polarisation observed in the gamma-ray prompt emission have remained controversial: Coburn and Boggs [73] reported a high degree $P = 80 \pm 20\%$ of linear polarisation of the prompt emission of GRB 021206, but reanalysis of the data showed null polarisation [74, 75]. In other cases, BATSE data of two bursts were reported to

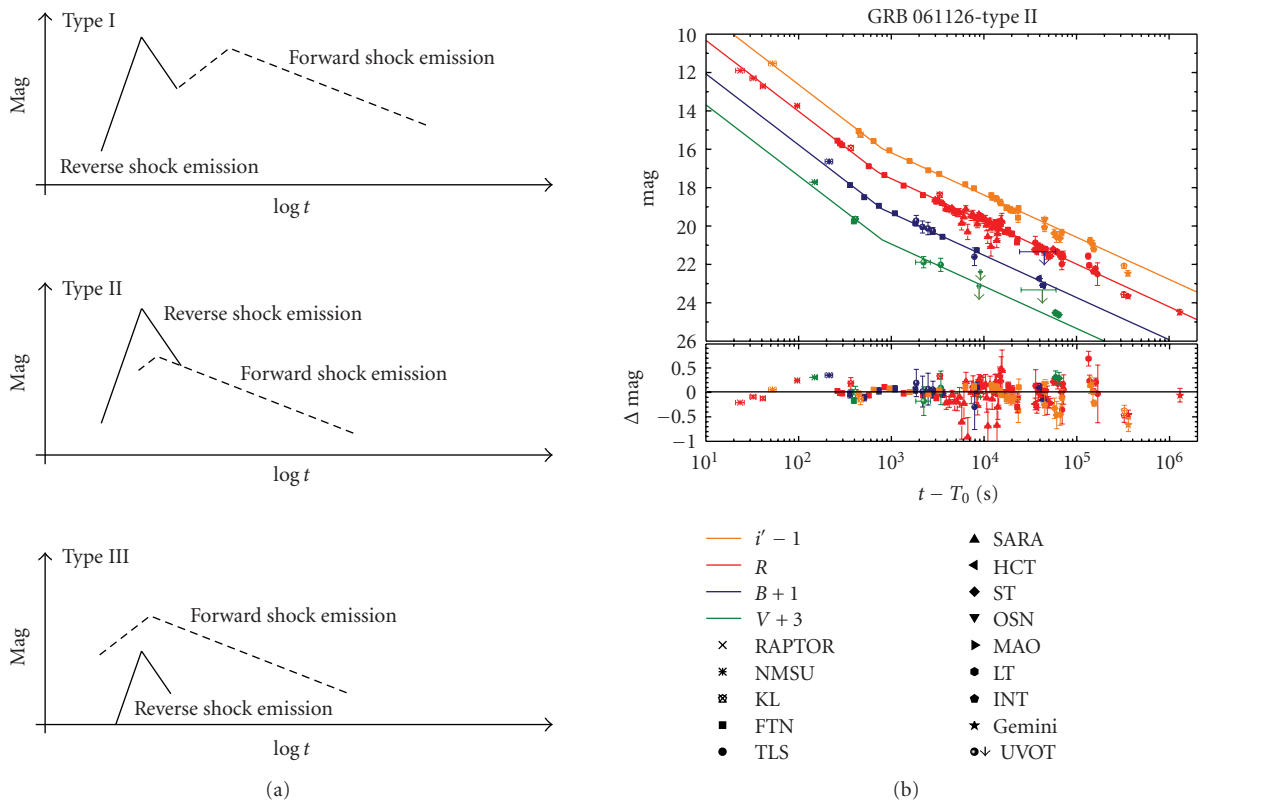



FIGURE 6: (a) Light-curves with different reverse-forward shock contributions. Magnetic energy density determines the relative contributions [61]. (b) Optical light curves of GRB 061126 showing the steep-to-shallow temporal break characteristic of a Type II reverse-forward shock observed after the reverse-shock peak [62].

