

## EXPLAINING THE HIGH-ENERGY SPECTRAL COMPONENT IN GRB 941017

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### ABSTRACT

The gamma-ray burst (GRB) of 1994 October 17 (GRB 941017) showed a distinct high-energy spectral component extending from  $\lesssim$ a few to  $\gtrsim$ 200 MeV, in addition to the typical GRB emission, which peaked at  $\lesssim$ a few hundred keV. The high-energy component carried at least  $\sim$ 3 times more energy than the lower energy component. It displayed an almost constant flux with a rather hard spectrum ( $F_\nu \propto \nu^{-\alpha}$  with  $\alpha \sim 0$ ) from  $\lesssim$ 20 s into the burst up to  $\sim$ 200 s, while the duration of the GRB, where 90% of the energy in the lower energy component was emitted, was only 77 s. Such a high-energy component was seen in only one out of  $\sim$ 30 GRBs in which a similar component could have been detected and thus appears to be quite rare. We examine possible explanations for this high-energy spectral component and find that most models fail. The only emission region that provides the right temporal behavior is the reverse shock that goes into the GRB ejecta as it is decelerated by the ambient medium, or possibly the very early forward shock while the reverse shock is still going on. The best candidate for the emission mechanism is synchrotron self-Compton emission from the reverse shock. Even in this model the most natural spectral slope is only marginally consistent with the observed value, and some degree of fine-tuning is required in order to improve the agreement. This might suggest that an additional or alternative emission mechanism is at work here. A prediction of this interpretation is that such a high-energy component should be accompanied by a bright optical transient, similar to the one observed in GRB 990123.

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

### 1. INTRODUCTION

The spectrum of the prompt emission in gamma-ray bursts (GRBs) is usually well described by the empirical Band function (Band et al. 1993), which features two power laws that join smoothly near the typical photon energy  $E_{\text{peak}}$ , where  $\nu F_\nu$  peaks. In the vast majority of cases,  $E_{\text{peak}}$  ranges between a few tens of keV and a few MeV. This familiar and well-studied spectral component is most likely from synchrotron radiation of relativistic electrons in a strong magnetic field, as is suggested by the recent measurement of a very high degree of linear polarization in the prompt  $\gamma$ -ray emission of GRB 021206 (Coburn & Boggs 2003).

The highly variable light curve of most GRBs suggests that they originate from internal shocks (Rees & Mészáros 1994; Sari & Piran 1997) within a variable relativistic outflow from a compact source. When the ejecta sweeps up enough external medium, it is decelerated by a reverse shock that propagates back into the ejecta, while a strong relativistic forward shock is driven into the ambient medium. The forward shock is believed to produce the afterglow emission observed in the X-ray, optical, and radio over a timescale of days, weeks, and months, respectively, after the GRB (for a review see van Paradijs, Kouveliotou, & Wijers 2000). The reverse shock produces a much shorter lived emission that rapidly decays after the shock finishes crossing the shell of ejecta, which typically occurs on a timescale similar to the duration of the GRB,  $T_{\text{GRB}}$ . The synchrotron emission from the reverse shock is expected to peak around the near UV or optical (Sari & Piran 1999b). A very bright optical transient, that reached ninth magnitude in the optical, was observed during the prompt  $\gamma$ -ray emission of GRB 990123 (Akerlof et al. 1999) and was suc-

cessfully interpreted as emission from the reverse shock (Sari & Piran 1999a; Mészáros & Rees 1999). Similar optical observations within the first  $\sim$ 100 s in other GRBs produced only upper limits of  $\sim$ 13–15 mag (Kehoe et al. 2001).

In a recent paper, González et al. (2003, hereafter G03) presented new data for GRB 941017 that show clear evidence for a distinct high-energy spectral component, in addition to the usual lower energy spectral component. The latter is well fitted by a Band function with  $E_{\text{peak}}$  decreasing from  $\sim$ 500 keV to a few tens of keV during the GRB and is similar to other GRBs, suggesting a common origin; it emitted 90% of its energy over a time  $T_{\text{GRB}} = 77$  s. The high-energy component appears  $\sim$ 10–20 s after the start of the GRB<sup>4</sup> and displays a roughly constant flux with a relatively hard spectral slope ( $F_\nu \propto \nu^{-\alpha}$  with  $\alpha \sim 0$ ) up to  $\sim$ 200 s. The very different temporal behavior of the two components may suggest a different physical origin.

