On the Prompt Emission Mechanism in Gamma-Ray Bursts

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We examine the prompt emission mechanisms that take place in Gamma-Ray Bursts (GRBs). The nature of this process is still one of the interesting puzzles in GRBs. Recent simultaneous observations of both optical and gamma-rays from 080319c, the naked eye bursts, suggested, at first, that the observed gamma-rays are Inverse Compton (IC) scattering of the optical emission. However, optical upper limits rule out this possibility for most burst and even for 080319c, whose optical emission was extremely powerful.

1 Introduction

The mechanism that produces the prompt gamma-ray emission in Gamma Ray Burst (GRBs) is still uncertain. The non-thermal character together with the short time scale variability led to the compactness problem[1]. The resolution of the compactness problem have led to the commonly accepted paradigm that the emitting regions must be moving relativistically (at 0.99c or faster) towards us and to the fireball model. While this was an important step in understanding GRBs we still have to understand what is the origin of the non-thermal emission.

Among non-thermal emission processes two: Inverse Compton (IC) and synchrotron, stand out as the natural candidates. Other processes like curvature emission, or cascade due to proton proton collisions are incapable of producing the huge observed luminosities with reasonable physical parameters. Among IC and synchrotron the latter become, somehow, the "standard" process but the former remained always a serious alternative [2–9] The observations of numerous bursts with low energy spectral slopes that are inconsistent with synchrotron [10,11,12,7] provided additional motivation to consider IC. Recently, Kumar & McMahon [13] have argued that the overall synchrotron model is inconsistent and suggested that Synchrotron Self-Compton (SSC) can resolve some of the problems.

The observations [14,15,16] of a naked eye optical flash that coincided with the prompt $\gamma-$ray emission from GRB080319b provided further motivation to consider IC as the source of the prompt γ-rays. Among the different models that appeared so far [17–21], several favor scenarios in which the prompt γ-ray emission is IC of the optical flash and there have been suggestions that this is generic.

Motivated by these ideas we [22] have explored the possibility that SSC is the source of the prompt γ-ray emission in GRBs. The analysis is very general. It depends only on the observed fluxes (in the optical and in soft γ-rays, as well in the GeV-TeV regime) and on the conditions in the emitting regions, where the main parameters of interest are the Lorentz factor of the emitting electrons, γ_e, and the bulk Lorentz factor, Γ. It is independent of the nature of the relativistic

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[a] Talk given by T. Piran

ejecta (baryonic or Poynting flux), of the relativistic electrons (internal or external shocks, or something else) and of the acceleration process. We don't even use the usual constraints on the size of the emitting region and the Lorentz factor that arise from variability considerations[23]. We show that current observations rule out the possibility that the soft γ-ray emission is produced via SSC or more generally of IC of low energy photons that are produced in the moving jet. We then [19] turn to GRB080319b, that has motivated this research, and show that even though its optical emission was much brighter even in this case the soft γ-ray emission was not an SSC of the optical signal and that the optical photons and γ-rays must have arisen from different sources.

2 Inverse Compton

IC requires a soft seed component at the IR-UV range. The flux of these seed photons is constrained by observations (or upper limits) of the prompt optical emission. GRB 990123 [24] and GRB 080319B [14] are rare exceptions with very strong optical emission, ~ 9 and ~ 5.3 mag respectively. However most bursts are much dimer optically with observations or upper limits around 14 mag [25] (In the following we use very conservatively optical upper limits of 11 mag corresponding to $F_{opt} \approx$100 mJy). . This should be compared with fluxes of mJy in soft gamma rays for a modest burst. The flux ratio F_γ/F_{opt} which is typically larger than 0.01 (corresponding to an energy ratio, $\nu_\gamma F_\gamma/\nu_{opt} F_{opt} > 1500$) during the peak soft γ-rays emission [25] .

