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, Nanjing, P.R.China
Email:xywang@nju.edu.cn; daizigao@public1.ptt.js.cn; tlu@nju.edu.cn

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 from GRB930131.

Subject headings: gamma rays: bursts—radiation mechanisms: non-thermal

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 ultra-relativistic 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 which 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 time scale 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 9-th magnitude, optical flash has been recently detected (Akerlof et al.
1999) accompanying GRB990123. 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 which 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 Compton Telescope (COMPTEL) on
board Compton Gamma-Ray Observatory (CGRO). Early discussions on the synchrotron
self-Compton process in the reverse shock include the works of, e.g., Mészáros et al. (1993)
and Sari et al. (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 time scale \( \Delta t_{\text{tran}} \)
comparable to the longer of the two time scales set by the initial conditions: the (observed)
GRB duration \( \Delta t_{\text{GRB}} \) and the (observed) deceleration time scale \( t_{\text{dec}} \) of the fireball ejecta,
at which the self-similar Lorentz factor (\( \Gamma \)) equals the initial ejecta Lorentz factor \( \eta \), i.e.
\( \Delta t_{\text{tran}} = \max [\Delta t_{\text{GRB}}, t_{\text{dec}}] \) (Sari & Piran 1999b; Waxman & Draine 2000).

The deceleration time \( t_{\text{dec}} \) is in fact the observer time at which the heated interstellar
medium (ISM) energy is comparable to the initial energy \( E \), i.e.
\[
t_{\text{dec}} = \frac{r_{\text{dec}}}{2\eta^2 c}(1 + z) = 10\sec\frac{1 + z}{2}E_{53}^{1/3}n_0^{-1/3}\eta_{300}^{-8/3},
\]  (1)
where
\[ r_{\text{dec}} = \left( \frac{E}{4\pi \eta^2 n m_p c^2} \right)^{1/3} = 3.7 \times 10^{16} \text{cm} E_{53}^{1/3} n_0^{-1/3} \eta_{300}^{-2/3} \]  
(2)

is the deceleration radius, \( E = 10^{53} \text{E}_{53}\text{erg}, n = 1n_0\text{cm}^{-3}, \eta = 300\eta_{300}, \) and \( z \) is the redshift of the GRB source. Since even long duration GRBs have durations of order of 10sec, which is comparable to \( t_{\text{dec}} \), 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 \( \eta \) and the Lorentz factor of the plasma shocked by the reverse shock in the rest frame of the unshocked ejecta is \( \bar{\gamma}_{rs} \sim \eta/\Gamma \). According to Sari & Piran (1995), the reverse shock Lorentz factor \( \bar{\gamma}_{rs} \) depends on the parameter \( \xi \equiv (l/\Delta)^{1/2} \eta^{-4/3} = 2E_{53}^{1/3} n_0^{-1/3} \Delta_{10}^{-1/2} \eta_{300}^{-4/3} \), where \( l = \left( \frac{E}{n m_p c^2} \right)^{1/3} \) 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 \( \bar{\gamma}_{rs} \sim 1 \), while if \( \xi \ll 1 \), the reverse shock is relativistic and \( \bar{\gamma}_{rs} \gg 1 \). 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 (\( \bar{\gamma}_{rs} \sim 1 \)) 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 \( \gamma_m = \frac{m_e}{m} \xi_e \gamma_{sh} \), where \( \xi_e \) is the fraction of thermal energy carried by electrons (Waxman 1997a,b). Here \( \gamma_{sh} = \Gamma \) for the forward shock while \( \gamma_{sh} = \bar{\gamma}_{rs} \) for the reverse shock. Assuming that \( \xi_B \) is the fraction of the thermal energy carried by the magnetic field, we have the peak frequency of the reverse shock emission

