Magnetized GRB outflow model: weak reverse shock emission and short energy transfer timescale

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Abstract. We show that the absence of the bright optical flashes in most Swift Gamma-Ray Burst (GRB) afterglows can be explained, if the reverse shock region is magnetized with a $\sigma \sim 1$, or the emission spectrum of the electrons accelerated in the mildly magnetized ($0.1 < \sigma < 1$) reverse shock front is very soft, or the reverse shock of a non-magnetized outflow is sub-relativistic, where $\sigma$ is the ratio of the magnetic energy flux to the particle energy flux. We also find that for $\sigma \gg 1$, the energy transfer between the magnetized ejecta and the forward shock may be too quick to account for the shallow decline phase that is well detected in many Swift GRB X-ray afterglows.

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MAGNETIZED GRB OUTFLOW MODEL

Though extensively discussed, the physical composition of the GRB outflow is not clear yet (see [30, 38] for reviews). In principle, the outflows could be either Poynting-flux dominated or baryon dominated. The former is favored if the central engine is a millisecond magnetar [36] or the outflow is launched from a black hole–torus system through MHD processes. For a magnetized outflow, the prompt $\gamma$-rays are powered by the magnetic energy dissipation [36, 21, 13] or magnetized internal shocks [9]. A signature is the high linear polarization of the prompt emission [22, 15], which was reported [5] in GRB 021206 but afterwards ruled out [33]. In a few other events, high linear polarization has been claimed but independent measurements for each burst are needed to confirm these discoveries.

A “robust” evidence for the magnetized GRB outflow model may be the magnetization of the GRB reverse shock (RS). Shortly after the discovery of the very bright optical flash of GRB 990123 [1], Sari & Piran [34] and Mészáros & Rees [23] showed that the $t^{-2}$ decline of the optical flash can be well interpreted by the adiabatically cooling of the RS electrons. The self-consistent fitting of the very early and the late time afterglow data requires that $\varepsilon_B$, the fraction of the shock energy given to the magnetic field, of the RS is much larger than that of the forward shock (FS) [6, 41, 29]. It is very interesting to note that such a finding has been confirmed in almost all optical flash modelings, such as for GRB 021211 [11, 20, 41, 19, 29], GRB 041219a [2, 10], GRB 050401 [3], GRB 050904 [4, 37], GRB 060111B [17], GRB 061126 [14], and GRB 080319B [31]. A natural interpretation for this finding is that the GRB outflow is magnetized and the magnetic field in the RS region is dominated by the component carried from the central engine.

The magnetized outflow model also helps to solve the puzzle why optical flashes have not been detected in most Swift GRBs [32]. This is because for a highly magnetized GRB outflow, under the ideal MHD limit, the magnetic energy can not be converted into the RS energy effectively. The emission of a magnetized GRB RS has been calculated by Fan et al. [8] and Zhang & Kobayashi [40] (see also [12] for the existence of such shocks). With reasonable parameters ($\sigma < 10$), the resulting RS emission is very bright and is inconsistent with the observational data. It is the time to revisit these preliminary calculations.

1 My presentation is based on arXiv:0805.2221, a review article published in Front. Phys. China. The current paper focuses on the 17th slide of that PPT (http://grb.physics.unlv.edu/nj/talks/6.26/Fan_Yizhong.ppt).
WEAK REVERSE SHOCK EMISSION

Following [8], we calculate the emission of magnetized RSs. Some important modifications include: (i) The arrival time of the RS emission photons has been calculated more accurately (see the Appendix for details). (ii) The electron energy distribution is calculated by solving the continuity equation with the power-law source function \( Q = K \gamma^{-p} \), normalized by a local injection rate [7]. (iii) The cooling of the electrons, due to both synchrotron and inverse Compton radiation, has been considered[2] (iv) The synchrotron self-absorption has also been taken into account.

We find a bright (RS) optical flash is absent in the following scenarios:

**Significant magnetization.** After the important corrections mentioned above, we find a \( \sigma \sim 1 \) is enough to suppress the RS emission effectively and thus be able to explain the absence of the bright optical flashes in most GRB afterglows (see Fig.1). This renders the magnetization interpretation more attractive because \( \sigma \) declines with radius after the prompt emission and is expected to be \(< 10\) at a radius \( > 10^{16} \) cm [36, 13].

For clarity, in Fig.1 we plot the FS emission for \( \sigma = 1 \) while the RS emission is presented for \( \sigma = (0.1, 0.3, 1, 3) \), respectively. The \( \epsilon_e \) values are assumed to be the same for both RS and FS. The new results are significantly different from those obtained in [8, 40].

