COSMOLOGY WITH THE $E_{p,i} - E_{iso}$ CORRELATION OF GAMMA–RAY BURSTS

LORENZO AMATI

*INAF – IASF Bologna, via P. Gobetti 101,
 40129 Bologna, Italy
 amati@iasfbo.inaf.it*

Gamma–Ray Bursts (GRBs) are the brightest sources in the universe, emit mostly in the hard X–ray energy band and have been detected at redshifts up to about 8.2. Thus, they are in principle very powerful probes for cosmology. I shortly review the researches aimed to use GRBs for the measurement of cosmological parameters, which are mainly based on the correlation between spectral peak photon energy and total radiated energy or luminosity. In particular, based on an enriched sample of 120 GRBs, I will provide an update of the analysis by Amati et al. (2008) aimed at extracting information on Ω_M and, to a less extent, on Ω_Λ , from the $E_{p,i} - E_{iso}$ correlation.

Keywords: gamma–rays: observations; gamma–rays: bursts; cosmology.

1. Introduction

The evidence, emerged at the end of the '90s, that we are living in a flat Universe undergoing accelerated expansion and in which the baryonic matter contributes only a small fraction ($\sim 4\text{--}5\%$) of the total matter–energy density is mostly based on combined observations of high redshift type Ia SNe and of the Cosmic Microwave Background (CMB). Other complementary probes like Galaxy Clusters and Baryonic Acoustic Oscillations (BAO) further support this scenario.

However, each of these probes is affected by specific systematics, which may bias significantly the estimate of cosmological parameters, like Ω_M , Ω_Λ and the equation of state of the "dark energy". More probes are available and more cross–checks between the results obtained with each of them can be done, thus minimizing the effects of the systematics of single probes. In addition, each different class of probes has a different "sensitivity" to cosmological parameters depending on its redshift distribution. Thus, the search for more classes of sources that can be used as "standard candles" to study the geometry and the evolution of the expansion rate of the Universe is highly motivated.

With an observed redshift distribution extending from ~ 0.01 up to ~ 8.2 and isotropic–equivalent radiated energies up to more than $\sim 10^{53}$ erg, released typically in a few tens or hundreds of seconds, Gamma–Ray Bursts (GRBs) are the brightest cosmological sources in the Universe. In addition, they emit most of their radiation

Fig. 1. Typical νF_ν (energy) spectrum of a GRB in its cosmological rest-frame.

in the hard X-rays, thus the. Unfortunately, they are not standard candles, given that their radiated energies, or luminosities, span several orders of magnitude. However, as I discuss in the next Sections, the recent discovery of a strong correlation between the photon energy at which the νF_ν spectrum peaks and the GRB intensity opened to us the possibility of "standardizing" these sources in a way similar to type Ia SNe and use them as cosmological probes.

2. Spectra and energetics of GRBs

The spectrum of GRBs is non thermal and can be empirically described with the so-called Band function, i.e., a smoothly broken power-law with parameters the low-energy spectral index α , the high energy spectral index β and the "roll-over" energy E_0 . As can be seen in Fig. 1, when converted into νF_ν , i.e., the distribution of the emitted energy as a function of photon energy, the spectrum shows a peak; the photon energy at which this peak occurs is a characteristic quantity in GRB emission models and is called "peak energy", E_p . Since the late '90s, thanks to the first discoveries of GRBs optical counterpart and host galaxies and the measurement of their redshift, it has been possible, for a small fraction of GRBs, to convert the measured spectrum into a cosmological rest-frame spectrum. This allowed the estimate of two key intrinsic quantities: the total radiated energy computed by integrating the spectrum in a standard (1–10000 keV) energy band and assuming isotropic emission, E_{iso} , and the peak energy of the cosmological rest-frame νF_ν spectra of GRBs, $E_{p,i} = E_p \times (1 + z)$. As of the end of 2010, the number of GRBs with measurements of the redshift and of the spectral parameters accurate enough to allow a reliable computation of $E_{p,i}$ and E_{iso} is ~ 120 . The distribution of $E_{p,i}$ for these events, shown in Fig. 2, is approximately a Gaussian centered at a few hundreds of keV and with a low energy extension down to a few keV, corresponding to the so-called X-Ray Flashes (XRFs) or X-Ray Rich (XRR) events. Whether this distribution is significantly biased by instrumental effects or is an intrinsic properties

Fig. 2. Distribution of the photon energy, $E_{p,i}$, at which the cosmological rest-frame νF_ν spectrum of GRB reaches its maximum.

