GAMMA–RAY BURSTS AS COSMOLOGICAL PROBES

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Gamma–Ray Bursts (GRB) are the most powerful cosmological phenomena in the universe, with isotropic–equivalent luminosities up to 10^{53} erg $s^{-1}$and a redshift distribution extending from ~0.1 up to at least ~6.4. Thus, they are a very promising tool for cosmology, complementary to other probes like SN Ia, clusters, BAO and the CMB. However, GRBs 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) will allow to constrain Ω_M, Ω_Λ and hopefully to get clues on dark energy evolution

1 GRBs: the most luminous cosmological sources

Gamma–Ray Bursts (GRB) are sudden flashes of hard X–ray radiation (typically from a few keV to 1–2 MeV) coming at unpredictable times from random and isotropically distributed directions in the sky, lasting typically tens of s (but their durations range from tens of ms up to thousands of s) and detected with a rate of ~0.8 event/day by all–sky GRB experiment on board low Earth orbit satellites . 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, and/or by the shock of the fireball itself with the ISM[1].

As can be seen in Fig. 1a, the redshift distribution of GRBs extends much above that of cosmological probes like type Ia SNe; this property, combined with the huge luminosities and the

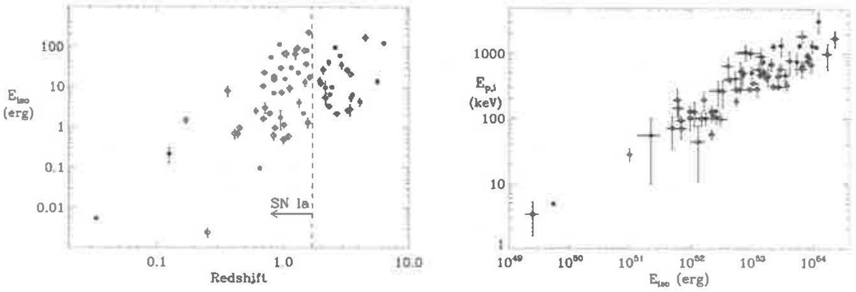

Figure 1: E_{iso} vs. redshift (left) and $E_{p,i}$ vs. E_{iso} (right) for the sample of 70 GRBs with known redshift and well defined time–integrated spectrum analyzed by Amati et al. (2008). *Swift* GRBs are shown as filled squares. In the left panel, the present upper limit of the redshift distribution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

fact that X–ray measurements are not affected by the extinction problems typical of the optical ones, makes GRBs ideal sources for cosmology. For instance, they could be used to estimate comological 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_{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. As I will discuss in the next sections, 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_νspectrum peaks, and the radiated energy or luminosity[2].

2 GRBs spectrum–ener[illegible]rrelations

GRB prompt X/gamma–ray emission is characterized by non thermal spectra that 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 parametrized 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_νspectra of GRBs typically show a peak at a photon energy $E_p = (2 + \alpha) \times E_0$, hence called "peak energy". E_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 $E_p$values from ~50 keV to 700-800 keV, but a sub–population of events showing low E_p values (down to a few keV or even less) and named X–Ray Flashes (XRF) was later discoverd 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 $E_{p,i} = E_p \times (1 + z)$ and the total radiated energy in a "bolometric" energy

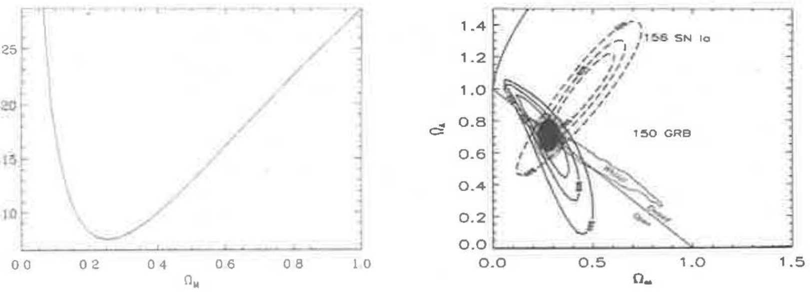

Figure 2: Left: χ^2value of the fit of the $E_{p,i} - E_{iso}$ correlation (70 GRBs in the sample of Amati et al. 2008) with a simple power-law as a function of the value of Ω_M assumed to compute the E_{iso}values. Right: simulations of the Ω_M, Ω_Λ contours expected by using the $E_{p,i} - E_\gamma$ correlation on a future sample of 150 GRBs with known z and $E_{p,i}$ (from Ghirlanda et al. 2006).

range (the commonly adopted band is 1–10000 keV in the cosmological rest–frame)

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

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

$$E_{p,i} = K \times E_{iso}^m \tag{2}$$

, with m~0.5 and K~95 [2]. In the past, there were debates about possible selection effects affecting the correlation, introduced, e.g., by detection thresholds as a function 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). However, the fact that all long GRBs and XRFs with known redshift and E_p, detected by several instruments with different thresholds, and in particular *Swift* GRBs, are consistent with the $E_{p,i} - E_{iso}$ correlation (except for the very peculiar, very close and sub–energetic GRB 980425) show that the impact of selection effects is not significant.

3 Estimating cosmological parameters

Given that it links a cosmology–independent observable, $E_{p,i}$, to the total radiated energy E_{iso} (or the luminosity), which obviously depends, through the luminosity distance D_l, on the assumed cosmology, 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 $E_\gamma = E_{\rm iso} \times [1\text{-}\cos(\theta_j)]$, the extrinsic variance of the correlation shows a substantial reduction (a factor of $\sim$2). Later on it was also found that another three–parameters spectrum–energy correlation, the $L_{\rm p,iso}$–$E_{\rm p,i}$–$T_{0.45}$ correlation, based only on GRB prompt emission properties ($L_{\rm p,iso}$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 $E_{\rm p,i}$ - $E_{\rm iso}$ correlation [3].

Given that all GRBs with known redshift and $E_{\rm p,i}$ 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, $\Omega_M = 0.27$–0.30, $\Omega_\Lambda = 1 - \Omega_M$). Thus, in order to avoid trivial circularity problems, they cannot be used directly to derive $E_{\rm iso}$ or $L_{\rm p,iso}$from $E_{\rm p,i}$ (and t_b or $T_{0.45}$), construct an Hubble diagram and fit it with a cosmological model. The most commonly adopted method consists in computing the $E_{\rm iso}$ values for each set of cosmological parameters (e.g., for each value of Ω_M in the assumption of a flat universe), fit the correlation and obtain a χ^2, or likelihood function, value [3,4] . 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. Other methods, based, e.g., on more sophisticated Bayesian approaches, have been proposed, providing slightly more constrained values of cosmological parameters.

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 $\Omega_M \sim 0.25$-0.30) [3]. 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) [4] 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 $\sim$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 Ω_M and minimizes around 0.25–0.30, in agreement with the "concordance" cosmology. By releasing the flat universe hypothesis, the Ω_M can still be constrained to be <0.5, but only an upper limit (<1.1) can be set to Ω_Λ. However, as can be seen in Fig. 2 (right), simulations show that, with the enlarged 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, tight constraints on Ω_M and Ω_Λ, complementary to those from other cosmological probes (e.g., SN Ia, CMB, BAO, clusters) will be obtained. Moreover, given their redshift distribution, GRBs are the cosmological probes expected to be more sensitive to dark energy properties and evolution.

References

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