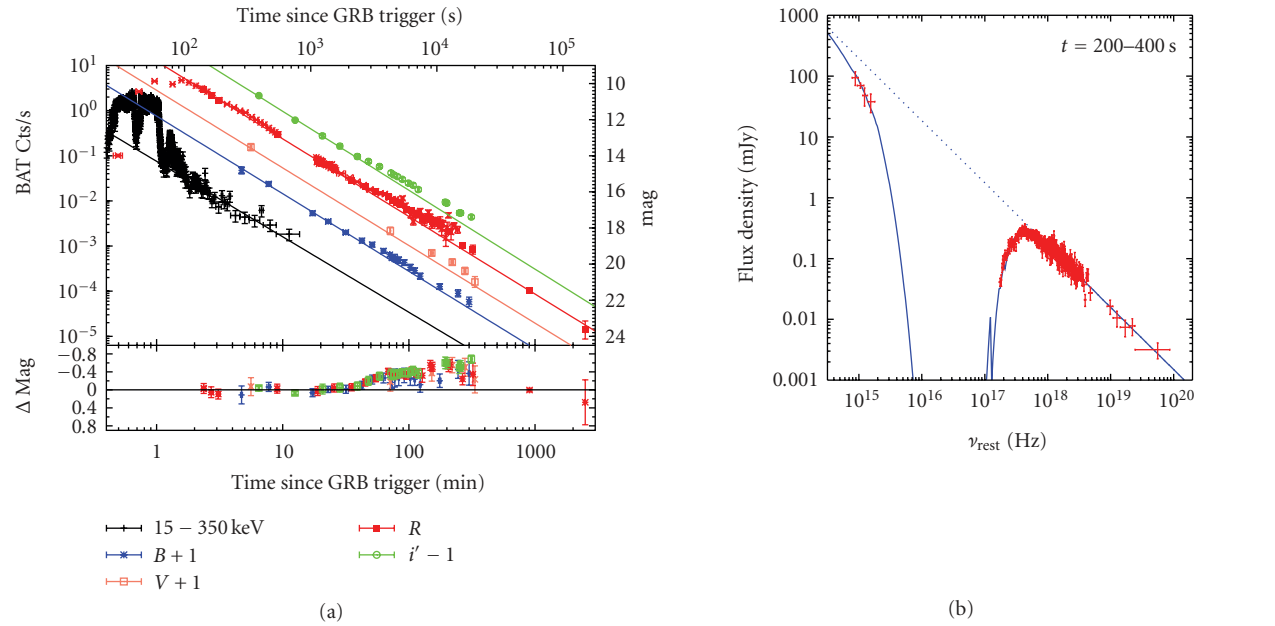



FIGURE 7: (a) $\gamma$-ray (black) and optical $BVRi'$ (colour) light curves of GRB 061007 all decaying with a steep power-law index $\alpha \sim 1.7$ from 137 seconds to $\sim 10^6$ seconds. Despite its optical brightness ($R \sim 10.3$ mag at 137 seconds), a reverse-shock optical flash is ruled out (adapted from [23, 60]). (b) Early-time (200–400 seconds) broad-band optical to $\gamma$-ray SED fitted with single absorbed power law $\beta$(opt-X-$\gamma$) = 1.02 $\pm$ 0.05 and rest-frame extinction $A_V$(SMC) = 0.48 $\pm$ 0.19 mag (from [60]).

