Mem. S.A.It. Vol. 80, 207
© SAIt 2009
Memorie della

Gamma–ray bursts as cosmological probes

L. Amati

Istituto Nazionale di Astrofisica – IASF Bologna, Via P. Gobetti 101, I-40129 Bologna, Italy, e-mail: amati@iasfbo.inaf.it

Abstract. Given their huge isotropic–equivalent luminosities, up to more than 10^{53} erg s^{-1}, and their redshift distribution extending up to at least ~6.4, Gamma–Ray Bursts (GRB) are in principle a powerful tool for cosmology, complementary to other probes like SN Ia, clusters, BAO and the CMB. However, they are not standard candles, given that their luminosities span several orders of magnitude, even when considering possible collimation angles. In the recent years, several attempts to use the correlation between the photon energy at which the νF_νspectrum peaks ("peak energy") and the luminosity or radiated energy to "standardize" GRBs and use them for the estimate of cosmological parameters have been made. These studies show that already with the present data GRBs can provide a significant and independent confirmation of Ω_M<0.5 for a flat ΛCDM universe and that the measurements expected from present and next GRB experiments (e.g. *Swift* , GLAST/GBM, SVOM) will allow to constrain Ω_M, Ω_Λ and hopefully to get clues on dark energy evolution.

Key words. Gamma–rays: observations – Gamma–rays: bursts – Cosmology: cosmological parameters

1. Introduction

The study of the properties and origin of cosmic Gamma–Ray Bursts (GRB), unpredictable huge flashes of hard X–ray radiation coming from random directions in the sky at a measured rate of ~300/year, is still one of the hottest topics in modern astrophysics. A break–through in the study of these phenomena occurred in 1997, with the discovery of afterglow emission and of the first optical counterparts and host galaxies, leading ultimately to the determination (through optical spectroscopy) of their cosmological distance scale. Since then, the redshift was estimated for ~130 GRBs, ranging from ~0.03 to ~6.4, with the exception of the very peculiar GRB 980425, lying at $z = 0.0008$. This high redshift values, combined with the very high fluxes (up to more than 10^{-5} erg cm^{-2} s^{-1}), make GRBs the most luminous sources in the universe, with isotropic–equivalent radiated energies typically ranging from ~10^{50} to more than ~10^{54} erg. The standard scenarios for GRB progenitors, based on further observational evidences, are core–collapse of peculiar massive stars for long (>1–2 s) ones and merging of binary systems made of two collapsed stars (NS–NS, NS–BH) for short ones. In both cases, but especially for long GRBs, the predominantly non–thermal emission is thought to be originated by shocks between shells within an ultra–relativistical (Γ>100) fireball made of pairs, photons and a small fraction of baryons,

Send offprint requests to: L. Amati

and/or by the shock of the fireball itself with the ISM (Meszáros 2006).

As can be seen in Fig. 1, the redshift distribution of GRBs extends much above that of cosmological probes like type Ia SNe; this property, combined with the huge luminosities, makes GRBs ideal sources for cosmology. For instance, they could be used to estimate cosmological parameters in an independent and complementary way to other cosmological probes (SN Ia, clusters, BAO, CMB, etc.), with particular sensitivity to dark–energy characteristics and evolution. However, as can be seen in Fig. 1, GRBs are not standard candles, showing values of the isotropic–equivalent radiated energy ($E_{\rm iso}$) which span several orders of magnitude. Even when applying a correction for the possible collimation angle inferred from the break observed in the optical light curve of ~20 GRBs, the luminosity / radiated energy spans at least 3 orders of magnitude. Thus, in order to use GRBs as cosmological probes, a way to standardize them has to be found. Under this respect the most promising and investigated GRB property is the correlation between the "peak energy", i.e. the photon energy at which the νF_ν spectrum peaks, and the radiated energy or luminosity (Amati 2006), as I will discuss in next Sections.

