

PROMPT HIGH-ENERGY GAMMA-RAY EMISSION FROM THE SYNCHROTRON SELF-COMPTON PROCESS IN THE REVERSE SHOCKS OF GAMMA-RAY BURSTS

X. Y. WANG, Z. G. DAI, AND T. LU

Department of Astronomy, Nanjing University, 22 Hankou Lu, Nanjing, Jiangsu, China
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ABSTRACT

In the standard scenario of the fireball model of gamma-ray bursts (GRBs), the huge initial energy release produces a relativistic blast wave expanding into the external medium and a reverse shock moving into and heating the fireball ejecta. We calculate the high-energy gamma-ray emission due to inverse Compton scattering of the synchrotron photons from relativistic electrons in the reverse shock. Under the favorable values of the physical parameters of the GRBs and the interstellar medium, our result shows that during the prompt phase, this emission dominates over the component from the forward shock at high-energy gamma-ray bands. This mechanism can excellently account for the observations of the prompt high-energy gamma rays detected by EGRET, such as those from GRB 930131.

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

1. INTRODUCTION

Gamma-ray bursts (GRBs) are widely believed to be caused by the dissipation of the kinetic energy of a relativistically expanding fireball with a Lorentz factor of $\eta \sim 10^2$ – 10^3 (see, e.g., Piran 1999 for a review). After producing the prompt GRB, the shell impacts on the surrounding gas, driving an ultrarelativistic shock into the ambient medium, which approaches a self-similar behavior (Blandford & McKee 1976) after a short transition phase. This forward shock continuously heats fresh gas and accelerates electrons, producing a long-term afterglow. The initial interaction between the ejecta with the surrounding gas also leads to a reverse shock that propagates into and decelerates the ejecta. This shock, heating up the shell's matter and accelerating its electrons, operates only once. Once the reverse shock crosses the ejecta, the ejecta expands and cools adiabatically. Transition of the fireball to the self-similar behavior occurs on a timescale comparable to the reverse shock crossing time of the ejecta. Thus, emission from the fireball ejecta is suppressed after the transition to the self-similar expansion.

A prompt ninth magnitude, optical flash has been recently detected (Akerlof et al. 1999) accompanying GRB 990123. The most natural explanation of this flash is synchrotron emission from a reverse shock propagating into the fireball ejecta after it interacts with the surrounding gas (Sari & Piran 1999a; Mészáros & Rees 1999). The reverse shock, at its peak, contains energy that is comparable to that of the GRB itself and the forward shock but has much lower temperature than that of the forward shock. So, it radiates at considerably lower frequencies. Since, during the prompt phase, the number of heated electrons in the reverse shock is $\eta(\sim 10^2$ – $10^3)$ times larger than in the forward shock and the seed photon source is stronger, we expect a strong synchrotron self-Compton emission flux at high-energy gamma-ray bands in the reverse shock. Here we present an analytic calculation of this synchrotron self-Compton emission and consider its implications for the prompt high-energy gamma-ray emission detected from some GRBs by the Energetic Gamma-Ray Experiment Telescope (EGRET) and the Compton Telescope on board the *Compton Gamma-Ray Observatory*. Early discussions on the synchrotron self-Compton process in the reverse shock include the works of, e.g., Mészáros, Laguna, & Rees (1993) and Sari, Narayan, & Piran (1996), both of which,

however, are quite different from our subject in many fundamental aspects.

2. THE SYNCHROTRON SELF-COMPTON EMISSION FROM THE REVERSE SHOCK

2.1. Reverse Shock Model

Transition of the fireball ejecta to the self-similar expansion occurs on timescale Δt_{tran} comparable to the longer of the two timescales set by the initial conditions: the (observed) GRB duration Δt_{GRB} and the (observed) deceleration timescale t_{dec} of the fireball ejecta, at which the self-similar Lorentz factor (Γ) equals the initial ejecta Lorentz factor η , i.e., $\Delta t_{\text{tran}} = \max(\Delta t_{\text{GRB}}, t_{\text{dec}})$ (Sari & Piran 1999b; Waxman & Draine 2000).