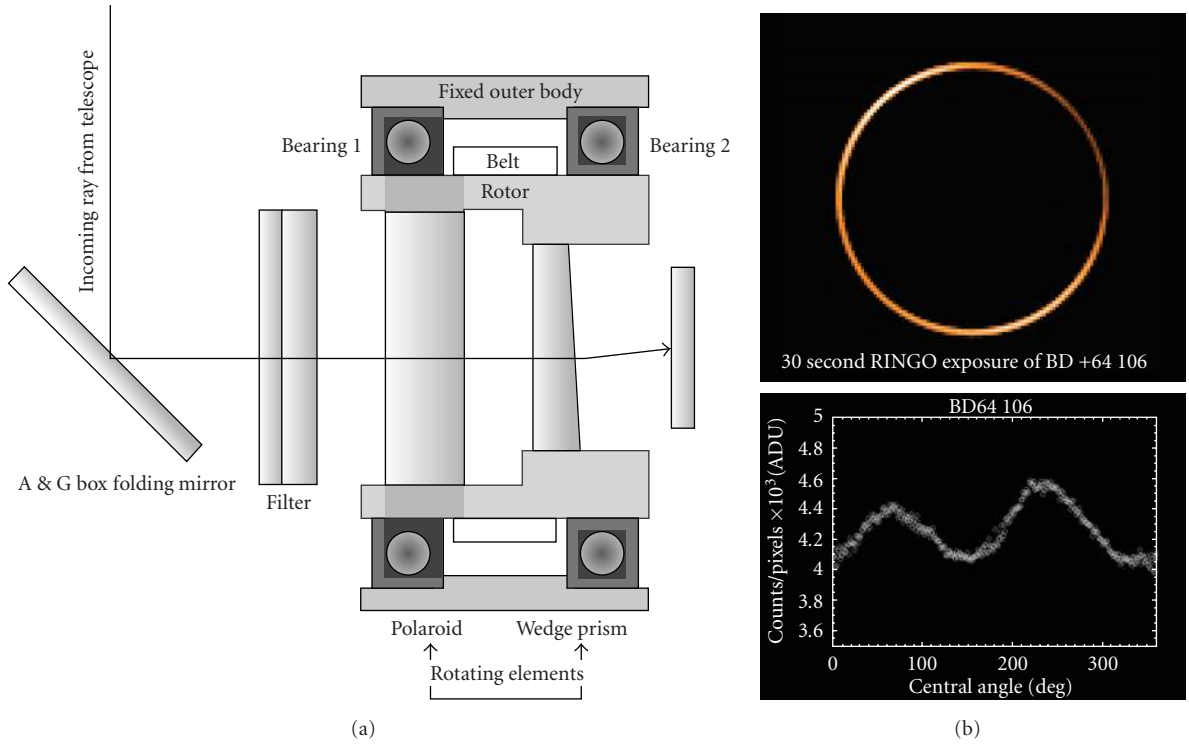
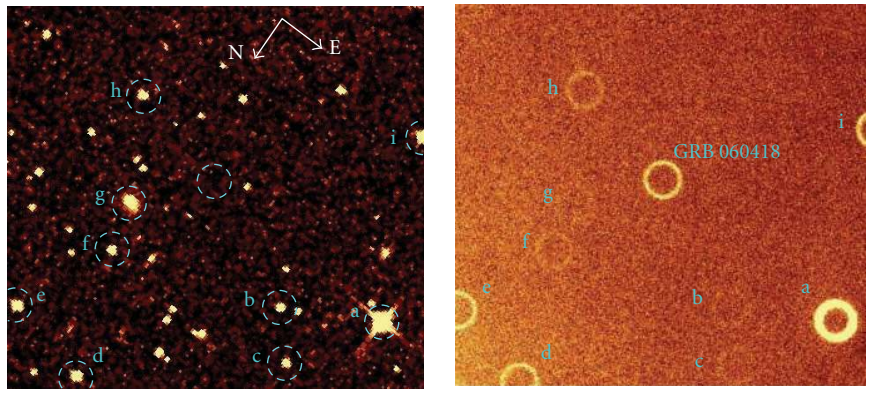



Figure 8: (a) Diagram illustrating design of RINGO. (b) Polarised star BD +64 106 observed through RINGO (top panel): calibrated trace around ring showing polarisation signature (from [82]).

show evidence for $P > 35\%$ and >50% using a GEANT4 model of the Earth albedo [76]. More recently, observations of GRB 041219A with the INTEGRAL imager IBIS show polarization up to 43% with rapid variability of degree and position angle [71], although independent confirmation with spectrometer SPI data remains difficult due to instrumental systematics [77, 78]. In the remaining cases, only upper limits to possible large polarisation degrees have been reported (e.g., [79]). Although careful calibration of instrumental systematics for $\gamma$-ray data remains challenging, these measurements show tantilising support for large-scale ordered magnetic fields in the region responsible for the prompt $\gamma$-ray production. Measuring the early optical polarisation provides a direct probe of the magnetic field configuration. Optical polarisation observations of GRBs have the advantage that stars in the GRB field of view can be used as simultaneous independent checks on any instrumental systematics. Theoretical models of GRBs predict that mildly magnetized outflows produce strong reverse shock emission that should be polarised [51, 52, 68, 69, 80, 81], making early-time optical polarisation measurements vital for direct determination of the magnetic field structure.

