Observation and implications of the $E_{\text{peak}} - E_{\text{iso}}$ correlation in Gamma-Ray Bursts

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Abstract. The availability of a few dozen GRB redshifts now allows studies of the intrinsic properties of these high energy transients. Amati et al. recently discovered a correlation between $E_{\text{peak}}$, the intrinsic peak energy of the $\nu f(\nu)$ spectrum, and $E_{\text{iso}}$, the isotropic equivalent energy radiated by the source. Lamb et al. have shown that HETE-2 data confirm and extend this correlation. We discuss here one of the consequences of this correlation: the existence of a ’spectral standard candle’, which can be used to construct a simple redshift indicator for GRBs.

THE $E_{\text{PEAK}} - E_{\text{ISO}}$ RELATION FOR GAMMA-RAY BURSTS

The growing sample of GRBs with spectroscopic redshifts allows the measure of some intrinsic properties of these explosions, like the energy radiated at various wavelengths or the energy at which most of the power is emitted. In 2002, Amati et al. performed a systematic analysis of 12 GRBs with known redshifts in order to derive their intrinsic spectral parameters (the spectral parameters at the source). In their paper, they report a strong correlation between $E_{\text{peak}}$, the intrinsic peak energy of the $\nu f(\nu)$ spectrum, and $E_{\text{iso}}$, the isotropic equivalent energy radiated by the source. For many years this correlation was suspected because it is the best way to explain the well known Hardness-Intensity correlation observed in GRBs (e.g. Mallozzi et al. 1995, Dezalay et al. 1997, Lloyd et al. 2000, Lloyd-Ronning & Ramirez-Ruiz 2002, and ref. therein). However the lack of distance measurements kept the work on the hardness-luminosity correlation qualitative. Recently Lamb et al. (2003) pointed out that HETE observations not only confirm this correlation, but also suggest its extension to the population of X-Ray Flashes (Fig. 11). According to (Fig. 11), the $E_{\text{peak}} - E_{\text{iso}}$ correlation can be approximated by the following relation: $E_{\text{peak}}/(100 \text{ keV}) = \sqrt{E_{\text{iso}}/(10^{52}\text{ erg})}$. The origin of this correlation (which is reminiscent of the Temperature-Luminosity correlation for clusters of galaxies) is not discussed here. The aim of this paper is to discuss one of its consequences: the existence of a ’spectral standard candle’, which can be used to construct a
redshift indicator for GRBs.

FIGURE 1. **Left Panel.** The $E_{\text{peak}} - E_{\text{iso}}$ correlation measured at the end of 2003 with 21 GRBs detected by BeppoSAX (Amati et al. 2002), HETE-2 (Sakamoto et al. 2003, Lamb et al. 2003), and the IPN (Andersen et al. 2000). Note the extent of the correlation in $E_{\text{iso}}$. **Right Panel.** Illustration of the fact that the ratio $\sqrt{E_{\text{iso}}}/E_{\text{peak}}$ is close to a standard candle. This ratio appears almost constant over 4-5 orders of magnitude in $E_{\text{iso}}$. The ratio $\sqrt{E_{\text{iso}}}/E_{\text{peak}}$ is plotted here for 20 GRBs with known redshift detected with BeppoSAX, HETE-2, and the IPN.

