GeV PHOTONS FROM THE UPSCATTERING OF SUPERNOVA SHOCK BREAKOUT X-RAYS BY AN OUTSIDE GAMMA-RAY BURST JET

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ABSTRACT

Shock breakout X-ray emission has been reported for the first time from a supernova connected with a gamma-ray burst, namely, GRB 060218/SN 2006aj. The gamma-ray emission and the power-law–decaying X-ray afterglow are ascribed to a highly relativistic jet, while the thermal soft X-rays are thought to be produced when the radiation-dominated shock breaks from the optically thick stellar wind. We study the inverse Compton (IC) emission of the breakout thermal soft X-rays scattered by relativistic electrons in the jet forward shock, which is expected to be at larger radii than the breakout shock. This IC emission produces sub-GeV to GeV photons, which may be detectable by GLAST. The detection of such GeV photons simultaneously with the supernova shock breakout emission would provide us with evidence for the presence of a GRB jet ahead of the shock while the shock is breaking out. The anisotropic scattering between the X-rays and relativistic electrons may lead to large angle emission outside of the jet opening angle. This has implications for the detection of GeV photons from “burstless” Type Ib/c hypernova shock breakout, which, due to its more isotropic emission, might be observed with wide-field X-ray cameras such as Lobster.

Subject headings: gamma rays: bursts — radiation mechanisms: nonthermal — supernovae: general

1. INTRODUCTION

Aside from providing new evidence that gamma-ray bursts (GRBs) are connected with supernovae (SNe), recent observations of GRB 060128/SN 2006aj (Modjaz et al. 2006; Soller-man et al. 2006; Pian et al. 2006; Mazzali et al. 2006) also provide for the first time direct evidence of shock breakout soft thermal X-ray emission (Campana et al. 2006). The gamma-ray bursts are, as usual, thought to arise from the internal dissipation of ultrarelativistic jets. The power-law–decaying afterglow at times $>10^4$ s is consistent with this standard picture of GRBs (e.g., Zhang & Mészáros 2004; Piran 2005). The thermal soft X-ray emission is interpreted as arising from the breakout of a radiation-dominated shock, which could be driven by the cocoon of the relativistic jet (Mészáros & Rees 2001; Ramirez-Ruiz et al. 2002; Zhang et al. 2003), the slower outer parts of the jet, or the outermost parts of the envelope that get accelerated to a mildly relativistic velocity (Colgate 1974; Tan et al. 2001). The relativistic jet accelerates after leaving the supernova photosphere and runs ahead of the shock while the less relativistic shock is breaking out from the stellar wind. The observed breakout X-ray emission continues after the end of the GRB prompt emission and lasts until the early afterglow phase. It contains two components, a thermal component and a nonthermal one. The thermal component becomes increasingly dominant during the first 3000 s after the trigger of this GRB. Since the relativistic GRB jet is expected to be located outside of the breakout shock, we point out here that the incoming shock X-rays will be upscattered by the nonthermal electrons accelerated in the afterglow forward shock to GeV energies.

Gamma-ray emission from bremsstrahlung and inverse Compton (IC) emission of thermal electrons during the supernova shock breakout were suggested by Colgate (1974). Tan et al. (2001) argued that the gamma rays of GRB 980425 associated with SN 1998bw are produced by the interaction of a mildly relativistic ejecta, which results from the acceleration of the supernova shock interacting with a dense circumstellar wind. Waxman & Loeb (2001) suggested that during the shock breakout of Type II supernovae, the shock may transition to a collisionless one and accelerate nonthermal electrons that might produce hard X-ray flares. In these scenarios, no GRB jets are required, leaving a power-law–decaying X-ray afterglow still in need of interpretation. The strong soft X-ray thermal photon bath and the compact size of the progenitor star of the Type Ib/c supernova would combine to make a large pair-production absorption optical depth for GeV photons if they could be produced in this scenario. This is different from the case of scattering by the jet forward-shock electrons, in which GeV photons do not suffer significant absorption because the jet has a relativistic motion and has reached a much larger radius. We suggest that the detection of the GeV emission that accompanies supernova shock breakout will favor the normal scenario, in which a highly relativistic jet produces the gamma-ray emission in supernova-connected GRBs like GRB 060218/ SN 2006aj.

In § 2, we first study the emission signature of this IC process, and then we consider the anisotropic scattering effect and the pair-production absorption effect on the received IC flux in §§ 3 and 4, respectively. Finally, in § 5, we give the conclusions.