**Mild magnetization but a very soft spectrum of the RS emission.** In all previous calculations, the energy distribution index, \( p \), of the RS electrons is taken to be the same as that of the FS electrons. But this treatment may be well wrong. We know that usually \( p \) is relevant to \( (\beta_u - \beta_d)^{-1} \), where \( \beta_u \) and \( \beta_d \) are the velocities (in units of the speed of light \( c \) and measured in the rest frame of the shock front) for the upstream and the downstream regions, respectively. For a relativistic un-magnetized shock, we have \( \beta_u \sim 1, \beta_d \sim 1/3, \) and \( (\beta_u - \beta_d)^{-1} \approx 3/2. \) However, for a relativistic magnetized shock, \( \beta_d \approx (1 + \chi + \sqrt{1 + 14\chi + \chi^2}), \) where \( \chi \equiv \sigma/(1 + \sigma) \) [9]. For \( \sigma \sim \text{a few} \times 0.1, (\beta_u - \beta_d)^{-1} \approx 3/(2 - 4\sigma) \), the energy distribution of the RS electrons may be much steeper than in the case of \( \sigma = 0 \)

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2 Sometimes the overlapping of prompt \( \gamma \)-ray flow with the RS region is very tight. In such cases the RS electrons will be cooled by the prompt \( \gamma \)-rays, too. As a result, the RS optical emission will be dimmer than what we get in this work.
There are two indication evidences for this speculation: (i) In a numerical calculation, Morlino et al. [27] found a $p \sim 3$ for $\sigma \sim 0.05$, and (ii) In the 2.5D ion-electron shock simulation, the acceleration of particles in the case of $\sigma \sim 0$ is much more efficient than in the case of $\sigma \sim 0.1$ [35].

Assuming that the RS electrons have a $p \sim p(\sigma=0) + \Delta p$, the RS optical emission will be weakened by a factor of $R_w \sim (\nu_{\text{opt}}/\nu_{\text{rs}}^m)^{-\frac{3}{2}}$ as long as $\nu_{\text{opt}} > \nu_{\text{rs}}^m$, where $\nu_{\text{opt}} \sim 4 \times 10^{14}$ Hz is the observer’s frequency and $\nu_{\text{rs}}^m$ is the typical synchrotron radiation frequency of the RS electrons. For $\nu_{\text{rs}}^m \leq 0.1 \nu_{\text{opt}}$ and $\Delta p \sim 1$, we have $R_w \leq 0.3$. Such a correction will render the RS optical emission for $\sigma = 0.3$, as shown in Fig.1 outshone by the FS emission. As a result, a bright RS optical flash is absent.

![Figure 2](image_url)

**FIGURE 2.** The RS emission in the case of $\sigma = 0$. The solid and the dotted lines are the RS emission component. The dashed and the dash-dotted lines are the FS emission. All parameters, except $T_90 = 60$ s and $E_k = 10^{53}$ erg, are the same as those in Fig.1.

*Non-magnetization but a very weak RS.* Nakar & Piran [28] and Jin & Fan [16] also got very weak RS optical emission in the case of $\sigma = 0$. Here we investigate the influence of the strength of the RS on the peak optical emission in such a particular case. The numerical results have been presented in Fig.2. As expected, the stronger the RS, the brighter the optical emission. The very weak RS emission implied by the *Swift* UVOT observation strongly suggests a sub-relativistic RS provided that $\sigma = 0$.

**MAGNETIC ENERGY TRANSFER TIMESCALE**

In the very early afterglow phase (during which both the RS and FS exist), the magnetic energy of the outflow can not be converted into the kinetic energy of the FS effectively. After the ceasing of the RS, a significant energy transfer between the magnetized outflow and the FS is possible. In about half of *Swift* GRB X-ray afterglows, a long term flattening is evident. This phenomenon motivates an idea that the magnetic energy has been transferred into the kinetic energy of the FS continually but slowly and then gives rise to a shallow X-ray decline phase [39]. If correct, the magnetized outflow model will be strongly favored because it can also naturally account for the absence of the bright optical flashes in most *Swift* GRBs (see the previous section). It is thus highly needed to calculate the transfer timescale of the magnetic energy.

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3 A speculation is that some prompt $\gamma$–ray emission with a very soft spectrum might be powered by the magnetized internal shocks and should be linearly polarized.
FIGURE 3. The kinetic energy of the FS driven by a magnetized outflow ($\sigma = 10$) as a function of the observer’s time. One can see that at an observer’s time $\sim 100$ s, most magnetic energy has been converted into the kinetic energy of the FS.

A preliminary investigation has been carried out by Fan & Piran in [7] (see §3.5 therein). The basic idea is that: For a highly magnetized outflow, the magnetic energy cannot be converted to the kinetic energy of the ejecta in a single passage of the reverse shock. There is a possibility to form multiple RSs as long as the total pressure behind the contact discontinuity is lower than the thermal pressure of the shocked medium. If the total pressure behind the contact discontinuity gets higher, the RS ceases and the magnetic pressure works upon the shocked medium and leads to the increase of the FS’s energy. The deceleration of the FS is thus suppressed and the afterglow light curves are flattened. The energy transfer timescale, however, seems to be too short (see Fig. 3 for illustration) to account for the shallow decline phase lasting $\sim 10^4$ sec that is detected in many *Swift* X-ray afterglows. The very recent numerical simulations confirm our conclusions [26, 25].

