A New Method for Studying the Hardness-Intensity Correlation in Gamma-Ray Bursts

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Abstract. We introduce a new method to study the hardness-intensity correlation (HIC) within gamma-ray bursts, in which the intensity is represented by the peak value of the $EF_{\rm E}$ spectrum. We compare it to the traditional method where the intensity over a finite energy range is used. This new method gives stronger correlations and is useful in studying several aspects of the HIC.

INTRODUCTION

Gamma-ray bursts (GRBs) often exhibit strong spectral evolution (see, e.g., [1] and references therein). This can be quantified by studying the evolution of the hardness of the spectrum versus its intensity. Such hardness-intensity correlations (HICs) can often be described with a power-law, especially over the decay phase of individual pulse structures in the GRB light curve [2–7]:

$$F \propto E_{\rm pk}^{\gamma}, \tag{1}$$

where F is the energy flux and $E_{\rm pk}$ is the peak energy of the $EF_{\rm E}$ spectrum. A general problem, encountered in HIC studies, arises from the limited spectral coverage of the used detector which might affect the assigned measure of the bolometric flux, i.e., the energy-integrated flux. A second problem, when one aims at studying the correlation over single pulses in the light curve, arises from the fact that the observed spectra may contain contributions from other pulses which even could be unresolved. Furthermore, additional soft components [8] could also affect the measured flux value and thus weakening the correlations.

We, therefore, introduce a new representation of the HIC which might resolve some of these complications. The GRB spectrum is often peaked in an $EF_{\rm E}$ representation [9] at some energy $E_{\rm pk}$ in the γ-ray band. The value of $EF_{\rm E}$ at $E_{\rm pk}$ is a representation of the energy-integrated flux as it is proportional to the total flux. We denote this quantity by ϕ and study the HIC correlation as

$$\phi \propto E_{\rm pk}^{\eta}, \tag{2}$$

where η is the new HIC index. Our discussion is limited to the cases where the peak actually exists within the studied band $[E_{\rm min}, E_{\rm max}]$. Representing the spectrum by the Band et al. model [9], this means that the low and high energy power law indices must have $\alpha > -2$ and $\beta < -2$. In the most common case where $E_{\rm max} > (\alpha-\beta)E_{\rm pk}/(\alpha+2)$, the proportionality between ϕ and F$=\int F_{\rm E} dE$ becomes

$$k(\alpha,\beta,y_{\rm min},y_{\rm max}) = \frac{F}{\phi} = \frac{e^{(\alpha+2)}}{(\alpha+2)^{\alpha+2}}\times \tag{3}$$
$$\left[\Gamma(\alpha+2)\{P(\alpha+2,\alpha-\beta)-P(\alpha+2,y_{\rm min})\} + \frac{(\alpha-\beta)^{\alpha-\beta}y_{\rm max}^{\beta+2}-(\alpha-\beta)^{\alpha+2}}{(\beta+2)e^{\alpha-\beta}}\right]$$

where $y_{\rm min} = (\alpha+2)E_{\rm min}/E_{\rm pk}$, and $y_{\rm max} = (\alpha+2)E_{\rm max}/E_{\rm pk}$. $\Gamma(\alpha+2)$ and $P(\alpha+2, y)$ are the gamma function and the incomplete gamma function, respectively (see, e.g., Press et al. [10]). In the case that α and β do not have a strong dependence on $E_{\rm pk}$, the only $E_{\rm pk}$ dependence in $k(\alpha,\beta,y_{\rm min},y_{\rm max})$ is in $y_{\rm min}$ and $y_{\rm max}$. In particular, when the integration is chosen over the whole energy range from 0 to ∞, there will be no dependence at all. The ϕ-value can be interpreted as integrating over the whole energy range, or, at least, over a range for which $y_{\rm min} << 1$ and $y_{\rm max} >> 1$, and should, under some circumstances, be a better representation of the bolometric flux for the study of the HIC.

COMPARING THE TWO METHODS

To compare the methods, represented by equations (1) and (2), we study a sample of 45 GRB pulse decays, introduced by [6], observed by the Burst and Transient Source Experiment (BATSE) on the *Compton Gamma-Ray Observatory*. These pulses have good power law HICs, as measured by the square of the correlation coefficients, R^2. The light curve for each burst in the sample was rebinned to achieve a signal-to-noise-ratio of at least 30. The spectrum for each time bin was fitted with the Band et al. [9] model, allowing a deconvolution to find the energy spectrum and the peak energy. The energy spectrum was integrated over the energy band of the BATSE detector ($\sim 25-1900$ keV), for the strongest illuminated large area detector (LAD), to find the instantaneous energy flux.

Then, for each pulse decay we analyzed the spectral evolution and determined both the γ values, according to the F-method, Equation (1), and the η values, according to the ϕ-method, Equation (2). In Figure 1, a typical example of a HIC in a strong GRB pulse is shown. Graphically, in a plot of $\log EF_{\rm E}$ versus $\log E$, the correlation describes how the peak of the spectrum moves following a straight track during the pulse decay from hard to soft. In general, the HICs follow a power law better when the ϕ-method is used. When comparing the coefficients given by the two different methods, R^2_γ and R^2_η, we found that in 85% of the cases R^2_η is greater than R^2_γ, implying that the new method, in general, gives better correlations.