The time-variable nature of optical emission from GRBs, however, makes traditional polarisation instruments unsuitable; we therefore designed the novel RINGO polarimeter on the LT [82], whose overall layout is shown in Figure 8. Its design was based on a novel ring polarimeter concept explored by Clarke and Neumayer [83]. This makes use of a rotating Polaroid to modulate the incoming polarised flux to be studied and is followed by deviating optics which corotate. A filter equivalent to $V + R$ bands was chosen to optimise the signal to noise ratio, as estimated from the typical GRB colours and to avoid the fringing on the CCD that the I filter would have caused. The result of this design is that each source image is recorded on the CCD as a ring, with the polarisation signal mapped out along the ring in a $\sin(2\theta)$ pattern (Figure 8(b)). One benefit of this design is the reduction of the saturation constraints on high precision photometry, as the flux is spread over the pixels along the ring. The potential problem of many rings overlapping with each other is only a concern for crowded fields which correlate with low galactic latitudes, that is, where GRB optical counterparts are strongly extinguished and therefore observationally already disfavoured. The design was optimised through requirements on (i) the rotation speed, to minimise impact on the polarisation ring profiles; and (ii) the geometry of the deflecting optics, to optimise the ring size. The polarimetric accuracy of RINGO is a few percents for an $R = 15$-mag object in a 10-second long exposure and decreases to a few 0.1% in a 10-minute exposure. Further details on the RINGO polarimeter and its calibration and data reduction can be found in Steele et al. [82].

RINGO has now measured the optical polarisation of two GRBs (Figures 9, 10, and 11): Mundell et al. reported $P < 8\%$ in GRB 060418 at 203 seconds post burst [84] and Steele et al. 2009 measured $P = 10.2 \pm 1.3\%$ in GRB 090102 at 160.8 seconds post burst [85]. In the standard




(a) (b)

Figure 9: (a) DSS image of the field before the occurrence of GRB 060418. (b) RINGO image showing GRB 060418 and other field sources as rings (from [84]).

GRB fireball model both a forward shock, propagating into the circumburst medium, and a reverse shock, propagating into the GRB ejecta, contribute to the observed afterglow emission [61, 86] (Figure 6). The measurement in GRB 060418 was made close to the peak in the optical light curve at the time of deceleration of the fireball associated with the onset of the afterglow, when the reverse and forward shocks contributed equally to the detected light, while GRB 090102 was measured when the light curve was dominated by reverse-shock emission. Below we summarise the observations and suggest a unifying model to reconcile the two results.

*Optical Polarisation Measurements of GRB 060418 and GRB 090102.* The RINGO images of the fields containing GRB 060418 and 090102 are shown in Figures 9 and 10. GRB 060418 was detected by the Swift Burst Alert Telescope (BAT) on April 18, 2006 and showed a multipulsed gamma-ray profile with a total duration of 52 seconds, followed by a separate small bump at 130 seconds concomitant with a large X-ray flare observed with the Swift X-Ray Telescope (XRT) [87, 88] and probably due to prolonged internal activity (see Figure 11). A number of robotic facilities reacted to the prompt Swift alert and detected the optical and NIR counterpart: in particular, REM detected a smooth optical rise peaking at 153 seconds, interpreted as the onset of the afterglow [89], whereas the X-ray curve was seen to decline from the beginning, apart from the large flare mentioned above (Figure 11). The LT was triggered automatically, starting observations with a 30-second long exposure taken with the RINGO polarimeter at 203 seconds post GRB, that is, simultaneously with the fading tail of the prompt gamma-ray emission (Figure 11) and the close to the X-ray flare. However, the contribution in the optical band from the X-ray flare was estimated to be negligible, thus confirming that RINGO measured the afterglow [84].