Such a bright high-energy component appears to be quite rare in GRBs. EGRET observations of greater than 100 MeV photons from four other GRBs, as well as 25 other GRBs that were bright at 300 keV and were also detected by the Total Absorption Shower Counter, showed a high-energy emission that is consistent with the single spectral component observed by BATSE (G03). Therefore, any model that tries to explain the high-energy component in GRB 941017 should be able to explain at the same time why a similar component is not seen in most GRBs.

In this Letter, we analyze relevant physical mechanisms that might produce such a high-energy spectral component and examine their ability to explain this observation. The possible explanations are presented according to the relevant emission region, namely, either the internal shocks (§ 2) or the external shock (§ 3), which includes the reverse shock and the early emission from the forward shock. Different emission mecha-

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<sup>4</sup> There is a hint in the data of G03 that it may also be present from the very start.

nisms are considered for each region. Our conclusions are discussed in § 4.

## 2. INTERNAL SHOCKS

An important difficulty that arises when trying to explain the high-energy component as emission from the internal shocks is that in this case it is attributed to the same shocks that emit the lower energy component, and it is therefore expected to show a similar temporal behavior. However, in GRB 941017 the high-energy component is almost constant in time from  $\lesssim 20$  to  $\sim 200$  s, while the lower energy component decays on a shorter timescale, with  $T_{\text{GRB}} = 77$  s (G03). This poses a serious problem to most of the emission mechanisms mentioned below.

Let us first examine synchrotron self-Compton (SSC) emission, i.e., the inverse Compton (IC) upscattering of synchrotron photons by the same electrons that emit the synchrotron radiation (the latter is identified here with the lower energy spectral component). The SSC spectrum is similar to the synchrotron spectrum, with the peak of  $\nu F_\nu$  at a frequency and a flux higher by a factor of  $\sim \gamma_e^2 \sim 10^5$  and  $Y$ , respectively, where  $Y$  is the Compton  $y$ -parameter. While this might reasonably account for the spectral slope of the high-energy component, the peak energy is around  $\sim 10$ – $100$  GeV, implying  $Y \gtrsim 10^3$ , and  $\sim 3$  orders of magnitude more energy in the high-energy component, compared to the lower energy component, which is among the brightest BATSE bursts.<sup>5</sup> In addition to this,  $Y \sim (\epsilon_e/\epsilon_B)^{1/2}$  for  $Y \gg 1$ , where  $\epsilon_e$  ( $\epsilon_B$ ) is the fraction of the internal energy behind the shock in the relativistic electrons (magnetic field). Therefore,  $Y \gtrsim 10^3$  implies  $\epsilon_B \lesssim 10^{-6} \epsilon_e \sim 10^{-7}$  to  $10^{-6}$ , which is an extremely low value both compared to the values expected from the magnetic field advected with the ejecta from the central source (Spruit, Daigne, & Drenkhahn 2001) and compared to the magnetic field expected to be produced at the internal shocks themselves (Medvedev & Loeb 1999). Together with the difficulty mentioned above in explaining the different temporal behavior of the two spectral components, we find that this explanation can be ruled out.

Another emission mechanism, which was favored by G03, is a hadronic cascade, initiated by protons that are accelerated in the internal shocks up to  $\sim 10^{20}$  eV and make photomeson interactions with the synchrotron photons, producing pions that decay into high-energy photons. The latter pair produce with lower energy photons creating a cascade. The duration of the emission from this cascade is similar to that of the lower energy component ( $T_{\text{GRB}}$ ), since adiabatic cooling becomes significant on the timescale of a single pulse, that is typically  $\ll T_{\text{GRB}}$ . Also, the spectral slope is too soft,  $\alpha \approx 1$  (Begelman, Rudak, & Sikora 1990; A. Peer & E. Waxman 2003, in preparation). Therefore, this option does not work well.

