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The correlation between peak energy and isotropic radiated energy in GRBs(*)

L. Amati
INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica - via P. Gobetti 101, Bologna, Italy

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Summary. — I review the observational status and the main implications of the correlation between the GRBs peak energy $E_{p,i}$, *i.e.* the photon energy at which the intrinsic (*i.e.* corrected for cosmological redshift) $\nu F \nu$ spectrum peaks, and the isotropic equivalent radiated energy E_{iso}. This correlation, discovered basing on BeppoSAX measurements and confirmed and extended to X-Ray Rich GRBs and X-Ray Flashes by HETE–2 measurements, can be used to constrain the parameters ranges of the various scenarios for the prompt emission of GRBs, is a challenging test for jet and GRB/XRF unification models, provides hints on the GRB/SN connection and can be also used to build up redshift estimators and as an input or test for GRB synthesis models. I also include a brief summary and discussion of the correlations discovered building on the $E_{p,i}$-E_{iso} correlation, the most noticeable being the one between $E_{p,i}$ and the collimation-corrected radiated energy E_γ, and briefly comment on the recent debate concerning the possible impact of selection effects on this correlation.

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1. – Introduction

The aim of this paper is to review the observations and interpretations of the $E_{p,i}$-E_{iso} correlation, one of the most intriguing and discussed properties of *long* Gamma-Ray Bursts (GRBs). In the following, I will use $E_{p,i}$ to indicate the photon energy at which the intrinsic (*i.e.* in the GRB cosmological rest frame) $\nu F \nu$ spectrum peaks, and with E_{iso} the isotropic-equivalent energy radiated by the GRB during its prompt emission. I will start with a brief summary of the spectral properties of GRBs and their energetics (sect. **2**). Then, I will focus on the discovery, occurred in 2002, confirmation and extension to the X-ray richest events of this correlation (sect. **3**) and on some of its main implications and interpretations as discussed by several authors (sect. **4**). I will also briefly review the correlations discovered by building on the $E_{p,i}$-E_{iso} correlation, the most remarkable being the $E_{p,i}$-E_γ correlation (sect. **5**). Finally, I will briefly report

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on the present debate concerning the test of this correlation with BATSE GRBs with unknown redshift (sect. **6**). Given the limited space and the high and continuously growing number of works (both observational and theoretical) on this topic, this review is not intended to be exhaustive.

2. – GRB spectra and radiated energy

2˙1. *Spectra.* – The prompt emission spectra of GRBs are non-thermal and show in many cases substantial evolution. Most average and time-resolved spectra can be modeled with the Band function [1], a smoothly broken power law introduced to describe the BATSE (25–2000 keV) data, whose parameters are the low energy spectral index, α, the high energy spectral index, β, the break energy, E_0, and the overall normalization. The photon energy at which the $\nu F\nu$ spectrum peaks is given by $E_p = E_0 \times (2+\alpha)$ and is called the *peak energy.* The non thermal nature of GRBs spectra is at the basis of the standard scenario for their emission: the kinetic energy of an ultra-relativistic fireball (a plasma made of pairs, photons and a small quantity of baryons) is dissipated into electromagnetic radiation by means of synchrotron emission originated in internal shocks between colliding shells and/or the external shock of the fireball with the ISM (see, *e.g.*, [2] for a recent review). Indeed, the Band spectral shape of most GRBs can be satisfactorily reproduced by Synchrotron Shock Models (SSM) (*e.g.*, [3]); nevertheless, the time-resolved analysis of BATSE and BeppoSAX GRBs showed that during the initial phase of the emission of several events the low energy index is inconsistent with the prediction of SSM, *i.e.* α is found to be higher than the synchrotron limit of -0.67 (*e.g.*, [4, 5]). This evidence has been explained by invoking, *e.g.*, the presence of an additional X-ray component due to Compton up-scattering of UV photons surrounding the GRB source by the ultra relativistic electrons of the fireball, the presence of a thermal component emitted by the photosphere of the fireball, a particular distribution of the pitch angles of electrons radiating via synchrotron emission. Other relevant outcomes of the analysis of BATSE events were the evidences of a substantial clustering of E_p values around 200 keV, a positive correlation between GRBs intensity and spectral hardness and a negative correlation between GRBs duration and spectral hardness. In the recent years, the discovery and study of X-ray rich events and X-Ray Flashes (XRFs), due to the extension to the X-ray energy band of the detection and spectral analysis of GRBs allowed by BeppoSAX and HETE–2, showed that the distribution of E_p is much less clustered than inferred basing on BATSE data and, in particular, that it is characterized by a low energy tail extending down at least to ~ 1 keV [6, 7].