Swift detected GRB 090102 on 2 January 2009 at 02:55:45 UT, with a pulse of gamma rays lasting $T_{90} = 27$ seconds and comprising four overlapping peaks starting 14-second before the trigger time [91]. The automatic localization was communicated to ground-based facilities, and a single 60-second RINGO exposure was obtained starting 160.8 seconds after the burst. Simultaneous with our polarization observation of GRB 090102, a number of automated photometric followups were performed by other facilities [85]. The optical light curve (Figure 11), beginning at 40-second post burst, is fitted by a steep-shallow broken power law $\alpha_1 = 1.50 \pm 0.06$ and then $\alpha_2 = 0.97 \pm 0.03$ after approximately 1000 seconds [90]. In contrast, the X-ray light curve began at 396 seconds post burst and shows a steady decay consistent with a single power law with slope $\alpha = 1.36 \pm 0.01$ and no evidence of flares or breaks up to $t > 7 \times 10^5$ seconds [90]. The absence of additional emission components, for example, from late-time central engine activity, in the optical light curves of GRB 060418 and 090102 allows a straightforward interpretation of their early-time polarisation in the context of current GRB models.

Despite the brightness of the optical afterglow of GRB 060418, no dominant reverse shock was observed, similar to other cases in which the typical frequency is inferred to lie below the optical band at early-time such as GRB 061007 [60]. Instead, the light curve peak is typical of the forward shock. The forward shock peaks either when fireball decelerates or when the typical synchrotron frequency crosses the observed band: the latter was ruled out for GRB 060418, as no colour evolution was observed around the peak, thus supporting the deceleration interpretation with the synchrotron frequency lying below the NIR bands at the peak time [89]. This is also consistent with the steep ($|\alpha| \sim 2.7$) rise observed in the NIR bands (Figure 11), in agreement with the theoretical expectations for the forward shock deceleration [92]. The RINGO measurement of GRB 060418 was made close to the deceleration time at the onset of the afterglow and when any magnetic field would still be present in the emitting region because the detected light contains an equal contribution from forward and reverse shocks, that is, Type III [12, 61] (Figure 6).

In contrast to GRB 060418, GRB 090102 exhibited the steep-shallow optical decay typical of that expected from an

