THE MAGNETIZATION DEGREE OF THE OUTFLOW POWERING THE HIGHLY POLARIZED REVERSE-SHOCK EMISSION OF GRB 120308A

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ABSTRACT
GRB 120308A, a long duration γ-ray burst (GRB) detected by Swift, was distinguished by a highly polarized early optical afterglow emission that strongly suggests an ordered magnetic field component in the emitting region. In this work, we model the optical and X-ray emission in the reverse and forward shock scenario and show that the strength of the magnetic field in the reverse-shock region is ~10 times stronger than that in the forward shock region. Consequently, the outflow powering the highly polarized reverse-shock optical emission was mildly magnetized at a degree of σ ~ a few percent. Considering the plausible magnetic energy dissipation in both the acceleration and prompt emission phases of the GRB outflow, the afterglow data of GRB 120308A provides us with compelling evidence that, at least for some GRBs, a nonignorable fraction of the energy was released in the form of Poynting flux, confirming the finding first made in the reverse–forward shock emission modeling of the optical afterglow of GRB 990123 by Fan et al. in 2002 and Zhang et al. in 2003.

Key words: gamma rays: general – radiation mechanisms: non-thermal

1. INTRODUCTION
Gamma-ray bursts (GRBs) are brief soft γ-ray transients powered by either dying massive stars or the mergers of some compact objects. In the past decades, tremendous advances in understanding such violent explosions have been achieved (Piran 1999; Mészáros 2006; Kumar & Zhang 2014). However, the physical composition of the GRB outflows (magnetic or baryonic) is still to be better probed. In some well-studied relativistic jets, for example, those in active galactic nuclei, the initial ejecta are widely believed to be Poynting-flux-dominated because the accretion disk is too cool to launch relativistic outflow via the neutrino process (e.g., Shao et al. 2011). However, with an accretion rate that is high, up to ~1 M⊙s−1, the accretion disk surrounding the nascent stellar-mass black hole is extremely hot and the neutrino radiation is the main cooling channel. As a result, the annihilation of the neutrino and antineutrinos from the disk may be able to launch a baryonic/hot fireball (Eichler et al. 1989; Piran et al. 1993; Mészáros et al. 1993). Regardless of the nature of the central engine (either a stellar-mass black hole or a magnetized pulsar), the magnetic activity of the central engine can launch a magnetized/cold outflow (Usov 1992; Mészáros & Rees 1997).

Among the various methods of probing the physical composition of GRB outflows, one is to study the optical flash, which is believed to be powered by the reverse shock generated by the interaction between the outflow and the circum-burst medium. The idea is that as long as the ordered magnetic field component is much stronger than the random one generated by the shocks, the reverse-shock-accelerated electrons will radiate more efficiently and then give rise to brighter optical flash. The degree of the magnetization of the reverse-shock region can be inferred from the modeling of the reverse and forward emission self-consistently (Fan et al. 2002; Zhang et al. 2003). On the other hand, the synchrotron radiation of electrons in the ordered magnetic field is expected to be highly polarized and hence the optical polarimetry will be a smoking-gun signal of the magnetized outflow model (Granot & Königl 2003; Fan et al. 2004a). The reverse-shock emission model for optical flashes (Sari & Piran 1999; Mészáros & Rees 1999; Kobayashi 2000; Shao & Dai 2005) has been supported by the observations of a group of GRBs (e.g., Akerlof et al. 1999; Li et al. 2003; Blake et al. 2005; Boër et al. 2006; Klotz et al. 2006; Gomboc et al. 2008; Racusin et al. 2008; Steele et al. 2009; Jin et al. 2013). Interestingly, the modeling of almost all current optical flashes favors the weakly magnetized reverse-shock emission model (e.g., Fan et al. 2002, 2005; Zhang et al. 2003; Kumar & Panaitescu 2006; Wei et al. 2006; Klotz et al. 2006, 2009; Gomboc et al. 2008; Racusin et al. 2008; Gao 2011; Jin et al. 2013). The absence of optical flashes in other GRBs (Roming et al. 2006) can be attributed to a moderate or high magnetization of the outflow that can effectively suppress the reverse-shock emission. In general, for σ > 0.1, the stronger the magnetization, the weaker the reverse-shock emission (Fan et al. 2004a; Zhang & Kobayashi 2005; Mimica et al. 2009), where σ is the magnetization degree. In the “optimistic” scenario by which the spectrum of shocked-accelerated particles is independent of σ, usually we need high magnetization σ > 1 to account for the absence of the reverse-shock emission component in most GRBs (Zhang & Kobayashi 2005). However, it is possible or even likely that the larger the σ, the softer the particle spectrum. If so, σ ~ 0.1 may be large enough to explain the observation data (see Fan 2008 and the references therein). The polarimetry of the optical flashes is rather challenging. The successful polarization measurement of the a quickly decaying optical emission of GRB 090102 got a linear polarization degree of ~10% and has been taken as evidence for the presence of large-scale magnetic fields originating in the expanding fireball (Steele et al. 2009). However, a reasonable modeling of the optical and X-ray afterglow of GRB 090102 in the forward and reverse-shock emission scenario was found to be unachievable (Gendre et al. 2010). The physical origin of the “quickly decaying optical emission” is thus less clear.
Recently, Mundell et al. (2013) reported the detection of a very high linear polarization degree in the early optical emission of GRB 120308A. In this work, we examine whether the afterglow data is in support of the reverse-shock origin of the early optical emission or not. As shown later, the answer is positive, hence we estimate the magnetization degree of the outflow.

