Early time optical polarization of GRB Afterglows: GRB 060418 and GRB 090102

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Abstract

RINGO on the Liverpool Telescope has now measured the optical polarization of GRB 060418 (where a 2σ upper limit of $P < 8$ % was determined) and GRB 090102 (when a detection of P 10 ± 1 % was made). We discuss the implications of these observations for the various competing models of GRB jet magnetization and describe a possible unified model that can explain both measurements.

If GRB ejecta have large scale magnetic fields, then the prompt $\gamma-$ray, X-ray and optical emission and the reverse shock emission should be polarized[1]. Optical polarization is generally measured via a ratio of fluxes in two or more polarizations. Traditionally this is done by using a modulator/analyzer pair taking separate exposures. However this approach does not work for a rapidly varying object such as a GRB afterglow - a one per-cent "fade" between subsequent exposures implying a false one per-cent polarization signal for example. It was therefore decided to develop an instrument for the Liverpool Telescope[2] that can make a "single-shot" polarization measurement. The instrument also required a wide field of view (so that it could respond to SWIFT BAT alerts and be on target during the prompt/reverse shock emission phases). We therefore developed and built the RINGO[3] polarimeter, which uses a fast rotating Polaroid to modulate

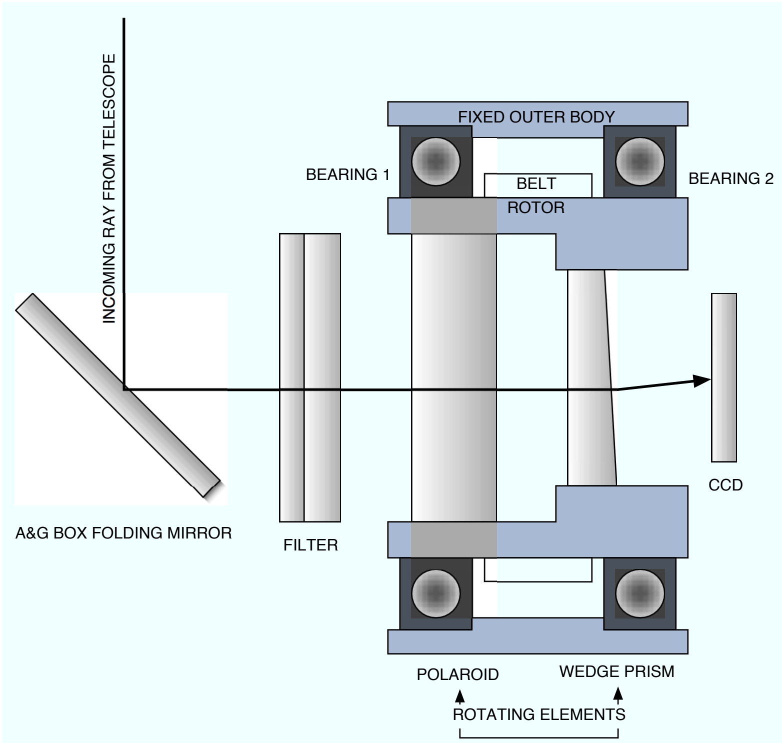

Figure 1: Layout of the RINGO instrument.

the incoming beam, followed by corotating deviating optics that transfer each star image into a ring that is recorded on a CCD (Figure 1). Any polarization signal present in the incoming light is mapped out around the ring in a $sin2\theta$ pattern.

RINGO was first used in 2006, when it observed GRB 060418 at 203s after the gamma ray burst and coincident with the time of deceleration of the fireball. At this time the reverse (assuming it was present) and forward shock components would have contributed equally to the observed light. For GRB 060418 a 2σ upper limit on optical polarization of P<8% was measured in the combined light from the emitting regions[4].