In order to explain the longer duration of the high-energy spectral component, one can turn to models where additional interactions occur outside of the internal shocks region, on the way to the observer, causing a delay in the arrival time of the high-energy photons. One example for such a model features interactions of high-energy photons emitted in the internal shocks with the cosmic IR background, producing  $e^\pm$  pairs that upscatter cosmic microwave background (CMB) photons (Dai & Lu 2002; Guetta & Granot 2003a). However, the expected duration of this emission is  $\gtrsim 10^3$  s, and the (time integrated)

<sup>5</sup> If this burst was very close, i.e., at a redshift  $z \ll 1$  instead of the typical  $z \sim 1$  for most GRBs, then the total energy that is required could be lowered. However, GRBs at  $z \ll 1$  are rare owing to the smaller available volume, and a very large Compton parameter,  $Y \gtrsim 10^3$ , would still be required.

spectral slope is too soft,  $F_\nu \propto \nu^{-\alpha}$  with  $\alpha = (p+2)/4 \approx 1$ – $1.25$ , where  $p \sim 2$ – $3$  is the electron power-law index. Another mechanism that produces delayed high-energy emission is the interaction of ultra-high-energy cosmic rays that are accelerated in the internal shocks with CMB photons, which produces by cascading GeV–TeV photons (Waxman & Coppi 1996). However, the typical timescale for this emission is hours to days, and the spectral slope is again too soft,  $\alpha \approx 0.8$ . Therefore, these two mechanisms do not provide a good explanation for the high-energy component in GRB 941017.

## 3. REVERSE SHOCK AND EARLY FORWARD SHOCK

Since the reverse shock is a physically distinct region from the internal shocks that emit the lower energy component in GRB 941017, the different temporal behavior of the two components arises naturally in this scenario.<sup>6</sup> The relevant parameters that determine the interaction of the shell of ejecta with the ambient medium are its (isotropic equivalent) energy  $E$ , initial Lorentz factor  $\eta$ , initial width  $\Delta_0$ , and the external mass density profile, which for simplicity is assumed to be a power law with the radius  $R$ ,  $\rho_{\text{ext}} = AR^{-k}$ . The most physically interesting external density profiles are  $k = 0$  and  $k = 2$ , which correspond to a constant density medium (like the interstellar medium [ISM]) and a stellar wind of a massive star progenitor, respectively. The behavior of the system divides into two limits according to the value of  $\xi \sim E/Ac^2\Delta_0^{3-k}\eta^{2(4-k)}$ .<sup>7</sup> For  $\xi > 1$ , or the “thin-shell” case, the emission from the reverse shock peaks after the end of the prompt GRB, and there is a temporal separation between the two (Sari 1997). For  $\xi < 1$ , or the “thick-shell” case, there is an overlap between the reverse shock emission and the prompt GRB. Since in GRB 941017 there is a significant temporal overlap between the two spectral components, a thick shell is clearly the relevant case here.

For a thick shell, the reverse shock is relativistic, either from the very start for  $k = 2$  or from  $t_N$  for  $k < 2$ , where  $t_N \approx 10\zeta^{3/2}E_{54}^{1/2}n_0^{-1/2}\eta_{2.5}^{-4}T_{80}^{-1/2}$  s for  $k = 0$ , where  $\zeta = (1+z)/2$ ,  $n = n_0$  cm $^{-3}$  is the external density, and  $T_{\text{GRB}} = (1+z)\Delta_0/c = 80T_{80}$  s. Unless specified otherwise,  $Q_x = Q/(10^x \times \text{the cgs units of } Q)$ . The reverse shock finishes crossing the shell at  $t_E \sim 2T_{\text{GRB}} = 160T_{80}$  s. After  $t_E$ , no new electrons are accelerated and the hot electrons quickly cool, both adiabatically and radiatively, so that the observed emission decays rapidly. This provides roughly the right timescale for the high-energy component in GRB 941017.

