Possible physical explanation of the intrinsic $E_{p,i}$ –"intensity" correlation commonly used to "standardize" GRBs

F. Frontera[1,2*], L. Amati[2], R. Farinelli[1], S. Dichiara[1], C. Guidorzi[1], R. Landi[2] and L. Titarchuk[1]

[1] *Physics and Earth Sciences Department, University of Ferrara*
[2] *INAF, IASF Bologna, Italy*
[*] *E-mail: frontera@fe.infn.it*

It is recognized that very likely the correlation between peak energy E_p and bolometric intensity is intrinsic to GRBs. However its physical origin is still debated. In this paper we will discuss a possible interpretation of the correlation in the light of a GRB prompt emission spectral model, GRBCOMP, proposed by Titarchuk et al. (2012). GRBCOMP is essentially a photospheric model for the prompt emission of GRBs. Its main ingredients are a thermal bath of soft seed photons and a subrelativistically expanding outflow plasma, consequence of the star explosion. The emerging spectrum is the result of two phases: first, up to the photospheric radius, Comptonization of a subrelativistic electron outflow with thermal bath of soft photons, then, convolution of the Comptonized photons in the first phase with a Green function. The result of this convolution is consistent with different physical processes, in particular Inverse Compton. GRBCOMP has been successfully tested using a significant sample of GRB time resolved spectra in the broad energy band from 2 keV to 2 MeV (Frontera et al. (2013)).

Keywords: GRBs; Prompt emission model; interpretation of the Ep-Eiso correlation.

1. Introduction

In spite of the huge advances in the knowledge of the GRB afterglow properties mainly with *Swift*, the GRB phenomenon is still poorly understood. It is recognized to be of crucial importance the study of the prompt emission, which is more directly connected with the original explosion. One of the still open issues is the radiation emission mechanism at work. This mechanism should give, among others, the interpretation of the correlation between the intrinsic peak energy $E_{p,i}$ of the $EF(E)$ function and either the GRB released energy E_{iso} [1] or the peak bolometric luminosity $L_{p,iso}$ [2]. Both correlations (the Amati correlation is shown in Fig. 1) have been derived from the time integrated spectra assuming isotropic emission.

Actually, the Amati relation ($E_{p,i} = aE_{iso}^m$, with $a = 98 \pm 7$ keV when E_{iso} is given in units of 10^{52} erg, and $m = 0.54 \pm 0.03$, Ref. 4) has been questioned by various authors [5–8], but it is a matter of fact that this relation is confirmed by all GRBs (more than 300) with known redshift z and determined $E_{p,i}$ discovered thus far, except GRB 980425 (but see Refs. 9,10), the nearest and less energetic event ever observed ($z = 0.0085$). But the most striking result is the very significant correlation between $E_{p,i}$ and L_{iso} found in time-resolved spectra of single GRBs [11–15]. Sawant et al.(2016, in preparation), analysing the time resolved spectra of a very large sample of GRBs, find similar results. Thus very likely this relation is intrinsic to the GRB phenomenon, and it is important to give a physical interpretation of the relation.

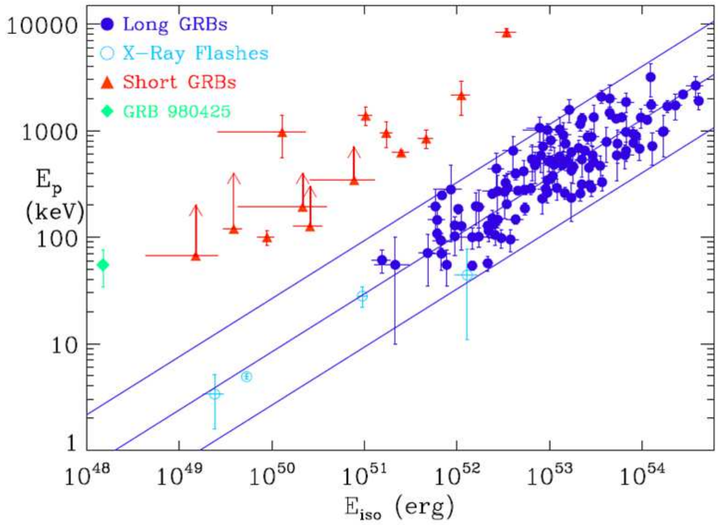

Fig. 1. Amati relation. The best fit parameters are given in the text. Reprinted from Ref. 3.