The relation between the two HIC indices γ and η for all pulse decays in the sample is shown in Figure 2. A linear fit to this data gives the proportionality constant 0.95 ± 0.07. This shows that there is a good average correspondence between the two methods. A scatter around an exact correspondence between the two methods is to be expected. As mentioned above additional flux components can be contributing to the estimated flux affecting the resulting HIC index. The ϕ-method is less dependent on this. Furthermore, the exact correspondence between

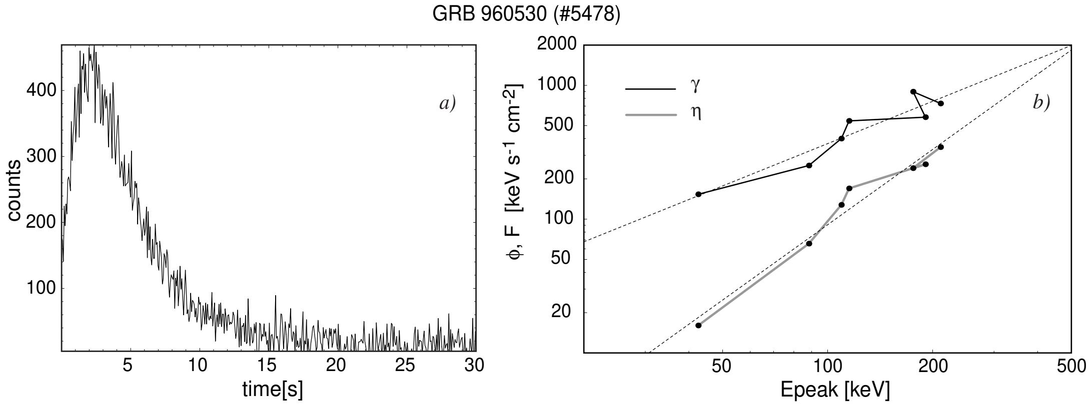

FIGURE 1. The HIC shown as measured by the two different methods, taking as example GRB 960530 (#5478). *a*) The count time history shows a single, long pulse. *b*) The HIC, during the decay phase of the pulse. In this case, we found $R_\gamma^2 = 0.884$ and $R_\eta^2 = 0.967$. In general, the ϕ-method results in better power law correlations.

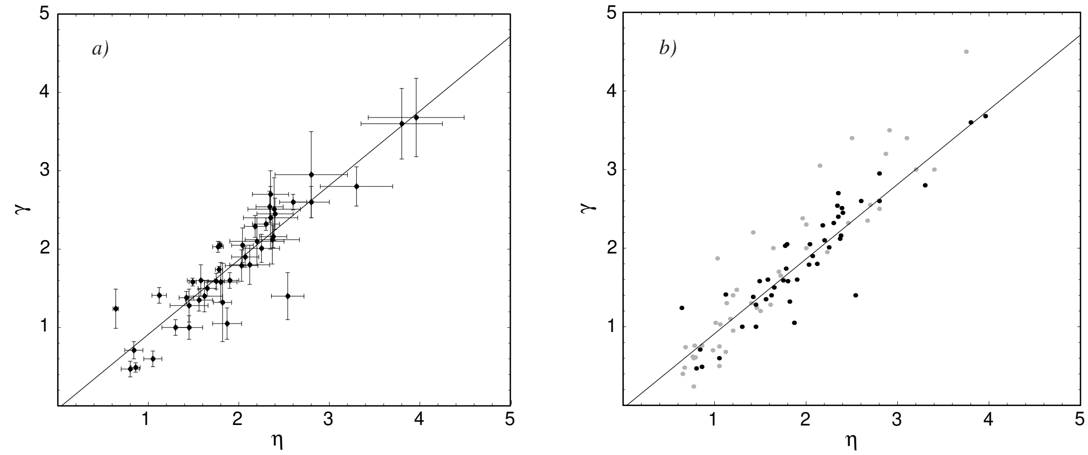

FIGURE 2. The relation between the two HIC indices γ and η. *a*) The correlation for the sample of 45 pulse decays. The straight line shows a linear fit to the data which gives a proportionality constant of 0.95 ± 0.07. The error bars given by the HIC fits are displayed. *b*) The dark dots represent the same pulses as shown in (*a*), but without error bars. Additional shorter pulses and weaker correlated cases are also included (grey dots). Note that the scatter across the line is larger for the pulse decays with weaker HICs.

