EMISSION PROCESSES OF HIGH-ENERGY GAMMA RAYS FROM GAMMA-RAY BURSTS

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Abstract Synchrotron self-Compton (SSC) process in the reverse shocks of gamma-ray bursts is suggested to be responsible for the observed prompt high-energy gamma-ray emissions from several gamma-ray bursts. We find that the SSC emission from the reverse shocks dominates over other emission processes in energy bands from tens of MeV to tens of GeV, for a wide range of shock parameters. This model is favorable for escape of energetic photons from the emitting regions due to a lower internal pair-production optical depth, as the characteristic size of the reverse shock region is much larger than that of internal shocks. We predict that, in this model, the prompt high-energy emissions are correlated with the prompt optical flashes, which can be test in the forthcoming GLAST era.

Keywords: gamma rays: bursts—radiation mechanisms: non-thermal

1. Introduction

EGRET has detected prompt emission above 30 MeV from several bright GRBs triggered by BATSE (Catelli et al. 1998), among which GeV photons have been detected from GRB930131 (Sommer et al. 1994; Ryan et al. 1994) and GRB940217 (Hurley et al. 1994). One is related to "Hadron processes". It is widely assumed that GRB shocks (internal and/or external) can accelerate protons to very high energies, a proposed mechanism for the production of ultra-high energy cosmic rays (Waxman 1995; Vietri 1995). The photo-meson processes (Waxman & Bahcall 1997; Böttcher & Dermer 1998) or synchrotron radiations of the protons (Vietri 1997; Totani 1998a,b) have been suggested to be responsible for the GeV emissions. Another class is related to the in-
verse Compton processes in GRB shocks, including internal shocks and external shocks. A strong prompt optical flash (Akerlof et al. 1999) and late time radio flare behavior (Kulkarni et al. 1999), accompanying GRB990123, have been attributed to the synchrotron emissions from the reverse shock (Sari & Piran 1999; Mészáros & Rees 1999). Papathanassiou & Meszaros (1994) proposed that electron IC processes in internal shocks produce GeV emissions, while Meszaros, Rees & Papathanassiou (1994), Dermer et al. (2000) and Zhang & Meszaros (2001) suggest that electron IC processes in forward shocks may be responsible for the prompt and delayed GeV emissions.

We here suggest an alternative mechanism, that is the SSC emissions from reverse shocks. As shown below, the SSC emission from the reverse shocks dominates over other emission processes in energy bands from tens of MeV to tens of GeV, for a wide range of shock parameters (Wang, Dai & Lu 2001a,b). Moreover, it involves a much larger emitting size, hence a lower internal pair-production optical depth than models related to internal shocks.

2. The analytic estimate

For typical parameters \( \xi_e = 0.6, \xi_B = 0.01, p = 2.5 \) and \( n = 1 \), we get the flux of the synchrotron self-Compton (SSC) component at two representative frequencies during the prompt phase of GRBs:

\[
\begin{align*}
    f^{rs,IC}(\varepsilon = 100 \text{MeV}) &= 1.0 \times 10^{-9} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53}^{4/3}; \\
    f^{rs,IC}(\varepsilon = 1 \text{GeV}) &= 1.5 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53}^{2/3}. 
\end{align*}
\]  

(1)

As a comparison, the derived high energy flux of the synchrotron and SSC emissions from forward shocks are, respectively,

\[
\begin{align*}
    f^{fs}(\varepsilon = 100 \text{MeV}) &= 1.0 \times 10^{-10} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53}; \\
    f^{fs}(\varepsilon = 1 \text{GeV}) &= 0.5 \times 10^{-11} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1} E_{53}, \\
    f^{fs,IC}_{m} &= 3 \times 10^{-13} \text{erg cm}^{-2} \text{s}^{-1} \text{MeV}^{-1}. 
\end{align*}
\]  

(2)  

(3)

Therefore, 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.

As an example, we try to fit the high-energy emissions from GRB930131. The photon spectrum of GRB990131 can be described 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), while our model prediction for \( \varepsilon > \hbar c f^{rs,IC} \) is \( dn/d\varepsilon \sim 2.2 \times 10^{-6} \).
photons \((\text{cm s MeV})^{-1}(\varepsilon/147\text{MeV})^{-2.25} E_{53}^{2/3}\). Thus, if the fireball shock energy \(E \sim 4 \times 10^{53}\text{erg}\) 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.