2. The $E_{\rm p,i}$ – $E_{\rm iso}$ correlation in GRBs

The spectra of GRB prompt X/gamma–ray emission are non–thermal and can be described by two smoothly jointed power–laws, with the high energy power–law usually substantially steeper than the low energy one. The empirical model adopted to fit GRBs photon spectra is the Band function, which is parameterized by a low energy index α, an high energy index β and a roll–over photon energy E_0, typically ranging from −0.5 to −1.5, −2.1 to −3 and from a few tens of keV to several hundreds of keV, respectively. The above values of the spectral indices imply that the νF_ν spectra of GRBs typically show a peak at a photon energy $E_{\rm p}= (2 + \alpha) \times E_0$, hence called "peak energy". $E_{\rm p}$ is a characteristic frequency in the standard models of GRB prompt emission, which are mostly based on synchrotron emission produced by fireball electrons in internal and/or external shocks plus possible contributions of Inverse Comtpton and direct or Comptonized thermal emission from the fireball photosphere. The bulk of long GRBs population, as measured by the BATSE experiment in the '90s, show $E_{\rm p}$ values from ~50 keV to 700-800 keV, but a sub–population of events showing low $E_{\rm p}$ values (down to a few keV or even less) and named X–Ray Flashes (XRF) was later discovered by *Beppo*SAX and HETE–2.

For those GRBs with known redshift, ~130 up to March 2008, it is possible to compute the cosmological rest–frame spectrum and thus derive interesting intrinsic properties like the intrinsic peak energy $E_{\rm p,i} = E_{\rm p}\times (1 + z)$ and the total radiated energy in a "bolometric" energy range (the commonly adopted band is 1–10000 keV in the cosmological rest–frame)

$$E_{iso} = \frac{4\pi D_l^2}{(1+z)} \int_{1/1+z}^{10^4/1+z} E\,N(E)\,dE \ \ \text{erg}\,, \quad (1)$$

where N(E) is the time integrated photon spectrum and D_l is the luminosity distance. As $E_{\rm iso}$, $E_{\rm p,i}$ is found to span several orders of magnitude, with a tail towards low energies corresponding to the observed XRFs. Based on a still small sample of *Beppo*SAX GRBs with known redshift and $E_{\rm p}$, Amati et al. (2002) discovered a very significant correlation between these two quantities $E_{\rm p,i}$ and $E_{\rm iso}$. This correlation, which is commonly called $E_{\rm p,i}$ – $E_{\rm iso}$, or "Amati", correlation, was confirmed and extended to XRFs by subsequent measurements (HETE–2, *Swift* , Konus–WIND; etc.) and has the functional form

$$E_{p,i} = K \times E_{iso}^m\,, \quad (2)$$

with m~0.5 and K~95 (Amati 2006). Detection thresholds as a function of GRB fluence and spectrum and/or the various steps leading to the estimates of redshift (GRB detection, follow–up, optical afterglow and/or host galaxy detection, optical spectroscopy), may introduce selection effects. However, long GRBs and XRFs in the present sample of GRBs with known z and $E_{\rm p,i}$ were detected by several instruments with different threshold,

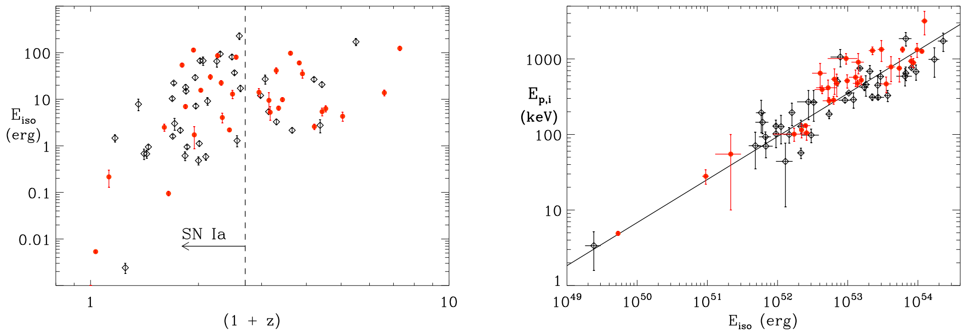

Fig. 1. E_{iso} vs. redshift (left) and $E_{p,i}$ vs. E_{iso} (right) for the sample of 70 GRBs with known redshift and well defined time–integrated spectrum analyzed by Amati et al. (2008). *Swift* GRBs are shown as filled squares. In the left panel, the present upper limit of the redshift distribution of type Ia SNe is shown as a dashed line. In the right panel, the best fit power–law from Amati (2006) is superimposed to the data.