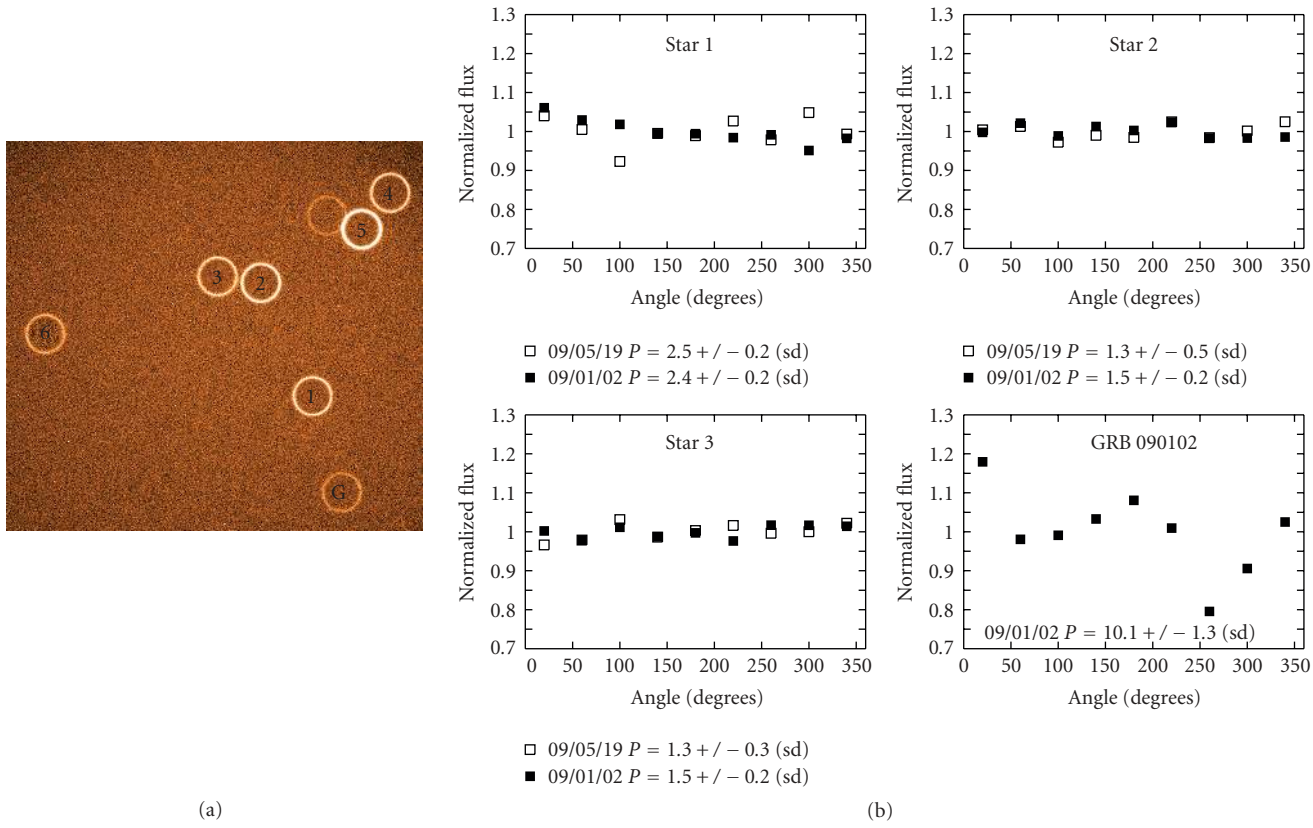



FIGURE 10: (a) RINGO image of field containing GRB 090102 (marked "G"); field stars are also visible. (b) Traces around rings for stars 1, 2, 3 and GRB 090102; derived polarisation % for each is quoted. [85].