Many models have already been suggested to explain the Amati relation. We list some of them: the model proposed by[16] in the context of the standard synchrotron shock scenario, which is based on the assumption that a considerable fraction of the prompt emission flux is due to blackbody[17–19], the model proposed in Ref. 20, which is based on the magnetic reconnection mechanism, in which the flow that powers a GRB is initially Poynting flux dominated, the model proposed in Ref. 21, in which the prompt emission is synchrotron radiation from the external shock. The tests already performed for these models show that either the theoretical expectations are not found in the data (see, e.g., Ref. 22) or the constraints imposed by the models could not be verified with the observations. Here we propose for the interpetation of the time–resolved E_p vs. L_{iso} the X–ray spectral model GRBCOMP proposed by some of us[23] (hereafter T12) for the description of the time–resolved spectra of the GRB prompt emission.

2. The grbcomp model

GRBCOMP is essentially a photospheric model for the prompt emission of GRBs. Its main ingredients are a thermal bath of soft seed photons which are Comptonized by a subrelativistically expanding outflow characterized by a Maxwellian electron plasma with temperature kT_e and Thomson optical depth τ (see Fig. 2).

The outgoing emerging spectrum, at least up to the peak of the $EF(E)$ diagram, is the result of multiple Compton scatterings of the seed photons in an hot environment having $\tau > 1$. Under these conditions, the Comptonization parameter $Y \propto \Theta\tau^2 \gg 1$ where $\Theta = kT_e/m_ec^2$, and quasi-saturated spectra are produced.

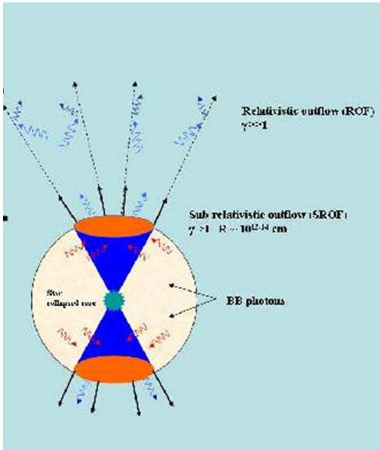

Fig. 2. The GRBCOMP model. Adapted from Ref. 23.

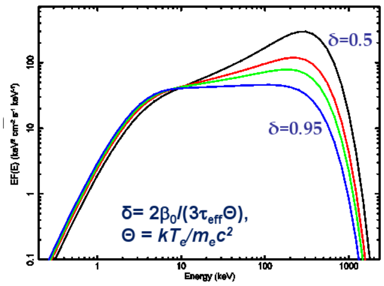

Fig. 3. Expected instantaneous spectra from GRBCOMP as a result of the first upscattering process only. Adapted from the original paper by Ref. 23.

The immediate consequence of this result is that the peak energy E_p of the $EF(E)$ spectrum mostly depends on the electron temperature kT_e, with a modification induced by the fact that the plasma is not static, but subrelativistically moving outwards (see Fig. 3). This is the first phase of the upscattering process.