RINGO was next used in 2009, when it observed GRB 090102[5]. The steep-shallow decay[5, 6, 7] of optical emission from GRB 090102 is characteristic of an afterglow whose early-time light is dominated by fading radiation generated in the reverse shock[8, 9]. A single 60-second RINGO exposure was obtained starting 160.8 seconds after the trigger time. RINGO measured the optical (4600 - 7200Å) polarization of GRB 090102

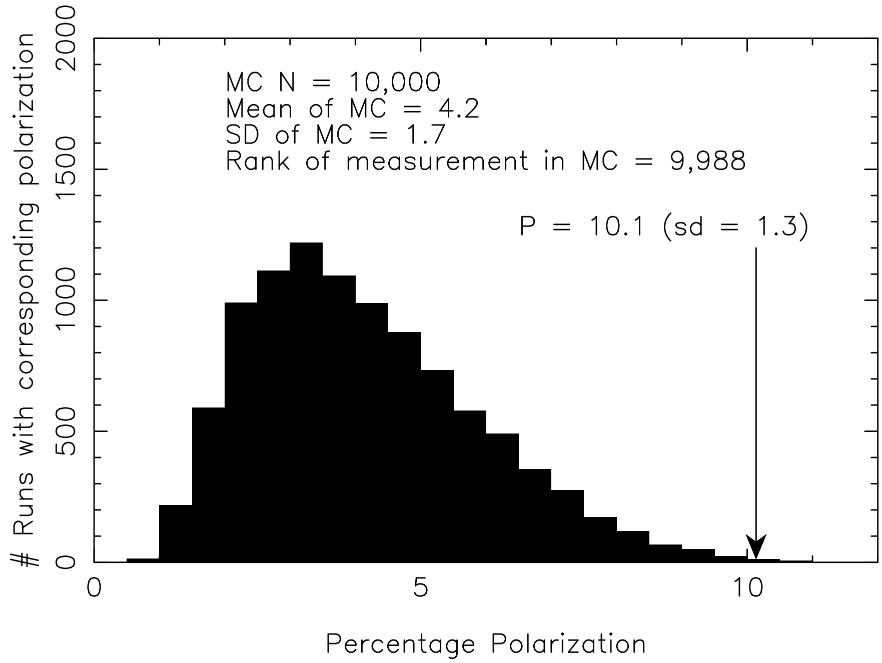

Figure 2: Monte Carlo simulation demonstrating the significance of the GRB 090102 result. See [10] for details.

as $P = 10.2 \pm 1.3\%$[10] (Figure 2).

In interpreting this measurement first we consider whether such a polarization could be produced via the production of magnetic instabilities in the shock front (Figure 3(c)). A very optimistic estimate of the coherence length can be made by assuming it grows at about the speed of light in the local fluid frame after the field is generated at the shock front - in this situation polarized radiation would come from a number of independent ordered magnetic field patches. A measured polarization of 10% is at the very uppermost bound for such a model [11] and therefore seems unlikely. As an alternative to the "patch" model, we have also considered the case where the observer's line of sight is close to the jet edge[12] (Figure 3(b)). In this case since the magnetic fields parallel and perpendicular to the shock front could have significantly different averaged strengths[13] a polarization signal can also be produced. However applying this model to GRB 090102 we would have expected a steepening of the light curve (a "jet-break") just after the time of our polarization measurement rather than the observed flattening. Similarly there is no evidence of a jet break in the X-ray light curve up to late times. Furthermore, our detection of 10% is much higher