BUILDING A REDSHIFT INDICATOR FOR GRBS

The good correlation between $E_{\text{peak}}$ and $E_{\text{iso}}$ suggests that the ratio $\sqrt{E_{\text{iso}}}/E_{\text{peak}}$ is close to a standard candle. This is illustrated in Fig. 1b which shows this ratio as a function of $E_{\text{iso}}$ for 20 gamma-ray bursts with known redshifts. Assuming that $\sqrt{E_{\text{iso}}}/E_{\text{peak}}$ is constant at the source, it is easy to compute its evolution with redshift. This is the dotted curve in the lower right panel of Fig. 2. This curve shows that unfortunately the observed ratio has a very small dependence on redshift beyond $z=1$. This illustrates the fact that when one wants to find a redshift indicator, it must find a quantity which has not only a small intrinsic dispersion, but also a strong dependence on redshift over a large range of redshifts. We performed an empirical search for such a quantity, starting from the fact that $\sqrt{E_{\text{iso}}}/E_{\text{peak}}$ is close to a standard candle. This work led us to conclude that the quantity $X_0 = N_\gamma/(E_{\text{peak}}\sqrt{T_{90}})$ has the right properties for a redshift indicator (we do not claim however that it is the best redshift indicator which can be constructed from gamma-ray data only). Fig. 2 shows the intrinsic dispersion of $X_0$ (lower left panel), and its dependence on redshift (solid curve in the lower right panel). In the definition of $X_0$, $E_{\text{peak}}$ is the peak energy of the $\nu f \nu$ spectrum, $N_\gamma$ is the number of photons emitted by the GRB between $(E_{\text{peak}}/100)$ and $(E_{\text{peak}}/2)$, and $T_{90}$ is the duration of the burst (see Atteia 2003 for additional precisions on $X_0$). All these parameters are measured at the source.

Using $X_0$ as a redshift indicator, we can compute pseudo-redshifts by assuming that $X_0$ at the source is constant and that the observed value $X=n_\gamma/(e_{\text{peak}}\sqrt{T_{90}})$ (the
lower case letters indicating that the parameters are now measured in the observer’s framework) differs from $X_0$ only for the effect of the redshift. The validity of these pseudo-redshifts can be assessed from Fig. 3 which compares pseudo-redshifts and spectroscopic redshifts of 20 GRBs detected and localized by BeppoSAX, HETE-2, and the IPN. Possible applications of these pseudo-redshifts are discussed in Atteia (2003).

**PSEUDO-REDSHIFTS OF HETE-2 GRBS**

Table II presents the pseudo-redshifts of 42 long GRBs detected by HETE-2, with comments on their spectral properties, and on the detection of an afterglow. Pseudo-redshifts range from 0.20 (GRB 030824) to 14.0 (GRB 031026). Nine of the GRBs in Table II have spectroscopic redshifts (in the range 0.25 to 3.2). The pseudo-redshifts of these bursts are all within a factor of two of the spectroscopic redshifts, which led us to conclude that pseudo-redshifts provide a robust redshift indicator in the range $z=0.2-3$. Table II contains three GRBs (in boldface) which have pseudo-redshifts larger than 5, suggesting that they could be GRBs at high redshifts. Unfortunately the
spectroscopic redshifts of these three GRBs have not been measured, leaving open the issue of whether pseudo-redshifts are reliable at large redshifts. If pseudo-redshifts are reliable beyond z=5-6, they may become a useful tool to quickly identify high-z GRBs, and trigger the follow-up actions which are appropriate for these bursts (e.g. X-ray and IR observations).

Finally, we would like to mention that after discussions with the participants at the grb2003 Conference in Santa Fe, the HETE-2 Science Team and Operation Team now routinely provide the spectral parameters and the pseudo-redshifts of GRBs localized by HETE-2. These parameters are made available to the community on a web page a few minutes only after the determination of the burst localization (see GCNs 2421 and 2444).