The second phase of the upscattering process shapes the high-energy power-law tail above the energy peak of the model (see Fig. 4). This is phenomenologically obtained by the convolution of the subrelativistic Comptonized spectrum with a broken power–law upscattering Green's function. The reason for this pure mathematical treatment of the second part of the spectrum resides on the fact that, whatever its origin, the underlying process giving rise to tails extending in some case up the GeV energies cannot be treated using classical Comptonization equations (e.g. Fokker-Planck approximation), but presumably will require a fully relativistic treatment of the photon-electron interaction. Possible physical interpretations of

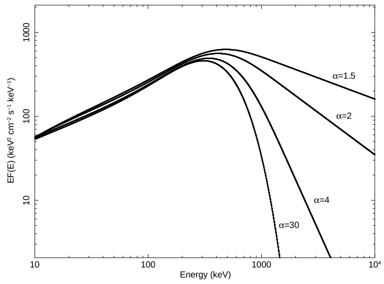

Fig. 4. Expected instantaneous spectra from GRBCOMP as a result of both upscattering processes, for different values of the power–law index in the convolution function. Reprinted from the original paper by Ref. 23.

the last convolution are discussed by T12 and Ref. 24. A possible interpretation is Inverse Compton of the relativistic plasma outflow with the Comptonized photons.

From the numerical simulations performed by T12, it results that the photon peak energy of the $EF(E)$ spectrum is mainly related to kT_e and, at lower level, to the bulk parameter δ defined below (see Fig. 3), while the released energy depends on both the electron and seed photon temperatures.

The GRBCOMP free parameters, in addition to its normalization constant $N = R_9^2/D_{Mpc}^2$, (where R_9 is the apparent photospheric radius R_{ph} in units of 10^9 cm, and D_{Mpc}^2 is the source distance in Mpc), are (in the rest frame) the temperature of the seed photons $kT_{s,i}$ (in keV), the plasma electron temperature $kT_{e,i}$ (in keV), the effective optical depth τ_{eff} of the plasma outflow, the plasma outflow bulk velocity v, and the power–law photon index α_{boost} of the component above the peak energy. From the model best–fit parameters, it is also possible to derive the bulk parameter δ, which, for the case of a constant outflow velocity, is defined as:

$$\delta = 2\beta/(3\tau_{eff}\Theta) \tag{1}$$

where $\beta = v/c$, and $\Theta = kT_{e,i}/m_e c^2$ and τ_{eff} is an effective optical depth such that $\tau_{eff} \lesssim \tau$. The definition of an effective optical depth τ_{eff} was introduced to separate the space and energy operators in the radiative transfer Fokker-Planck equation (see Eq. (6) in T12), which provides a much faster way for getting numerical solutions. To fit the measured time-resolved spectra, it is assumed $\tau_{eff} = 0.5\tau$, where τ is the actual free parameter of the model. Finally, despite being in principle a free parameter, the outflow subrelativistic velocity β is kept frozen to 0.2 in the fitting procedure, to avoid parameter degeneracy or too large uncertainties. The value of 0.2 is the median value of those values consistent with GRBCOMP.

Finally, in the light of the GRBCOMP model, for a given β, the GRB luminosity is expected to depend on the soft photon temperature $kT_{s,i}$, the blackbody emitting surface A_s and the Comptonization amplification factor η_{Comp}, defined in Refs. 25,26, i.e.,

$$L(t) = A_s(t)\,[kT_{i,s}(t)]^4\,\eta_{Comp}(t,\tau) \tag{2}$$

See also Ref. 23.

3. Observational test of the GRBCOMP model

The GRBCOMP model was tested using the time resolved spectra in the 2–2000 keV energy range of the brightest GRBs simultaneously detected with both the Wide Field Cameras (WFCs) aboard *BeppoSAX* and the BATSE experiment aboard the *Compton Gamma Ray Observatory*[24] (see Fig. reff:lc). These data are really unique. Indeed only WFCs and BATSE cover all together the 2–2000 keV energy range. The test results are very optimistic: the GRBCOMP model fits well all the available (42) time–resolved spectra, in some cases even better than the Band function. As an example, in Fig. 5 we show the correlation found between intrinsic electron temperature $kT_{e,i}$ and luminosity in each of the intervals in which we subdivided the light curves (see Fig. 6).