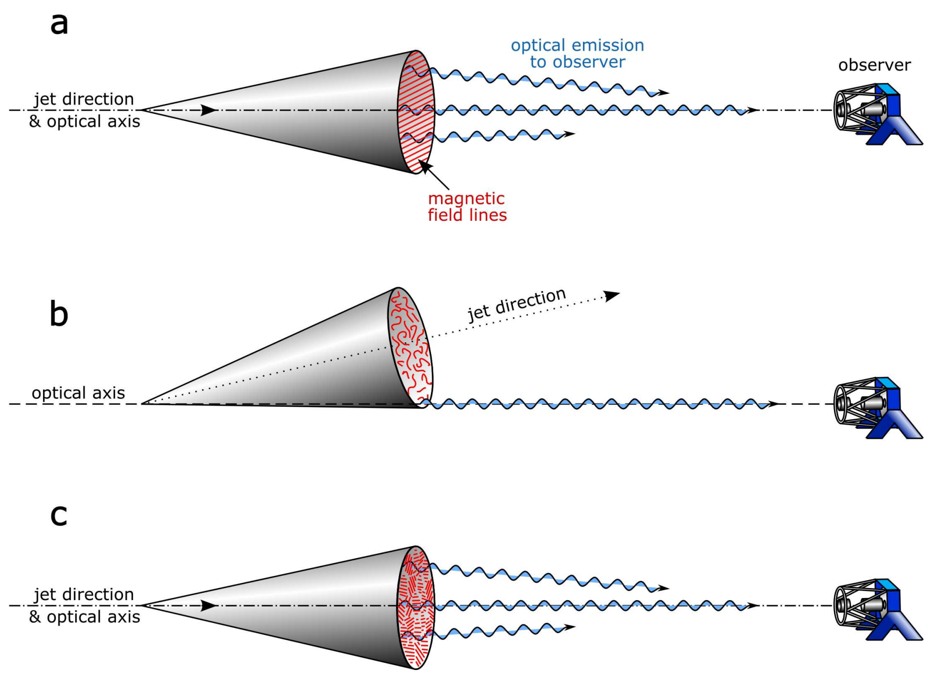

Figure 3: Alternative models for GRB polarization

than the reported polarization signal of a few % associated with a jet break in late time afterglow of other events[14, 15]. We also rule out an Inverse Compton origin for the optical polarization - a mechanism suggested to explain earlier γ-ray polarization measurements[16] - in which lower energy photons are scattered to higher energies by colliding with electrons in the relativistic flow. If Inverse Compton emission is present, it is more likely to contribute to the high-energy X-ray and γ-ray bands than the optical band and again requires the observer's line of sight to be close to the edge of the jet (Figure 3(b)) to produce significant polarization which (as we have already discussed) is not the case for GRB 090102.

It therefore seems apparent that in the case of GRB 090102 the high polarization signal requires the presence of large-scale ordered magnetic fields in the relativistic outflow (Figure 3(a)). As the measurement was obtained while the reverse-shock emission was dominant in GRB 090102, the detection of significant polarization provides the first direct evidence that such magnetic fields are present when significant reverse shock emission is produced.

Magnetization of the outflow can be expressed as a ratio of magnetic to kinetic energy flux, σ. The degree of magnetization cannot be sufficient for the jet to be completely Poynting flux dominated ($\sigma > 1$) since this would be expected to suppress a reverse shock[17]. We can therefore reconcile the detection of polarization in GRB 090102 and the non-detection in GRB 060418 in a unified manner if GRB jets have magnetization of $\sigma \sim 1$. In the GRB 060418 case, the jet would have had slightly higher magnetization than unity, resulting in the suppression of a reverse shock, while GRB 090102 would have σ slightly smaller than unity, which is optimal to produce bright reverse shock emission. Of course due to the small sample (only two objects), we can not rule out a possibility that each GRB jet had very different magnetization.

Finally we note recent claims of rapidly ($\sim$ 10 s) variable γ-ray polarization from less than 4% to 43% ($\pm$25%) in the prompt emission of GRB 041219A [18]. This lends further support to models with magnetized outflows and offers the possibility that the peak optical polarization from GRB 0901012 could have been even higher than that measured in our 60 second exposure. We are have therefore developed a new instrument (RINGO2) which will have greater sensitivity (to allow observations of several bursts per year) and time resolution ($\sim$ 1 second for bright bursts) and will begin operations on the Liverpool Telescope in late 2009.

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