\[ \nu_{m}^{rs} = \frac{1}{1+z} \frac{\Gamma(\bar{\gamma}_{m}) \xi_e B'}{2\pi m_e c} = 1.6 \times 10^{15} \text{Hz} \left( \frac{\xi_e}{0.3} \right)^{1/2} \left( \frac{\xi_B}{0.01} \right)^{1/2} \eta_{300}^{-2} n_0^{-1/2} \left( \frac{2}{1+z} \right), \]  
(3)

where \( B' = 12G(\frac{\xi_B}{0.01})^{1/2} \eta_{300} n_0^{1/2} \), is the magnetic field in the comoving frame. Here \( \xi_e \) and \( \xi_B \) are the values relevant for the reverse shock and have been assumed to be not different from the forward shock (Wang, Dai & Lu 2000). The numerical values we have used are those characteristic of the forward shock (Waxman 1997a; Freedman & Waxman 2000; Wijers & Galama 1999; Granot et al. 1999). As this peak frequency we estimated is slightly higher than the optical band and it decreases with time after the deceleration time \( t_{\text{dec}} \), we expect that the optical light curve should posses a short initial rise phase, and then decays with time, which is consistent with the light curve of the prompt optical flash from GRB990123. Waxman & Draine (2000) have also derived the peak flux for the reverse shock

\[ f_{m}^{rs} = 1.5 \text{Jy} h_{55}^{2} \left( \frac{\sqrt{2} - 1}{\sqrt{1+z} - 1} \right)^2 \left( \frac{\xi_B}{0.01} \right)^{1/2} \eta_{300}^{-1} n_0^{-1/4} E_{53}^{-5/4} \left( \frac{2}{1+z} \right) t_{\text{dec}}^{-3/4}, \]  
(4)
for a flat universe with zero cosmological constant and $H_0 = 65h_{65}\text{Km s}^{-1}\text{Mpc}^{-1}$. This flux is consistent with the observations of GRB990123 within a factor of two, whose peak flux is about 1Jy (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 $t_{\text{dec}}$ of the ejecta,

$$
\nu_{m}^{fs} = 1.4 \times 10^{20}\text{Hz} \left( \frac{\xi_e}{0.3} \right)^2 \left( \frac{\xi_B}{0.01} \right)^{1/2} n_{300}^{-1/2} \left( \frac{2}{1 + z} \right),
$$

(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

$$
\nu_{c}^{rs} = \frac{10^{17}\text{Hz}}{(Y_{rs} + 1)^2} \left( \frac{\xi_B}{0.01} \right)^{-3/2} n_{300}^{-4} \left( \frac{t_{\text{dec}}}{10\text{sec}} \right)^{-2} \left( \frac{1 + z}{2} \right),
$$

(6)

for the reverse shock, and

$$
\nu_{c}^{fs} = \frac{10^{17}\text{Hz}}{(Y_{fs} + 1)^2} \left( \frac{\xi_B}{0.01} \right)^{-3/2} n_{300}^{-4} \left( \frac{t_{\text{dec}}}{10\text{sec}} \right)^{-2} \left( \frac{1 + z}{2} \right)
$$