If the low energy seed emission is in the optical and the observed soft γ-rays are the first IC component, then the Y parameter ($\equiv \nu_\gamma F_g/\nu_{opt} F_{opt}$) is very large, typically greater than thousands. In this case the second IC component would be in the GeV-TeV range and it would carry an even larger amount of energy than the soft γ-rays. This will pose an "energy crisis" and even more important would violating upper limits from EGRET [26,27] and Fermi (even the powerful high energy emission of GRB080916C[28] did not carry that much energy)[b]. This problem is generic and it does not depend on the specific details of the overall model.

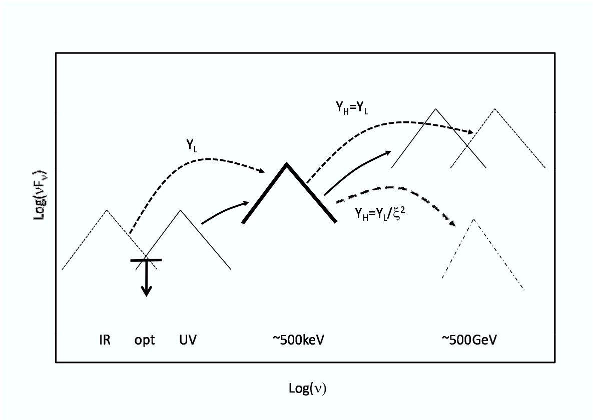

Figure 1: A schematic description of the IC process. Low energy photons at the IR (marked in dotted lines), optical or UV (marked in solid thin lines) are IC scattered to produce the observed soft gamma ray emission (marked in bold lines). A second IC scattering brings the soft gamma photons to the TeV region. If the initial seed photons are softer the higher energy component is harder. If the initial seed is in the IR then the second IC process might be in the KN regime, in which case this component is suppressed (dashed-dotted line). The seed low energy emission is constraint by upper limits on the optical prompt observations (bold solid arrow).

Two factors may alleviate the energy catastrophe. First, the frequency of the seed photons may differ from those where upper limits exist, allowing larger seed flux and reducing the lower limits on Y. Second, the Klein-Nishina (KN) suppression, which does not affect the first scattering, may affect the second, resulting in a lower Y parameter for the second scattering

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[b] If the second IC component is in the TeV it will be absorbed by the IGM and won't be observed. Still the "energy crisis" problem will persist.

than the first one. However [22], even when these factors are taken into account the IC solution is problematic.

Consider IC scattering of seed photons with a peak frequency ν_s and a peak flux F_s (both measured at the observer's frame). We assume that the seed photons are roughly isotropic in the fluid's frame. This would be the case if the seed photons are produced by a mechanism local to the moving fluid, synchrotron radiation is an example. For simplicity we assume that all the photons have the same energy and all the electrons have the same Lorentz factor. The energy and flux of the scattered photons are:

$$\nu_{IC} = \nu_s \gamma_e^2 \min(1,\xi^{-1}); \quad \nu_{IC} F_{IC} = Y \nu_s F_s \min(1,\xi^{-2}) \tag{1}$$

where $Y \equiv \tau \gamma_e^2$ and τ are the Compton parameter and the optical depth in the Thomson scattering regime. The factor, $\xi \equiv (\gamma_e/\Gamma) h\nu_s / m_e c^2$ describes the correction that arises if the scattering is in the KN regime ($\xi > 1$).

Extrapolating from ν_{opt} we can set a limit on the low energy peak flux F_L:

$$F_L \leq (\nu_L/\nu_{opt})^{\alpha} F_{opt}, \tag{2}$$

where ν_L is the frequency of the peak and α is the spectral index in the range (ν_L, ν_{opt}) or (ν_{opt}, ν_L). F_{opt} is taken as an upper limit. An *UV solution* is characterized by $\nu_L > \nu_{opt}$ and an *IR solution* is characterized by $\nu_L < \nu_{opt}$. Since by definition, the seed photon energy peaks at ν_L, we must have $\alpha > -1$ in the*UV solution* and $\alpha < -1$ in the *IR solution* . Moreover, since the spectrum around ν_L is up-scattered to create the familiar Band spectrum [29] around ν_γ, we can expect $\alpha \approx -1.25$ for the IR solution and $\alpha \approx 0$ for the*UV solution* .

