A CHARACTERISTIC DENSE ENVIRONMENT OR WIND SIGNATURE IN PROMPT GAMMA-RAY BURST AFTERTGLOWS
SHIHO KOBASHI,1,2 PETER MÉSZÁROS,1,2,3 AND BING ZHANG1
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ABSTRACT
We discuss the effects of synchrotron self-absorption in the prompt emission from the reverse shock of gamma-ray burst afterglows in a dense environment, such as the wind of a stellar progenitor or a dense interstellar medium in early galaxies. We point out that when synchrotron losses dominate over inverse Compton losses, the higher self-absorption frequency in a dense environment implies a bump in the reverse-shock emission spectrum, which can result in a more complex optical/IR light curve than previously thought. This bump is prominent especially if the burst ejecta is highly magnetized. In the opposite case of low magnetization, inverse Compton losses lead to a prompt X-ray flare. These effects give a possible new diagnostic for the magnetic energy density in the fireball and for the presence of a dense environment.

Subject headings: gamma rays: bursts — radiation mechanisms: thermal — shock waves

1. INTRODUCTION

Snapshot fits of the broadband spectrum of gamma-ray burst (GRB) afterglows to forward-shock models have been found, in many cases, to be consistent with an external environment density $n \lesssim 1$ cm$^{-3}$ typical of a diluted interstellar medium (ISM) that can be taken to be approximately independent of distance from the burst (Frail et al. 2001). In other cases, the forward shock is better fitted with an external density that depends on distance as $\rho \propto R^{-2}$, typical of a stellar wind environment (Chevalier & Li 1999, 2000; Li & Chevalier 2003). The two types of fits have been critically analyzed by, e.g., Panaitescu & Kumar (2002), the conclusion being that at least some bursts may occur in high mass-loss winds, as expected from massive progenitors. The parameters for such wind fits are uncertain because of poorly known stellar mass-loss rates.

In this Letter we show that observations of prompt optical/IR and/or X-ray emission attributable to reverse-shock emission could constrain the GRB environment. In high-density environments, the self-absorption (SA) frequency is much higher than in the normal ISM, and it could be higher than the cooling and the typical injection peak frequencies (Wu et al. 2003). Here we argue that in such situations the SA frequency and its scaling are different from, and the flux at the SA frequency is appreciably larger than, what had been previously estimated. This implies a different light-curve time behavior for the afterglow prompt flash in a dense environment. This is of significant interest, since observations of the SA frequency and the typical injection peak frequencies (Wu et al. 2003). The shell width is related to the intrinsic duration of the burst (Frail et al. 2001). In other cases, the self-absorption frequency would then provide a constraint on the magnetization parameter.

1 Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802.
2 Center for Gravitational Wave Physics, Pennsylvania State University, University Park, PA 16802.
3 Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540.

2. THE MODEL

We consider a relativistic shell with an isotropic energy $E$, an initial Lorentz factor $\gamma$, and an initial width $\Delta_r$, expanding into a surrounding medium with a density distribution $\rho = AR^{-2}$. The shell width $\Delta_r$ is given by the intrinsic duration of the burst (Chevalier & Li 1999, 2000; Li & Chevalier 2003). The density $\rho$ is amplified by a factor $\rho_\infty$, typical of a diluted interstellar medium, and it could be higher than the cooling density $\rho_{\text{cool}}$. The reverse-shock frequency $f_{\text{SA}}$ is characterized by $f_{\text{SA}}(\Delta_r, T_{\text{SA}}) = (\Delta_r/2)^{-1}c^2n_{\text{cool}}^2$, where $n_{\text{cool}}$ is the cooling density and $T_{\text{SA}}$ is the SA frequency.

In this Letter we discuss the effects of synchrotron self-absorption in the prompt emission from the reverse shock of gamma-ray burst afterglows in a dense environment, such as the wind of a stellar progenitor or a dense interstellar medium in early galaxies. We point out that when synchrotron losses dominate over inverse Compton losses, the higher self-absorption frequency in a dense environment implies a bump in the reverse-shock emission spectrum, which can result in a more complex optical/IR light curve than previously thought. This bump is prominent especially if the burst ejecta is highly magnetized. In the opposite case of low magnetization, inverse Compton losses lead to a prompt X-ray flare. These effects give a possible new diagnostic for the magnetic energy density in the fireball and for the presence of a dense environment.