The deceleration time t_{dec} is in fact the observer time at which the heated interstellar medium energy is comparable to the initial energy E , i.e.,

$$t_{\text{dec}} = \frac{r_{\text{dec}}}{2\eta^2 c} (1+z) = 10 \text{ s} \left(\frac{1+z}{2} \right) E_{53}^{1/3} n_0^{-1/3} \eta_{300}^{-8/3}, \quad (1)$$

where

$$r_{\text{dec}} = \left(\frac{E}{4\pi\eta^2 n m_p c^2} \right)^{1/3} = 3.7 \times 10^{16} E_{53}^{1/3} n_0^{-1/3} \eta_{300}^{-2/3} \text{ cm} \quad (2)$$

is the deceleration radius, $E = 10^{53} E_{53}$ ergs, $n = 1 n_0 \text{ cm}^{-3}$, $\eta = 300 \eta_{300}$, and z is the redshift of the GRB source. Since even long-duration GRBs have durations on the order of 10 s, which is comparable to t_{dec} , we therefore take $\Delta t_{\text{tran}} \sim t_{\text{dec}}$ for the following calculations.

During the transition, the unshocked fireball shell propagates at the original expansion Lorentz factor η , and the Lorentz factor of the plasma shocked by the reverse shock in the rest frame of the unshocked ejecta is $\bar{\gamma}^{\text{rs}} \approx \eta/\Gamma$. According to Sari & Piran (1995), the reverse shock Lorentz factor $\bar{\gamma}^{\text{rs}}$ depends on the parameter $\xi \equiv (l/\Delta)^{1/2} \eta^{-4/3} = 2 E_{53}^{1/3} n_0^{-1/3} \Delta_{10}^{-1/2} \eta_{300}^{-4/3}$, where $l = (E/n m_p c^2)^{1/3}$ is the Sedov length and $\Delta = c \Delta t_{\text{GRB}}$ is the shell width. If $\xi \gg 1$, the reverse shock is Newtonian and $\bar{\gamma}^{\text{rs}} \sim 1$, while if $\xi \ll 1$, the reverse shock is relativistic and $\bar{\gamma}^{\text{rs}} \gg 1$. Since the shell is likely to spread, which adjusts $\xi >$

1 to $\xi \approx 1$ (Sari & Piran 1995), the reverse shock we considered here will be always mildly relativistic ($\bar{\gamma}^{\text{rs}} \sim 1$) for typical parameter values of the fireball shock.

The distributions of the electrons in both the forward and reverse shocks are assumed to be a power law of index p [$N(\gamma) \propto \gamma^{-p}$], with the Lorentz factor of the random motion of a typical electron in the shell rest frame being $\gamma_m = (m_p/m_e) \xi_e \gamma_{\text{sh}}$, where ξ_e is the fraction of thermal energy carried by electrons (Waxman 1997a, 1997b). Here $\gamma_{\text{sh}} = \Gamma$ for the forward shock, while $\gamma_{\text{sh}} = \bar{\gamma}^{\text{rs}}$ for the reverse shock. Assuming that ξ_B is the fraction of the thermal energy carried by the magnetic field, we have the peak frequency of the reverse shock emission:

$$\begin{aligned} \nu_m^{\text{rs}} &= \frac{1}{1+z} \frac{\Gamma(\gamma_m^{\text{rs}})^2 e B'}{2\pi m_e c} \\ &= 1.6 \times 10^{15} \text{ Hz} \left(\frac{\xi_e}{0.3} \right)^2 \left(\frac{\xi_B}{0.01} \right)^{1/2} \eta_{300}^2 n_0^{1/2} \frac{2}{1+z}, \quad (3) \end{aligned}$$