of GRBs is still unclear, in particular concerning the real fraction of XRFs and XRRs w/r to "Normal GRBs". The distribution of E_{iso} is somewhat similar, extending from $\sim 10^{51}$ to more than $\sim 10^{54}$ erg, peaking at $\sim 10^{53}$ erg and with a few peculiar weak events ($\sim 10^{53}$ - $\sim 10^{53}$ erg). Of particular interest, is the distribution of E_{iso} as a function of redshift (Fig. 3). While the lack of detection of weak events at high redshift is expected and trivial, it is more difficult to understand the apparent missing of bright events at low redshifts. A combination of collimated emission and co-moving volume as a function of redshift, and/or a correlation between jet opening angle and GRB intensity have been proposed as possible explanations for this effect. Fig. 3 also shows that at $z > 0.1$ XRFs and short GRBs are located close to the detection limit, while the peculiar sub-energetic events GRB 980425 and GRB 060218, lying at very low z and with the most prominent association with a peculiar type Ic SN, lie exactly on the extrapolation of the upper limit of the distribution of normal long GRBs.

3. The $E_{p,i} - E_{\text{iso}}$ (Amati) correlation

In 2002, based on a small sample of *BeppoSAX* GRBs with known redshift and spectral parameters, it was discovered¹ that $E_{p,i}$ is significantly correlated with E_{iso} . This correlation, commonly called "Amati relation" within the GRB community, has the form

$$\log E_{p,i}(\text{keV}) = m \log E_{\text{iso}}(10^{52}\text{erg}) + q$$

Fig. 3. Distribution of the GRB isotropic-equivalent radiated energy, E_{iso} , as a function of redshift.

, with $m \sim 0.5$ and $q \sim 2$, and is characterized by an extra-Poissonian scatter normally distributed with a σ_{ext} of ~ 0.2 dex around the best-fit law. Subsequent observations with various detectors and spectrometers confirmed and extended the $E_{\text{p},i} - E_{\text{iso}}$ correlation, showing that it holds for all long GRBs and XRFs with well measured redshift and spectral parameters.^{2,3} The present distribution of GRBs and XRFs in the $E_{\text{p},i} - E_{\text{iso}}$ plane is shown in Fig. 4; part of the plotted data, together with the power-law best-fitting the long GRBs points and its confidence region, have been taken from Ref. 3, 4. For more recent bursts, the $E_{\text{p},i} - E_{\text{iso}}$ and $E_{\text{p},i}$ values were computed based on spectral data and fluences reported in the GCN Circulars (gc.gsfc.nasa.gov/gcn3archive.html) by following the method outlined, e.g., in Ref. 1, 2. The existence, properties (slope and dispersion) and extension over several orders of magnitude in both $E_{\text{p},i}$ and E_{iso} of the correlation are challenging observational evidences for the models of the physics and geometry of the prompt emission of GRBs (see, e.g., Refs. 5, 6, 2. In addition, as can be seen in Fig. 4, the $E_{\text{p},i} - E_{\text{iso}}$ plane can be used to identify different classes of GRBs and get clues on their different nature. The consistency of XRFs with the $E_{\text{p},i} - E_{\text{iso}}$ correlation strongly support that they are not a different class of sources but constitute an extension of the "normal" GRB population. In addition, there is clear evidence that short GRBs, for which redshift estimates became available only in the last few years, do not follow the correlation, indicating that their main emission mechanism, and/or the geometry of their emission, is different from long ones. Finally, the peculiarly close and weak long GRB 980425, which is also the "proto-type" event of the GRB-SN connection, is inconsistent with the $E_{\text{p},i} - E_{\text{iso}}$ correlation, suggesting

Fig. 4. Distribution of different classes of GRBs in the $E_{p,i} - E_{iso}$ plane. the dashed and continuous line show the best-fit power-law and the $\pm 2\sigma$ confidence region, respectively, of the correlation followed by long GRBs and XRFs.

the possible existence of a "local" population of sub-energetic GRBs with different properties w/r to cosmological long GRBs (see, e.g., Ref. 7 for a discussion).

4. Standardizing GRBs with the "Amati relation".

As discussed in the Introduction, finding new classes of sources suitable to complement present cosmological probes (e.g., SN Ia, Clusters) in the measurement of the geometry and expansion history of the Universe, given their luminosity and redshift distribution, GRBs would be very Given that it correlates a cosmological model independent quantity $E_{p,i}$, with a quantity, E_{iso} , whose computation requires the luminosity distance, D_L , and, thus, the assumption of a cosmology, in principle the $E_{p,i} - E_{iso}$ correlation could be used to "standardize GRBs", in a way similar to the use of the "Phillips" relation to standardize type Ia SNe. However, the significant extra-Poissonian scatter of the correlation. and the lack of a sufficient number of very low redshift GRBs allowing a cosmological-independent calibration, prevented for several years the use of the correlation to this purpose.