There are two emitting regions: the shocked ejecta behind the reverse shock and the shocked external medium behind the forward shock. This implies four IC components (Wang, Dai, & Lu 2001b), where the scattering electrons and seed synchrotron photons can be from either of these two regions. The SSC emission from the forward shock peaks at  $\sim$ TeV energies and is thus not relevant here.<sup>8</sup> The external Compton (EC) processes, where the seed photons are emitted in the reverse

<sup>6</sup> A more detailed analysis of the high-energy emission from the reverse shock and early forward shock is left for a different work, while here we briefly mention features that are relevant for GRB 941017.

<sup>7</sup> This parameter is a power of the usual parameter  $\xi = \xi^{1/(2-k)(3-k)}$  (Sari & Piran 1995) and is more convenient to work with, as it is well behaved at  $k = 2$ , which is of physical interest.

<sup>8</sup> This component, in the thin-shell case, was suggested by Mészáros & Rees (1994) as a possible explanation for the higher energy emission ( $\sim 1$ – $10$  GeV) that was detected by the EGRET spark chamber in a few GRBs (Hurley et al. 1994) over longer timescales (up to  $\sim 1.5$  hr for GRB 940217). For a thick shell, this component peaks at very high energies ( $\gamma_m^2 h\nu_m \sim$  TeV) at  $t < t_E$ , while at  $t > t_E$  it decays with time as  $\gamma_m^2 h\nu_m \propto t^{-(18-5k)/2(4-k)}$  and  $(\nu F_\nu)_{\text{max}} \propto t^{-1}$ , making it difficult to explain bright high-energy emission at  $t \gg T_{\text{GRB}}$ .

shock and the scattering electrons are in the forward shock, or vice versa, have a typical photon energy  $\sim 10\text{--}100$  GeV that implies a total energy  $\sim 10^2\text{--}10^3$  times higher than that in the observed energy range. Nevertheless, they may still be viable options for somewhat less typical parameters. For concreteness, we concentrate on the best candidate—SSC emission from the reverse shock, that naturally peaks at a few hundred MeV (Wang, Dai, & Lu 2001a), so that the total energy is comparable to that in the observed range.

For an external density typical of the ISM ( $n_0 \sim 1$ ), the reverse shock is in the slow cooling (SC) regime, while for a stellar wind with  $A = 5 \times 10^{11} A_* \text{ g cm}^{-1}$  there is fast cooling (FC; e.g., Chevalier & Li 2000). For simplicity, we neglect synchrotron self-absorption, and the effects of Klein-Nishina and opacity to pair production, which are typically not important in the observed energy range for GRB 941017. The SSC spectrum in the two cooling regimes is given to the lowest order approximation by the following broken power-law form:

$$\frac{\nu F_\nu^{\text{IC}}(\text{SC})}{Y(\nu F_\nu)^{\text{syn}}_{\text{max}}} = \begin{cases} (\nu_m^{\text{IC}}/\nu_c^{\text{IC}})^{(3-p)/2} (\nu/\nu_m^{\text{IC}})^{4/3}, & \nu < \nu_m^{\text{IC}}, \\ (\nu/\nu_c^{\text{IC}})^{(3-p)/2}, & \nu_m^{\text{IC}} < \nu < \nu_c^{\text{IC}}, \\ (\nu/\nu_c^{\text{IC}})^{(2-p)/2}, & \nu > \nu_c^{\text{IC}}, \end{cases} \quad (1)$$

$$\frac{\nu F_\nu^{\text{IC}}(\text{FC})}{Y(\nu F_\nu)^{\text{syn}}_{\text{max}}} = \begin{cases} (\nu_c^{\text{IC}}/\nu_m^{\text{IC}})^{1/2} (\nu/\nu_c^{\text{IC}})^{4/3}, & \nu < \nu_c^{\text{IC}}, \\ (\nu/\nu_m^{\text{IC}})^{1/2}, & \nu_c^{\text{IC}} < \nu < \nu_m^{\text{IC}}, \\ (\nu/\nu_m^{\text{IC}})^{(2-p)/2}, & \nu > \nu_m^{\text{IC}}, \end{cases} \quad (2)$$