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3 Institute for Advanced Study, Einstein Drive, Princeton, NJ 08540.
An alternative derivation of the SA frequency is obtained by requiring the electron synchrotron cooling rate and heating rate (through absorption) to be equal at $\gamma_{c}$. The cross section for the synchrotron absorption process is approximately $\sigma_{e} \sim \gamma^{-5.7} \tau_{r}$. (e.g., Ghisellini & Svensson 1991), where $r$ and $\tau_{r}$ are the classical electron radius and the Larmor radius, respectively. Using this cross section and the photon flux determined by equation (1), we can evaluate the heating rate, while the cooling rate is given by the electron synchrotron power. Equating these rates reproduces the SA frequency of equation (2).

Following Kobayashi & Zhang (2003b), we obtain the scalings at $t < t_{e}$ of the spectral quantities $\nu_{r} \propto t$, $\nu_{c} \propto t^{-1}$, $\nu_{r} \propto t^{-3/7}$, and $F_{r, \text{max}} \propto t^{p}$. The optical/IR luminosity initially increases as $-(\nu_{r}/\nu_{c}) F_{r} \propto t^{5/7}$. When the SA frequency passes through the observation band $\nu_{obs}$ at $t_{e}$, the flux reaches a peak of $F_{r}(t_{e}) \sim (\nu_{r}/\nu_{c})^{2/5} F_{r, \text{max}}/\nu_{obs}$, and then it rapidly decreases.

For electrons in the hump that are quasi-thermally distributed, the peak luminosity $F_{r}(t_{e})$, and the peak flux contrast $R$ relative to the subsequent power-law decay value are given by:

$$
R_{r} \sim \text{max } F_{r, \text{max}}/\nu_{obs},
$$

$$
F_{r}(t_{e}) \sim 10^{-2/5} \epsilon_{e} \nu_{c, \text{obs}}^{1/2} T_{35}^{1/2} T_{50}^{2/5} F_{r, \text{max}},
$$

$$
E_{a} \sim \epsilon_{e}^{1/10} \nu_{c, \text{obs}}^{-1/10} T_{35}^{1/10} T_{50}^{2/5} F_{r, \text{max}}^{1/5} \nu_{obs, \text{14.2}} /
$$

where $\nu_{obs, \text{14.2}} = \nu_{obs}/(1.6 \times 10^{14} \text{ Hz})$ and $p = 3$ was assumed. At this turnover, a color change from blue to red is expected (see Fig. 1). Since the polarization is zero for an optically thick quasi-thermal spectrum, the reverse-shock shell can emit polarized photons only above the turnover. If a turnover characterized by $t_{e}$ and $F_{r}(t_{e})$ is observed, we can constrain the mass-loss rate $\dot{M}$, assuming that the redshift $z$ is measured and the GRB explosion energy $E_{a}$ is determined from late-time afterglow observations. The peak flux determines $\epsilon_{e}$ via equation (4), and the peak time gives through equation (3) a constraint on the mass-loss rate $\dot{M} \sim 5 \times 10^{41} \text{ cm}^{-2} \text{ s}^{-1}$.

After the optical/IR reverse-shock emission drops to the level expected from the slow synchrotron model, the flux decreases steeply as $-\nu^{2p-1}$ (Kumar & Panaitescu 2000; Kobayashi & Zhang 2003b). No color change is expected around this break. The flux at this break for $p = 3$ is $F_{r}(T) \sim 0.1 T_{35}^{5/2} \epsilon_{e}^{-1/5} T_{50}^{1/5} T_{14.2}^{1/10} \nu_{obs, \text{14.2}}$. These two breaks are schematically shown in Figure 2, the break sharpness being an idealization; in reality these would be rounded. In our treatment, we have ignored pair formation ahead of the blast wave, e.g., Beloborodov (2002), which may modify the forward-shock spectrum and light curve.