2. INTERPRETING THE X-RAY AND OPTICAL AFTERGLOW EMISSION OF GRB 120308A IN THE REVERSE–FORWARD SHOCK SCENARIO

The Swift satellite triggered and located GRB 120308A, a single broad pulse of γ-rays, on 8 2012 March at $T_0 = 06:13:38$ UT. The duration $T_{90}$ (15–350 keV) is $60.6 \pm 17.1$ s and the time-averaged spectrum from $T_0 - 24.15$ to $T_0 + 58.20$ s is best fit by a simple power-law model and the power-law index of the time-averaged spectrum is $1.71 \pm 0.13$ (Sakamoto et al. 2012). The X-ray Telescope began observing the field at 06:15:11.3 UT, 92.6 s after the Burst Alert Telescope (BAT) trigger. A bright, uncalculated and fading X-ray source was detected (Baumgartner et al. 2012). The optical afterglow was detected by the Liverpool Telescope and other ground-based telescopes (Mundell et al. 2013). The optical emission was so bright that time-resolved polarimetry was carried out by the Liverpool Telescope with the purpose-built RINGO2 polarimeter. At the peak time of optical emission, the linear polarization degree reached $P \approx 28\% \pm 4\%$ and then declined to $P = 16.7\% \pm 4\%$ hundreds seconds later (Mundell et al. 2013). It is a very robust detection and $P = 28\% \pm 4\%$ is the highest polarization degree of optical afterglow that people have observed in all GRBs. The straightforward interpretation of the polarization properties is that the early optical emission was dominated by the reverse-shock component and the outflow had large-scale uniform fields that survive long after the initial explosion, as initially identified/speculated in GRB 990123 (Fan et al. 2002; Zhang et al. 2003).

In the first 300 s, the X-ray emission was dominated by a giant X-ray flare with a peak of $0.3–10$ keV flux $\sim 10^{-8}$ erg s$^{-1}$, which is most likely attributed to the prolonged activity of the central engine. The subsequent X-ray afterglow decayed with time as $F_\nu \propto \nu^{-0.455\pm0.006}$ (Evans et al. 2009) for $300 < t < 10^4$ s and was significantly softened later on. In the standard fireball model, such spectral and temporal behaviors can be understood if at early times $v_m < v_c < v_{\nu m}$ and $p \sim 2.1–2.2$ suppose the circumburst medium has a constant density profile (i.e., the medium is interstellar medium-like (ISM-like) rather than stellar-wind like), where $v_c$ ($v_{\nu m}$) is the cooling frequency (typical synchrotron radiation frequency) of the forward shock accelerated electrons and $p$ is the power-law energy distribution index of the shock accelerated electrons. In view of the spectrum change at $t \sim 1.6 \times 10^4$ s, we expect that the cooling frequency is $v_c \sim 0.3$ keV at that time. On the other hand, as shown in Mundell et al. (2013) the optical emission in the first $\sim 2000$ s is likely dominated by a reverse-shock emission component and the forward shock emission peaked at a time of $\sim 10^3$ s with a flux $F_{\nu,\text{opt,peak}} \sim 0.3$ mJy when $v_m$ crossed the observer’s frequency $v_{\text{opt}} = 5 \times 10^{-4}$ Hz. In the ISM model, the maximal specific flux of the forward shock emission ($F_{\nu,\text{max}}$) is a constant. Hence we have $F_{\nu,\text{max}} = F_{\nu,\text{opt,peak}}$.