where $B' = 12 \text{ G} (\xi_B/0.01)^{1/2} \eta_{300} n_0^{1/2}$ is the magnetic field in the comoving frame. Here ξ_e and ξ_B are the values relevant for the reverse shock and have been assumed to not be different from the forward shock (Wang, Dai, & Lu 2001). The numerical values we have used are those characteristic of the forward shock (Waxman 1997a; Freedman & Waxman 2001; Wijers & Galama 1999; Granot, Piran, & Sari 1999). As this peak frequency we estimated is slightly higher than the optical band and it decreases with time after the deceleration time t_{dec} , we expect that the optical light curve possesses a short initial rise phase and then decays with time, which is consistent with the light curve of the prompt optical flash from GRB 990123. Waxman & Draine (2000) have also derived the peak flux for the reverse shock:

$$\begin{aligned} f_m^{\text{rs}} &= 1.5 \text{ Jy } h_{65}^2 \left(\frac{\sqrt{2}-1}{\sqrt{1+z}-1} \right)^2 \\ &\times \left(\frac{\xi_B}{0.01} \right)^{1/2} \eta_{300}^{-1} n_0^{-1/4} E_{53}^{5/4} \left(\frac{2}{1+z} \frac{t_{\text{dec}}}{10 \text{ s}} \right)^{-3/4} \quad (4) \end{aligned}$$

for a flat universe with zero cosmological constant and $H_0 = 65 \text{ h}_{65} \text{ km s}^{-1} \text{ Mpc}^{-1}$. This flux is consistent with the observations of GRB 990123 within a factor of 2, whose peak flux is about 1 Jy (Akerlof et al. 1999). The peak frequency of synchrotron emission from the forward shock is larger than that of the reverse shock by a factor $\sim (\Gamma^2/\eta)^2$ and is, at the deceleration time t_{dec} of the ejecta,

$$\nu_m^{\text{fs}} = 1.4 \times 10^{20} \text{ Hz} \left(\frac{\xi_e}{0.3} \right)^2 \left(\frac{\xi_B}{0.01} \right)^{1/2} \eta_{300}^4 n_0^{1/2} \frac{2}{1+z}, \quad (5)$$

since at this time the self-similar Lorentz factor $\Gamma \simeq \eta$.

The cooling break frequencies, at which the cooling time-scale of electrons equals that of the expansion dynamic time,

are given by

$$\nu_c^{\text{rs}} = \frac{10^{17} \text{ Hz}}{(Y_{\text{rs}} + 1)^2} \left(\frac{\xi_B}{0.01} \right)^{-3/2} \eta_{300}^{-4} n_0^{-3/2} \left(\frac{t_{\text{dec}}}{10 \text{ s}} \right)^{-2} \frac{1+z}{2} \quad (6)$$

for the reverse shock and

$$\nu_c^{\text{fs}} = \frac{10^{17} \text{ Hz}}{(Y_{\text{fs}} + 1)^2} \left(\frac{\xi_B}{0.01} \right)^{-3/2} \eta_{300}^{-4} n_0^{-3/2} \left(\frac{t_{\text{dec}}}{10 \text{ s}} \right)^{-2} \frac{1+z}{2} \quad (7)$$