The investigations of GRBs as cosmological probes started in 2004, when it was found evidence^{8,9} that the $E_{p,i} - E_{iso}$ correlation tightens by substituting E_{iso} with the collimation-corrected radiated energy $E_\gamma = (1 - \cos \theta_{jet}) \times E_{iso}$. This result was based on a small sub-sample of GRBs with known $E_{p,i}$ and E_{iso} for which it was possible to infer the jet opening angle θ_{jet} from the "break time", t_b , at which the decay index of the light curve of the optical afterglow sharply changes

Fig. 5. Dispersion of the $E_{p,i} - E_{iso}$ correlation of long GRBs, expressed in terms of fraction of the maximum dispersion, as a function of the value of Ω_M used to compute the E_{iso} values in a standard Λ CDM flat universe.

to a steeper one, under the assumption of a simple jet and afterglow model.¹⁰ By exploiting the low scatter of the $E_{p,i} - E_\gamma$ correlation and applying statistical methods accounting for the lack of calibration (so called "circularity problem"), it was possible to derive, within the "standard" Λ CDM cosmological model, estimates of Ω_M and Ω_Λ consistent with the "concordance" values mostly coming from the analysis of Type Ia SNe and the CMB. A review of these methods and results is provided in Ref. 11. The results of these investigations were encouraging, and prompted other studies aimed at deriving a GRB Hubble diagram, based, e.g., on the joint use of the $E_{p,i} - E_\gamma$ correlation together with other weaker correlations between luminosity and observed properties¹², or the calibration of the $E_{p,i} - E_\gamma$ correlation with Type Ia SNe^{13,14}.

However, in the last years, the simple jet model assumed to compute θ_{jet} from the break time of the optical afterglow light curve has been seriously challenged by the observed different behavior of the X-ray afterglow light curves, which, in several cases, show no "jet-break" or show a break not simultaneous to the optical one. This makes the determination of E_γ , and thus the characterization and use of the $E_{p,i} - E_\gamma$ correlation, less firm.

Thus, recently it was investigated³ the possibility of using, for the estimate of cosmological parameters, the simple $E_{p,i} - E_{iso}$ correlation, which, with respect to the $E_{p,i} - E_\gamma$ correlation, has the advantage of allowing the use of a sample about four time larger, is based on only two observables (the $E_{p,i} - E_\gamma$ correlation requires, in addition to E_{iso} and $E_{p,i}$, also t_b) and avoids the model-dependent assumptions (jet model, afterglow model, density and profile of the circum-burst environment, efficiency of conversion of fireball kinetic energy into radiated energy) which affect

Table 1. Comparison of the confidence intervals on Ω_M for a flat Λ CDM Universe obtained with the sample of 70 GRBs by Ref. 3 and the sample of 122 GRBs available at the end of 2010.

GRB #	Ω_M (68%)	Ω_M (90%)
70	0.04 – 0.43	0.02 – 0.71
122	0.07 – 0.37	0.04 – 0.62

the computation of E_γ . Based on the sample of 70 long GRBs with known $E_{p,i}$ and E_{iso} , it was found that, by assuming a flat Λ CDM Universe, the χ^2 obtained by fitting the correlation with a simple power-law is a function of the value of Ω_M assumed in the computation of E_{iso} . In particular, as can be seen in Fig. 5, where I show the result obtained with the improved sample of 122 GRBs available as of the end of 2010, the function $\chi^2(\Omega_M)$ shows a nice parabolic shape with a minimum at $\Omega_M \sim 0.25-0.30$. This is a very very simple but relevant result: a) it shows that the $E_{p,i} - E_{iso}$ correlation can indeed be used to extract information on cosmological parameters; b) it provides evidence, independently on type Ia SNe or other probes, that, if we live in a flat Universe as implied by inflation and supported by CMB measurements, the density of the Universe is dominated by an unknown component (e.g., "dark energy").