2˙2. *Radiated energy.* – Since the BeppoSAX breakthrough discoveries in 1997, more than 45 redshift estimates have become available, all concerning long duration GRBs. As a consequence, for these events it is possible to compute the total radiated energy in a given (cosmological rest frame) energy band by exploiting the distance estimate and the measured average spectrum and fluence, following, *e.g.*, the methods described in [8] and [9]. In the simplest assumption of isotropic emission, the radiated energy, E_{iso}, ranges from $\sim 10^{51}$ erg to $\sim 10^{54}$ erg for most GRBs and extends down to $\sim 10^{49}$ erg when including XRFs, see, *e.g.*, [10]. The highest energy values are very difficult to explain even for the most popular models for the progenitors of bright-long GRBs, the hypernova-collapsar models, especially when taking into account the very low efficiency in converting the kinetic energy of the fireball into electromagnetic radiated energy. This difficulty is, at least partially, overcome by assuming that the GRB emission is collimated. Indeed, the achromatic breaks observed in the afterglow decay curves of several GRBs can be interpreted in the light of simple uniform jet models. In these scenarios, a break is expected when, because of the deceleration of the fireball, the relativistic beaming angle exceeds the jet opening angle, which can be derived from the break time by making assumptions on the properties of the fireball (*e.g.*, the kinetic-to-radiated energy conversion efficiency) and the circum-burst environment (*e.g.*, density). Basing on the achromatic breaks in the decay light curves of the afterglows of GRBs with known redshift, the distribution of the total radiated energies in the jet hypothesis, E_γ, is found to be clustered around $\sim 10^{51}$ erg, see *e.g.*, [11], although recently [9] it has been shown that, when considering a larger sample of GRBs with known redshift, the E_γ distribution is broader than inferred before.

3. – Discovery, confirmation and extension of the $E_{p,i}$-E_{iso} correlation

In 2002, Amati *et al.* [8] presented the results of the analysis of the average WFC (2–28 keV) and GRBM (40–700 keV) spectra of 12 BeppoSAX GRBs with known redshift (9 firm measurements and 3 possible values). By fitting the redshift-corrected spectra with the Band function, they were able to estimate the intrinsic (*i.e.* in the source cosmological rest frame) values of the spectral parameters. Also, by integrating the best fit model of the intrinsic time integrated spectrum and adopting a standard cosmology, they computed the total radiated energy in the 1–10000 keV band assuming isotropic emission, E_{iso}, and performed correlations studies between intrinsic spectral parameters, E_{iso} and the redshift z. Thanks to the extension of the analysis down to X-rays, the truncation effects in the determination of spectral parameters, in particular of the low energy index α and of the intrinsic peak energy $E_{p,i}$, were substantially reduced with respect to previous analysis based *e.g.*, on BATSE data. In addition, all the GRBs in the sample had peak fluxes and fluences well above the detection threshold. The more relevant outcomes of this work were an indication of a positive trend between E_{iso} and z and, in particular, the evidence of a strong correlation between $E_{p,i}$ and E_{iso} . The correlation coefficient between $\log(E_{p,i})$ and $\log(E_{iso})$ was found to be 0.949 for the 9 GRBs with firm redshift estimates, corresponding to a chance probability of 0.005%. The slope of the power law best describing the trend of $E_{p,i}$ as a function of E_{iso} was ~ 0.5. This work was extended by [13] by including in the sample 10 more events with known redshift for which new spectral data (BeppoSAX events) or published best fit spectral parameters (BATSE and HETE–2 events) were available. The $E_{p,i}$-E_{iso} correlation was confirmed and its significance increased, giving a correlation coefficient similar to that derived by [8] but with a much higher number of events. Basing on HETE–2 measurements, [10] not only confirmed the $E_{p,i}$-E_{iso} correlation but remarkably extended it to XRFs, showing that it holds over three orders of magnitude in $E_{p,i}$ and five orders of magnitude in E_{iso}, as can be seen in fig. 1 (see caption for details). The addition of new data, as more redshift estimates became available, confirmed the correlation and increased its significance, as found, *e.g.*, by [9] (29 events, chance probability of 7.6×10^{-7}). The correlation analysis performed on the most updated sample of GRBs with firm estimates of z and E_p (indicated by rombs in fig. 1) gives a chance probability as low as 3.4×10^{-9} (`http://www.merate.mi.astro.it/∼ghirla/deep/blink.htm`). We note that, despite the correlation is very highly significant, the scatter of the data is such that its slope depends on the addition or subtraction of few events and is found to range between ~ 0.35 and ~ 0.55 [8, 13, 9, 14]. However, as can be seen in fig. 1, all the region covered by the data in the $E_{p,i}$-E_{iso} plane is well delimited by two power laws with index 0.5.