for the forward shock, where Y_{rs} and Y_{fs} are the Compton parameters for the reverse shock and forward shock, respectively (Panaitescu & Kumar 2000). The Compton parameter Y , expressing the cooling rate of electrons due to inverse Compton effect, is defined as $Y = (4/3) \tau_e \int \gamma^2 N_e(\gamma) d\gamma$, where $N_e(\gamma)$ is the normalized electron distribution and τ_e is the optical thickness to electron scattering. According to Panaitescu & Kumar (2000), $Y_{\text{fs}} = \frac{1}{2} \{ [\frac{5}{6} (\xi_e/\xi_B) + 1]^{1/2} - 1 \} \sim 2$, since the forward shock is in the fast cooling regime, while $Y_{\text{rs}} \sim (\gamma_m^{\text{rs}})^{p-1} (\gamma_c^{\text{rs}})^{3-p} \tau_e^{\text{rs}} \sim 3$ for the reverse shock, where τ_e^{rs} is the optical thickness of the shocked ejecta to electron scattering, which will be calculated in the next subsection, and γ_c is the Lorentz factor where the total energy emitted at the time t_{dec} is comparable to the electron's energy: $\gamma_c = 6\pi m_e c(1+z)/\sigma_T \Gamma(B')^2 t_{\text{dec}} = [4500/(Y+1)] (\xi_B/0.01)^{-1} \eta_{300}^{-3} (t_{\text{dec}}/10 \text{ s})^{-1} [(1+z)/2] n_0^{-1}$. The synchrotron spectrum of the forward shock is thus described as $f_\nu^{\text{fs}} = f_m^{\text{fs}} (\nu/\nu_c^{\text{fs}})^{-1/2}$ for $\nu_m^{\text{fs}} > \nu > \nu_c^{\text{fs}}$ and $f_\nu^{\text{fs}} = f_m^{\text{fs}} (\nu/\nu_c^{\text{fs}})^{-1/2} (\nu/\nu_m^{\text{fs}})^{-p/2}$ for $\nu > \nu_m^{\text{fs}}$; while for the reverse shock, $f_\nu^{\text{rs}} = f_m^{\text{rs}} (\nu/\nu_m^{\text{rs}})^{-(p-1)/2}$ for $\nu_c^{\text{rs}} > \nu > \nu_m^{\text{rs}}$ and $f_\nu^{\text{rs}} = f_m^{\text{rs}} (\nu/\nu_m^{\text{rs}})^{-(p-1)/2} (\nu/\nu_c^{\text{rs}})^{-p/2}$ for $\nu > \nu_c^{\text{rs}}$.

2.2. The Synchrotron Self-Compton Emission from the Reverse Shock

The synchrotron self-Compton emission from the reverse shock can be calculated by using the above equations for the synchrotron spectrum and the Thomson optical depth of the shocked fireball material, which is

$$\tau_e^{\text{rs}} = \frac{\sigma_T N}{4\pi r_{\text{dec}}^2} = 8.4 \times 10^{-6} E_{53}^{1/3} n_0^{2/3} \eta_{300}^{1/3} \left(\frac{t_{\text{obs}}}{t_{\text{dec}}} \right)^{-1/2}, \quad (8)$$

where N is the total number of electrons in the fireball and σ_T is the Thomson scattering cross section. This inverse Compton luminosity for the reverse shock is larger than the synchrotron luminosity by a factor $L_{\text{IC}}/L_{\text{sy}} \sim Y_{\text{rs}} \sim 3$, dominating the synchrotron cooling rate of the electrons, and radiates at a much higher energy band than the synchrotron emission. We need consider only the first-order inverse Compton and neglect the higher order inverse Compton process, because a once-scattered synchrotron photon has energy on the order of $(h\nu_{\text{min}})_{\text{com}} \gamma_e^3 > m_e c^2$ in the rest frame of the second scattering electron with the Lorentz factor being γ_e , and thus the Thomson limit no longer applies. Since the reverse shock is in the slow cooling regime, the upscattered spectrum peaks at

$$\begin{aligned} \nu_m^{\text{rs, IC}} &= 2(\gamma_m^{\text{rs}})^2 \nu_m^{\text{rs}} = 1.0 \times 10^{21} \text{ Hz} \\ &\times \left(\frac{\xi_e}{0.3} \right)^4 \left(\frac{\xi_B}{0.01} \right)^{1/2} \eta_{300}^2 n_0^{1/2} \left(\frac{\bar{\gamma}_{\text{rs}}}{1} \right)^2 \frac{2}{1+z}, \quad (9) \end{aligned}$$

and the cooling break frequency, at the deceleration time t_{dec} ,

is

$$\nu_c^{rs, IC} = 2(\gamma_c^{rs})^2 \nu_c^{rs} = 2.1 \times 10^{22} \text{ Hz} \\ \times \left(\frac{\xi_B}{0.01} \right)^{-7/2} \eta_{300}^{2/3} n_0^{-13/6} E_{53}^{-4/3} \frac{2}{1+z}, \quad (10)$$