Using Eqs. (1,2) we set a limit on the Compton parameter Y_L, in the first scattering:

$$Y_L \geq \left(\frac{\nu_\gamma F_\gamma}{\nu_{opt} F_{opt}}\right) \left(\frac{\nu_L}{\nu_{opt}}\right)^{-(1+\alpha)} . \tag{3}$$

The second IC scattering produces photons in the GeV-TeV range. Y_H is the ratio of energy emitted via the second IC scattering in the high energy (GeV- TeV) band and in the lower energy gamma-rays:

$$h\nu_H = 0.08\text{TeV} \left(\frac{h\nu_\gamma}{500\text{keV}}\right) \left(\frac{\gamma_e}{400}\right)^2 \min\left[1, \frac{\Gamma m_e c^2}{\gamma_e h \nu_\gamma}\right] \tag{4}$$

and

$$Y_H \geq 1500 \left(\frac{F_\gamma}{10^{-26}} \frac{10^{-24}}{F_{opt}}\right) \left(\frac{h\nu_\gamma}{500\,\text{keV}} \frac{8\cdot 10^{14}\,\text{Hz}}{\nu_{opt}}\right) \left(\frac{\nu_L}{\nu_{opt}}\right)^{-(1+\alpha)} \min\left[1, \left(\frac{\Gamma m_e c^2}{\gamma_e h\nu_\gamma}\right)^2\right] . \tag{5}$$

We have used here typical values $\nu_{opt} = 8 \cdot 10^{14}$Hz and $h\nu_\gamma = 500$keV (both are before cosmological redshift hence they are larger by a factor of $(1+z) \approx 2$ than the observed frequencies, R band and 250keV). For the canonical values of the observer fluxes we use very conservative values: R magnitude of 11.2, ($F_{opt} \leq 10^{-24}\text{ergs}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{Hz}^{-1}$), as an upper limit on the optical flux, while many limits are much stronger. Similarly, for the γ-ray flux we take, $F_\gamma = 10^{-26}\text{erg}\,\text{cm}^{-2}\,\text{s}^{-1}\,\text{Hz}^{-1}$, which is quite modest.

The very large value of Y_H is the essence of the IC problem. It arises from the fact that the energy released in prompt gamma-rays is at least a factor of 1500 larger than the energy released in prompt optical emission (see Eq. 3). The large values of Y_H implies that the energy emitted in the GeV-TeV range would exceeds the observed soft γ-rays by a few orders of magnitude.

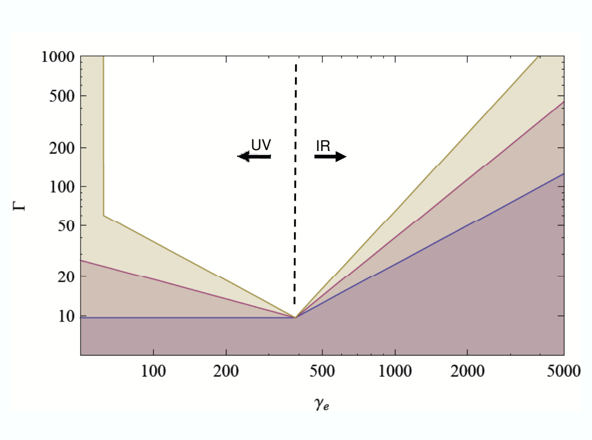

Figure 2: The allowed (colored) phase space in which $Y_H \leq 1$. For three spectral indexes $\alpha = 0, 0.5, 1$ (from bottom to top) for $\nu_L > \nu_{opt}$ and $\alpha = -1, -1.5, -2$ for $\nu_L < \nu_{opt}$(from bottom to top). Parameters used are: $F_\gamma/F_{opt} = 0.01$, $\nu_{opt} = 8 \cdot 10^{14}$Hz and $h\nu_\gamma = 500$keV. The γ_e axis corresponds to values of ν_L ranging from $15\nu_{opt} = 4.8 \cdot 10^{16}$Hz=0.2keV for $\gamma_e = 50$ to $0.006\nu_{opt} = 4.8 \cdot 10^{12}$Hz for $\gamma_e = 5000$.

