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PROMPT ULTRAVIOLET–TO–SOFT X-RAY EMISSION OF GAMMA-RAY BURSTS: APPLICATION TO GRB 031203?

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ABSTRACT

We discuss the prompt emission of gamma-ray bursts (GRBs), allowing for $\gamma\gamma$ pair production and synchrotron self-absorption. The observed hard spectra suggest heavy pair loading in GRBs. The reemission of the generated pairs results in the energy transmission from high-energy gamma rays to long-wavelength radiation. Because of strong self-absorption, the synchrotron radiation by pairs is in an optically thick regime, showing a thermal-like spectral bump in the extreme-ultraviolet/soft X-ray band, other than the peak from the main burst. Recently, the prompt soft X-ray emission of GRB 031203 was detected thanks to the discovery of a delayed dust echo, and it seems to be consistent with the model prediction of a double-peak structure. The confirmation of the thermal-like feature and the double-peak structure by observation would indicate that the dominant radiation mechanism in GRBs is synchrotron rather than inverse Compton radiation.

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

1. INTRODUCTION

In the past few years, a standard model was well established in which the gamma-ray burst (GRB) afterglows result from the relativistic blast waves sweeping up the ambient medium of GRBs (Mészáros 2002). However, the prompt emission of GRBs is believed to be irrelevant to ambient medium, and its radiation mechanism is still poorly known so far.

The recent definite proof of GRB 030329 associated with a Type Ib/c supernova confirmed, as long suspected, that GRBs, at least the long class, originate from explosions of massive stars in distant galaxies (Stanek et al. 2003; Hjorth et al. 2003). Since GRBs are events occurring on stars, the emission region may be compact, and the huge energy release will lead to the formation of $e^{\pm}$, γ fireballs, exhibiting thermal-like spectra. But the GRB spectra are nonthermal and hard, with a significant fraction of the energy above the $e^{\pm}$ pair formation energy threshold. For a photon with tens of MeV to escape freely, avoiding $\gamma\gamma$ interactions, the fireball must be ultrarelativistic expanding, with $\Gamma \gtrsim 100$ (Lithwick & Sari 2001 and references therein). The afterglow studies have also confirmed the presence of ultrarelativistic motion. However, if the intrinsic emission, before leaking out from the fireball, includes radiation with even higher energy, say, beyond GeV, this radiation still suffers $\gamma\gamma$ absorption, leading to pair loading in GRBs. In the context of the relativistic fireball model, Li et al. (2003, hereafter L03) found that in a wide range of model parameters, the resulting pairs may dominate those electrons associated with fireball baryons. The presence of abundant pairs would affect the behaviors of the early afterglow from reverse shocks (L03) and may also emit particular signals in the bursting phase.

We discuss in this Letter the prompt GRB emission, with emphasis on the reemission by the secondary $e^{\pm}$ pairs. If the energy density in the emission region is dominated by the magnetic field, the pairs would reemit mainly by synchrotron radiation, rather than the inverse Compton (IC) process (e.g., Pilla & Loeb 1998). Because of strong self-absorption, the pair emission appears as a thermal-like bump in the GRB spectrum, similar to the feature discussed by Kobayashi et al. (2004) in the context of reverse shock emission. (Fan & Wei 2004 have also studied the pair emission, but with less stress on the self-absorption effect.) We further show that the intense soft X-ray emission in GRB 031203, inferred by the delayed dust halo (Vaughan et al. 2004, hereafter V04; Watson et al. 2004, hereafter W04), can be accounted for by the spectral bump due to pair loading. This is of significant interest, since this feature could give a diagnostic for the magnetic field in the fireball (Kobayashi et al. 2004) and the dominant radiation mechanism in GRBs.

2. PAIR LOADING IN GRB FIREBALLS

Consider a GRB central engine that produces a relativistic wind outflow, with an isotropic energy E, a bulk Lorentz factor Γ, and a width Δ. The energy carried in the outflow may be composed of two components, the bulk kinetic energy of baryons (E_k) and the energy of the magnetic field (E_B). The ratio between them can be defined as $\sigma \equiv E_B/E_k$ (e.g., Zhang & Mészáros 2002). These energies are carried from the central engine to some radius R where GRB emission arises. As in L03, the emission site can be constrained by the nonthermal spectra and rapid varying light curves of GRBs, leading to a typical value of $R \sim 10^{14}$ cm for $\Gamma \sim 300$. The width of outflow is $\Delta \lesssim 10^{12}$ cm for a wind lasting a duration of $T \lesssim 100$ s. Thus the emission region can be regarded as a thin shell with $\Delta \ll R$.