3. Numerical Result

Four IC processes, including the synchrotron self-Compton (SSC) processes in GRB forward and reverse shocks, and two combined-IC processes (i.e. scattering of reverse shock photons on the electrons in forward shocks and forward shock photons on the electrons in reverse shocks), are considered now (Wang, Dai & Lu 2001b).

We derive the formula for computing the IC flux

\[
f^{IC}_\nu = 3\Delta r' \sigma_T \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} d\gamma N(\gamma) \int_0^1 dxg(x)f_\nu(x)
\]

where \(g(x) = 1 + x + 2x\ln(x) - 2x^2\) reflects the angular dependence of the scattering cross section for \(\gamma_e \gg 1\) (Blumenthal & Gould 1970), \(\Delta r'\) is the comoving width of the shocked shell or ISM medium, \(N(\gamma)\) is the distribution of scattering electrons and \(f_\nu\) is the synchrotron spectrum.

Our main calculation results are as follows:

i) In Fig.1, we present the energy spectra \((\nu f^{IC}_\nu)\) of the IC emissions with various shock parameters. We find that a) for a wide range of shock parameters, the SSC component from reverse shocks is the most important at energy bands from tens of MeV to tens of GeV, to which EGRET is sensitive. b) For small value of \(p\) (e.g. \(p = 2.2\)), the SSC emission from the reverse shock dominates over the synchrotron and IC processes even in the TeV energy bands (see Fig. 1(d)). Fig.1 also suggest that strong TeV emission should also be emitted from the two combined-IC and forward shock SSC processes for most GRBs. For a moderate steep distribution of the shocked electrons (e.g. \(p = 2.5\)), the combined-IC and/or forward shock SSC become increasing dominated at TeV bands. However, it would only be detected from nearby, low-redshift bursts for which the attenuation due to intergalactic infrared emission is small.

ii) We here compute the slope of the photon spectrum at high energy bands and plot it in Fig. 2. We can see that at energy bands from tens of MeV to tens of GeV, the photon spectrum index \(\alpha\) (the photon number \(dn(h\nu)/d\nu \propto \nu^\alpha\)) ranges from 1.7 to 2.15, which is consistent with the observed high energy gamma-ray photon spectrum by EGRET from some bright GRBs (e.g. Sommer et al. 1994).
Figure 1. The energy spectra of synchrotron and IC emissions at the reverse shock peak time for the ISM circumburst environment case with various shock parameters: a) $E = 10^{53}$ erg, $\xi_e = 0.6$, $\xi_B = 0.01$, $p = 2.5$ and $n_1 = 1$; b) $E = 10^{52}$ erg, $\xi_e = 0.6$, $\xi_B = 0.01$, $p = 2.5$ and $n_1 = 1$; c) $E = 10^{53}$ erg, $\xi_e = 0.6$, $\xi_B = 10^{-4}$, $p = 2.5$ and $n_1 = 1$; d) $E = 10^{53}$ erg, $\xi_e = 0.6$, $\xi_B = 0.01$, $p = 2.2$ and $n_1 = 1$. The thin dash-dotted and dashed curves represent the synchrotron spectra of the reverse shock and forward shock, respectively. The solid and dotted curves represent the SSC emissions from the reverse shock and forward shock, respectively. Also plotted are the IC emissions of scatterings of reverse shock photons on the forward shock electrons (dash-dotted curve) and forward shock photons on the reversely shocked electrons (dashed curve).

Figure 2. The high energy gamma-ray photon spectrum index $\alpha$ of the SSC emission from the reverse shock with typical shock parameters as used in Fig. 1 a).
4. Conclusions and Discussions

If optical flashes and GeV emissions are, respectively, resulting from synchrotron and SSC emissions from reverse shocks, they should show correlations in both their light curves and spectra. In summary, we showed that the SSC process in the reverse shocks of gamma-ray bursts is a plausible model for the observed prompt high-energy gamma-ray emissions from several bursts. It is found that the SSC emission from the reverse shocks dominates over other emission processes in energy bands from tens of MeV to tens of GeV, for a wide range of shock parameters. This model is more favorable for energetic photons than those related to internal shocks, since it involves a much lower internal pair-production optical depth due to a much larger emitting size. We predict that, in this model, the prompt high-energy emissions are correlated with the prompt optical flashes, which can be test in the forthcoming GLAST era.

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