2. IC SCATTERING OF THE SHOCK BREAKOUT X-RAYS BY AFTERGLOW SHOCK ELECTRONS

We consider the IC scattering of shock breakout X-rays after the end of the prompt gamma-ray emission but before the sharp X-ray decay, namely, from 1000 to 3000 s after the GRB trigger. During this time, the X-ray emission detected by the Swift X-Ray Telescope can be divided into two components, one being a thermal component and the other a nonthermal one (Campana et al. 2006). The thermal X-ray component becomes increasingly dominant and has a luminosity of $\sim 10^{46}$ erg s$^{-1}$. After $\sim 3000$ s, the X-ray emission undergoes a sharp decay, and an
X-ray afterglow, decaying as a power law in time, emerges later. The underlying afterglow flux extrapolated from the late power-law—decaying afterglow is more than 30 times lower than the thermal X-ray emission, and it is not enough to account for the nonthermal emission of the previous phase. This early nonthermal component could come from the shock breakout itself or from the extended internal shock emission.

The equipartition factor (hereafter frame is lower than that of the breakout X-ray emission if the nonthermal component could come from the shock breakout X-ray emission, and it is not enough to account for the nonthermal emission of the previous phase. This early nonthermal component could come from the shock breakout itself or from the extended internal shock emission. Below we will show that the strong shock breakout X-ray emission will cause the afterglow electrons to be in the fast-cooling regime, and therefore most of the energy of the shocked electrons during this period goes into the IC emission.

The gamma-ray emission of GRB 060218 is weak compared to a typical GRB with an isotropic gamma-ray energy $E_{\gamma} = 10^{50}$ ergs. Here we consider a jet with an isotropic kinetic energy $E = 10^{50}$ ergs expanding in a surrounding wind medium with density profile $\rho = K r^{-\alpha}$, where $K = M/4\pi v_\infty$, $M$ is the mass-loss rate, and $v_\infty$ is the wind velocity. From the energy conservation of the adiabatic shock, we can get the Lorentz factor and radius of the afterglow shock (Chevalier & Li 1999):

$$\Gamma = 4.3 E_\text{IC}^{1/4} m^{-1/4} t_s^{-1/4},$$

$$R = 1.7 \times 10^{15} E_\text{IC}^{1/2} m^{-1/2} t_s^{1/2} \text{ cm},$$

respectively, where $m = (M/10^{53} M_\odot \text{ yr}^{-1})/(v_\infty / 10^3 \text{ km s}^{-1})$.

From $L_\gamma = 4\pi R^2 \Gamma^4 U_\gamma c$, we find that the energy density of shock breakout X-ray photons in the forward-shock frame is $U_\gamma = L_\gamma/(4\pi R^2 c)$, where $L_\gamma = 10^{50}$ erg s$^{-1}$ is the observed luminosity of the shock breakout X-rays. The Lorentz factor of the electrons that cool by the IC scattering of the shock breakout X-rays in the dynamical time, $R/c$, is

$$\gamma_e = \frac{3\pi m c^3 \Gamma R}{\sigma_T L_\gamma} = 6 L_\text{IC}^{-1} E_\text{IC}^{7/8} m^{-7/8} t_s^{-1/4},$$

while the minimum Lorentz factor of the postshock electrons is

$$\gamma_m = \bar{c}_e (m_p/m_e)(\Gamma - 1) \approx 610 \bar{c}_e^{-1} E_\text{IC}^{1/4} m^{-1/4} t_s^{-1/4},$$

where $\bar{c}_e$ is the usual equipartition factor ($c_e$) of shocked electrons multiplied by a factor of $(p - 2)/(p - 1)$ ($p$ is the energy distribution index of the electrons). So if the breakout emission has a luminosity larger than

$$L_\gamma > 2 \times 10^{44} \bar{c}_e^{-1} E_\text{IC}^{5/8} m^{-5/8} \text{ ergs s}^{-1},$$

one obtains $\gamma_m > \gamma_e$, which implies that most of the energy of the afterglow shocked electrons during the shock breakout period would go into the IC emission.