4. IC EFFECTS AND PROMPT REVERSE X-RAY FLASH

The above discussion assumed magnetized ejecta with $\epsilon_{e}/\epsilon_{B} \ll 1$ and $Y < 1$. However, for weaker ejecta magnetization with $\epsilon_{e}/\epsilon_{B} \gg 1$, the IC process can affect the observed spectrum.
and the light curve, resulting in a reverse-shock prompt X-ray flare. (For forward shocks, the importance of IC emission has been discussed, e.g., by Sari & Esin 2001 and Panaiteșcu & Kumar 2001). The energy available for the synchrotron process is reduced from the injected energy $E_I$ by a factor of $(1 + Y)$, where $Y \sim (e_I/e_B)^{1/2}$ (e.g., Zhang & Mészáros 2001). The IC process enhances the electron cooling, so $v_I$ is smaller by a factor of $(1 + Y)$ than its previous (synchrotron-only) value. The thermal bump is shifted to a lower frequency, becoming less prominent or even disappearing. As a consequence of the IC cooling, the flux at $v_I$ becomes smaller by a factor of $\sim (1 + Y)$ than the value given by equation (1). If $v_I$ is shifted below $v_{\text{iso}}$, most of the energy available for the synchrotron process is radiated between $v_I$ and $v_{\text{iso}}$. The flux at $v_I$ is reduced from equation (1) by a factor of $\sim (1 + Y)(v_I/v_{\text{iso}})^{1/2}$. By equating the flux at $v_I$ and the blackbody flux at the reverse-shock characteristic temperature, we can obtain the SA frequency. For the same parameters as for equation (1) but taking $e_{\text{iso}} = e_I/10^5$ and $e_{\text{iso}} = e_I/10^7$, we get $v_I(T) \sim 5.8 \times 10^{11} (e_I/10^5)^{1/2} (E_{53}/1.2)^{1/2} (T_{50}/1.2)^{3/2} (T_{50}/1.2)^{1/2}$ Hz and $v_I(T) \sim 5.0 \times 10^{10} (e_I/10^5)^{1/2} (E_{53}/1.2)^{1/2} (T_{50}/1.2)^{3/2} (T_{50}/1.2)^{1/2}$ Hz. When $v_I \leq v_{\text{iso}}$, in this case, the contrast $R$ is $\approx 2$ and the bump practically disappears. The optical/IR light curve initially increases as $\sim (v/v_I)^{2/3}F_{\nu_I} \propto t^{2/3}$, and after $v_I$ crosses the observation band, it decreases as $t^{-1-2/3}$.

Since at the shock crossing time, the forward- and reverse-shocked regions have roughly comparable energy, the $vF_\nu$ peaks of the synchrotron emissions reach roughly similar levels. Assuming that the characteristic reverse-shock IC frequency $v_{\text{sc,ic}} \sim \gamma_2^2 v_I$ is close to the typical (peak) frequency of the forward-shock synchrotron emission, we can infer that in the case of $Y \ll 1$ the reverse-shock IC component is generally masked by the forward-shock synchrotron emission, whereas in the case of $Y \gg 1$ the reverse-shock IC peak sticks out above the forward-shock synchrotron peak. Therefore, for weakly magnetized fireballs (with $Y \lesssim 1$), a prompt X-ray flare is expected from the reverse shock. The characteristic photon energy and the flux at this frequency are $h\nu_{\text{sc,ic}}(T) \sim 20^{3/2} E_{53}^{1/2} T_{50}^{-1/2} E_{32}^{1/2} T_{30}^{1/2} \text{keV}$ and $F_{\nu_{\text{sc,ic}}}(T) \sim 10^{32} E_{53}^{-1} T_{50}^{3/2} E_{32}^{-1} T_{30}^{3/2} \text{erg} \text{cm}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}$, respectively. The typical duration of this X-ray flare at $v \gg v_{\text{sc,ic}}$ is of the order of the shock crossing time $t_s \approx T/50 T_{50}$. Since the reverse shock crosses the shell, electrons are no longer heated and the (on-axis) synchrotron flux at $v > v_I(T)$ drops, as does the IC emission at $v > v_{\text{iso}}$, and one starts to observe high-latitude emission. The X-ray emission from the reverse shock decays steeply as $t^{-1-2/3}$, whereas the forward-shock emission decays proportional to $t^{-1-2/3}$. Thus the slower decaying forward-shock component eventually starts to dominate.

5. DENSE ISM IN EARLY GALAXIES

We consider a specific model in which the ISM density of early galaxies scales with redshift as $n \sim (1 + z)^\alpha n_0$ cm$^{-3}$ (e.g., Ciardi & Loeb 2000). In this case (or in general when the ISM density is much larger than a typical $n_0 \sim 1$ cm$^{-3}$ at $z = 0$), a discussion analogous to that of the previous section can also lead to a bump in the reverse-shock spectrum and in the optical/IR light curve.