To demonstrate the severity of the constraint we plot (Fig. 2) the "allowed region" in the (γ_e, Γ) phase space for which $Y_H < 1$. The expected parameter region for internal shocks $\gamma_e \approx 500$, $\Gamma \approx 300$ is deep inside the ruled out region. We find two possible regions which don't over produce GeV-TeV emission: An *IR solution* with a very large γ_e and a *UV solution* with a very low γ_e. In both cases ν_L is far from the optical regime and hence the observational limits on F_L are weak, allowing a modest Y solution. We consider these two possibilities now.

2.1 The UV solution

For low values of γ_e the whole Γ range is seemingly allowed. This happens at rather low values $\gamma_e < 62, 34, 10$ for $\alpha = 1., 0.5, 0$ respectively, corresponding to seed photon energies in the hard UV. The second Compton scattering is not in the KN regime and therefore $Y_L \approx Y_H$. The total energy, given by $(1/Y_L + 1 + Y_H)E_\gamma$, is at least $3E_\gamma$. UV solutions with $Y_L = Y_H < 1$ are therefore also somewhat wasteful as they require a large (E_γ/Y_L) low energy component. A second problem arises, for this solution, with the spectral shape. The observed low energy spectral index (in the X-ray band) is typically close to zero, while this solution requires a steeply rising flux from ν_{opt} to ν_L.

The analysis above is based on the optical limits but for the modest values of γ_e needed for the *UV solution* , ν_L, the peak flux frequency of the seed photons becomes large (Eq. 1) and F_L is now limited also by prompt soft X-ray observations. We use α_1 and α_2 as the low energy and high energy spectral indices in the γ-ray band, respectively. As stated before, the canonical values are $\alpha_1 = 0$ and $\alpha_2 = -1.25$ [29][c]. One can estimate the X-ray flux at $\nu_x = 20$ keV directly from the observations at this energy or using the flux at $\nu_\gamma \approx 500$ keV and the low energy spectral slope α_1. Recalling that the IC does not change the spectral slope, we use the same indices both around ν_γ and around ν_L. Therefore:

$$F_L < (\nu_L/\nu_x)^{\alpha_2}(\nu_x/\nu_\gamma)^{\alpha_1}F_\gamma. \tag{6}$$

Using Eq. 1 we obtain:

$$Y > \frac{\nu_\gamma^{\alpha_1+1}\nu_x^{\alpha_2-\alpha_1}}{\nu_L^{\alpha_2+1}} = (\nu_\gamma/\nu_x)^{\alpha_1-\alpha_2}\gamma_e^{2(\alpha_2+1)}. \tag{7}$$

If we impose the condition $Y \cong 1$ (where the total energy required is minimized to $3E_\gamma$), we find that $\gamma_e > 3000$ or $\nu_L < \nu_{opt}$ - thus the whole UV regime is ruled out. This condition depends

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[c] Since we consider flux rather than photon counts the indices are shifted by 1 relative to Band's.

strongly on the spectral indices: α_1 and α_2. Clearly if α_2 is smaller (a steeper drop on the high energy side) ν_L can be larger and Y is smaller. Thus, the available X-ray data rules out the *UV solution* for most of the phase space.

2.2 The IR Solution and Self Absorption

The *IR solution* holds for $\nu_L < 0.1\nu_{opt} = 8 \cdot 10^{13}$Hz and $\alpha \leq -1.5$. It requires a large electron's Lorentz factor $\gamma_e \geq 1000$ and a relatively low bulk Lorentz factor $\Gamma < 300$. The solution is deep in the KN regime and the KN suppression is very significant. It allows for a large amplification between the IR and the soft γ-rays and no amplification between the low energy γ and the TeV emission. A solution is possible in a small region of the parameter space if the high energy spectrum is steep ($\alpha \leq -1.5$) - this increases the allowed flux at ν_L. Such a spectrum above the peak frequency, though steeper than the canonical $\alpha = -1.25$, is not rare in the observations of prompt γ-ray bursts. However, the large seed flux that is needed at such low frequencies is usually limited by self absorption.