In the kinetic energy–dominated model ($\sigma < 1$), the bulk kinetic energy is dissipated by internal shock waves within the unsteady outflow, where the magnetic field strength B is in the equipartition value $B \sim (8\pi U_\gamma)^{1/2} = 10^4 L_{\gamma,51}^{1/2}\Gamma_{300}^{-1}R_{14}^{-1}$ G, with $L_\gamma = 10^{51}L_{\gamma,51}$ ergs s^{-1} the GRB luminosity, $\Gamma_{300} = \Gamma/300$, and $R_{14} = R/10^{14}$ cm. In the magnetic energy–dominated model, the magnetic field could be stronger than the equipartition value, leading to a small radiation–to–magnetic energy ratio in the emission region, $Y \equiv U_\gamma/U_B < 1$. Although broadband fits of afterglows generally give $Y > 1$ for the shocked medium, the presence of highly magnetized ejecta is suggested by some recent works (e.g., Zhang et al. 2003). Here we assume $Y < 1$ for GRBs and scale the magnetic field as $B = 10^4 B_4$ G.

Because of the large luminosity and hard spectrum of a GRB, intrinsic high-energy gamma rays produced in the GRB emission region could be absorbed for pair production. As in L03, the cutoff energy, above which the photons suffer strong absorption, and the number of produced pairs can be estimated from the observed GRB spectra. The observed photon spectra of GRBs

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can be approximated by a broken power law, with a high-energy portion of the form $dN_\gamma/d\epsilon \propto \epsilon^{-\beta}$ for $\epsilon > \epsilon_p$, where $\epsilon_p \sim m_e c^2$ is the energy at the broken point and the index $\beta \sim 2$–3. The number of the produced secondary pairs is equal to the absorbed photons above $\epsilon_{\rm cut}$. Assuming that the intrinsic spectrum above $\epsilon_{\rm cut}$ follows the same power law below $\epsilon_{\rm cut}$, we calculate the pair number as $N_\pm = N_\gamma(>\epsilon_{\rm cut}) \simeq (E_\gamma/\epsilon_p)(\epsilon_{\rm cut}/\epsilon_p)^{-(\beta-1)}$. Since the timescale of $\gamma\gamma$ collisions (comoving frame), $t'_{\gamma\gamma} \simeq [(\sigma_T/5)n'_\gamma c]^{-1} = 0.2\Gamma_{300}R_{14}^2 L_{\gamma,51}^{-1}$, is usually shorter than the dynamical time (comoving frame), $t'_{\rm dyn} \simeq R/\Gamma c = 10R_{14}\Gamma_{300}^{-1}$ s, the resulting pairs remain inside the outflow.

As in L03, $\epsilon_{\rm cut}$ should be defined by the photon energy at which the optical depth for $\gamma\gamma$ absorption equals unity, $\tau_{\gamma\gamma}(\epsilon) = 1$, where the optical depth can be given by a simplified expression under the thin-shell assumption of the emission region, $\tau_{\gamma\gamma}(\epsilon) = (11/180)\sigma_T N_\gamma(>\epsilon)/4\pi R^2$ (Lithwick & Sari 2001). Furthermore, the observed cutoff energy must be larger than $\Gamma m_e c^2$. In summary,

$$\epsilon_{\rm cut} = \max\left[0.3\left(\frac{R_{14}^2}{E_{\gamma,52}\epsilon_0^{\beta-2}}\right)^{1/(\beta-1)}\Gamma_{300}^2;\ \ 0.2\Gamma_{300}\right]\ {\rm GeV}, \quad (1)$$

where $\epsilon_0 = \epsilon_p/m_e c^2$, and hereafter the numerical coefficient corresponds to $\beta = 2.4$. It can be seen that the detection of the cutoff energy can help to constrain Γ and R. EGRET had detected prompt GeV emission, without obvious attenuation, in several GRBs (e.g., GRB 930131; Sommer et al. 1994). We expect that the future satellite *GLAST*, which works in the 10 MeV–300 GeV range, could observe such a cutoff at multi-GeV.[2] With $\epsilon_{\rm GeV} = \epsilon_{\rm cut}/1$ GeV, the pair number is written as

$$N_\pm \simeq 3\times 10^{53}E_{\gamma,52}\epsilon_{\rm GeV}^{-(\beta-1)}\epsilon_0^{\beta-2}. \quad (2)$$

For comparison, the number of baryonic electrons in the fireball is $N_b = E/(1+\sigma)\Gamma m_p c^2 = 2\times 10^{52}E_{52}\Gamma_{300}^{-1}(1+\sigma)^{-1}$, with $E_{52} = E/10^{52}$ ergs. Therefore, pairs become the dominant component. The baryonic electrons are expected to be responsible for the prompt hard X-ray emission, while the pairs might give rise to low-energy emission, discussed below.