A large fraction of GRBs are expected to be classified as thick shell cases in this model, whose spectral quantities are given by (Kobayashi & Zhang 2003a) $v(T) \sim 2.0 \times 10^{11} n_0^{1/2} (1 + z)^\alpha \times e_{\text{iso}}^{1/2} E_{53}^{1/2} T_{50}^{-1/2}$ Hz, $n_{\text{iso}}(T) \sim 7.2 \times 10^{11} n_0^{1/2} (1 + z)^\alpha \times e_{\text{iso}}^{1/2} E_{53}^{1/2} T_{50}^{-1/2}$ Hz, and $F_{\nu_{\text{max}}}(T) \sim 27 n_0^{1/14} T_{50}^{1/14} E_{53}^{1/14} \eta_2^{1/2} T_{50}^{1/2} \text{Jy}$, where $n_0 = (1 + z)/6$, $T_{50} = T/150 \text{ s}$, $D = d_L(z)/1.5 \times 10^{29}$ cm is the normalized luminosity distance, and $D(z) = 5$. Equating $F_{\nu_{\text{max}}} \propto F_{\nu_I}$, we obtain $v_I(T) \sim 3.7 \times 10^{10} n_0^{1/2} (1 + z)^\alpha \times e_{\text{iso}}^{1/2} E_{53}^{1/2} T_{50}^{1/2}$ Hz. Using the scalings by Kobayashi (2000), one can show that $v_I \sim \tau^{-1}$ during the shock crossing. The optical/IR light curve initially increases as $\sim (v/v_I)^{2/3}F_{\nu_I} \propto t^{2/3}$. When $v_I$ passes through the $K$ band at $t_s \sim 5.1 n_0^{-1/2} E_{53}^{1/2} (1 + z)^{\alpha/2} T_{50}^{1/2} \text{days}$, the flux reaches a peak of $F_{\nu_{\text{max}}}(t_s) \sim 1.0 D_T^{1/2} n_0^{1/2} E_{53}^{1/2} T_{50}^{1/2} \text{Jy}$, and then it rapidly decreases by a (bump contrast) factor of $R \sim 30 h_5^{1/2} n_0^{-1/2} (1 + z)^{\alpha/2} T_{50}^{1/2}$ s, the flux reaches a peak of $F_{\nu_{\text{max}}}(t_s) \sim 1.0 D_T^{1/2} n_0^{1/2} E_{53}^{1/2} T_{50}^{1/2} \text{Jy}$, and then it rapidly decreases by a (bump contrast) factor of $R \sim 30 h_5^{1/2} n_0^{-1/2} (1 + z)^{\alpha/2} T_{50}^{1/2}$ s.

6. DISCUSSION AND CONCLUSIONS

We have analyzed the prompt afterglow emission from the reverse shocks of GRBs occurring in dense environments, such as the stellar wind of a massive progenitor or a dense ISM as might be expected in early galaxies. Usually in the fast cooling case, the $vF_\nu$ flux is normalized at the typical frequency $v_m$ by using the energy ejected into electrons. However, here we point out that if the synchrotron SA frequency $v_{\text{sc}}$ is higher than the typical frequency $v_m$, the usual prescription should be inapplicable for estimating the flux at $v_m$ and below $v_{\text{sc}}$. Such conditions can occur in the reverse shock of a GRB fireball in a dense environment. The radiation flux suppressed by the SA effect is redistributed among the electrons and photons in the optically thick regime, and most of it is emitted at $v_m$ in a dynamical time. As a result, the SA frequency is different and scales differently with the shock parameters, and the flux at the SA frequency shows a bump that is a factor of $2(v/v_m)^{1-2/3}$ (approximately several) above the usual power-law flux estimate for typical parameters. The flux well above $v_m$ is the same as before, but the flux below $v_m$ is larger by the same factor $2(v/v_m)^{1-2/3}$. This results in a new type of temporal behavior for the prompt optical flash of afterglows from fireballs in dense (e.g., wind or early galaxy) environments. These new features will be prominent when the IC process is not important for electron cooling, i.e., for ejecta with $e_{\text{iso}}/e_B \ll 1$. This may be the case in fireball ejecta that are highly magnetized, as suggested by some recent studies. If, on the other hand, the burst occurs in a dense environment and such features are absent, this may be an indication that $e_{\text{iso}}/e_B \gg 1$, and in this case a prompt reverse-shock X-ray flare is expected.

Massive stars appear implicated in producing long GRBs (e.g., Stanek et al. 2003). Wind mass loss is expected from
such stars previous to the GRB explosion, but snapshot fits to forward-shock late emission (e.g., Panaitescu & Kumar 2002) are compatible with such wind mass loss in only a handful of cases. In general the parameters of stellar winds are poorly known, and the uncertainties are further increased at high redshifts, where massive stars are expected to be metal-poor. For this reason, signatures of a wind mass loss or a dense environment would be extremely valuable, both for GRB astrophysics and for tracing the properties of star formation at high redshifts. The prompt optical flashes expected after tens of seconds from the reverse shock in a dense environment would give characteristic signatures in the spectral and temporal behavior. These may help us to test for the presence of winds and constrain the wind mass loss, in moderate-redshift environment, or alternatively, at high redshifts they may provide evidence for a denser ISM than at low redshifts. In such winds or dense ISM the spectra and light-curve time behavior can also give constraints on the strength of the magnetic field in the ejecta. Large numbers of prompt X-ray detections with future missions such as Swift, complemented by ground-based follow-ups, should be able to test for such wind or dense ISM signatures and trace any changes with redshifts, if they exist, thus constraining the GRB environment as well as the radiation mechanisms.

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