Self absorption limits the flux at ν_L to be below the black body flux, F_{sa}, for a local temperature $kT \approx \Gamma\gamma_e m_e c^2$:

$$\begin{aligned} F_{sa}(\nu_L) &= \frac{2\pi_L^2}{c^2}\gamma_e m_e c^2 \frac{R^2}{\Gamma d_L^2} \\ &\approx 1.3 \cdot 10^{-20}\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}} \frac{(R/10^{17}\mathrm{cm})^2}{d_L^2(z=1)} \frac{(\nu_\gamma/500)^2}{(\gamma_e/400)^3(\Gamma/300)}, \end{aligned} \tag{8}$$

where R is the radius of the source and $d_L(z=1)$ is the luminosity distance for z=1. In the following examples we use conservatively $R = 10^{17}$cm as the emission radius of the prompt emission.

The combined limits on the (Γ, γ_e) parameter space from self absorption with $Y_H = 1$ are shown in fig. 2.2. Only an extremely small region around $\gamma_e \approx 1800$ (corresponding to $\nu_L = 3.7 \cdot 10^{13}$Hz) and $\Gamma \approx 120$ is allowed. This used a conservative over estimate for the emission radius $R = 10^{17}$ cm. If we use the variability time scale $\delta t < 1$sec, with $R \sim \Gamma^2 c\delta t$ and the low values of Γ obtained, R will be much smaller, invalidating even this solution. The self absorption limit rules out also the region in the parameter space that corresponds to external shocks ($\Gamma \approx 100$, $\gamma_e \approx 5 \times 10^4$). This solutions requires a very low seed frequency that would have implied a very small self-absorption limit.

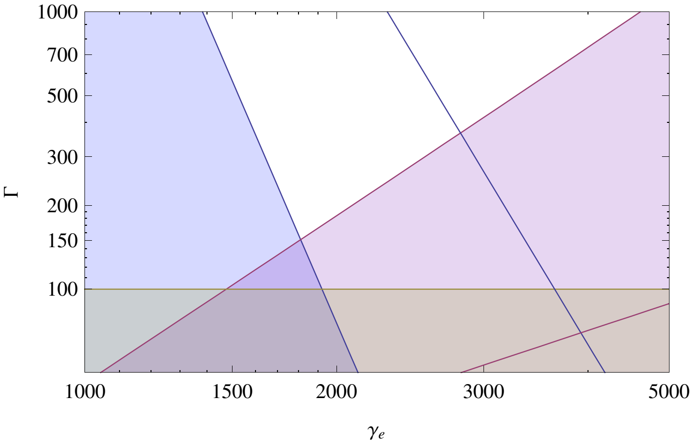

Figure 3: Allowed region for the *IR solution* in the (Γ, γ_e) parameter space. The limit on the left (decreasing curve) corresponds to the condition $F_{sa} \geq F_L$. The limit on the right (increasing curve) corresponds to $Y_H = 1$. Also marked is $\Gamma = 100$, which is considered as a minimal value for the bulk Lorentz factor to resolve the compactness problem. The limits are shown for $\alpha = -2$. (On the right side around $\gamma_e = 4000$ shown are the corresponding curves for $\alpha = -1.$). The γ_e range from 1000 to 5000 corresponds to $\nu_L = 1.2 \cdot 10^{14}$Hz to $\nu_L = 4.8 \cdot 10^{12}$Hz. Parameters used in this figure are: $F_\gamma/F_{opt} = 0.01$, $\nu_{opt} = 8 \cdot 10^{14}$Hz and $h\nu_\gamma = 500$keV. For $\alpha = -2$ an extremely small region around $\gamma_e \approx 1800$ (corresponding to $\nu_L = 3.7 \cdot 10^{13}$Hz) and $\Gamma \approx 120$ is allowed.