energy bands, etc., suggesting that the impact of selection effects on the $E_{p,i} - E_{iso}$ correlation is not significant. This evidence is further confirmed by the fact that all long GRBs with known z and $E_{p,i}$ detected by *Swift* , whose fast and accurate localizations allow the reduction of selection effects in optical counterparts detection and thus in redshift estimates, are consistent with the correlation too.

3. Constraining cosmological parameters with GRBs

The computation of E_{iso} (or the luminosity) obviously depends, through the luminosity distance D_l, on the assumed cosmological parameters (i.e., Ω_M and Ω_Λ, in the standard ΛCDM cosmology), whereas $E_{p,i}$ can be estimated based only on measure quantities (E_p and z). Thus, the use of the $E_{p,i} - E_{iso}$ correlation for standardizing GRBs, in a way similar, e.g., to SN Ia, is tempting. However, despite its very high significance, the $E_{p,i} - E_{iso}$ correlation is characterized by a significant extrinsic variance, i.e., a scatter of the data around the best–fit power–law in excess to that due to Poissonian (”intrinsic”) fluctuations of the data. This means that, in addition to possible systematics in the estimates of $E_{p,i}$ and E_{iso}, there is one or more ”hidden” variable, linked to GRB physics and/or geometry, playing a not negligible role. Thus, despite the correlation was discovered in 2002, the investigations of its use for cosmology started only in 2004, prompted by the evidence that by including as a third observable the time t_b at which the optical afterglow light curve of some GRBs breaks (i.e., the slope of its power–law decay becomes steeper), or by using the jet opening angle θ_j inferred from t_b assuming a standard afterglow model to compute the collimation–corrected radiated energy $E_\gamma = E_{iso} \times [1\text{-}\cos(\theta_j)]$, the extrinsic variance of the correlation shows a substantial reduction (a factor of ∼2). Later on it was also found that another three–parameters spectrum–energy correlation, the $L_{p,iso}$–$E_{p,i}$–$T_{0.45}$ correlation, based only on GRB prompt emission properties ($L_{p,iso}$ is the isotropic–equivalent peak luminosity, $T_{0.45}$ is an ”high signal” time scale used for GRB variability studies and is a fraction of the total GRB duration) shows a lower extrinsic scatter with respect to the simple $E_{p,i} - E_{iso}$ correlation (Ghirlanda et al. 2006). Given that all GRBs with known redshift and $E_{p,i}$ lie at $z > \sim 0.1$, these correlations were discovered by assuming standard values for the cosmological parameters (typically H_0 =0.65–0.70, Ω_M=0.27–0.30, Ω_Λ= 1 - Ω_M). Thus, in order to avoid trivial circularity problems, they cannot be used directly to derive E_{iso} or $L_{p,iso}$ from $E_{p,i}$ (and t_b or $T_{0.45}$), construct an Hubble diagram and fit it with a cosmological model. The most commonly adopted method consists

