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Cosmology with Gamma–Ray Bursts

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Abstract. Thanks to their large luminosity, GRBs are detectable up to very high redshift (z=8.2 the present record holder). This makes GRBs very appealing for cosmological purposes as, for example, the possibility to put some independent constraints on the cosmological parameters. Similarly to Supernovae type Ia, GRBs are not characterised by a unique value of their luminosity/energetics. The use of several empirical correlations between the energy/power of GRBs and their peak energy has been proposed to overcome this problem. This solution, however, faces several problems, such as the lack of low redshift calibrators for all the proposed correlations, the large dispersion of several of these correlations, the lack of their theoretical interpretation and the still small number of objects. We review the methods proposed to use GRBs as standard candles. We discuss advantages and limitations of the correlations commonly used and the present status of constraining the cosmological parameters through GRBs.

Key words. Gamma-ray burst: general – Cosmology: cosmological parameters

1. Introduction

Gamma–Ray Bursts (GRBs) are cosmological sources. Their redshift distribution peaks at $z \sim 2$ and extends up to $z = 8.27$, making GRBs very appealing as cosmological tools. In particular, their use as standard candles to estimate the cosmological parameters ($\Omega_{\rm m}$ and Ω_Λ) has been proposed. This possibility is very attractive. In fact, GRBs can extend the Hubble diagram to higher redshifts as compared to Supernovae type Ia (SNIa – that can be detected up to $z \sim 1.7$) and cover the gap with other cosmological probes. Moreover, GRBs are not affected by the same problems related to SNIa, such as dust extinction. These properties make GRBs a cosmological tool which is not only complementary to but also independent of SNIa.

Similarly to SNIa, GRBs are not standard candles strictly speaking since they do not have the same peak luminosity (nor the same energetics). However, their energetic and luminosity correlate with observed quantities that are independent of the cosmological parameters. Several correlations have been discovered in long GRBs. The most remarkable ones involve the rest frame peak energy of the νF_ν prompt spectrum $E_{\rm peak}$. This quantity correlates with i) the isotropic energy $E_{\rm iso}$ (Amati et al. 2002), ii) the isotropic peak luminosity $L_{\rm iso}$ (Yonetoku et al. 2004) and iii) the collimation–corrected energy E_γ (Ghirlanda et al. 2004a). Moreover, it has been claimed that the peak luminosity correlates with other quantities that are related to

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the prompt lightcurves, such as the variability, the time lag, the number of peaks and the minimum rise time. All these correlations, characterised by different properties, have been considered for cosmological purposes. Different authors have considered different methods. We review some of the proposed methods and their results.

2. Methods

We identified three main approaches proposed to estimate Ω_m and Ω_Λ with GRBs:

– the use of a correlation with a small dispersion, i.e. characterised by a scatter which is consistent with the statistical errors on the involved quantities (Ghirlanda et al. 2004b, Liang & Zhang 2005);
– the use of a correlation with a large dispersion (Amati et al. 2008, Kodama et al. 2008);
– the simultaneous use of several correlations (Schaefer 2007).

In the following, we discuss the advantages, limitations and results of each approach.

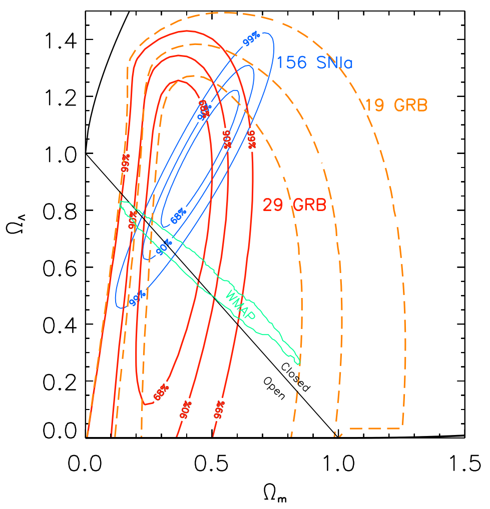

Fig. 1. Constraints on the cosmological parameters obtained with the E_{peak}–E_γ correlation updated to Jan 2011 (29 bursts – solid line) compared to the previous update (19 GRBs – dashed line). Also shown are the constraints obtained from 156 SNIa (blue thin line) and those from the WMAP data (green thin line).