3 GRB080319B

GRB080319B [14] was most notable due to its huge total energy and its extremely strong prompt optical emission that could have been seen with naked eyes. This burst was located at redshift $z = 0.937$. Its duration T_{90} was $\sim$ 57s. The peak flux is $F_p \sim 2.26 \pm 0.21 \times 10^{-5}\mathrm{erg\,cm^{-2}s^{-1}}$ at peak energy of the νF_ν spectrum $E_p \simeq 675\pm22$keV(i.e., $\nu_p \sim 1.6 \times 10^{20}$Hz, and consequently $f_{\nu,p} \sim 2.7 \times 10^{-25}\mathrm{erg\,cm^{-2}Hz^{-1}s^{-1}}$), and the photon indexes lower and higher than the E_p are $-0.855^{+0.014}_{-0.013}$ and $-3.59^{+0.32}_{-0.62}$ respectively [14]. Choosing standard cosmological parameters $H_0 = 70\mathrm{km\,s^{-1}\,Mpc^{-1}}, \Omega_m = 0.3, \Omega_\lambda = 0.7$, we have a peak luminosity $L_p \sim 9.7 \times 10^{52}\mathrm{erg}\,s^{-1}$ and an isotropic energy $E_{\gamma,\mathrm{iso}} \simeq 1.3 \times 10^{54}$ erg.

GRB 080319B was different from most other bursts (but similar in many ways to GRB990123, whose optical emission was slightly weaker) because of its enormous optical luminosity. The extremely bright optical flash that accompanied GRB 080319B suggested, at first glance, that the prompt γ-rays in this burst were produced by SSC. In fact the arguments presented above (that depend on F_γ/F_{opt}) cannot be used to constrain directly the IC process. However, a detailed analysis [19] reveals that the very strong optical emission poses, due to self absorption, very strong constraints and puts the origin of the optical emission at a very large radius, almost inconsistent with internal shock. Alternatively it requires a very large random Lorentz factor for the electrons. Both are inconsistent with the conditions needed for the γ-rays being IC of this optical emission. In fact the optical emission and the γ rays could not even have been produced by synchrotron emission from two populations of electron within the same emitting region. Thus we must conclude that the optical and the γ-rays were produced in different physical regions. A possible interpretation of the observations is that the γ-rays arose from internal shocks but the optical flash resulted from external reverse shock emission. This would have been consistent with the few seconds delay observed between the optical and γ-rays signals. Naturally the analysis of this burst is more specific and not as generic as the earlier discussion.

The very strong optical flash that accompanied GRB 080319B poses the strongest constraints on the emission mechanism. A lot can be learnt from studying this flash on its own. The observed optical signal, $F_{\nu,\mathrm{opt}}$, must be less or equal than the corresponding black body emission:

$$F_{\nu,\mathrm{opt}} \leq F_{BB} = 2\pi(1+z)^3\nu_{\mathrm{opt}}^2\Gamma\gamma_e m_e\left(\frac{R}{\Gamma d_L}\right)^2 = 1.1\times10^{-24}\left(\frac{\gamma_e}{100}\right)\left(\frac{R}{10^{15}\mathrm{cm}}\right)^2\left(\frac{\Gamma}{1000}\right)^{-1}, \tag{9}$$

where R is the emission radius and d_L is the luminosity distance. This value should be compared with the observed optical flux $F_{\nu,\mathrm{opt}} \sim 2.9 \times 10^{-22}\mathrm{erg\,cm^{-2}\,Hz^{-1}\,s^{-1}}$ which is more than two orders of magnitude larger than the one found for F_{BB} with "typical" values. This is the essence of the problem of finding a reasonable solution for the emission mechanism in GRB080319B. By itself this constraint imposes a rather large γ_e for reasonable values of R and Γ, or alternatively a very large value of R.