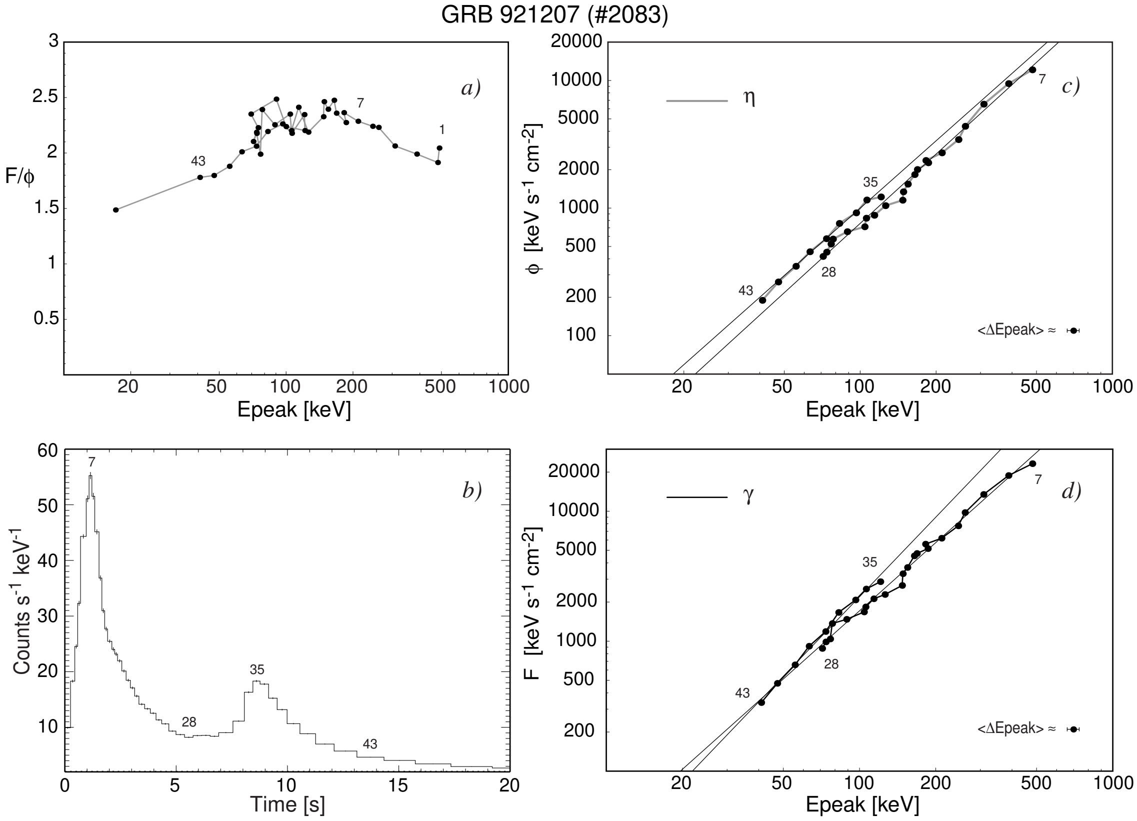

FIGURE 3. *a*) The time evolution of the ratio $k = F/\phi$, in equation (3), for the case GRB 921207 (#2083). The integration of the flux was made over the energy range 24–2000 keV. The F-measure will suffer from window problems at high and low energies. *b*) The count time history showing the time binning used to study the spectral evolution. A few bin numbers are shown. *c*) The HIC measured with the ϕ-method. Error bars are excluded for clarity, and only a typical average value is shown separately. The numbers refer to the time-bins in (*b*). We found, for each pulse decay, the power law indices $\eta_1 = 1.78 \pm 0.04$ and $\eta_2 = 1.77 \pm 0.06$. Only the decay phases are shown here. *d*) Same as (*c*), now using the F-method. The corresponding indices are $\gamma_1 = 1.74 \pm 0.04$ and $\gamma_2 = 2.03 \pm 0.07$. Note that, as in general, the similarity between the HIC indices of pulses within a burst is more evident using the ϕ-method.

the power law indices measured by the two methods is only valid in the case that α and β do not vary with $E_{\rm pk}$, which they do in many bursts. The F-method also suffers from the finite detector range and might not be measuring the actual bolometric γ-ray flux. In fact, the behavior in Figure 3a, with a decline in k at high and low peak energies, is expected due to this [6]. Furthermore, the flux F is found from integrating the deconvolved spectrum. This spectrum is model-dependent as the deconvolution is based on the model spectrum. This could introduce additional scatter into the HIC relation.

Note that in studying the HICs, the measured errors of $E_{\rm pk}$ and the energy flux measure, as found in the fitting procedure, were not used. The data points were simply compared to the power-law behavior. One reason for doing this is that these errors are often overestimated, see discussion in [6].

DISCUSSION

The fact that the power law correlations that we find using the ϕ-method are better than the ones given by the F-method, could indicate that the F-method suffers from effects which are not part of the correlation. The ϕ-method thus provides an efficient way of studying detailed features in the observed HICs. The two methods are compared, in detail, in Borgonovo & Ryde [6], where, for instance, the distribution of the indices, γ and η, are given both in between bursts and within bursts. When comparing pulses within a burst, HIC indices are similar, and in particular, η indices are equal to within the estimated errors, see Figure 3. Furthermore, Borgonovo & Ryde [7] uses this method to analyze a feature, that we call *track jumps*, found in some HICs.

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