3. EXTREME-ULTRAVIOLET BUMP IN THE PROMPT EMISSION

Since the energy of a generated e^+ (e^-) comes primarily from the photon with larger energy between the two colliding ones, the initial energy distribution of the generated pairs would follow the form of the high-energy spectral tail, i.e., $dn_\pm/d\gamma_e \propto \gamma_e^{-\beta}$ for $\gamma_e > \gamma_\pm$, where $\gamma_\pm$ corresponds to the cutoff energy, $\gamma_\pm = \epsilon_{\rm cut}/2\Gamma m_e c^2 \simeq 3.3\epsilon_{\rm GeV}\Gamma_{300}^{-1}$. These pairs will cool down by synchrotron rather than IC radiation in the $Y \lesssim 1$ condition here. Because of the strong magnetic field in the emission region, the synchrotron-cooling timescale of pairs, $t'_{\rm syn} = 8B_4^{-2}\gamma_\pm^{-1}$ s, is shorter than the fireball dynamical time, implying that the pairs are always fast cooling. We assume that pair annihilation is negligible, which is confirmed later.

For these fast-cooling pairs, their energies are emitted quickly. As a result, the energy above $\epsilon_{\rm cut}$ in the intrinsic spectrum arises again as the pair emission. The luminosity of the pair emission is given by

$$L_\pm \simeq \frac{\beta-1}{\beta-2}\frac{N_\pm\epsilon_{\rm cut}}{T} \simeq 2\times 10^{50}L_{\gamma,51}\left(\frac{\epsilon_0}{\epsilon_{\rm GeV}}\right)^{\beta-2}\ {\rm ergs\ s^{-1}}, \quad (3)$$

with $L_\gamma = E_\gamma/T = 10^{51}L_{\gamma,51}$ ergs s^{-1} the GRB luminosity, and the characteristic synchrotron frequency is

$$\nu_\pm = 0.9\times 10^{14}\Gamma_{300}^{-1}\epsilon_{\rm GeV}^2 B_4\ {\rm Hz}. \quad (4)$$

If we assume $Y \ll 1$, the synchrotron radiation plays a dominant role of pair cooling, rather than the IC process. In this condition, the luminosity $L_\pm$ will peak at frequency $\nu_\pm$. Thus a very intense optical flash will emerge accompanying the prompt gamma rays if neglecting the self-absorption. However, as shown in the following, the self-absorption is strong in such a low-energy range, with the absorption frequency $\nu_a \gg \nu_\pm$; i.e., most of the pair emission occurs in the optically thick regime. Similar to the case of reverse flash in the condition of $\nu_c < \nu_m < \nu_a$, which is discussed by Kobayashi et al. (2004), a thermal-like bump will arise in the low-energy range of a GRB spectrum.

The self-absorption suppresses the emission below absorption frequency ν_a, and the suppressed emission energy is redistributed again among the pairs, preventing the pairs from cooling down immediately. So, the pairs and the radiation obtain a mechanism to exchange their energies. The final result is that the initial injected pair energy is redistributed among pairs and radiation, leading to a bump in the spectrum. The emission in the hard X-ray band is not in the optically thick regime and is not involved in the energy redistribution. In the GRB duration T, the pair energy is radiated around ν_a, where the flux is given by $F_{\nu_a} \simeq L_\pm/4\pi D_L^2\nu_a$, with D_L the GRB luminosity distance. We follow the simple way used by Sari & Piran (1999) to estimate the maximal flux as a blackbody with the pair temperature, $F_{\nu_a,\rm bb} \approx \pi(R_\perp/D_L)^2(2\nu_a^2/c^2)kT_\pm$, where $R_\perp \simeq R/\Gamma$ is the observed size of the fireball, the pair temperature is $kT_\pm \simeq \Gamma\gamma_a m_e c^2/3$, and γ_a is the pair Lorentz factor that corresponds to ν_a and is given by $(2\pi m_e c\nu_a/\Gamma eB)^{1/2}$. Equating $F_{\nu_a,\rm bb} \simeq F_{\nu_a}$ yields the self-absorption frequency