where we have substituted the expression of t_{dec} (eq. [1]) into it. At this deceleration time of the ejecta, the peak flux of the inverse Compton component is

$$f_{\text{max}}^{rs, IC} = \tau_e^{rs} f_m^{rs} = 2.6 \times 10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} \\ \times E_{53}^{4/3} n_0^{7/6} \eta_{300}^{4/3} \left(\frac{\xi_B}{0.01} \right)^{1/2} h_{65}^2 \left(\frac{\sqrt{2}-1}{\sqrt{1+z}-1} \right)^2. \quad (11)$$

For the simplicity of the analysis, we use the broken power-law approximation to the inverse Compton component, although the presence of logarithmic terms makes some corrections to the spectrum for $\nu > \nu_m^{rs, IC}$ (Sari & Esin 2001), i.e., $f_{\nu}^{rs, IC} = f_m^{rs, IC} (\nu/\nu_m^{rs, IC})^{-(p-1)/2}$ for $\nu_c^{rs, IC} > \nu > \nu_m^{rs, IC}$ and $f_{\nu}^{rs, IC} = f_m^{rs, IC} (\nu_c^{rs, IC}/\nu_m^{rs, IC})^{-(p-1)/2} (\nu/\nu_c^{rs, IC})^{-p/2}$ for $\nu > \nu_c^{rs, IC}$. For the sake of comparison, we give the flux of the inverse Compton component at three representative frequencies:

$$f_{\nu}^{rs, IC}(\varepsilon = 5 \text{ MeV}) \\ = 2.6 \times 10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} (E_{53}^{4/3}), \\ f_{\nu}^{rs, IC}(\varepsilon = 100 \text{ MeV}) \\ = 2.7 \times 10^{-9} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} (E_{53}^{4/3}), \\ f_{\nu}^{rs, IC}(\varepsilon = 1 \text{ GeV}) \\ = 1.5 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} (E_{53}^{2/3}), \quad (12)$$

where we have retained only the relations with the shock energy E_{53} and replaced other shock parameters and the redshift with the typical values.

After the reverse shock has passed through the ejecta, the ejecta cools adiabatically. Sari & Piran (1999a) assumed that the ejecta follows the Blandford & McKee (1976) self-similar solution, in which a given fluid element evolves with a bulk Lorentz factor of $\gamma \sim R^{-7/2}$, and successfully explained the decaying light curve of the optical flash and the radio flare behavior of GRB 990123 (Kulkarni et al. 1999). Below we will give the decaying light curve of the synchrotron self-Compton component of the reverse shock after it has passed through the ejecta ($t_{\text{obs}} > t_{\text{dec}}$). Since $f_m^{rs} \propto t_{\text{obs}}^{-47/48} \sim t_{\text{obs}}^{-1}$ and $\tau_e^{rs} \propto t_{\text{obs}}^{-1/2}$, the peak flux of the inverse Compton spectral component $f_m^{rs, IC} = f_m^{rs} \tau_e^{rs} \propto t_{\text{obs}}^{-3/2}$. If the observed frequency locates between the two break frequencies ($\nu_c^{rs, IC} < \nu < \nu_m^{rs, IC}$), then $f_{\nu}^{rs, IC} = f_m^{rs, IC} (\nu/\nu_m^{rs, IC})^{-(p-1)/2}$. According to Sari & Piran (1999a), $\gamma_m \propto t_{\text{obs}}^{-13/48}$ and $\nu_m^{rs} \propto t_{\text{obs}}^{-73/48}$, so $\nu_m^{rs, IC} = 2\gamma_m^2 \nu_m^{rs} \propto t_{\text{obs}}^{-33/16} \sim t_{\text{obs}}^{-2}$, thus, $f_{\nu}^{rs, IC} \propto t_{\text{obs}}^{-1/2-p} \propto t_{\text{obs}}^{-3}$ for $p = 2.5$. On the other hand, if the observed frequency is above $\nu_c^{rs, IC}$, the flux drops exponentially with time since all the electrons above the corresponding energy cool and no fresh electrons are accelerated once the reverse shock has crossed the ejecta shell. Therefore, in general, we expect to see a rapidly decaying high-energy flux from the reverse shock, which constitutes a unique characteristic distinguished from other models (see the next subsection) suggested for the observed high-energy gamma-ray emission from some GRBs. Measurements of the time de-