(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 $Y = \frac{4}{3}\tau_e \int \gamma^2 \bar{N}_e(\gamma) d\gamma$, where $\bar{N}_e(\gamma)$ is the normalized electron distribution and $\tau_e$ is the optical thickness to electron scattering. According to Panaitescu & Kumar (2000), $Y_{fs} = \frac{1}{2} \left( \frac{\xi_B}{0.01} + 1 - 1 \right) \sim 2$, since the forward shock is in the fast cooling regime, while $Y_{rs} \sim \eta_{rs}^{-1} (\gamma_s)^{-3} \sim 3$ for the reverse shock, where $\tau_{e}^{rs}$ is the optical thickness of the shocked ejecta to electron scattering, which will be calculated in the next subsection and $\gamma_c$ is the Lorentz factor where the total energy emitted at the time $t_{\text{dec}}$ is comparable to the electron’s energy: $\gamma_c = \frac{6m_e c (1 + z)}{\sigma_T (B')^2 t_{\text{dec}}} = \frac{4500}{Y + 1} (\xi_B/0.01)^{-3} n_{300}^{-4} (t_{\text{dec}}/10\text{sec})^{-1} (1 + z) n_0^{-1}$. The synchrotron spectrum of the forward shock is thus described as $f^r_s = f^r_{m}(\nu/\nu^{fs}_c)^{-p/2}$ for $\nu_m^{fs} > \nu > \nu_c^{fs}$ and $f^r_s = f^r_{m}(\nu^{fs}_m/\nu^{fs}_c)^{-1/2} (\nu/\nu^{fs}_m)^{-p/2}$ for $\nu > \nu_m^{fs}$, while for the reverse shock, $f^r_s = f^r_{m}(\nu/\nu^{rs}_m)^{-p/4}$ for $\nu_m^{rs} > \nu > \nu_c^{rs}$ and $f^r_s = f^r_{m}(\nu^{rs}_m/\nu^{rs}_c)^{-1/4} (\nu/\nu^{rs}_c)^{-p/2}$ for $\nu > \nu_c^{rs}$.

**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

\[ \tau_e^{rs} = \frac{\sigma_T N}{4\pi r_{dec}^2} = 8.4 \times 10^{-6} E_{53}^{1/3} n_0^{2/3} \eta_{300}^{1/3} \frac{t_{obs}}{t_{dec}}^{-1/2}, \tag{8} \]

where \( N \) is the total number of electrons in the fireball and \( \sigma_T \) is the Thomson scattering cross section. This inverse Compton luminosity for the reverse shock is larger than the synchrotron luminosity by a factor \( L_{IC}/L_{syn} \sim Y_{rs} \sim 3 \), dominating the synchrotron cooling rate of the electrons, and radiates at 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 of order \( (h\nu_{min})_{com} \gamma_e^3 > m_e c^2 \) in the rest frame of the second scattering electron with Lorentz factor being \( \gamma_e \) and thus the Thomson limit no longer applies. Since the reverse shock is in the slow cooling regime, the up-scattered spectrum peaks at

\[ \nu_m^{rs,IC} = 2(\gamma_m^{rs})^2 \nu_m = 1.0 \times 10^{21} \text{Hz} \left( \frac{\xi_B}{0.01} \right)^{1/2} \eta_{300}^{1/2} n_0^{1/2} \left( \frac{\tau_{rs}}{1} \right)^2 \left( \frac{2.0}{1+z} \right), \tag{9} \]

and the cooling break frequency, at the deceleration time \( t_{dec} \), is

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

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

\[ f_{\nu_{max}}^{rs,IC} = f_{\nu}^{rs} = 2.6 \times 10^{-8} \text{erg cm}^{-2}\text{s}^{-1}\text{MeV}^{-1} E_{53}^{4/3} \eta_{300}^{7/6} n_0^{1/2} \left( \frac{\xi_B}{0.01} \right)^{1/2} \eta_{65}^{2} \left( \frac{\sqrt{2} - 1}{\sqrt{1+z} - 1} \right)^2. \tag{11} \]

For the simplicity of the analysis, we use the broken-power law approximation to the inverse Compton component, though the presence of logarithmic terms makes some corrections to the spectrum for \( \nu > \nu_m^{rs,IC} \) (Sari & Esin 2000), i.e.

\[ f_{\nu}^{rs,IC} = f_{\nu_{max}}^{rs,IC} \left( \frac{\nu}{\nu_{max}^{rs,IC}} \right)^{-\frac{2}{3}} \]

for \( \nu_{c,IC} > \nu > \nu_{m,IC}^{rs} \) and

\[ f_{\nu}^{rs,IC} = f_{\nu_{max}}^{rs,IC} \left( \frac{\nu_{c,IC}}{\nu_{m,IC}} \right)^{-\frac{2}{3}} \]

for \( \nu > \nu_{c,IC}^{rs} \). For the sake of comparison, we give the flux of the inverse Compton component at three representative frequencies:

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

where we have only retained 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 GRB990123 (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 \( f_{\text{rs}} \propto t_{\text{obs}}^{-47/48} \) and \( \tau_{\text{rs}} \propto t_{\text{obs}}^{-1/2} \), the peak flux of the inverse Compton spectral component \( f^{\text{rs,IC}} \propto t_{\text{obs}}^{-3/2} \). If the observed frequency locates between the two break frequencies \( \nu_{\text{rs,IC}}^c < \nu < \nu_{\text{rs,IC}}^m \), then \( f^{\text{rs,IC}} \propto t_{\text{obs}}^{-1/2} \). According to Sari & Piran (1999a), \( \gamma_m \propto t_{\text{obs}}^{-13/48} \) and \( \nu_m \propto t_{\text{obs}}^{-73/48} \), so \( \nu_{\text{rs,IC}} \propto 2^{9/2} \gamma_m^{2} \nu_m^{16/16} \propto t_{\text{obs}}^{-2/2} \), thus \( f^{\text{rs,IC}} \propto t_{\text{obs}}^{-1/2-p} \propto t_{\text{obs}}^{-3} \) for \( p = 2.5 \).

On the other hand, if the observed frequency is above \( \nu_{\text{rs,IC}}^c \), 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 dependence 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. Detectablity of the prompt high energy gamma-rays and the case of GRB930131

EGRET has detected prompt emission above 30MeV from seven bright GRBs triggered by BATSE (Catelli et al. 1998), among which 1.2GeV and 3.4GeV photons have been detected from GRB930131 (Sommer et al. 1994; Ryan et al. 1994) and GRB940217 (Hurley et al. 1994), respectively. GRB940217 also displays delayed high energy gamma-ray emission, about 90 minutes after the initial trigger. There are a handful models suggested to explain the delayed and prompt GeV emission. For examples, 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 \( \pi^0 \) decay; Waxman & Coppi (1996) proposed that the cascading of ultra high energy \( (\geq 10^{19} \text{eV}) \) cosmic rays (accelerated in cosmological GRBs) off infra-red and cosmic microwave background fields can produce delayed GeV-TeV emission due to the deflections by the intergalactic magnetic field; Dermer et al. (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 EGERT. As an example, we discuss the case of GRB930131. The high energy gamma-ray emission from GRB930131 extends for about 25s. Totally sixteen gamma rays above 30MeV were detected, including two with energy about 1GeV, and the power-law fit of their photon spectrum is given by $\frac{dn}{d\varepsilon} \sim \frac{7.4 \times 10^{-6}}{(\varepsilon/147\text{MeV})^{2.07 \pm 0.36}}$ (Sommer et al. 1994). In the last subsection, we have found that the inverse Compton emission intensity from the reverse shock is $f_{\nu,\text{IC}} \sim \frac{2 \times 10^{-9}}{E^{2/3}} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} (\varepsilon/100\text{MeV})^{-1.25} E_{53}^{2/3}$ for $\varepsilon < h\nu_{\text{c}}^{r,s,\text{IC}}$, and $f_{\nu,\text{IC}}^{r,s,\text{IC}} \sim \frac{2.7 \times 10^{-9}}{E^{2/3}} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} (\varepsilon/100\text{MeV})^{-1.25} E_{53}^{2/3}$ for $\varepsilon > h\nu_{\text{c}}^{r,s,\text{IC}}$ with $p = 2.5$, that is, the differential photon flux is
\[
\frac{dn}{d\varepsilon} \sim \frac{6.0 \times 10^{-6}}{(\varepsilon/147\text{MeV})^{2.25} E_{53}^{2/3}}.
\]
Thus, if the fireball shock energy $E \sim 1.5 \times 10^{53}\text{erg}$ and other parameters such as $\xi_e$, $\xi_B$, $\eta$, $z$ 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 GRB940217, 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
\[
f_{m}^{f,s} = 8 \text{mJy} h_{65}^{2} \left( \frac{\sqrt{2} - 1}{\sqrt{1 + z} - 1} \right)^{2} \left( \frac{\xi_{B}}{0.01} \right) E_{53}^{1/2} n_{0}^{1/2},
\]
(Waxman 1997b; Wijers & Galama 1999), and the two break frequencies $\nu_{m}^{f,s}$ and $\nu_{c}^{f,s}$ are given by Eq.(5) and Eq.(7). Please note that here the flux peaks at $\nu_{c}^{f,s}$. 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:
\[
\begin{align*}
f_{m}^{f,s}(\varepsilon = 5\text{MeV}) &= 1.2 \times 10^{-8} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53}; \\
f_{m}^{f,s}(\varepsilon = 100\text{MeV}) &= 2.5 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53}; \\
f_{m}^{f,s}(\varepsilon = 1\text{GeV}) &= 1.4 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53}.
\end{align*}
\]
We can see that the flux at $\sim 5\text{MeV}$ is comparable to the inverse Compton component of the reverse shock, while at higher energies ($> 100\text{MeV}$) it is about one order of magnitude lower. As in the reverse shock, we also need 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 of the order of $(h\nu^s_{\text{com}}\gamma_e) \ll m_e c^2$, 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