2.1. Correlations with a small scatter

The E_{peak}–E_γ correlation (Ghirlanda et al. 2004a) has a small dispersion of points around its best fit line and this dispersion is consistent with the statistical errors on E_{peak} and E_γ. Ghirlanda et al. (2004b) showed that it is possible to use this relation to put constraints on Ω_m and Ω_Λ. Their results are consistent with those derived from SNIa and from other probes (as the microwave background) but the constraints are not competitive (Fig. 1). By simulating a sample of 150 GRBs, they demonstrated that this is due to the small number of GRBs that populate the E_{peak}–E_γ correlation (29 at present). This number is strongly limited by the difficulty of measuring the jet break time from the afterglow lightcurves, and consequently, of estimating the jet opening angle θ_{jet}. The main criticism addressed to the use of this correlation concerns its dependence from a theoretical model (the jet model). The jet model predicts that to derive the jet opening angle some (unknown) properties as the prompt emission efficiency and the density of the interstellar medium are needed. The dependence of θ_{jet} on these quantities is quite weak. The assumption that all bursts have the same values of efficiency and density does not strongly affect the estimate of the collimation–corrected energy E_γ. The main issue related to the model–dependence of the E_{peak}–E_γ correlation concerns, instead, the assumption on the radial profile of the circumburst medium. Different radial profiles lead to different equations for the estimate of θ_{jet} and lead to quite different E_{peak}–E_γ relations, characterised by similar scatter but different slopes (the slope is ~ 1 for a wind–like density profile and ~ 0.7 for a homogeneous profile, Nava et al. 2006).

Liang & Zhang (2005) proposed a correlation between three parameters: E_{peak}, E_{iso} and the break time T_{break} measured from the optical light curve. These quantities are the same involved in the E_{peak}–E_γ correlation, but in this case T_{break} is not interpreted as due to the conical geometry of the emission. This correlation is empirical, since it is not based on the jet model and it does not require any assumption on the ISM density profile and on the prompt emission efficiency. Even if this correlation allows to overcome the criticism related to the model dependence of the E_{peak}–E_γ correlation, the number of objects populating the correlation is equally small and the constraints on Ω_m and Ω_Λ are again not competitive.

2.2. Correlations with a large scatter

In order to avoid the problem related to the small number of events, other authors proposed the use of more populated correlations, like the E_{peak}–E_{iso} and E_{peak}–L_{iso} ones. However, these relations are characterised by a large dispersion of points around the best fit line. The statistical errors on the involved quantities cannot explain this large dispersion, which is likely related to the presence of an hidden quantity. The large χ^2 does not allow to use these correlations to standardise the energetics/luminosity of GRBs.

Amati et al. (2008) proposed a method to avoid this issue and apply GRBs to cosmology by means of the E_{peak}–E_{iso} correlation. They introduce an extra term to account for the extrinsic scatter. In particular, they assume that this term is equal for all bursts, acts on E_{peak} and is gaussian. Their idea is motivated by the fact that they found that this extra–variance term depends on Ω_m (for a flat Universe) and shows a minimum around $\Omega_m \sim 0.15$.

The results on the confidence contours in the Ω_m–Ω_Λ plane (Amati et al. 2008) are similar to those obtained with less scattered correlations: the introduction of this method, that allows to use more populated (and more scattered) relations, does not produce an improvement on the constraints found with less populated (an less scattered) correlations. Moreover, this method requires the introduction of strong and questionable assumptions on the shape and characteristic of this extrinsic variance term. To test the robustness of this method we consider the following case. We adopt the same method proposed by Amati et al. (2008) but we associate the extrinsic variance term to E_{iso} instead of E_{peak}. This seems a more appropriate choice, since it is E_{iso} (and not E_{peak}) that depends on the cosmology. This different assumption produces very different results: the extra–variance term has a weak dependence on Ω_m and a weak minimum in $\Omega_m \sim 0.6$ (Fig. 2).