$$\nu_a \simeq 1\times 10^{16}L_{\pm,50}^{2/7}\Gamma_{300}^{3/7}R_{14}^{-4/7}B_4^{1/7}\ {\rm Hz}, \quad (5)$$

which is in the extreme-ultraviolet (EUV) band. Since $\nu_a \gg \nu_\pm$, most of the emission is absorbed and redistributed, giving rise to a blackbody-like bump in the GRB spectrum, with peak frequency around ν_a (eq. [5]) and luminosity $L_\pm$ (eq. [3]).

The comoving-frame annihilation timescale of the pairs in the thermal-like bump, with the comoving-frame temperature $\gamma_a m_e c^2/3$, is $t'_{\rm ann} \simeq (\sigma_{\rm ann}n_\pm c)^{-1}$, where $\sigma_{\rm ann} \simeq (3\sigma_T/8\gamma_a)\times(\ln 2\gamma_a - 1)$ is the annihilation cross section, and the pair number density is given by $n_\pm \approx n_\gamma(>\epsilon_{\rm cut}) \simeq L_\pm/4\pi R^2\Gamma c\epsilon_{\rm cut}$. Note that the baryonic electrons are neglected. The annihilation fraction of pairs, $f_{\rm ann}$, can be estimated by $t'^{-1}_{\rm ann}$ times the comoving-frame dynamical timescale $t'_{\rm dyn}$, $f_{\rm ann} \sim 0.08(L_{\pm,51}/\Gamma_{300}^3 R_{14})(\gamma_\pm\gamma_a/10)^{-1}$. Since $f_{\rm ann} \ll 1$, the annihilation in the bump is really negligible.

Note that ν_a is insensitive to all the parameters (eq. [5]) and would be fixed in the EUV range for various GRBs. However, as it propagates, the EUV radiation from a GRB is subject to intergalactic or galactic absorption (e.g., Gou et al. 2004); hence, only the optical/UV or soft X-ray emission is expected for observation. Below ν_a the spectrum behaves as $F_{\nu<\nu_a} = F_{\nu_a}(\nu/\nu_a)^2$; then the observed pair emission at 1 eV is

$$F_\nu^{\rm ob}(1\ {\rm eV}) \simeq 0.9\frac{L_{\gamma,51}(1+z)^3}{D_{28}^2\nu_{a,16}^3}\left(\frac{\epsilon_0}{\epsilon_{\rm GeV}}\right)^{\beta-2}\ {\rm mJy}, \quad (6)$$

where $\nu_{a,16} = \nu_a/10^{16}$ Hz, and we have obviously shown the dependence on redshift z. Whereas in the band above ν_a, the emission is in an optically thin regime and still exhibits the

[2] Cosmic infrared background can also absorb high-energy photons but primarily in the TeV range (Salamon & Stecker 1998).

form radiated by the initial pairs, $F_{\nu>\nu_a} = F_{\nu_\pm}(\nu/\nu_\pm)^{-\beta/2}$, where $F_{\nu_\pm} \simeq L_\pm/4\pi D_L^2\nu_\pm$. If observed at 1 keV, the flux contributed by pairs is then

$$F_\nu^{\rm ob}(1\ {\rm keV}) \simeq 3 \times 10^{-8}\frac{L_{\gamma,51}}{D_{28}^2}\left[\frac{\epsilon_0^2 B_4}{\Gamma_{300}(1+z)}\right]^{(\beta-2)/2} \qquad (7)$$

(in units of ergs cm^{-2} s^{-1} keV^{-1}). This calculation is valid until at high enough frequency where the main GRB peak dominates the emission. For the typical parameters, the contrast of the thermal bump relative to the power-law spectrum $(\nu_a/\nu_\pm)^{\beta/2-1}$ (Fig. 1) is a factor of a few, and the bump is weak. For a larger index $\beta \sim 3$ the contrast is larger, and although the energy injected into the pairs becomes smaller, the thermal bump still sticks out above the primary emission component. The prompt optical/UV (eq. [6]) and X-ray (eq. [7]) emission are expected to be observed by the UV/Optical Telescope and X-Ray Telescope, respectively, on board the upcoming *Swift* satellite.