2.1. Constraining the Physical Parameters of the Forward Shock

It is widely known that the forward shock emission is governed by the following physical parameters that can be parameterized as (e.g., Piran 1999; Yost et al. 2003; Fan & Piran 2006)

$$F_{\nu,\text{max}} = 6.6 \text{ mJy} \left(\frac{1+z}{2}\right) D_L^{-2} \nu_{\text{opt}}^{1/2} E_{k,53}^{-1/2} n_0^{-1/2},$$

$$v_m = 2.4 \times 10^{16} \text{ Hz} \left(\frac{c}{\nu_{\text{opt}}}\right)^{1/2} \left(\frac{1+z}{2}\right)^{1/2} t_d^{-3/2},$$

$$v_c = 4.4 \times 10^{16} \text{ Hz} \left(\frac{c}{\nu_{\text{opt}}}\right)^{-1/2} \left(\frac{1+z}{2}\right)^{-1/2} \frac{1}{(1+Y)^2},$$

where $C_p \equiv 13(p-2)/[3(p-1)], \epsilon_e (\epsilon_B)$ is the fraction of shock energy given to the electrons (magnetic field), the Compton parameter $Y \sim (-1+\sqrt{1+4\epsilon_e\epsilon_B})/2, \eta = \min[1, (v_m/v_c)^{(p-2)/2}]$ and $v_c = (1+Y)^2v_{\nu m}$. Here and throughout this text, the convention $Q_y = Q/10^y$ has been adopted. As inferred from the optical and X-ray afterglow emission, we have $v_c(t \sim 1.6 \times 10^4)$ Hz, $v_{\nu m}(t \sim 10^3)$ s $\sim 5 \times 10^{-14}$ Hz and $F_{\nu,\text{max}} \sim 0.3$ mJy, which yield

$$\epsilon_{B,53}^{-1/2} E_{k,53}^{-1/2} n_0^{-1/2} \approx a,$$

and

$$E_{k,53}^{-1/2} E_{\nu,53}^{-1/2} n_0^{-1} (1+Y)^{-2} \approx c,$$

where:

$$a = \frac{1}{6.6} F_{\nu,\text{max}} D_L^{-2} \nu_{\text{opt}}^{1/2} \left(\frac{1+z}{2}\right)^{-1},$$

$$b = \frac{1}{2.4} \times 10^{-16} v_m C_p^{-2} \left(\frac{1+z}{2}\right)^{1/2} t_d^{-3/2},$$

$$c = \frac{1}{4.4} \times 10^{-16} v_c \left(\frac{1+z}{2}\right)^{1/2} \left(\frac{1+z}{2}\right)^{1/2} t_d^{-3/2}.$$
GRB efficiency by applying a function of the forward shock peak optical emission is estimated by (see Green, red, blue, and black lines represent (x, y) in Figure 1, respectively, where ηF is the GRB efficiency. The dashed, solid, and dotted lines correspond to p = 2.1, 2.15, and 2.2, respectively.

where d = ((2.4)/(4.4))C_2^2((1+z)(2)/r_0^{-1})(p-2)/2 and a, b, c are constant. Comparing with the case of Y ≲ 1, the dependence of ϵb and E_k is rather sensitive.

For z = 2.2 and p = 2.15, we have a = 0.20, b = 0.33, and c = 28.37, and then we get

\[
\begin{align*}
\epsilon_{b,-2} &= 8.48 \times 10^{-9} n_0^{-1.26}, \\
\epsilon_{e,-1} &= 8.82 n_0^{0.66}, \\
E_{k,53} &= 2166.2 n_0^{1.63}.
\end{align*}
\]

We have solved Equations (4)–(6) numerically. As shown in Figure 1, E_k grows quickly while ϵ_b drops sharply for n > 0.01 cm^{-3} in the case of p = 2.15. We also calculated the GRB efficiency by applying a K correction with a reasonable factor of k = 3. Considering that for typical GRB the efficiency is ηF ≳ 10% and ϵ_e ≲ ϵ_e, we find that the value of n_0 is around 0.01 for p = 2.15.