As the forward shock propagates in the surrounding medium, the energy that goes into the newly shocked electrons per unit observer’s time is $L_\gamma = 2 \times 10^{44} \bar{c}_e^{-1} E_\text{IC} t_s^{-1}$ ergs (Wang et al. 2006). The bolometric luminosity $L_\text{IC}$ of the IC emission is equal to $L_\gamma$, and so the total energy loss of the shocked electrons during the time from 1000 to 3000 s is about $E_\text{IC} = 2 \times 10^{48} \bar{c}_e^{-1} E_\text{IC}$ ergs, and the total IC emission fluence is

$$\Psi_\text{IC} = 10^{-7} \bar{c}_e^{-1} E_\text{IC} (D/145 \text{ Mpc})^{-2} \text{ ergs cm}^{-2},$$

where $D = 145$ Mpc is the distance of GRB 060218. The observed IC $\nu F_\nu$ flux peaks at

$$\epsilon_{\text{IC, p}} = 2\gamma_m^2 (3kT) = 0.22 \bar{c}_e^{-1} E_\text{IC}^{1/2} m^{-1/2} t_s^{1/2} (kT/0.1 \text{ keV}) \text{ GeV},$$

where $kT = 0.16$ keV is the blackbody temperature of the thermal spectrum of the shock breakout emission (Campana et al. 2006). The IC energy spectrum ($\nu F_\nu$) has indices of 1/2 and $-(p - 2)/2$ before and after the break at $\epsilon_{\text{IC, p}}$, respectively. The upcoming Gamma-Ray Large Area Space Telescope (GLAST) LAT detector has an effective detection area of $10^4$ cm$^2$, and so it can detect the sub-GeV to GeV photons with the above flux and may even identify the peak energy of this IC emission.

The jet afterglow electrons may also produce high-energy emission through the self-synchrotron Compton process (Zhang & Mészáros 2001). However, based on the assumption that the extrapolated synchrotron flux during the early afterglow is $>30$ times lower than the shock breakout X-ray flux, the self-synchrotron Compton flux is then lower by the same factor.

After the shock breaks out of the optically thick wind, its emission drops very sharply, and the jet afterglow emission becomes dominant. The remaining energy, $E - E_\text{IC}$, of the jet continues to power the power-law—decaying afterglow at later times. The jet is likely to enter into the subrelativistic phase around $t \sim 10^5 - 10^6$ s for a low burst energy, and the power decay rate should transition from $t^{-3/4}$ to $t^{-5/6}$ (Waxman 2004), when the cooling frequency is below the X-ray band. However, for $p \sim 2$, the decay index is almost unchanged and is consistent with the observed single decay rate $F_\nu \propto t^{-1.15 \pm 0.15}$ (Cusumano et al. 2006).

3. THE ANISOTROPIC IC SCATTERING EFFECT AND THE CASE OF OFF-AXIS JETS

The shock breakout emission comes from the region of the immediate stellar wind surrounding the SN/GRB progenitor at $R \sim 5 \times 10^{12}$ cm (Campana et al. 2006), which is much smaller than the afterglow shock radius, so the shock breakout X-ray photons move outward almost radially, viewed from the afterglow region. The seed photons are anisotropic when seen by the scattered photons and relativistic electrons are anisotropic, and there would be more head-on scatterings (e.g., Ghisellini et al. 1991). In the comoving frame of the forward shock, the IC emission power depends on the relative angle $\theta_\gamma$ between the scattered photon direction and the seed photon beam direction as $P(\gamma_\gamma) \propto (1 - \cos \theta_j)^{q + 1/2} \sin \theta_j d\theta_j$ (e.g., Brunetti 2000; Fan & Piran 2006), where $q$ is the power-law energy distribution index of the scattering electrons. For the fast cooling of relativistic electrons in our case, $q = p + 1 \approx 3$. The factor $(1 - \cos \theta_j)^{q + 1/2}$ results in more power emitted at large angles relative to the seed photon beam direction.

The real contribution to the X-ray flux by the synchrotron emission would be suppressed due to the enhanced cooling of electrons by the shock breakout X-ray emission (Wang et al. 2006).
By simple algebraical calculation, one can obtain the fraction of photons scattered into the angles $0 \leq \theta \leq \pi/2$ in the shock frame (corresponding to the $1/\Gamma$ cone of the relativistic afterglow jet in the observer frame due to the aberration of light); i.e.,

$$f_s = \frac{\frac{1}{2\pi} (1 - \cos \theta)^3 \sin \theta \, d\theta}{\frac{1}{2\pi} (1 - \cos \theta)^3 \sin \theta \, d\theta} = \frac{1}{8}. \quad (8)$$