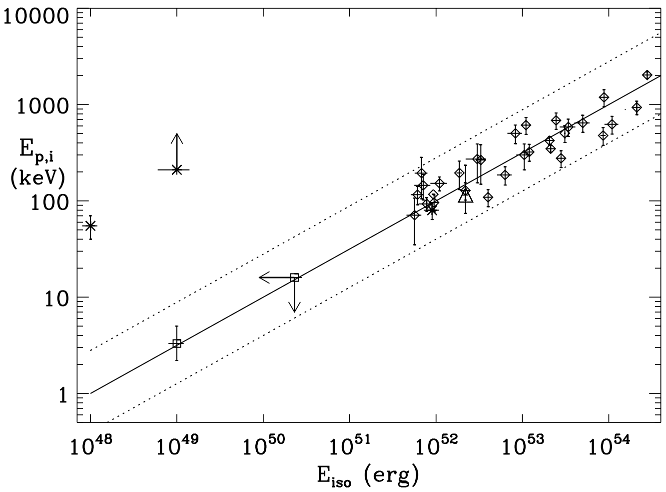

Fig. 1. – $E_{p,i}$ and E_{iso} values for 31 GRBs with firm redshift and $E_{p,i}$ estimates and included in the samples of [8, 13, 9] (rombs), for the two XRFs (XRF020903 and XRF030723) included in the sample of [18] (squares), for the three GRBs most firmly associated with a SN event (GRB980425, GRB030329, GRB031203, asterisks) and for the Swift event GRB050318 (triangle). The continuous line is the law $E_{p,i} = 100 \times E_{iso}^{0.5}$; the dotted lines are two power laws with the same slope (0.5) and delimitate the region covered by the data. The $E_{p,i}$ and E_{iso} values for XRF020903 and GRB050318 are based on spectral information published by [7] and [12], respectively, and the errors on $E_{p,i}$ are at 90% confidence

Interestingly, two of the GRBs for which there is the most firm evidence of association with a SN event, GRB980425 and GRB031203, are characterized by values (or lower limit) of $E_{p,i}$ and E_{iso} completely inconsistent with the correlation, whereas the values of GRB030329, associated with SN2003dh, are fully consistent with it. For GRB980425, this is only partly surprising, given that this event is peculiar under many other aspects; we shall discuss this in next section together with the other peculiar case of GRB031203.