The black body limit Eq. (9) can be compared now with two expression that link R and Γ: The angular time scale $\delta t > R/2\Gamma^2 c$, and the deceleration radius: $R < R_\gamma = (3E/4\pi n\Gamma^2 m_p c^2)^{1/3}$, (for uniform ISM), where E is the energy of the outflow and n is the ISM density. This comparison shows that while the Black Body limit pushes the emitting radius to large values, the two others limit R to small values. The allowed region is rather small and the radii are typically large and they won't be consistent with those needed for emitting the γ-rays. Note that the allowed region shrinks to zero if we take $\delta t \leq 0.1$sec as implied from the γ-ray observations.

To examine the SSC model we use the four observables, $F_{\nu,\gamma}$, $F_{\nu,\mathrm{opt}}$,ν_γ, ν_{opt} to determine the conditions N_e, B, Γ, γ_e and R in the emitting region [19]. The overall spectral distribution is shown in Fig. 3. As there are five variables and four equations we need to have one free parameter, which we conveniently choose to by the Compton parameter Y. Once we solve for these parameters we plug the results into the black body equation Eq. (9 and find[19]:

$$F_{\nu,opt} = 500 F_{BB} Y^{-1.75} \frac{\Gamma}{1000}. \tag{10}$$

For reasonable values of Γ and for Y less than unity, the observed optical flux is larger than the black body limit. This is the essence of the optical self-absorption problem that forbids any low Y SSC solution for GRB 080319B. A large Y will lead to an energy crisis where most of the energy of this (already very powerful) burst would have been emitted in the GeV regime leading to a huge overall energy requirement.

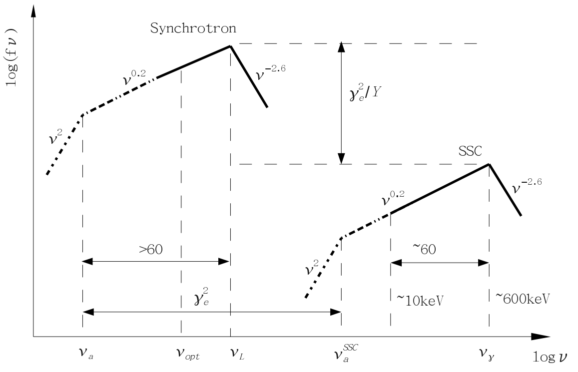

Figure 4: A schematic description of the spectrum in an SSC model. Note that if $10\text{keV}/\gamma_e^2 > \nu_{opt}$, that is if γ_e is small enough, ν_{opt} might be below ν_a.

4 Conclusions

For a typical GRB, IC has to amplify the total energy of a low energy seed photon flux by a factor of $\approx$ 1000 to produce the observed prompt gamma-ray flux. The same relativistic electrons will, however, continue and upscatter the gamma-ray flux to very high energies in the TeV range. In many cases this second generation IC will be in the Klein-Nishiha regime (that is the photon's energy will be larger than the electrons rest mass, in the electron's rest frame). This will suppress somewhat the efficiency of conversion of γ-rays to very high energy gamma-rays, however it won't stop it altogether. Our analysis focused on the case that the low energy seed photons are produced within the moving region that includes the IC scattering relativistic electrons. Such will be the case, for example, in SSC. The analysis is also limited to the important implicit assumption that the emitting region is homogenous. It is possible that very strong inhomogeneities could change this picture.

Under quite general conservative assumptions, if IC produces the prompt sub-MeV photons, then a second scattering will over produce a very high (GeV-TeV) prompt component that will carry significantly more energy than the prompt gamma-rays themselves. On the theoretical front such a component will cause an "energy crisis" for most current progenitor models. From an observational point of view, this component is possibly already ruled out by EGRET upper limits[26,27]. Fermi should have seen such strong emission had it existed. For example, a burst with a "modest" isotropic energy $E_{\gamma,iso} = 10^{53}$erg, locating at $z = 1$, should produce $\sim 10 Y_H (E_H/10\text{GeV})$ photons detected by Fermi.

It turns out that even for GRB080319B, the naked eye burst, that motivated this study, the observed fluxes are inconsistent with a simple SSC model. In fact one can even show that it is unlikely that the prompt γ-rays and the optical have been emitted from the same emitting region. Such a conclusion was reached, based on much less detailed data for GRB990123 as well.

Acknowledgments

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