As a result, the intrinsic high-energy emission in the GRB spectrum is absorbed and then transferred to a thermal-like bump in the EUV band, as shown in Figure 1. Since these features are expected to arise if $Y \ll 1$, the observation would provide a constraint on the magnetization parameter and the radiation mechanism in GRBs.

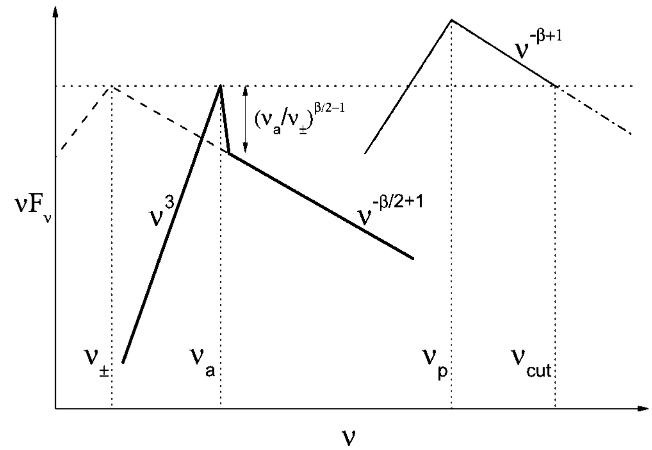

FIG. 1.—Schematic diagram of the νF_ν spectrum of the GRB prompt emission. Note that $\nu_p = \epsilon_p/h$ and $\nu_{\rm cut} = \epsilon_{\rm cut}/h$. The thin solid line shows the GRB emission with cutoff above $\nu_{\rm cut}$ due to $\gamma\gamma$ pair production, while the dash-dotted line is the intrinsic spectrum without cutoff. The synchrotron radiation by the resulting pairs is shown by the thick solid or dashed lines, corresponding to with or without self-absorption, respectively. The maximum around ν_a would appear as a thermal-like peak.

4. GRB 031203

GRB 031203 was detected by *INTEGRAL* as a single-pulse burst with a duration of 30 s and a peak flux of 1.3×10^{-7} ergs s^{-1} cm^{-2} in the 20–200 keV band (Götz et al. 2003; Mereghetti & Götz 2003). A double exponential approximation to the single-pulse light curve yields an estimated fluence of 4×10^{-7} ergs cm^{-2} (20–200 keV; Prochaska et al. 2004, hereafter P04). With the redshift $z = 0.1055$ measured from the optical observation of the host galaxy, the *k*-correction isotropic-equivalent energy release is estimated to be $E_{\rm iso}$(20–2000 keV) $= 2.6 \times 10^{49}$ ergs ($h = 0.7$, $\Omega_\Lambda = 0.7$, and $\Omega_m = 0.3$; P04).

Six hours after the burst, *XMM-Newton* discovers a time-dependent dust-scattered X-ray halo around the burst (V04; W04). The halo brightness implies an initial soft X-ray pulse consistent with the burst. Since few satellites observe GRBs in the soft X-ray band, this observation is important for us to know the emission features of GRBs in such a low-energy range. On the basis of the hypothesis of the column of dust along the sight line toward GRB 031203, V04 and W04 estimate a source flux of $1.5 \pm 0.8 \times 10^{-7}$ ergs cm^{-2} s^{-1} with photon index $\beta_{\rm X} = 2.2 \pm 0.3$ in the 0.2–10 keV band. This leads them to regard GRB 031203 as an X-ray flash with peak energy at $\lesssim$10 keV. However, P04 argue that the above analysis has overestimated the scattering column of dust, which may be 4.4 (or even 27) times larger, and hence the source should be 4.4 (27) times smaller in flux. Thus, we take in the following discussion the source flux of the dust halo as 3.4 ± 1.8 (0.56 ± 0.30) $\times 10^{-8}$ ergs cm^{-2} s^{-1} in the 0.2–10 keV band, which corresponds to a fluence of 10 ± 5.4 (1.7 ± 0.9) $\times 10^{-7}$ ergs cm^{-2} for a duration of 30 s.