$$(\nu F_\nu)^{\text{syn}}_{\text{max}} = \frac{10^{-6} f_*}{(1+Y)} \zeta a g \epsilon_{e,0.3} E_{54} T_{80}^{-1} d_{L28}^{-2} \text{ ergs cm}^{-2} \text{ s}^{-1}, \quad (3)$$

where  $f_* \approx 0.4\text{--}0.8$  for  $0 \leq k \leq 2$ ,  $d_L$  is the luminosity distance to the GRB,  $g = 3(p-2)/(p-1)$ ,  $a = \min[1, (\gamma_m/\gamma_c)^{p-2}]$ , and  $\epsilon_{e,0.3} = \epsilon_e/0.3$ . In order to minimize the total required energy, we would like  $Y(\nu F_\nu^{\text{IC}})^{\text{syn}}_{\text{max}}$  to be close to the maximal observed value of  $\nu F_\nu$  for the high-energy component, i.e.,  $\sim 3 \times 10^{-6} \text{ ergs cm}^{-2} \text{ s}^{-1}$ . Together with the roughly constant flux, and assuming  $Y \geq 1$ , this requires a peak frequency,  $\max(\nu_m^{\text{IC}}, \nu_c^{\text{IC}}) \sim$  a few hundred MeV, and roughly constant in time. Since  $\nu_m^{\text{IC}} \propto t^{2(1-k)/(4-k)}$  and  $\nu_c^{\text{IC}} \propto t^{6(k-1)/(4-k)}$ , both frequencies are constant in time for  $k = 1$ , for which

$$h\nu_m^{\text{IC}} = 160 \zeta^{-3/2} g^4 \epsilon_{B,-2}^{1/2} \epsilon_{e,0.5}^4 E_{54}^{-1/2} T_{80}^{1/2} A_{-5} \eta_3^4 \text{ MeV}, \quad (4)$$

$$h\nu_c^{\text{IC}} = 0.02 \zeta^{-3/2} \epsilon_{B,-2}^{-3/2} \epsilon_{e,0.5}^{-2} E_{54}^{-1/2} T_{80}^{1/2} A_{-5}^{-3} \text{ eV}. \quad (5)$$

However, if the lower energy component is attributed to synchrotron emission from the internal shocks, then

$$E_{\text{peak}} = h\nu_m^{\text{syn}} = 1.2 \zeta^{-1/2} g^2 \epsilon_{B,-2}^{1/2} \epsilon_{e,0.5}^2 E_{54}^{1/2} T_{80}^{-1/2} \eta_3^{-2} t_{v,-3}^{-1} \text{ keV}, \quad (6)$$

where  $t_v$  is the variability time of the source. The finite size  $l_s$  of the central source implies  $t_v \geq 10^{-4} (l_s/30 \text{ km}) \text{ s}$ , so that  $t_{v,-3} \geq 0.1$  for a reasonable source size. Since the reverse shock and the internal shocks propagate into the same ejecta, it is reasonable to expect similar values of  $\epsilon_B$  and  $\epsilon_e$ . For  $E = 10^{54.5} \text{ ergs}$ ,  $\eta = 500$ ,  $t_v = 10^{-4} \text{ s}$ ,  $A = 10^{-3.5} \text{ g cm}^{-2}$ , and the other parameters at their fiducial values, we obtain  $E_{\text{peak}} \sim 100 \text{ keV}$ ,  $h\nu_m^{\text{IC}} \sim 200 \text{ MeV}$ , and  $\nu_m^{\text{IC}} F_{\nu_m^{\text{IC}}} \sim 2 \times 10^{-6} \text{ ergs cm}^{-2}$

$\text{s}^{-1}$ . Therefore, reasonable parameters<sup>9</sup> can yield a reasonable fit to the data, with one major drawback: the spectral slope is  $\alpha = \frac{1}{2}$ , which is only marginally consistent with the observed value of  $\alpha \sim 0$ . In order not to see the synchrotron emission from the forward shock at  $t \leq 200 \text{ s}$ , we need  $Y \geq 100$  in the forward shock, or  $\epsilon_B \leq 10^{-4}$ .<sup>10</sup>