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REFERENCES

1. Amati, L., Frontera, F., Tavani, M., et al. 2002, A&A, 364, L54
2. Andersen, M.L., Hjorth, J., Pedersen, H. et al. 2000, A&A, 390, 81
3. Atteia, J-L. 2003, A&A, 407, L1
4. Barraud, C., Olive, J-F., Lestrade, J.P., et al. 2002, A&A, 400, 1021
5. Dezalay, J-P., Atteia, J-L., Barat, C. et al. 1997, ApJ, 490, L17
6. Lamb, D.Q., et al. 2003, ApJ, submitted
7. Lloyd, N.M., Petrossian, V, Mallozzi, R.S. 2000, Apj, 534, 227
8. Lloyd-Ronning, N.M., & Ramirez-Ruiz, E. 2002, Apj, 576, 101
9. Mallozzi, R.S., Paciesas, W.S., Pendleton, G.N., et al. 1995, Apj, 454, 597
10. Sakamoto, T., et al. 2003, Apj, in press
TABLE 1. Pseudo-redshifts of 42 long GRBs detected by HETE. The pseudo-redshifts of a few HETE GRBs could not be calculated because their $e_{\text{peak}}$ is outside the energy range of HETE (e.g. GRB 021004). The 'Comment' column indicates the spectral hardness of the burst, and the detection of an afterglow when appropriate. OA, XA, RA, and IRA respectively stand for Optical Afterglow, X-ray Afterglow, Radio Afterglow, and Infra-Red Afterglow. Three GRBs with pseudo-redshifts greater than 5 are indicated in bold.

| Name     | redshift | pseudo-redshift | Comment     | Name     | redshift | pseudo-redshift | Comment     |
|----------|----------|-----------------|-------------|----------|----------|-----------------|-------------|
| grb001225| 0.69     | 0.69            | Bright GRB  | grb021104| 0.88     | 0.88            | X-Ray Flash |
| grb010126| 1.52     | 1.01            | X-Ray Flash | grb021211| 1.01     | 0.86            | OA          |
| grb010213| 0.23     | 0.23            | X-Ray Flash | grb030115| 1.98     | 1.44            | X-Ray Rich  |
| grb010326| 3.43     | 3.43            | X-Ray Rich  | grb030226| 1.98     | 3.56            | XA, OA      |
| grb010612| 9.50     | 9.50            | X-Ray Rich  | grb030324| 3.93     | 3.93            | dark, X-Ray Rich |
| grb010613| 0.70     | 0.70            |             | grb030328| 1.52     | 1.39            | OA, XA      |
| grb010629| 0.57     | 0.57            | X-Ray Rich  | grb030329| 0.17     | 0.24            | Bright, OA, XA, RA, SN 2003dh, X-Ray Rich |
| grb010921| 0.45     | 0.62            | OA, RA      | grb030418| 1.10     | 1.10            | X-Ray Flash |
| grb010928| 3.22     | 3.22            | OA          | grb030429| 2.65     | 1.44            | OA          |
| grb020124| 3.20     | 2.28            | OA          | grb030519| 2.53     |                |             |
| grb020217| 2.67     | 2.67            | OA          | grb030528| 0.36     | 0.36            | IRA, XA     |
| grb020305| 5.88     | 5.88            | OA          | grb030723| 0.59     | 0.59            | OA, XA, SN, X-Ray Flash |
| grb020317| 1.86     | 1.86            | X-Ray Flash | grb030725| 1.21     | 1.21            | OA          |
| grb020331| 2.90     | 2.90            | OA          | grb030821| 2.36     | 2.36            | X-Ray Rich  |
| grb020418| 1.92     | 1.92            | X-Ray Rich  | grb030823| 0.64     | 0.64            | X-Ray Flash |
| grb020801| 0.95     | 0.95            | X-Ray Rich  | grb030824| 0.20     | 0.20            | X-Ray Flash |
| grb020812| 3.03     | 3.03            |             | grb031026| 14.0     |                |             |
| grb020813| 1.25     | 1.37            | OA, XA, RA  | grb031109a| 1.29     |                |             |
| grb020819| 1.52     | 1.52            | RA, X-Ray Rich | grb031109b| 1.39     | 1.39            | X-Ray Flash |
| grb020903| 0.25     | 0.31            | OA, RA      | grb031111a| 4.20     |                |             |
| grb021016| 1.45     | 1.45            |             | grb031111b| 0.56     | 0.56            | X-Ray Rich  |