Given the significant extra-Poissonian scatter of the correlation, the simple χ^2 method cannot be used to obtain reliable confidence levels on both the parameters of the correlation (normalization and slope) and the cosmological parameters. To this purpose, in Ref. 3 it was adopted a maximum likelihood method accounting for the uncertainties on both the X and Y quantities and the extra variance σ_{ext} . In Table 1, I show the 68% and 90% c.l. intervals for Ω_M , in the assumption of a flat Universe, obtained in this way with the sample of 70 GRBs used by Ref. 3 and the 122 GRBs presently available. As can be seen, by increasing the number of GRBs in the sample the accuracy of the estimate of Ω_M improves. This is confirmed also by the investigation of the confidence contours in the $\Omega_M - \Omega_\Lambda$ plane computed by following the same method as above but releasing the flat Universe assumption. As can be seen in Fig. 6, the 68% confidence region obtained with the present 122 GRBs is smaller than that corresponding to the 70 GRBs by Ref. 3.

5. Future perspectives

The improvement in the accuracy of the estimate of cosmological parameters with the $E_{p,i} - E_{iso}$ correlation obtained by enlarging the sample on which the analysis is performed (Tab. 1 and Fig. 6), confirms that the method is reliable and promising. Presently, the main contribution to the number of GRBs that populate the $E_{p,i} - E_{iso}$ plane comes from joint detections by *Swift* the Fermi/GBM or Konus-WIND. Indeed, while the Swift/BAT allow high sensitivity detection and prompt accurate localization of GRBs, which allows very early optical follow-up thus increasing

Fig. 6. 68% confidence level contours in the $\Omega_M - \Omega_\Lambda$ plane obtained by releasing the flat Universe assumption with the sample of 70 GRBs by Ref. 3 (dashed contour) and the sample of 122 GRBs available at the end of 2010 (continuous contour).

substantially the chance of measuring the redshift, broad energy band spectroscopy (from ~ 10 –15 keV up to several MeVs) is required to get a reliable estimate of $E_{p,i}$ and E_{iso} . Hopefully, these missions will continue to operate for at least a few years, providing us with a rate of ~ 15 –20 GRB/year, useful to further enrich the $E_{p,i} - E_{iso}$ sample and refine the present estimates of cosmological parameters. However, a real breakthrough in these field should come from next generation missions capable to perform both the task of prompt accurate localization and broad-band spectroscopy of GRBs, like the French–Chinese SVOM¹⁵, planned for 2015–2016, or the Brazilian–Italian MIRAX¹⁶, presently under study.

References

1. L. Amati, F. Frontera, M. Tavani et al., *Astronomy & Astrophysics* **390** (2002) 81.
2. L. Amati, *Monthly Notices of the Royal Astronomical Society* **372** (2006) 233.
3. L. Amati, C. Guidorzi, F. Frontera et al., *Monthly Notices of the Royal Astronomical Society* **391** (2008) 577.
4. L. Amati, F. Frontera and C. Guidorzi et al., *Astronomy & Astrophysics* **508** (2009) 173.
5. B. Zhang and P. Mészáros, *The Astrophysical Journal* **581** (2002) 1236.
6. D.Q. Lamb, G.R. Ricker, J-L. Atteia et al. *New Astronomy Reviews* **48** (2004) 323.
7. L. Amati, M. della Valle, F. Frontera, *Astronomy & Astrophysics* **463** (2007) 913.
8. G. Ghirlanda, G. Ghisellini and D. Lazzati, *The Astrophysical Journal* **616** (2004) 331.
9. Z.G. Dai, E.W. Liang and D. Xu *The Astrophysical Journal* **612** (2004) L101.
10. R. Sari, T. Piran and J.P. Halpern *The Astrophysical Journal* **519** (1999) L17.
11. G. Ghirlanda, G. Ghisellini and C. Firmani, *New Journal of Physics* **8** (2006) 123.
12. B.E. Schaefer, *The Astrophysical Journal* **660** (2007) 16.

13. Y. Kodama, D. Yonetoku, T. Murakami et al, *Monthly Notices of the Royal Astronomical Society* **391** (2008) L1.
14. M. Demianski, E. Piedipalumbo, C. Rubano, *Monthly Notices of the Royal Astronomical Society* **411** (2011) 1213.
15. D. Gotz, J. Paul, S. Basa et al., SVOM: a new mission for Gamma-Ray Burst Studies, in *GAMMA-RAY BURST: Sixth Huntsville Symposium*, AIP Conference Proceedings, Vol. 1133 (Springer-Verlag, New York, 1999), p. 25.
16. L. Amati, M. Feroci, F. Frontera et al., A proposed Italian contribution to the MIRAX Scientific Payload, to appear in *Il Nuovo Cimento C*.