It is possible to bring the spectral slope closer to  $\alpha \sim 0$  if  $h\nu_c^{\text{IC}} \sim 1 \text{ MeV}$ , since then  $\alpha$  would gradually change from  $-\frac{1}{3}$  to  $\frac{1}{2}$  (e.g., Sari & Esin 2001) and could pass for a power law with  $\alpha \sim 0$  in the relatively narrow range from a few to  $\leq 200 \text{ MeV}$ . However,  $h\nu_c^{\text{IC}} \sim 1 \text{ MeV}$  requires  $\epsilon_B \leq 10^{-4}$  and  $A \leq 10^{-6} \text{ g cm}^{-2}$ , which in turn requires  $\eta \sim 10^{3.5}$  in order to keep  $h\nu_m^{\text{IC}} \sim 200 \text{ MeV}$ . This would imply a very low  $E_{\text{peak}}$  for the internal shocks, if it is identified with  $h\nu_m^{\text{syn}}$ . This problem can be solved if for this GRB, unlike most GRBs, the prompt GRB emission is SSC emission from the internal shocks, rather than synchrotron emission (Panaitescu & Mészáros 2000). This picture works, but with somewhat extreme parameters. For example, with  $A = 10^{-6.5} \text{ g cm}^{-2}$ ,  $\eta = 10^{3.5}$ ,  $g = 1.5$ , and  $t_v = 10^{-1.5} \text{ s}$ , we obtain  $h\nu_m^{\text{IC}} \approx 250 \text{ MeV}$ ,  $h\nu_c^{\text{IC}} \approx 1 \text{ MeV}$ , and  $E_{\text{peak}}^{\text{SSC}} \approx 200 \text{ keV}$ . The fact that extreme parameters are required can explain why such a high-energy component is relatively rare in GRBs.

GRB 941017 was exceptionally bright with a fluence of  $f = 1.6 \times 10^{-4} \text{ ergs cm}^{-2}$  (Preece et al. 2000), comparable to the famous GRB 990123 with  $f = 2.7 \times 10^{-4} \text{ ergs cm}^{-2}$ ,  $z = 1.6$ , and an isotropic equivalent energy output in  $\gamma$ -rays of  $1.4 \times 10^{54} \text{ ergs}$  (Kulkarni et al. 1999). For a reasonable radiative efficiency ( $\sim 20\%$ ) and  $z \sim 1$ , this implies<sup>11</sup>  $E \sim 10^{54}\text{--}10^{55} \text{ ergs}$  for GRB 941017, in agreement with the values used above. This interpretation implies a bright prompt optical emission, similar to the ‘‘optical flash’’ in GRB 990123, for GRBs like 941017 with a bright high-energy spectral component.<sup>12</sup> If the prompt GRB is due to SSC emission from the internal shocks, then the synchrotron component should peak near the optical and produce bright optical emission with the same temporal behavior as the prompt GRB.

An alternative explanation mentioned by G03 arises in the supranova model, where the GRB is expected to occur inside a pulsar wind bubble (PWB; Königl & Granot 2002). The PWB photons can be upscattered by the electrons behind the reverse and forward shocks, producing high-energy EC emission (Inoue, Guetta, & Pacini 2003; Guetta & Granot 2003b). However, the flux level and the temporal behavior of the EC component are not consistent with the data.

Another emission process that was considered by G03 is the hadronic cascade. Protons may be accelerated in the reverse shock up to  $\sim 10^{20} \text{ eV}$  and can carry an energy comparable to

<sup>9</sup> This value of  $A$  implies  $n \sim 200 \text{ cm}^{-3}$  at  $R \sim 10^{18} \text{ cm}$ , which is a bit high. However, for these parameters the reverse shock finishes crossing the shell at  $R = 2.8 \times 10^{16} \text{ cm}$ , so that if  $k \approx 1$  only at small radii  $\leq (0.3\text{--}1) \times 10^{17} \text{ cm}$ , and  $k \approx 2$  at larger radii, then we can have  $n \sim 6\text{--}20 \text{ cm}^{-3}$  at  $R \sim 10^{18} \text{ cm}$ , which is more reasonable. Such a variation in  $k$  with radius might possibly result from a variation in the mass-loss rate or wind velocity of the massive star progenitor toward the end of its life.