Similarly, one can see that the fraction of photons falling into the cone of $2/\Gamma$ (corresponding to $\theta = 2 \arccot 2$) is $1/2$. Therefore, the effect of increased head-on scattering can decrease the IC emission in the $1/\Gamma$ cone along the direction of the photon beam but can enhance the emission at larger angles, if the jet has an opening angle $\theta \leq 1/\Gamma$. However, if the opening angle is $\theta > 1/\Gamma$, the jet geometry can be approximately regarded as a sphere, and the observed IC power after integration over angles should be the same in every direction in the observer frame (Wang et al. 2006; Fan & Piran 2006). Therefore, the received IC fluence will no longer be reduced. At $t \sim 10^6$ s, the jet Lorentz factor is $\Gamma = 4.3E_{50}^{1/4} m^{-1/4}$. So for a typical mass-loss rate with $m = 1$ and a weak burst such as GRB 060218 with energy $E = 10^{50}$ erg, a jet with an opening angle $\theta > 1/\Gamma \approx 0.25$ is needed to avoid a significant reduction of the received IC fluence. Considering that the jet has a low energy, such an opening angle may not be unreasonable.

An interesting phenomenon arises when the jet opening angle is not larger than $1/\Gamma$ (i.e., $\theta \approx 1/\Gamma$) and when the observer lies outside of the cone of the GRB jet, e.g., when it lies between $1/\Gamma$ and $2/\Gamma$, the probability of which may be somewhat larger than the case within the $1/\Gamma$ cone. The observer would miss the GRB, but it may still detect the IC emission associated with the SN shock breakout because the prompt gamma-ray flux decreases very sharply as $[\Gamma_{\gamma} (\theta_{\text{obs}} - \theta_0)]^{-6}$ while the anisotropic IC emission decreases modestly with the relative angle (almost constant within $2/\Gamma$), where $\Gamma_{\gamma}$ is the jet initial Lorentz factor, and $\theta_{\text{obs}}$ and $\theta_0$ are the observing angles relative to the jet axis and jet opening angle, respectively. The breakout X-ray emission could be detected by wide-field X-ray detectors such as the future Lobster mission (Calzavara & Matzner 2004) even if there is no trigger in a GRB detector. Lobster would have the capability of detecting the shock breakout X-ray flash from Type II supernova explosions up to 100 Mpc, as the shocked gas of Type II supernova is predicted to emit $\sim 10^{45}$ ergs s$^{-1}$ with an effective temperature of $2 \times 10^5$ K (Klein & Chevalier 1978; Ensman & Burrows 1992). For shock breakout from Type Ib/c supernovae like SN 2006aj, the soft X-ray flux is larger by about 2 orders of magnitude, so Lobster could detect this kind of explosions up to $\sim 1$ Gpc. The IC emission will be delayed relative to the shock breakout emission due to a longer light-travel distance. It is important to note that this IC GeV emission will not be polluted by other possible high-energy emission processes from the jet itself.

Another nearby supernova-connected GRB, GRB 031203/ SN 2003lw, which is a similar weak burst (Sazonov et al. 2004; Soderberg et al. 2004; Watson et al. 2004), has been suggested to be a possible off-axis burst (Ramirez-Ruiz et al. 2005); i.e., the line of sight of the observer is outside of the jet opening angle. If this Type Ic SN also has a shock breakout soft X-ray emission like GRB 060218/SN 2006aj, which is possibly not observed due to the energy threshold of the INTEGRAL detector, GeV photons produced by the upscattering of these X-rays by relativistic electrons in the jet forward shock are expected to have a fluence detectable with GLAST, considering that the on-axis isotropic energy of the jet could be $E \sim 10^{48}$ ergs (Ramirez-Ruiz et al. 2005).

4. PAIR-PRODUCTION OPACITY FOR HIGH-ENERGY PHOTONS

Here we consider the pair-production opacity and the high-energy photon cutoff due to the absorption by the shock breakout thermal photons. First we calculate the optical depth for high-energy photons that originate from some possible non-thermal process occurring in the shock breakout itself. The optical depth for high-energy photons, $\tau_{\gamma\gamma} = 2(m_e c^2)^2 \epsilon_{X} = (5kT/0.1 \text{ keV})^{-1}$ GeV, annihilating with thermal photons of characteristic energy $\epsilon_X = kT$ is

$$\tau_{\gamma\gamma} = 0.1 \sigma_T \left( \frac{L}{4\pi R^2 c kT} \right) \left( \frac{R}{\eta} \right) \left( \frac{\eta}{20} \right)^{-1} \left( \frac{kT}{0.1 \text{ keV}} \right)^{-1}, \quad (9)$$

where $R = 5 \times 10^{12}$ cm is the inferred radius of the breakout shock and $R/\eta$ is shocked shell thickness. Considering the exponential tail of the Planck function of the thermal spectrum, this very large optical depth will induce a cutoff at $E_{\text{cut}} = \epsilon_{X}/\ln(\tau_{\gamma\gamma}) \sim 0.4(kT/0.1 \text{ keV})^{-1}$ GeV.