pendence of the high-energy gamma-ray flux with the planned *Gamma-Ray Large-Area Space Telescope (GLAST)* mission will test this synchrotron self-Compton scenario.

2.3. Detachability of the Prompt High-Energy Gamma Rays and the Case of GRB 930131

EGRET has detected *prompt* emission above 30 MeV from seven bright GRBs triggered by BATSE (Catelli, Dingus, & Schneid 1998), among which 1.2 and 3.4 GeV photons have been detected from GRB 930131 (Sommer et al. 1994; Ryan et al. 1994) and GRB 940217 (Hurley et al. 1994), respectively. GRB 940217 also displays delayed high-energy gamma-ray emission, about 90 minutes after the initial trigger. There are a handful of models suggested to explain the delayed and prompt GeV emission. For example, Katz (1994) suggested that the impact of the fireballs with dense clouds ($n \geq 10^9 \text{ cm}^{-3}$) could yield high-energy gamma-ray emission via π^0 decay; Waxman & Coppi (1996) proposed that the cascading of ultra high energy ($\geq 10^{19} \text{ eV}$) cosmic rays (accelerated in cosmological GRBs) off infrared and cosmic microwave background fields can produce delayed GeV-TeV emission as a result of the deflections by the intergalactic magnetic field; Dermer, Chiang, & Mitman (2000) argued that the synchrotron self-Compton emission from the forward shock expanding into a rather dense circumburst medium ($n \sim 100 \text{ cm}^{-3}$) may be responsible for the prompt and delayed high-energy gamma-ray emission; Vietri (1997) and Totani (1998) suggested that the synchrotron emission of the protons may be responsible for the GeV-TeV emission. Here we suggest that the synchrotron self-Compton emission from the reverse shock could explain both the flux level and the spectrum of the high-energy gamma rays detected by EGRET. As an example, we discuss the case of GRB 930131. The high-energy gamma-ray emission from GRB 930131 extends for about 25 s. A total of 16 gamma rays above 30 MeV were detected, including two with energy of about 1 GeV, and the power-law fit of their photon spectrum is given by $(dn/d\varepsilon) \sim 7.4 \times 10^{-6} \text{ photons (cm s MeV)}^{-1} (\varepsilon/147 \text{ MeV})^{-2.07 \pm 0.36}$ (Sommer et al. 1994). In the last subsection, we found that the inverse Compton emission intensity from the reverse shock is $f_{\nu}^{rs, IC} \sim 2.7 \times 10^{-9} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} (\varepsilon/100 \text{ MeV})^{-0.75} E_{53}^{4/3}$ for $\varepsilon < h\nu_c^{rs, IC}$ and $f_{\nu}^{rs, IC} \sim 2.7 \times 10^{-9} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} (\varepsilon/100 \text{ MeV})^{-1.25} E_{53}^{2/3}$ for $\varepsilon > h\nu_c^{rs, IC}$ with $p = 2.5$, that is, the differential photon flux is $(dn/d\varepsilon) \sim 6.0 \times 10^{-6} \text{ photons (cm s MeV)}^{-1} (\varepsilon/147 \text{ MeV})^{-2.25} E_{53}^{2/3}$. Thus, if the fireball shock energy $E \sim 1.5 \times 10^{53} \text{ ergs}$ and other parameters such as ξ_e , ξ_B , η , z , and the number density n of the surrounding medium take the above representative values, then both the flux level and the spectrum agree well with the observations. However, since this emission process lasts only a time comparable to the crossing time of the reverse shock, it cannot explain the delayed high-energy gamma-ray emission, as observed from GRB 940217, which may, for example, be due to deflections of ultra high energy cosmic rays accelerated in the GRB fireballs by the intergalactic field (see Waxman & Coppi 1996).