<sup>10</sup> This is not so extreme, as the external medium typically has a weak magnetic field, and there is also evidence from a recent GRB (021211) suggesting that  $\epsilon_B$  is smaller in the forward shock compared to the reverse shock (Kumar & Panaitescu 2003).

<sup>11</sup> In this picture, GRB 941017 was likely collimated into a very narrow jet, just like GRB 990123, so that the true kinetic energy in the ejecta shell is probably  $\sim 2\text{--}3$  orders of magnitude lower than the isotropic equivalent value, i.e.,  $\leq 10^{52} \text{ ergs}$ , similar to or slightly lower than the value estimated for GRB 990123.

<sup>12</sup> In GRB 990123, the optical flash emission reached  $\sim 1 \text{ Jy}$  (or ninth magnitude; Akerlof et al. 1999), while for GRB 941017 we estimate the the prompt optical emission to be  $\sim 5 \text{ Jy}$  (or  $\sim$ seventh magnitude).

the that in  $\gamma$ -rays. Most of this energy may be converted into pions, through photomeson interactions, if the shell is significantly decelerated as happens for “thick” shells. The pions decay into high-energy photons, which pair produce with lower energy photons, thus generating a cascade. However, as in the case of the internal shocks, the spectral slope is too soft,  $\alpha \approx 1$  (Begelman et al. 1990; A. Peer & E. Waxman 2003, in preparation).

#### 4. DISCUSSION

We have analyzed different possible explanations for the high-energy spectral component detected in GRB 941017 and find that it is hard to explain. Most models fail quite badly. The only reasonable explanation we could find is emission from the reverse shock or possibly from the very early forward shock. In this picture, the high-energy component is emitted at a different physical region than the lower energy component (i.e., the prompt GRB that is emitted in the internal shocks). This naturally explains the different temporal behavior of the two components. The long duration of the GRB suggests that we are in the thick-shell case, which also accounts for the temporal overlap between the two components and provides the right timescale for the duration of the high-energy component. Therefore, we are relatively confident that the high-energy component is emitted from the reverse shock (or possibly from the very early forward shock, while the reverse shock is still going on).

The most promising emission mechanism is SSC emission from the reverse shock. The spectral slope in this picture is most naturally  $F_\nu \propto \nu^{-\alpha}$  with  $\alpha = \frac{1}{2}$ , which is only marginally consistent with the observed value of  $\alpha \sim 0$ . This might suggest that an alternative or additional emission mechanism is involved here. Nevertheless,  $\alpha \approx 0$  can be obtained for pure SSC emission from the reverse shock with somewhat extreme pa-

rameters, for which the prompt GRB is attributed to SSC emission from the internal shocks, rather than synchrotron emission, which is usually responsible for the prompt GRB. This might explain why such a high-energy component appears to be rare among GRBs.

In this picture, GRBs with a similarly bright high-energy component should be accompanied by a bright optical flash, as bright or even brighter than in GRB 990123. The fact that most GRBs are not accompanied by optical flashes of such brightness (Kehoe et al. 2001) is nicely consistent with such a bright high-energy component being similarly rare.<sup>13</sup>

Future missions, such as the *Gamma-Ray Large Area Space Telescope (GLAST)*,<sup>14</sup> will have a better sensitivity and a wider energy range (up to 300 GeV for *GLAST*) and should provide a much clearer picture as to how common such high-energy spectral components are in GRBs. The wider energy range may cover the peak of  $\nu F_\nu$  and thus tell us how much energy is in the high-energy component. A more accurate measurement of the spectrum and the temporal behavior would help constrain the different models and pinpoint the source of the high-energy emission.

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<sup>13</sup> A bright optical flash from the reverse shock should generally be accompanied by a bright high-energy component. However, the values of the peak flux and peak energy can vary considerably between different GRBs and are not related to the optical emission in a very simple way. Therefore, the lack of detection of a similar high-energy component in GRB 990123 (e.g., Briggs et al. 1999) is perfectly consistent with this picture.

<sup>14</sup> See <http://glast.gsfc.nasa.gov>.

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