Then we calculate the optical depth for high-energy photons produced through the upscattering of breakout X-rays by afterglow shock electrons. The energy of the photons annihilating with the thermal photons with characteristic energy $\epsilon_X = kT$ is $\epsilon_{\gamma} = 2T^2 (m_e c^2)^2 \epsilon_X = 90(4.3)^2 (kT/0.1 \text{ keV})^{-1}$ GeV, where $\Gamma$ is the bulk Lorentz factor of the afterglow shock. The pair-production absorption optical depth for this energy is

$$\tau_{\gamma\gamma} = 0.1 \sigma_T \left( \frac{U_X}{kT \Gamma} \right) \left( \frac{R}{\Gamma} \right) = 400 L_{46} E_{50}^{-1/8} \left( \frac{kT}{0.1 \text{ keV}} \right)^{-1}. \quad (10)$$

In this case, for representative parameter values, the cutoff energy is

$$E_{\text{cut}} \sim 15E_{50}^{1/2} m^{-1/2} \epsilon_{X}^{1/2} (kT/0.1 \text{ keV})^{-1} \text{ GeV.} \quad (11)$$

Thus, we conclude that, at the radius of the shock breakout, only a negligible fraction of $\sim$ GeV photons can escape from the strong thermal photon bath, while at the larger radius of the afterglow shock, up to $\sim 10$ GeV photons can escape the pair-production absorption. This implies that future detections of GeV photons accompanying the SN shock breakout in GRBs like GRB 060218/SN 2006aj can provide us with evidence of a relativistic jet ahead of the supernova shock breakout.

5. CONCLUSIONS

The large energy and thermal spectrum of the soft X-ray emission observed in the early stages of a nearby GRB/SN, GRB 060218/SN 2006aj, supports the view that this arises from a radiation-dominated shock that is breaking out of the strong stellar wind. The prompt gamma-ray emission and the power-law–decaying afterglow can be interpreted conventionally as

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5 See http://www.srl.le.ac.uk/projects/lobster.
evidence of a highly relativistic jet, which presumably has moved to larger radii while the shock is breaking out. In this Letter we have suggested that the upscattering of the shock breakout soft X-rays by relativistic electrons in the GRB jet forward shock would produce sub-GeV to GeV photons that could be detected by GLAST.

It is possible that some nonthermal processes in the breakout shock itself could also produce GeV emission. However, in this case, the photons with energies above a few hundred MeV cannot escape the absorption by the abundant soft photons and thus will be undetectable. Therefore, detection of high-energy photons with energies above GeV accompanying the shock breakout of GRBs/SNe like GRB 060218/SN 2006aj will favor the scenario involving a relativistic jet producing the GRB, which outruns the slower supernova shock.

We also discussed the anisotropic IC scattering effect on the received GeV fluence. When the jet opening angle $\theta_0$ is significantly larger than the beaming angle of the jet, $1/\Gamma$, at the considered time, the geometry is equivalent to the isotropic case for observers inside the jet angle cone, and the received fluence will not be depressed. For a weak burst like GRB 060218 and a typical stellar wind, this requires that the jet opening angle be larger than 0.25 rad, which may be reasonable considering that the jet has a low energy. However, for a jet with an opening angle comparable to $1/\Gamma$, the received fluence will be reduced by a factor of $\sim 8$. Nonetheless, in the event of GRB 060218/SN 2006aj, even considering this effect, the sub-GeV photon fluence could be detected by GLAST.

The anisotropic IC scattering effect can reduce the emission inside the $1/\Gamma$ cone of the jet but can enhance the emission at larger angles. This has potentially important implications for detecting GeV emission from “burstless” (untriggered) hypernovae during the early stages of their explosions, when the observer lies off-axis with respect to the GRB jet. The shock breakout soft X-ray flash could still be observed by wide-field X-ray cameras, such as the proposed future Lobster mission, although they would not trigger GRB detectors.

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