2.3. Simultaneous use of several correlations

Schaefer (2007) proposed the simultaneous use of five luminosity indicators and constructed the Hubble diagram for GRBs. For a given burst in their sample, they calculate the distance modulus. Since they have five luminosity indicators, they derive for each GRB five estimates of the distance modulus and then derive the best estimate from the weighted average of all estimates. Since the slope and normalization of each correlation depend on the assumed values of Ω_m and Ω_Λ, the Hubble diagram (in the form distance modulus vs redshift) for the considered sample changes accordingly to the assumed cosmology. To calculate the goodness of a particular cosmology, they compare the Hubble diagram (obtained from the luminosity indicators obtained in that cosmology) to the theoretical model.

They derive the cosmological parameters with an accuracy which is compatible with the accuracy found following the other methods.

3. Conclusions

The use of GRBs as cosmological tools is very appealing, since they can extend the Hubble diagram to redshifts not accessible to SNIa. Correlations between the energy (or the luminosity) and a cosmology–independent observable are needed. Several correlations have been found in long GRBs. The best candidates are those with a small scatter (E_{peak}–E_γ and E_{peak}–E_{iso}–T_{break}). These correlations are populated by a quite small number of objects (29 events at present). Correlations with a larger sample (such as the Amati and Yonetoku relations, containing at present more than 130 events) are

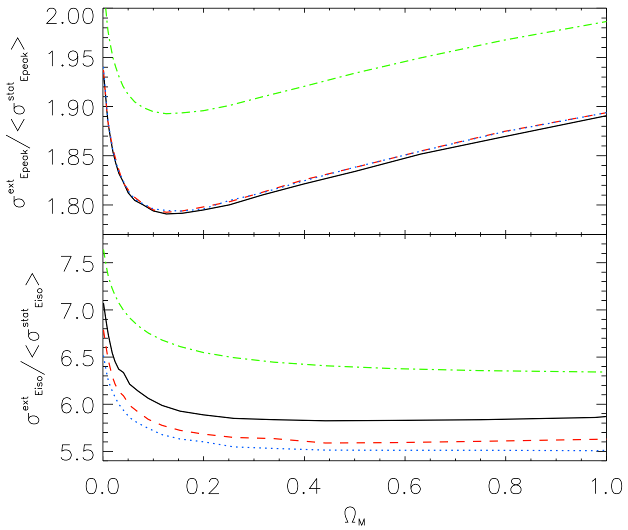

Fig. 2. Test of the use of the E_{peak}–E_{iso} correlation for constraining the cosmological parameters. The extra-scatter term σ^{ext} is normalized to the average value of the statistical error associated to the variable it is assigned to. Top panel: σ^{ext} is assigned to E_{peak} and results similar to those of Amati et al. (2008) are found (a minimum is found for $\Omega_m \sim 0.15$). The solid curve is found with the likelihood function, the dotted and dashed curves are found with the symmetric likelihood function. The dot-dashed line is found with the χ^2 fitting method. Bottom panel: σ^{ext} is assigned to E_{iso}. No minimum of the extra-scatter term is found in this case for any value of Ω_m.

characterised by larger scatters, not compatible with measure errors. It has been proposed that this extra variance can be modelled and varies with Ω_m, showing a minimum in $\Omega_m \sim 0.15$. The first attempt to adopt this method (Amati et al. 2008) revealed that there was no improvement in the confidence contours with respect to the results obtained by considering less scattered correlations (that do not require the introduction of any extrinsic variance term). Moreover, the method itself is questionable for the strong assumptions on the extra variance term. We also found that the dependence of this extra-varance term on the cosmology has a very different shape when it is associated to E_{iso} (instead of E_{peak}): in this case a slight minimum is present at $\Omega_m \sim 0.6$. This test questions the robustness of the proposed method.

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