$$\nu_{m,\text{fs,IC}} = 2(\gamma_{m,\text{fs}})^2 \nu_{m} = 8.0 \times 10^{39}\text{Hz}(\frac{\xi_e}{0.3})^4(\frac{\xi_B}{0.01})^{1/2}n_{300}^{-6/2}(\frac{2.0}{1+z})$$

and

$$\nu_{c,\text{fs,IC}} = 2(\gamma_{c,\text{fs}})^2 \nu_{c} = 5.0 \times 10^{22}\text{Hz}(\frac{\xi_B}{0.01})^{-7/2}n_{300}^{-2/3}E_{53}^{-4/3}(\frac{2}{1+z}).$$

The peak flux of this inverse Compton component is

$$f_{m,\text{fs,IC}} = \sigma_Tn_r f_{m} \sim 3 \times 10^{-13}\text{erg cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}(\frac{r}{r_{\text{dec}}}E_{53}(\frac{\xi_B}{0.01}))^{1/2}n_0^{3/2}.$$  (17)

Therefore the inverse Compton flux from the forward shock at $\varepsilon \sim 250\text{MeV}$ band is $\sim 3 \times 10^{-13}\text{erg cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}$, much lower than that from the reverse shock. They are comparable only at $\varepsilon \sim 10\text{TeV}$ 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 GRB990123 has given positive evidence for the reverse shock model. In this paper, we calculated analytically the synchrotron self-Compton emission from the reverse shock. Assumed 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 GRB930131, GRB910503 and GRB940217 etc. As an example, we compared our calculated result with the observations of GRB930131 and found that both the flux level and spectrum agree quite well, provided the initial fireball shock energy is a few times $10^{53}$ erg, 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 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 can not explain the delayed GeV emission, as observed from GRB940217.

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. Till 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 we here take a naive assumption that the internal shock emission extends from BATSE band to GeV bands with $f_{\nu} \propto \nu^{-p/2}$, the simple extrapolation gives a flux of $f_{\nu}(\varepsilon = 100$ MeV) $\sim 1.0 \times 10^{-8}$ erg cm$^{-2}$ s$^{-1}$ MeV$^{-1}$ for typical GRB fluence of $F_{\gamma}(20$ KeV $- 2$ MeV) $\sim 10^{-5}$ erg 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 quasi-thermal comptonization process in internal shocks and ends with an exponential cutoff at energies higher than a few MeV.

In all our calculation, we considered a fireball shock expanding into a uniform interstellar medium with constant density of $n \sim 1$ 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 the massive star origin of these bursts (Woosley 1993; Paczyński 1998). As having been pointed out in Chevalier & Li (2000) and Dai & Lu (2000), the peak flux 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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