2.2. The Magnetized Reverse-shock Emission

As already mentioned, the early optical emission is likely due to the strong reverse-shock emission and the crossing time of the reverse shock is just the time past the optical emission (i.e., t_x ~ 300 s). Since t_x ≫ t_0 (i.e., the reverse shock crossed the outflow at a time much later than the end of the prompt emission), the fireball is thin. On the other hand, the crossing time is usually estimated as

\[
t_x \sim 60(1+z)s E_{k,54}^{1/3} n_0^{-2/3} \Gamma_0^{1/3} \sim 300 s,
\]

where Γ_0 is the initial Lorentz factor of the GRB outflow. Since Γ_0 is very weakly dependent on E_{k,54} and n_0, thus, with the above equation, we know that Γ_0 ~ 300, i.e., the initial GRB outflow is ultra-relativistic.

The forward-reverse-shock emission has been extensively investigated. As first found in GRB 990123, the physical parameters of the reverse shock can be dramatically different from that of the forward shock (Fan et al. 2002; Zhang et al. 2003). For the reverse-shock emission, we usually have \nu_m < \nu_{opt} < \nu_e and the ratio between the reverse-shock optical emission and the forward shock peak optical emission is estimated by (see Equation (16) of Jin & Fan (2007); a similar expression can be found in Equation (5) of Zhang et al. (2003))

\[
\frac{F_{\nu_{opt}}(t_x)}{F_{\nu_{opt}}(t_p)} = 0.08 R_c^{-p} R_B^{p+1/2} \left( \frac{\gamma_{34,X} - 1}{0.25} \right)^{p-1} \left( \frac{\nu_e}{\nu_0} \right)^{3(p-1)/4},
\]

(20)

where \gamma_{34,X} ≈ 1.25 is the strength of the reverse-shock emission at the crossing time (i.e., it is assumed that at that time the Lorentz factor of the decelerating outflow is half of the initial, as found in the numerical calculations), and \Re = \epsilon_l^1/\epsilon_e and \R_B = \epsilon_F^1/\epsilon_B (\epsilon_l^1 and \epsilon_B are the fractions of reverse-shock energy given to the electrons and magnetic field, respectively).

On the one hand, the reverse-shock emission peaked at \sim t_x ~ 300 s and the peak flux is \sim F_{\nu_{opt}}(t_x) ~ 2 mJy. On the other hand, the forward shock optical emission likely peaked at \sim t \sim 3^3 s with a flux of \sim 0.3 mJy. With Equation (20), we have

\[
\frac{R_B}{R_c} \sim 10 R_c^{2(1-p)/(p+1)} \left( \frac{\gamma_{34,X} - 1}{0.25} \right)^{2(1-p)/(p+1)}.
\]

In this work, we assume that \epsilon_e = 1 and thus \epsilon_B \sim 10 for \gamma_{34,X} \approx 1.25, i.e., the reverse-shock region contains magnetic field \sim 100 times stronger than that in the forward shock region. One reason for this assumption is that the initial outflow is orderly magnetized or alternatively the magnetic field generated in the internal-shock phase may have not been dissipated effectively in a short time and would play a dominant role in the reverse-shock region. Since an ordered magnetic field is highly needed to reproduce the rather high linear polarization detected in the reverse-shock emission, we conclude that the initial outflow was magnetized. A similar conclusion was drawn in Mundell et al. (2013). However, they found a R_B^2 ~ 500 since the smaller \gamma_{34,X} \approx 1.08 was adopted in the estimate, based on Harrison & Kobayashi’s (2013) numerical calculation with the outflow spreading effect.