2.4. Comparison with the High-Energy Gamma-Ray Emission Flux from the Forward Shock

For completeness, we also compute the high-energy gamma-ray emission flux from the synchrotron and self-Compton process in the forward shock and compare them with that from

the reverse shock. The peak flux of the forward shock is

$$f_m^{fs} = 8 \text{ mJy } h_{65}^2 \left(\frac{\sqrt{2} - 1}{\sqrt{1+z} - 1} \right)^2 \left(\frac{\xi_B}{0.01} \right)^{1/2} E_{53} n_0^{1/2} \quad (13)$$

(Waxman 1997b; Wijers & Galama 1999), and the two break frequencies ν_m^{fs} and ν_c^{fs} are given by equations (5) and (7). Please note that here the flux peaks at ν_c^{fs} . For typical parameter values of GRBs, during the prompt phase the forward shock is in the fast cooling regime, and we get the high-energy flux at those three representative frequencies:

$$\begin{aligned} f^{fs}(\varepsilon = 5 \text{ MeV}) &= 1.2 \times 10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} (E_{53}), \\ f^{fs}(\varepsilon = 100 \text{ MeV}) &= 2.5 \times 10^{-10} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} (E_{53}), \\ f^{fs}(\varepsilon = 1 \text{ GeV}) &= 1.4 \times 10^{-11} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} (E_{53}). \end{aligned} \quad (14)$$

We can see that the flux at ~ 5 MeV is comparable to the inverse Compton component of the reverse shock, while at higher energies (>100 MeV) it is about 1 order of magnitude lower. As in the reverse shock, we also need to consider the synchrotron self-Compton emission process in the forward shock, since the typical energy of the synchrotron photon in the rest frame of the scattering electrons is on the order of $(h\nu_c^{fs})_{\text{com}} \gamma_e \ll m_e c^2$, which is still in the Thomson limit range. At the deceleration time ($t_{\text{obs}} \approx t_{\text{dec}}$), the characteristic break frequencies of the inverse component of the forward shock are

$$\begin{aligned} \nu_m^{fs, \text{IC}} &= 2(\gamma_m^{fs})^2 \nu_m^{fs} \\ &= 8.0 \times 10^{30} \text{ Hz} \left(\frac{\xi_e}{0.3} \right)^4 \left(\frac{\xi_B}{0.01} \right)^{1/2} \eta_{300}^6 n_0^{1/2} \frac{2}{1+z}, \end{aligned} \quad (15)$$

$$\begin{aligned} \nu_c^{fs, \text{IC}} &= 2(\gamma_c^{fs})^2 \nu_c^{fs} \\ &= 5.0 \times 10^{22} \text{ Hz} \left(\frac{\xi_B}{0.01} \right)^{-7/2} \eta_{300}^{2/3} n_0^{-13/6} E_{53}^{-4/3} \frac{2}{1+z}. \end{aligned} \quad (16)$$

The peak flux of this inverse Compton component is

$$\begin{aligned} f_m^{fs, \text{IC}} &= \tau_e^{fs} f_m^{fs} \sim \sigma_T n r f_m^{fs} \\ &= 3 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1} \\ &\quad \times \left(\frac{r}{r_{\text{dec}}} \right) E_{53} \left(\frac{\xi_B}{0.01} \right)^{1/2} n_0^{3/2}. \end{aligned} \quad (17)$$

Therefore, the inverse Compton flux from the forward shock at the $\varepsilon \sim 250$ MeV band is $\sim 3 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$, much lower than that from the reverse shock. They are comparable only at the $\varepsilon \sim 10$ TeV band. So, we conclude that for the typical parameter values of the shock and the surrounding medium, the synchrotron self-Compton emission from the reverse shock dominates over the synchrotron and synchrotron self-Compton emissions from the forward shock at high-energy gamma-ray bands. Our result is different from that of Dermer et al. (2000), who argue that the synchrotron self-Compton

emission from the forward shock may be responsible for the prompt and delayed high-energy gamma-ray emission. The key point of the difference is that they considered a rather dense circumburst medium with number density $n \sim 100 \text{ cm}^{-3}$, while we consider a typical interstellar medium with $n \sim 1 \text{ cm}^{-3}$.