4. – Main implications of the $E_{p,i}$-E_{iso} correlation

The discovery of the $E_{p,i}$-E_{iso} correlation confirms and explains observational evidences found before the BeppoSAX era, when redshift estimates were not available, like, *e.g.*, the hardness-intensity correlation. Moreover, basing on the spectral analysis of BATSE data [15] inferred the existence of a power law correlation between $E_{p,i}$ and E_{iso}, with a slope in the range 0.4–0.7, consistent with the value of ~ 0.5 found by [8]. As we will discuss below, the $E_{p,i}$-E_{iso} correlation, with its extension over several orders of magnitude both in $E_{p,i}$ and E_{iso} has a strong impact for the mechanisms and the geometry of the emission of GRBs.

4·1. *Testing prompt emission models.* – The physics of the prompt emission is still far from being settled and a variety of scenarios, within the standard fireball picture, have been proposed, *e.g.*, SSM internal shocks, Inverse Compton (IC) dominated internal shocks, external shocks, innermost models, occurring in a kinetic-energy–dominated fireball or a Poynting-flux–dominated fireball (see [16] for a review). In general, both

$E_{p,i}$ and E_{iso} depend on the fireball bulk Lorentz factor, Γ, in a way that varies in each scenario. Thus, the existence of a correlation between $E_{p,i}$ and E_{iso} is predicted in nearly all scenarios, but the fact that it is positive and has a slope of ∼0.5 allows to discriminate between models and to constrain the range of values of the parameters of each model [16,17]. Also, this correlation shows that the distribution of $E_{p,i}$ is broader than inferred previously basing on the observed E_p values of bright BATSE GRBs. As for the slope of the correlation, the broadness of the $E_{p,i}$ distribution is a crucial test for the prompt emission models [16].

4·2. *Challenging jet and GRB/XRF unification models.* – The validity of the $E_{p,i}$-E_{iso} correlation from the most energetic GRBs to XRFs confirms that these two phenomena have the same origin and is a very challenging observable for jet models. Indeed, these models have to explain not only how E_{iso} and $E_{p,i}$ are linked to the jet opening angle, θ_{jet}, and or to the viewing angle with respect to the jet axis, θ_v, but also how E_{iso} can span over several orders of magnitudes. In the most simple scenario, the uniform jet model, jet opening angles are variable and the observer measures the same value of E_{iso} independently of θ_v. In the other popular scenario, the universal structured jet model, E_{iso} depends on θ_v. As discussed in the previous section, in the hypothesis that the achromatic breaks found in the afterglow light curves of GRBs with known redshift are due to collimated emission, it is found that the "true" radiated energy, E_γ, is of the same order for most GRBs and that $E_{iso} \propto \theta_{jet}^{-2}$, assuming a uniform jet. In the case of structured jet models, which assume that θ_{jet} is similar for all GRBs (hence this scenario is also called universal jet model) the same observations imply that $E_{iso} \propto \theta_v^{-2}$. Thus, the found $E_{p,i}$-E_{iso} correlation implies $E_{p,i} \propto \theta_{jet}^{-1}$ and $E_{p,i} \propto \theta_v^{-1}$ for the uniform and structured jet models, respectively. The authors of [18,19] argue that the structured universal jet model, in order to explain the validity of the $E_{p,i}$-E_{iso} correlation from XRFs to energetic GRBs, predicts a number of detected XRFs several orders of magnitude higher than the observed one (∼ 1/3 than that of GRBs). In their view, the uniform jet model can overcome these problems by assuming a distribution of jet opening angles $N(\theta_{jet}) \propto \theta_{jet}^{-2}$. This implies that the great majority of GRBs have opening angles smaller than ∼ 1° and that the true rate of GRBs is several orders of magnitude higher than observed and comparable to that of SN Ic. On the other hand, in [20] it is shown that the requirement that most GRBs have jet opening angles less than 1 degree, needed in the uniform jet scenario in order to explain the $E_{p,i}$-E_{iso} correlation, as discussed above, implies values of the fireball kinetic energy and/or of the interstellar medium density much higher than those inferred from the afterglow decay light curves. Together with other authors, *e.g.*, [21], they propose a modification of the universal structured jet model, the quasi-universal Gaussian structured jet. In this model, the measured E_{iso} undergoes a mild variation for values of θ_v inside a typical angle, which has a quasi-universal value for all GRBs/XRFs, whereas it decreases very rapidly (*e.g.*, exponentially) for values outside the typical angle. In this way, the universal structured jet scenario can reproduce the $E_{p,i}$-E_{iso} correlation and predict the observed ratio between the number of XRFs and that of GRBs. Recently, a universal Fisher-shaped jet model has been proposed [22] as a very promising alternative to the above models, in particular for the explanation of the validity of the $E_{p,i}$-E_{iso} correlation from the brightest GRBs to XRFs. Other jet models proposed very recently that can explain both the correlation and the existence of outliers like GRB980425 and, possibly, GRB031203 include the ring-shaped jet model [23] and the multi-component (subjets) model [24]. Of particular interest are the off-axis scenarios, in which the jet is assumed to be uniform but the measured E_{iso} does not sharply go to zero for $\theta_v > \theta_{jet}$, see *e.g.*, [25,26]. Due to relativistic beaming and Doppler effects, the event is detected by the observer with E_{iso} and $E_{p,i}$ dropping rapidly as θ_v increases. In this models, XRFs are those events seen very off-axis and the XRFs rate with respect to GRBs and the $E_{p,i}$-E_{iso} correlation can be correctly predicted. In addition to the uniform jet model, the off-axis explanation for very weak and soft events can be applied in a similar way in the context of the cannon ball (CB) model for GRBs [27].