CONCLUSIONS

In this work, we find that:

- The magnetization of the GRB outflows plays a crucial role in suppressing the reverse shock optical emission. Bright optical flashes are only expected in the case of $\sigma < 0.1$. Polarimetry of the optical flashes should have significant detections.
- The energy transfer between a highly magnetized ejecta and the forward shock may be too quick to account for the shallow decline phase that is detected in a good fraction of *Swift* GRB X-ray afterglows.

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THE PROPAGATION OF PHOTONS: SHAPING THE REVERSE SHOCK EMISSION LIGHT CURVE

At a radius $R_x$, the RS crosses the GRB ejecta with a width $\Delta \simeq cT_{90}/(1+z)$. The RS “crossing time” is estimated as

$$t_x = (1+z) \int_0^{R_x} \frac{dR}{1 - \beta_{T_3}}$$

where $dR = cd\tau / (\beta_0 - \beta_{sh})$, $\Gamma_3$ and $\eta (\equiv \Gamma_0)$ are the bulk Lorentz factors of regions 3 and 4, respectively (measured in the observer’s frame), and $\beta$ is the corresponding velocity in units of $c$. With the relation $\Gamma_{sh} \approx (\gamma_3 - u_3)\Gamma_3$, we have

$$t_x \approx \frac{1}{(\gamma_{3,x} + u_{3,x})} T_{90},$$

where $\gamma_3$ is the Lorentz factor of the shocked fluid (measured in the reverse shock frame) and $u_3 = \sqrt{\gamma_3^2 - 1}$. In the case of $\sigma = 0$ and the RS is relativistic, we have $\gamma_{3,x} \approx \sqrt{9/8}$ and $t_x \approx T_{90}/2$. While for $\sigma \gg 1$, we have $\gamma_{3,x} \approx \sqrt{\sigma}$.
and \( t_x \approx T_{90}/4\sigma \) \(^4\). So the simple treatment that takes \( t_x \) as the RS emission timescale may violate the causality and thus be flawed.

We then have to look for a more reliable calculation of the arrival time of the RS emission (see also \([37]\)). The zero point of the observer’s time is that of the first \( \gamma \)-ray photon we detected. For illustration, we consider the case of \( \theta = 0 \) (i.e., on the line of sight), a \( \gamma \)-ray photon \( \gamma_p \) arriving at \( t_{em.p} \) implies that the distance from the corresponding electron (i.e., point \( P \), at which the bulk lorentz factor is \( \eta \)) to the initial outflow front is \( \approx c t_{em.p}/(1+z) \). The radial distance from the FS front to the central engine is \( R_P \) when the RS crosses point \( P \). At that time, the separation between photon \( \gamma_p \) and point \( P \) is \( \approx (1 - \beta \eta) R_P \). Therefore, the arrival time of the RS emission from point \( P \) should be (see Fig.4 for illustration)

\[
t_{arr.p} = t_{em.p} + (1+z)(1 - \beta \eta) R_P/c.
\]

If \( P \) is the rear of the GRB outflow, \( t_{arr.p} \) should be always larger than \( T_{90} \). So, in Fig.1 and Fig.2 of \([8]\), the RS emission duration has been underestimated and the flux overestimated significantly because the total energy emitted in that phase is fixed.

The crossing radius for point \( P \) can be calculated as \( R_P \approx 2\Gamma_{rsh.p}^2 c t_{em.p}/(1+z) \). Similarly, for point \( Q \), \( R_Q \approx 2\Gamma_{rsh,Q}^2 c t_{em,Q}/(1+z) \). The corresponding crossing times are \( t_{x,p} \approx t_{em,p} \Gamma_{rsh,p}^2/\Gamma_{3.p}^2 \), and \( t_{x,Q} \approx t_{em,Q} \Gamma_{rsh,Q}^2/\Gamma_{3.Q}^2 \), respectively. The arrival times, however, are \( t_{arr,p} \approx t_{em.p} \) and \( t_{arr,Q} \approx t_{em,Q} \), respectively since both \( \Gamma_{rsh,p}/\eta^2 \) and \( \Gamma_{rsh,Q}/\eta^2 \) are \( \ll 1 \). Following \([18]\), we can calculate the RS emission. However, the resulting light curves are scaled by the “crossing” time, which should be transferred into what are scaled by the arrival time. Because of the energy conservation, for \( P \rightarrow Q \), the emissions are related by

\[
F_{opt}(t_{arr.p})/F_{opt}(t_{arr.p}) = \frac{F_{opt}(t_{x,p})}{2} (t_{x,Q} - t_{x,p}) \approx \frac{F_{opt}(t_{arr.p})}{2} (t_{arr,Q} - t_{arr.p}),
\]

which yields

\[
F_{opt}(t_{arr.p}) = \frac{t_{x,p}}{t_{arr,p}} F_{opt}(t_{x,p}).
\]

\(^4\) The magnetized RS does have a shorter crossing time, as confirmed by the numerical simulation \([24]\).