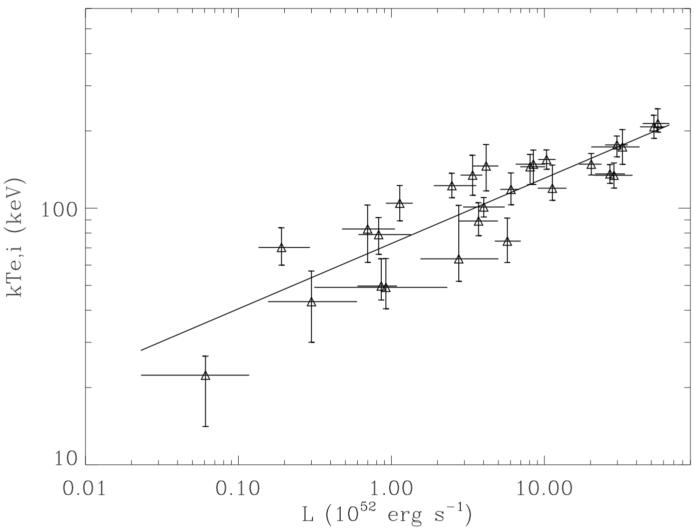

Fig. 5. Intrinsic electron temperature versus luminosity in the time intervals in which the light curve of GRBs 990123 and 990710, for which the redshift is known, was subdivided. Reprinted from Ref. 24.

4. GRBCOMP interpretation of the time–resolved $E_p(t)$ vs. $L(t)$ relation and its dispersion

It has been shown by T12 that the GRBCOMP model gives a physical interpretation of the $E_{p,i}$–E_{iso} relation. We show now that the same model cane give an interpretation of the time–resolved $E_{p,i}$–L_{iso} relation, that, as above discussed, was

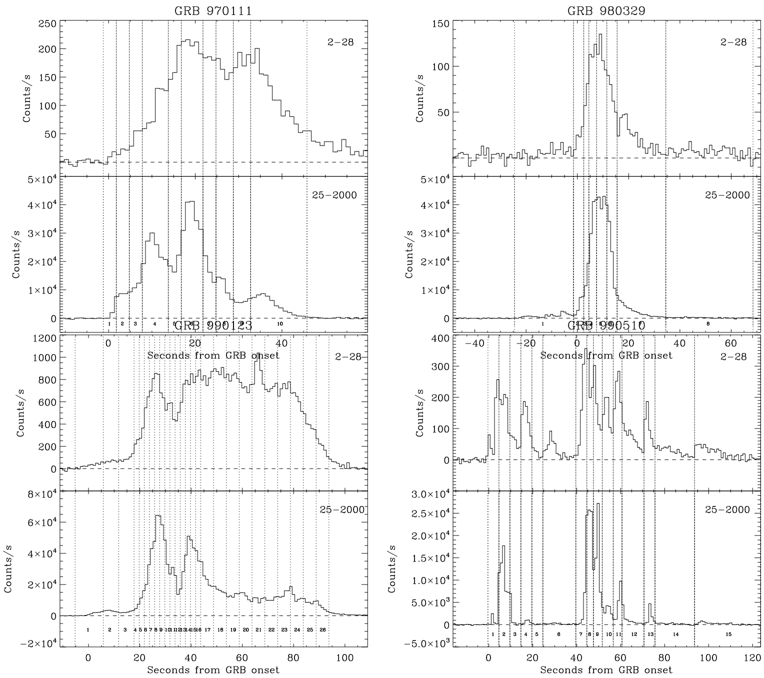

Fig. 6. Light curves of the GRBs used for testing the GRBCOMP model. The time–resolved spectra were those extracted in the sub–intervals shown in each panel. Reprinted from Ref. 24.