3. SUMMARY AND DISCUSSION

The detection of the prompt optical flash and the radio flare from GRB 990123 has given positive evidence for the reverse shock model. In this Letter, we calculated analytically the synchrotron self-Compton emission from the reverse shock. Assuming favorable parameter values for the fireball shock and the density of the interstellar medium to be $\xi_e = 0.3$, $\xi_B = 0.01$, $E_{53} = 1$, $p = 2.5$, $\eta = 300$, and $n = 1 \text{ cm}^{-3}$, the result shows that during the prompt phase, this emission dominates over the emission due to other processes of the shocked electrons in both the forward and reverse external shocks at high-energy gamma-ray bands. We suggest that this process provides a new explanation for the *prompt* high-energy gamma rays detected by EGRET from some bright bursts, such as GRB 930131, GRB 910503, GRB 940217, etc. As an example, we compared our calculated result with the observations of GRB 930131 and found that both the flux level and spectrum agree quite well, provided the initial fireball shock energy is a few times 10^{53} ergs, which is consistent with the fact that all the bursts detected by EGRET are bright bursts in the BATSE range. We also derived the decaying light curves of the inverse Compton component and found that it decays quite rapidly, regardless of whether the observed band locates above or below the cooling break frequency of the inverse Compton component. This unique feature can act as a test of our model if in the future *GLAST* is capable of describing the time evolution of the high-energy gamma-ray flux. Because once the reverse shock has crossed that ejecta all electrons cool by adiabatic expansion and no fresh electrons are accelerated, our model cannot explain the delayed GeV emission, as observed from GRB 940217.

GRBs are generally believed to be produced by the internal collisions between the relativistic shells at a radius $r \sim 10^{12}$ – 10^{13} cm, which is much smaller than the distance at which the external shock takes place. Until now, the mechanism of prompt GRB emission is not as well understood as that of afterglows, and we do not know whether the usual GRBs and high-energy gamma rays have a common origin. If here we take a naive assumption that the internal shock emission extends from the BATSE band to GeV bands with $f_\nu \propto \nu^{-p/2}$, the simple extrapolation gives a flux of $f_\nu(\varepsilon = 100 \text{ MeV}) \sim 1.0 \times 10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ MeV}^{-1}$ for a typical GRB fluence of $F_\gamma(20 \text{ KeV} - 2 \text{ MeV}) \sim 10^{-5} \text{ ergs cm}^{-2}$. This flux at $\varepsilon = 100$ MeV is comparable to that from the reverse shock. However, this simple extrapolation may be incorrect if there is a sharp cutoff at some high-energy band, as shown in the model of Ghisellini & Celotti (1999), in which the prompt GRB emission is due to a quasi-thermal Comptonization process in internal shocks and ends with an exponential cutoff at energies higher than a few MeV.

In all our calculations, we considered a fireball shock expanding into a uniform interstellar medium with a constant density of $n \sim 1 \text{ cm}^{-3}$. The observations of some afterglows have shown that some GRBs may occur in a stellar wind environment (Dai & Lu 1998; Chevalier & Li 1999), implying a massive star origin of these bursts (Woosley 1993; Paczyński 1998). As having been pointed out in Chevalier & Li (2000) and Dai & Lu (2001), the peak frequency of the reverse shock formed by the initial interaction between the fireball ejecta with

the stellar wind medium is significantly lower than that in the case of the interstellar medium for similar shock parameters. For this reason, we conjecture that the high-energy gamma-ray emission in this kind of reverse shock is too weak to be detected by high-energy gamma-ray detectors.

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