4·3. *Hints to the understanding of the GRB/SN connection.* – As we have discussed in previous section, the prototype event for the GRB/SN connection (GRB980425) is characterized by values of $E_{p,i}$ and E_{iso} completely inconsistent with the correlation holding for the other events. From an observational point of view, this is a direct consequence of the fact that the event is characterized by a fluence and a measured peak energy in the range of normal GRBs, while its redshift is much more lower ($z = 0.0085$). It has been pointed out that also another event associated with a SN event, GRB031203, is characterized by a lower limit of $E_{p,i}$ which, combined with the value of and E_{iso}, makes it completely inconsistent with the correlation (fig. 1). Given that GRB031203 is the most similar event to GRB980425 under several points of view (although lying at a much larger distance, $z \sim 0.1$), in particular the low afterglow energy inferred from the radio afterglow [28,29], this inconsistency has been invoked as a further evidence of the existence of a class of sub-energetic GRBs. However, the lower limit on $E_{p,i}$ based on ISGRI data should be considered with some cautions, given the narrow energy band of the instrument and the fact that the spectrum can be fitted by a single power law with photon index not so far from 2 [29]. The fact the two closest among those GRBs most clearly associated with a SN are outliers to the $E_{p,i}$-E_{iso} correlation is very challenging for GRB-XRF-SN unification models; the most popular explanations assume that the peculiarity of these events is due to particular and uncommon viewing angles (*e.g.*, [30] for GRB980525 and [31] for GRB031203). These evidences also indicate a potential use of the $E_{p,i}$-E_{iso} plane to distinguish among different sub-classes of GRBs, in a way similar to the H-R diagram for stars.

4·4. *The correlation as a tool and a test.* – Finally, the $E_{p,i}$ and E_{iso} correlation can be used to build up redshift indicators, like the one developed by [32] and currently used to estimate pseudo-redshifts of HETE–2 GRBs. With respect to other correlations found between GRB observables (*e.g.*, the variability-luminosity correlation [33]), the $E_{p,i}$-E_{iso} correlation has the advantage of being tighter and more firmly established. In turn, the redshifts estimated based on the $E_{p,i}$-E_{iso} correlation can then be used to estimate the luminosity of large samples of GRBs and infer their luminosity function and, given the association of GRBs with star-forming regions, the Star Formation Rate (SFR) evolution. In addition, several authors assume the validity of $E_{p,i}$-E_{iso} correlation as an ingredient of their GRB models or a test output for their GRB synthesis models.