observationally found within each GRB by us[13,14] and other authors[12,15]. Indeed, from eq. 2, if the integration time interval (t_1, t_2) of the time–resolved spectra is short enough that all intrinsic quantities (in the following we omit the index i) are almost constant, we get:

$$< L >= (kT)^4_s \; \eta_{comp}(kT_{\rm e}, \tau) \; \frac{\int_{t_1}^{t_2} A_s(t) {\rm d}t}{t_2 - t_1} \tag{3}$$

However the emission area propagates with the proton velocity V_p, thus:

$$A_s(t) \propto (V_p t)^2 = V_p^2 t^2 \propto kT_p t^2 = kT_e t^2 \tag{4}$$

(at the thermodynamical equilibrium $T_p = T_e$). Thus it follows:

$$< L > \propto (kT)^4_s \; \eta_{comp}(kT_{\rm e}, \tau) kT_e f(t_1, t_2) \tag{5}$$

where $f(t_1, t_2)$ is the factor obtained by simply integrating the function t^2 over the interval (t_1, t_2).

On the other hand, the dependence of the Compton amplification factor η_{Comp} on kT_e and τ, as discussed in Ref. 24, can be approximated by a power law

$$\eta_{comp}(kT_{\rm e},\tau) = p(\tau)\ kT_{\rm e}^{q(\tau)}. \tag{6}$$

where the dependence on τ of the parameters $p(\tau)$ and $q(\tau)$ can be best fit by two following empirical functions described in Ref. 24.

Substituting eq. (6) into eq. (5) we get

$$< L > \propto\ (kT)_s^4\ kT_{\rm e}^{q(\tau)+1}\ f(t_1,t_2), \tag{7}$$

which can be reverted and get

$$kT_{\rm e} \propto < L >^{\frac{1}{1+q(\tau)}}\ \ (kT_s)^{-\frac{4}{1+q(\tau)}}\ f(t)^{\frac{1}{1+q(\tau)}} \tag{8}$$

Now, taking into account that GRBCOMP expects and data confirm[24] that

$$< E_p > = a(\tau)\ kT_e^{b(\tau)} \tag{9}$$

we finally get

$$E_{\rm p} \propto < L >^{\frac{b(\tau)}{1+q(\tau)}}\ \ (kT)_s^{-\frac{4b(\tau)}{1+q(\tau)}}\ f(t)^{-\frac{b(\tau)}{1+q(\tau)}} \tag{10}$$

In the asymptotic case in which $\tau \gg 1$, we have[24] $b(\tau) \to 1$ and $q(\tau) \to 1$, and thus

$$E_{\rm p} \propto < L >^{1/2}\ \ (kT)_s^{-2}\ f(t)^{-1/2} \tag{11}$$

Similarly, in the asymptotic case of very large optical depth when $q(\tau) \to 1$, we get

$$kT_{\rm e} \propto < L >^{\frac{1}{2}}\ \ (kT_s)^{-2}\ f(t)^{\frac{1}{2}}. \tag{12}$$

We actually find that, within each GRB, the measured flux is correlated with the electron temperature, while a correlation between flux and peak energy $E_{p,o}$ within each GRB is well established see, e.g.,[13,14].

The GRBCOMP model gives also a possible intepretation of the origin of the time–resolved $E_{p,i}$–L_{iso} dispersion. From eq. 10, it results that dispersion can be originated by three possible causes:

- The time behaviour of kT_e during the prompt emission can change from one GRB to the other;
- The temperature of the seed photons can also change from one GRB to the other;
- The integration time of the single time–resolved spectra is fixed by the statistical quality of the data, and not from the condition that all intrinsic quantities are almost constant.

5. Conclusions

The time–resolved correlation between $E_{p,i}$ and L_{iso} is a strong result in favour of the physical origin of the Amati relation.

The Comptonization model GRBCOMP well describes all the time–resolved spectra of the GRB sample in our hand. All its predictions are confirmed by the data.

GRBCOMP gives a reasonable interpretation of the $E_{p,i}$ vs. L_{iso} relation and of its spread.

We need to extend the test of GRBCOMP to other GRBs.

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