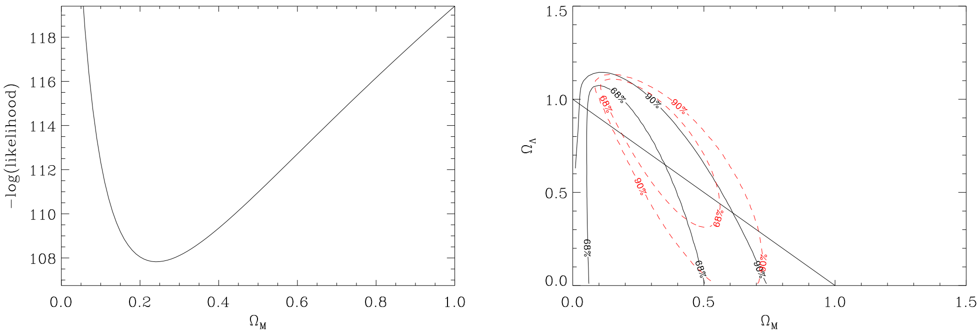

Fig. 2. Left: −log–(likelihood) as a function of $\Omega_{\rm M}$ (for a flat ΛCDM universe) obtained by fitting with a simple power–law the $E_{\rm p,i}$ – $E_{\rm iso}$ values of the 70 GRBs in the sample of Amati et al. (2008). Right: Confidence contour levels of $\Omega_{\rm M}$ and Ω_{Λ} obtained by fitting with a likelihood method accounting for extrinsic variance (see Amati et al. 2008, for details) the present (70 events, continuous lines) and the future (70 real events + 150 simulated events, dashed lines) GRB samples from Amati et al. (2008).

in computing the $E_{\rm iso}$ values for each set of cosmological parameters (e.g., for each value of $\Omega_{\rm M}$ in the assumption of a flat universe), fit the correlation and obtain a χ^2, or likelihood function, value (Ghirlanda et al. 2006; Amati et al. 2008). Values and confidence levels for the cosmological parameters are then obtained by using chi–square or likelihood statistics. In other words, these methods assume that a fraction of the scatter of the correlation depends on the assumed cosmological model. As mentioned above, the first analysis of this kind were performed basing on three–parameters correlations ($E_{\rm p,i} - E_\gamma$, $E_{\rm p,i} - E_{\rm iso} - t_b$, $L_{\rm p,iso}$–$E_{\rm p,i}$–$T_{0.45}$) and provided results consistent with the "concordance cosmology" (i.e., a flat ΛCDM universe with $\Omega_{\rm M}$~0.25-0.30) (Ghirlanda et al. 2006). However, recently there were observational evidences that the extrinsic scatter of these correlations could be larger than thought before, and that the estimate of the third observable (t_b or $T_{0.45}$) is dependent on specific assumptions. This prompted Amati et al. (2008) to investigate the cosmological use, always based on the scatter method described above, of the $E_{\rm p,i} - E_{\rm iso}$ correlation, which has the advantages of being based only on two observables, thus implying lower systematics and a much larger sample (e.g., by a factor of ~3 with respect to the $E_{\rm p,i} - E_\gamma$ or $E_{\rm p,i} - E_{\rm iso} - t_b$ correlations). As can be seen in Fig. 2 (left) for the case of a flat universe, the scatter of the $E_{\rm p,i} - E_{\rm iso}$ correlation is indeed sensitive to $\Omega_{\rm M}$ and minimizes around 0.25–0.30, in agreement with the "concordance" cosmology. It is important to note that these constraints are complementary to those from other cosmological probes (e.g., SN Ia, CMB, BAO, clusters) and that, given their redshift distribution, GRBs are expected to be the more sensitive probes to dark energy properties and evolution. By releasing the flat universe hypothesis, $\Omega_{\rm M}$ can still be constrained to be <0.5, but only an upper limit (<1.1) can be set to Ω_Λ (Fig. 2, right). However, simulations show that, with the enriched sample of GRBs with known z and $E_{\rm p,i}$ expected in the next few years by GRB experiments like *Swift*, Konus–WIND, GLAST/GBM and SVOM, significant constraints on $\Omega_{\rm M}$ and Ω_Λ will be obtained (Ghirlanda et al. 2006; Amati et al. 2008).

References

Amati, L., et al., 2002, A&A, 390, 81
Amati, L., 2006, MNRAS, 372, 233
Amati, L., et al., 2008, `ArXiv:0805.0377`, MNRAS, submitted
Ghirlanda, G., Ghisellini, G. & Firmani C., 2006, New Journal of Physics, 8, 123
Meszáros P., 2006, Prog.Phys., 69, 2269