Let us estimate the magnetization degree of the outflow (σ), supposing the magnetic field in the reverse-shock region is dominated by the ordered component. Then, at t_x, we have

\[
R_B = \sqrt{\rho'_B/\epsilon_B \epsilon'_f},
\]

(21)

where \rho'_B is the comoving magnetic pressure in the reverse-shock region while \epsilon'_f is the comoving thermal energy density in the forward shock region. Since \rho'_B/\epsilon'_f = (\rho'_B/\rho'_r,th)(\Gamma - 1)/\epsilon'_r,th/\epsilon'_f (where \Gamma is the adiabatic index), with \rho'_B/\rho'_r,th = [\sigma/(2\Gamma - 1)](u_{th}/u_{rms}) (n'_r/m_e c^2)^{-1} (see Equation (12) of Fan et al. 2004b), in the condition of σ < 1, we have

\[
\sigma \approx 2 R_B^2 (\epsilon'_f/n'_r m_e c^2)(u_{th}/u_{rms}),
\]

(22)

where n'_r is the comoving number density of the reverse-shock region, u_{th} is the velocity of the unshocked GRB outflow relative to the surface of the reverse shock (see Figure 1(a) of Fan et al. 2004b) to see the result; note that the \nu_{12} used in Fan et al. (2004b) is just the current \gamma_{34,X}, and u_{th} is the velocity of the shocked GRB outflow relative to the surface of the reverse shock, which is calculated through the Lorentz transformation, i.e.,

\[
u_{us} = \gamma_{34,X} (c \beta_{th} + \beta_{34,X}).
\]

(23)
which the allowed value of the reverse shock of GRB120308A is only mildly relativistic, for magnetization degree is significantly larger. On the one hand, If the inferred events are encouraged to better reveal the physical composition. observations (including also polarimetry) of GRB 120308A-like might be higher. On the other hand, multi-wavelength follow-up we have (2013), Virgili et al. (2012), Elenin et al. (2012), and Bikmaev et al. (2012). The numerical fit (see Section 2.3). If the outflow shell spreading effect is significant and the reverse-shock region is magnetic energy dominated, we then have

$$\sigma \approx 2 R_B^2 \epsilon_B \frac{\beta_{ds}}{\gamma_{34,x} (\beta_{ds} + \beta_{34,x})} \frac{e'_f}{n' m_p c^2}. \quad (24)$$

where $\beta$ is the velocity in the unit of the speed of light $c$ and $u = \gamma \beta$. Now we have

$$\sigma \approx 2 R_B^2 \epsilon_B \frac{\beta_{ds}}{\gamma_{34,x} (\beta_{ds} + \beta_{34,x})} \frac{e'_f}{n' m_p c^2}. \quad (24)$$

On the other hand, since $e'_f \approx e'_f \approx (\gamma_{34,x} - 1) n' m_p c^2$ unless the reverse-shock region is magnetic energy dominated, we then have

$$\sigma \approx R_B^2 \epsilon_B \frac{\gamma_{34,x} - 1}{\gamma_{34,x}} \frac{2 \beta_{ds}}{(\beta_{ds} + \beta_{34,x})}. \quad (25)$$

If $\beta_{ds} \approx \beta_{34,x}$, the above equation reduced to the form found in Harrison & Kobayashi (2013), i.e., $\sigma \approx R_B^2 \epsilon_B (\gamma_{34,x} - 1)/\gamma_{34,x}$. For $\gamma_{34,x} \approx 1.25$, the fiducial value adopted in this work, we have

$$\sigma \approx R_B^2 \epsilon_B \sim 0.01(R_B/10)^2(\epsilon_B/0.002),$$

where $\epsilon_B$ is normalized to 0.002, the value obtained in our numerical fit (see Section 2.3). If the outflow shell spreading effect is significant and $\gamma_{34,x} \approx 1.08$, the magnetization degree is expected to be $\sigma \approx 0.03(R_B/500)(\epsilon_B/0.002)$.

In some numerical simulations, it is found that it is difficult to accelerate nonthermal particles in relativistic shocks for $\sigma > 10^{-3}$ (e.g., Sironi & Spitkovsky 2011). While our derived magnetization degree is significantly larger. On the one hand, the reverse shock of GRB120308A is only mildly relativistic, for which the allowed value of $\sigma$ for efficient particle acceleration might be higher. On the other hand, multi-wavelength follow-up observations (including also polarimetry) of GRB 120308A-like events are encouraged to better reveal the physical composition. If the inferred $\sigma$ is still in the order of $10^{-2}$, some novel effects of particle acceleration in magnetized shocks should be taken into account.

2.3. Numerical Fit to the Data

The code used here to fit the X-ray and optical light curves has been developed by Yan et al. (2007), in which both the reverse and the forward shock emission have been taken into account. As already mentioned, we assume that $\epsilon_e$ and the electron spectral index $p$ are essentially the same for the forward shock and reverse shock, but we allow different $\epsilon_B$ values in these two regions.