5. – Correlation of E_p with other GRB intensity indicators

The discovery of the $E_{p,i}$-E_{iso} correlation, its confirmation and extension to weak and soft events and its impact in the GRB field stimulated the exploration of correlations of E_p with GRB intensity indicators other than E_{iso}. Firstly, it was shown (*e.g.*, [10]) that the correlation holds also when substituting E_{iso} with the average isotropic equivalent luminosity L_{iso}. In particular, the slope of this correlation and its significance are consistent with those of the $E_{p,i}$-E_{iso} relation. Basing on the spectral analysis of BATSE bright GRBs with unknown redshift and assuming a GRB redshift distribution derived from star formation rate models, it was inferred [34] that the $E_{p,i}$-L_{iso} correlation holds also within GRBs. Also, a tight correlation has been found between the peak isotropic equivalent luminosity L_p and $E_{p,i}$ [35, 36]. These correlations are clearly linked to the $E_{p,i}$-E_{iso} correlation, mainly due to the fact that GRB radiated energy, luminosity and peak luminosity are strongly correlated (*e.g.*, [18, 19, 36]). Comparative studies of these correlations can help in better understanding GRB radiation mechanisms and, *e.g.*, the evolution of the jet during the prompt phase. But the most remarkable correlation found building on the $E_{p,i}$-E_{iso} correlation is that between $E_{p,i}$ and the total radiated energy in the assumption of collimated emission, E_γ [9]. This correlation, although if based on a lower number of events with respect to the $E_{p,i}$-E_{iso} correlation and requiring assumptions, *e.g.*, on the circum-burst environment density and the kinetic-to-radiated energy conversion efficiency, is very promising for its possible use to constrain the values of cosmological parameters, in a similar way to type Ia SN [37-40]. Also, the existence of both the $E_{p,i}$-E_{iso} and $E_{p,i}$-E_γ correlations supports the idea that the collimation angles of GRBs are not distributed over a wide range and at least part of the scatter of the $E_{p,i}$-E_{iso} correlation reflects that of jet opening angles. For example, the comparison of the two correlations can be used to infer the distribution of jet opening angles (*e.g.*, [14, 41]). Finally, very recently a multi-variable correlation analysis including both prompt emission and afterglow observables [42] put in evidence a strong correlation between E_{iso}, $E_{p,i}$ and the afterglow break time t_b. This correlation suggests a link between radiated energy and jet opening angle and has the advantage of linking quantities that can be derived in a model-independent way.

6. – The debate: is the $E_{p,i}$-E_{iso} correlation an artifact of selection effects ?

Recently, two research groups [43, 44], by applying a specific test to BATSE GRBs without known redshift, inferred that ∼half [43] or even ∼90% [44] of the whole GRB population cannot satisfy the correlation for any values of redshift. Thus, they conclude that strong selection effects are introduced in the various steps leading from GRB detection to the final z estimate and that we are measuring the redshift of only those events that follow the correlation. However, this conclusion has been questioned by several other authors [14, 41, 45], who found instead that peak energy and fluences of BATSE GRBs with unknown redshift are fully consistent with the $E_{p,i}$-E_{iso} correlation. Among the sources of discrepancies between these two different conclusions there are: i) accounting or not for the observed dispersion of the correlation, and ii) considering it as a power law with a given slope instead of taking into account the fact that, given the scatter of the data and although the correlation is very highly significant, no power law gives an acceptable fit and the index is very sensitive to the inclusion or exclusion of few events from the sample (*e.g.*, [8, 13, 9, 14]). Here I will not enter this debate; I just remark that a direct and unambiguous test of the $E_{p,i}$-E_{iso} correlation can be performed only by substantially enlarging the sample of GRBs with known redshift both in number and in the coverage of the E_p-fluence plane. Unfortunately, given the narrow energy band of BAT, Swift, which is providing fantastic results concerning the connection between prompt and afterglow emission, will hardly help in clarifying this issue. Indeed, based on preliminary spectral analysis published in GCNs, all BAT spectra can be fitted with a simple power law and probably even a refined analysis will allow the estimate of E_p values only for a small fraction of Swift GRBs.

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