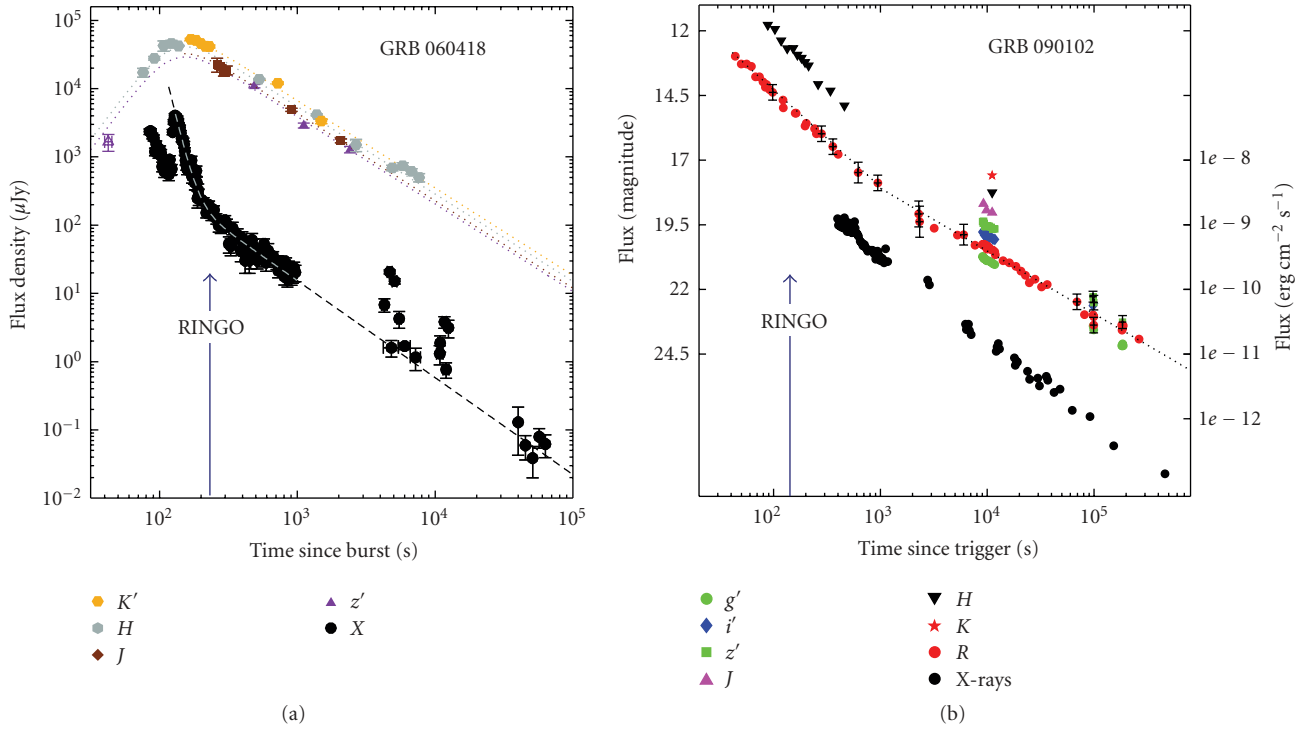



FIGURE 11: Light curves of GRB 060418 and GRB 090102 with time of RINGO observation marked at 203 seconds and 160 seconds (adapted from [89] and [90]), respectively.

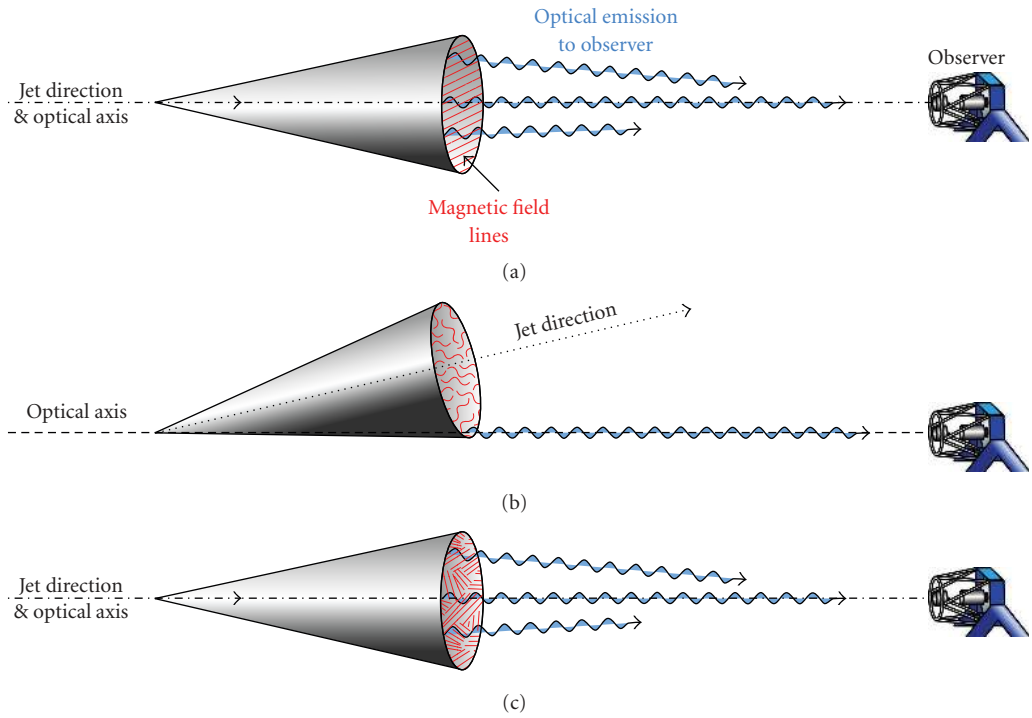



Figure 12: Competing models of GRB magnetic field structure for standard fireball model: (a) large-scale ordered magnetic field (favoured for GRB 090102); (b) tangled magnetic field in shock front and line of sight close to jet edge, and (c) shock front contains some independent patches of locally ordered magnetic fields [85].

afterglow whose emission is dominated by the reverse shock emission at early-times (Figure 11); this is the first GRB for which polarized optical light at early-time has been detected and its high level of polarisation $P = 10.2 \pm 1.3\%$ requires the presence of large-scale ordered magnetic fields in the outflow [85] (Figure 12). As the RINGO measurement was made when the reverse shock emission dominated the light curve, the large polarisation signal provides the first *direct* evidence that reverse shocks are produced in the presence of such fields.