The observational results of GRB 031203 are consistent with the double-peak spectral shape described in § 3. This rests on two points. First, the photon index of ∼2.2 in the 0.2–10 keV band implies a soft X-ray peak, with most energy released at $\lesssim$0.2 keV. And second, the fluence in the 20–200 keV band is larger than that extrapolated from the 0.2–10 keV band using the photon index $\beta_{\rm X} \sim 2.2$, suggesting a second peak in the hard X-ray band. The observed hard X-ray emission is only comparable to or even slightly smaller than the soft X-ray one in fluence, but we expect that since the redshift of GRB 031203 is low and hence the peak energy is less redshifted, the hard X-ray emission could peak at higher energy, $\epsilon_p > 200$ keV. If peaking at ∼1 MeV, the hard X-ray fluence would be larger by a factor of ∼5 and dominates the soft one. It is unfortunate that a reliable time-integrated spectrum of GRB 031203 above 20 keV is not given. Therefore we cannot compare the two peaks for more details. Since the soft X-ray spectrum of GRB 031203 follows a power law, the thermal-like bump should be at an energy below the observation window, $\lesssim$0.2 keV, consistent with that predicted in equation (5).

There may be some caveats here. One may think that a double-peak structure can also be interpreted as synchrotron self-Compton radiation provided $Y > 1$. But in this condition, the pairs from $\gamma\gamma$ production will lose energy by IC radiation and result in a spectral bump at $\gamma_\pm^2\epsilon_p \lesssim 100$ MeV, something conflicting with the observation of GRBs in the high-energy band (Schaefer et al. 1998). A further difficulty for synchrotron self-Compton radiation in interpreting the double peaks is that there may be many Compton orders if $Y > 1$, and each higher Compton order will dominate over the previous one by the same amount Y until the typical emitted energy reaches the electron energy. Only a small fraction of the radiated power would therefore be observed in the sub-MeV band (e.g., Ghisellini et al. 2000), resulting in an energy crisis of GRBs.

One may also think that the source of the dust halo is the X-ray afterglow in early time rather than the prompt burst. We believe that this can be ruled out. The dust halo consists of two narrow rings, and V04 have interpreted them as being due to the prompt burst scattered by two distinct scattering screens. One may still propose that only a single scattering screen is required as long as there is a complex early time structure of the X-ray afterglow. However, if so the later ring should evolve with a certain time delay with respect to the first one, which is in contrast with the observation (see $\theta - t$ curves in Fig. 3 of V04). The ring is rather narrow, implying that the intrinsic emission is a short pulse, as opposed to the smooth afterglow behavior. In fact, since the ring is narrow, $\Delta\theta \sim 20''$ in angular width, the pulse duration is limited to $\Delta t \lesssim D\Delta\theta^2/c \sim 800$ s, where the distances of the screens from earth are $D \sim 1$ kpc for both rings (V04). Because of causality, the dynamical time is also limited to $t \sim \Delta t \lesssim 800$ s.

5. SUMMARY AND DISCUSSION

We have studied the prompt GRB emission, allowing for $\gamma\gamma$ pair production and synchrotron self-absorption. Inferred by the observed characteristics of GRB emission, the resulting pairs usually dominate the baryonic electrons. The pairs will give rise to further emission by synchrotron radiation if in the strong magnetic field, which is also responsible for the prompt sub-MeV emission. However, because of strong self-absorption the pair emission exhibits a thermal-like bump in the extreme UV/soft X-ray band, other than the peak in the hard X-ray band. Since the feature emerges for $Y < 1$, its observation gives a diagnostic for the magnetic energy density in the fireball (Kobayashi et al. 2004). The recent observation of a dust halo around GRB 031203 infers a spectral peak of the prompt burst emission in the soft X-ray band, which seems to be consistent with the predicted double-peak structure.

Some primary hypotheses have been taken in our calculation. First, we assume that the emission region is transparent for Compton scattering, even though the secondary pairs increase significantly the total optical depth. For typical parameter values this assumption is protected. However, in some extreme cases with quite small Γ and R, the secondary pairs may form an optically thick screen again (Guetta et al. 2001; Kobayashi et al. 2002), which degrades the gamma rays and results in an X-ray flash (XRF; Mészáros et al. 2002). If so, our calculation using equation (2) may underestimate the pair loading in XRFs, which may need detailed works of numerical simulation (e.g., Pe'er & Waxman 2003). Second, we assume a strong magnetic field, $Y < 1$, in the emission region. If $Y > 1$, the pairs lose most energy by IC scattering the GRB photons, and the IC photons are not self-absorbed again since beyond the optically thick regime, hence no effective energy exchange between pairs and photons is established and the bump disappears. Therefore, once UV/soft X-ray bumps are detected, this will infer that $Y < 1$ and that it is synchrotron rather than IC radiation that gives rise to the sub-MeV emission of GRBs.

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