The numerical results are presented in Figures 2 and 3, and the fitting parameters are $(E_{k,53}, n_0, \epsilon_e, R_B, p, \theta_j, \Gamma_0) \sim (5, 0.01, 0.05, 0.002, 7, 2.15, 0.015, 300)$, where $\theta_j$ is the opening angle of the GRB outflow to account for the jet break presented in both X-ray and optical data. These parameters are well consistent with that found in our analytical estimate (see Sections 2.1 and 2.2).

3. DISCUSSION

The polarization degree of the early afterglow of GRB 120308A decreased from $P = 28\% \pm 4\%$ to $P = 16^{+5}_{-3}\%$ during hundreds of seconds. This evolution is consistent with the predictions of the reverse–forward shock model. At the early time the reverse-shock emission dominated, and it is speculated that the large-scale ordered magnetic field survived after the initial explosion. At later times, when the contribution of the forward shock emission is important, the random magnetic component arising from plasma instability would eventually dominate the outflow magnetic field configuration; therefore, the polarization degree would decrease with time. This behavior can also be explained by the ICMART model (Zhang & Yan 2011). In the ICMART model, the GRB ejecta carry an ordered magnetic field configuration, although the degree of ordered magnetic field would be reduced after ICMART processes within the 1/4 cone, there is still a net linear polarization because of the residue of the initially ordered magnetic field configuration. As a result, when the ejecta is decelerated, the reverse-shock region is more magnetized and the optical emission should be moderately polarized. The superposition effect with the forward shock leads to the drop of the polarization degree, which is consistent with the observations of GRB 120308A.

The very early optical afterglow emission, in particular, the bright optical flash expected in the reverse-shock emission model, is very valuable to constrain the nature of the GRB outflow. This is because at such early times, the outflow likely still carries some information on the magnetization of the initial outflow. If the outflow is just weakly magnetized, there are two interesting observational signatures: (1) the reverse-shock...
optical emission can be significantly brightened and then outshine the forward shock optical emission (Fan et al. 2002; Zhang et al. 2003); (2) the reverse-shock optical emission will be significantly polarized and a moderate/high linear polarization is expected (Granot & Königl 2003; Fan et al. 2004a). Both signals have been detected in GRB 120308A, which thus provide compelling evidence for the large-scale ordered magnetic field in the initial GRB outflow (see also Mundell et al. 2013). To set a tighter constraint on the magnetization of the outflow, in this work, we have modeled both the X-ray and optical emission. Due to the lack of radio detection/spectrum and then the absence of a reasonable estimate of synchrotron self-absorption frequency of the forward shock, the shock parameters \((E_k, n,\epsilon_e,\epsilon_B)\) cannot be uniquely determined (see Section 2.1 for the details). Even so, if we assume a typical GRB efficiency that is not expected to be smaller than \(\sim 10\%\) (note that the isotropic-equivalent \(\gamma\)-ray radiation energy of GRB 120308A is \(\sim 6 \times 10^{52}\) erg), then we have \(\epsilon_B \geq 0.002\) (see the numerical fit result). The magnetization degree of the outflow in the reverse-shock region is thus \(\sigma \sim 0.02\) (see the numerical fit result).

There are hot debates regarding whether the prompt emission is from the photosphere or an optically thin region (internal shock or magnetic dissipation site; Zhang 2014). Considering the plausible magnetic energy dissipation in both the acceleration and prompt emission phases of the GRB outflow, we conclude that the afterglow data of GRB 120308A provides us with compelling evidence that, at least for some GRBs, a non-negligible fraction of the energy was released in the form of Poynting-flux.

Finally, we would like to point out that in addition to the measurement of the synchrotron self-absorption frequency in radio bands, the degeneracy between the shock parameters \((E_k, n,\epsilon_e,\epsilon_B)\) can also be broken by the observation of the synchrotron self-Compton GeV–TeV emission together with the optical and X-ray data because the synchrotron self-Compton parameter \(Y\) is also related to these shock parameters as well. In view of these possibilities, we urge the multi-wavelength afterglow (radio, optical, X-ray, and hard \(\gamma\)-ray) observations of the GRBs with early optical polarimetry information.

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