Figure 12 shows three competing models of GRB magnetic field structure for the standard fireball model that could produce polarised light: (a) large-scale ordered magnetic field threaded through the GRB outflow—this model is favoured for GRB 090102; (b) tangled magnetic field generated in the shock front and an off-axis line-of-sight close to the jet edge—a scenario ruled out by the optical light curves for which an off-axis jet would require a shallow-to-steep decay, where the opposite is observed in GRB 090102; (c) a shock front containing independent patches of locally ordered magnetic fields—a scenario that is unlikely to account for GRB 090102 because the *maximum* predicted polarisation is 10% under the extreme assumption that the coherence length grows at the speed of light in the local fluid frame after the field is generated.

In summary, the polarisation properties of GRB 060418 and GRB 090102 can be reconciled in a single model in which the outflow is mildly magnetised ($\sigma \sim 1$) and contains large-scale ordered magnetic fields. In GRB 060418, $\sigma$ slightly larger than unity is needed to suppress the reverse shock emission (and hence polarisation), while in GRB 090102, $\sigma$ slightly less than unity will produce the bright polarised reverse shock emission that is observed.

## 5. Summary and Prospects

Exploring the extreme physics exhibited by GRB explosions is technically challenging due to (a) the unpredictability of their occurrence, (b) their short-lifetime rapidly fading emission, and (c) the wide range of observed brightnesses of optical counterparts, ranging from $R = 5$ to >22 mag within minutes of the burst itself—all drivers of autonomous followup technology. Deep, fast, and multifilter observations are crucial to identify the counterparts to these events that represent the brightest stellar objects observed out to the epoch of reionization. With the advent of Swift, discoveries such as the canonical early X-ray decay, the X-ray flares, the detection of the afterglows of short-duration GRBs, and the recognition that GRB-producing stars exist out at least to $z = 8.2$ keep GRB studies at the forefront of astrophysics.

Efforts continue to understand the complexity of the X-ray versus optical afterglow temporal evolution, the circumburst environment properties, in particular the dust versus gas content around the GRB progenitor and along the line of sight through the host galaxy, and the origin(s) of optical flares and their possible interpretations (e.g., GRB 080129 [43]: residual collisions in the GRB outflow or hot spots in strongly magnetized ejecta? [93]). Questions remain on

the fundamental nature of the relativistic ejecta, the underlying radiation mechanisms, and the role of magnetic fields. Observational surprises such as the relative lack of GeV emission from many bursts detected by Fermi and the rich variety in optical properties of GRB counterparts continue to drive developments in GRB modelling and observational technology. The 2 m robotic telescopes described here are proving decisive in tackling many of these issues: the variety of light curves has been investigated both on statistical grounds [12] as well as in individual cases of special interests: the dark GRB population and the luminosity function distribution have been characterised over a broad range of apparent brightnesses and the presence and lack of reverse shock emission in specific cases was investigated.

The interplay between forward and reverse shocks within the standard fireball model, as determined by the magnetic properties of the outflow, may yet succeed in explaining the dearth of reverse shocks previously expected from pre-Swift observations. The use of the RINGO polarimeter on the LT, capable of measuring the polarisation of optical counterparts to GRBs as early as a few minutes after the onset of the prompt $\gamma$-ray emission, has provided the earliest measurements and detection of GRB polarisation, setting important direct constraints on the magnetic field structure of the fireball and on the jet configuration [84, 85]. Further progress made in understanding the magnetic field structure of the fireball—large-scale ordered fields are currently preferred over locally tangled fields in the shock layer—will contribute to our knowledge of the nature of the outflow along the jets. Time-resolved early-time polarisation light curves (% and PA) from the newly commissioned RINGO2 promise to provide unprecedented diagnostic information on the structure and evolution of the outflow and its magnetic field for a statistically significant sample of GRBs down to $R < 17$ mag and thus allow powerful discrimination between predictions of the hydrodynamical versus magnetised jet models and ultimately constrain the physics of GRB central engines.

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## Endnotes

1. Now owned by Las Cumbres Observatory, are operated with support from the Dill Faulkes Educational Trust.

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