On the future of Gamma-Ray Burst Cosmology

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Abstract. With the understanding that the enigmatic Gamma-Ray Bursts (GRBs) are beamed explosions, and with the recently discovered “Ghirlanda-relation”, the dream of using GRBs as cosmological yardsticks may have come a few steps closer to reality. Assuming the Ghirlanda-relation is real, we have investigated possible constraints on cosmological parameters using a simulated future sample of a large number of GRBs inspired by the ongoing SWIFT mission. Comparing with constraints from a future sample of Type Ia supernovae, we find that GRBs are not efficient in constraining the amount of dark energy or its equation of state. The main reason for this is that very few bursts are available at low redshifts.

Key words. gamma rays: bursts – cosmology

1. Introduction

The usage of thermonuclear Type Ia supernovae (SNe Ia) has revolutionized cosmology. These intrinsically bright explosions are almost standard candles in optical light. With a simple light-curve correction they can be standardized to high enough precision to probe in detail the energy content of the universe. This led to the discovery that dark energy dominates the presently accelerating universe (e.g., Riess et al. 1998; Perlmutter et al. 1999). Today, SN Ia data is approaching the quality and quantity where it is possible to constrain not only the amount of dark energy but also dark energy properties (e.g., Hannestad & Mörtsell 2002; 2004).

Gamma-Ray Bursts are even more powerful explosions. They have recently been firmly linked to energetic core-collaps supernovae (Hjorth et al. 2003; Matheson et al. 2003). Their isotropic energy appears to outpower thermonuclear supernovae, which allows studies at even higher redshifts. Also, in contrast to the case of SNe Ia where the rate is unknown at \(z > 1.5\) (Dahlén et al. 2004), we know that GRBs exist at high redshifts (e.g., Andersen et al. 2000). Moreover, the released burst of gamma-rays can penetrate the dust that obscures our view of the distant universe in optical light. For current constraints on dust attenuation of SNe Ia, see Östman & Mörtsell (2005). The potential of GRBs as probes for cosmological investigations thus appears to be very good.

The realization that the total gamma-ray energy of a GRB, when corrected for the effects of beaming, spans a reasonably narrow range of energies (Frail et al. 2001) has renewed the hope for GRB cosmology. This relation allows an empirical correction to the determined luminosity distances for each GRB, in much the same way as light-curve shape corrections are applied to SNe Ia, with a scatter along the GRB Hubble diagram of ~ 0.5 mag (Ghirlanda et al. 2004b). This has caused a fierce activity of research in the area of GRB cosmology (e.g., Ghirlanda et al. 2004a; Dai et al. 2004; Firmani et al. 2005; Xu et al. 2005; Xu 2005).

There is, however, much to be done before GRB cosmology can be established. The reality of the Ghirlanda relation is still under discussion (Band & Preece 2003; Friedman & Bloom 2005; Ghirlanda et al. 2005). Moreover, very different results on GRB cosmology are obtained by the different authors, based on the current sample of GRBs. Friedman & Bloom (2005) thoroughly examined pros and cons of GRB cosmology with the presently limited sample of well studied GRBs, and show that the obtained results are crucially dependent on the choice of (poorly known) input parameters. The way to select which GRBs to include also influence the results. Friedman & Bloom (2005) are therefore rightfully cautious concerning claims of the utility of GRBs for cosmology. A larger dataset is clearly needed to establish this issue.

The recently launched SWIFT satellite (Gehrels et al. 2004) will find hundreds of GRBs. In this paper we simulate the potential effect of such a large number of GRBs for the use of determining cosmological parameters, assuming that the Ghirlanda relation holds.

In Sect. 2 we present the method used for deriving cosmological parameters from GRBs. We also discuss various assumptions for the constructed input samples that we use for the simulations. The results are discussed in Sect. 3.
The aim of this paper is to investigate the future potential of GRB cosmology by simulating a larger sample of GRBs. For supernova cosmology, many such investigations have been performed, in particular in conjunction with the planned SNAP mission (e.g., Goliath et al. 2004; Wang et al. 2004).

To simulate the effect of a larger future sample we have chosen 200 GRBs with essentially similar properties as the current sample. This number of GRBs is in line with the expectations on the SWIFT satellite, which is predicted to find about 100 bursts every year for a life time of 2-8 years (Gehrels et al. 2004).

2. Simulations

2.1. The method

In the following, we have basically followed the formalism laid out in, e.g., Friedman & Bloom (2005). GRBs are used in much the same way as SN Ia standard candles in constraining cosmological parameters, i.e., by comparing observed luminosity distances to theoretical predictions. However, since the process of standardizing the GRB candles is cosmology dependent, the Ghirlanda relation needs to be recalibrated for each cosmology. Effectively, this amounts to refitting for each cosmology the $E_{\text{peak}} - E_y$ power-law

$$E_{\text{peak}} = \kappa \left( \frac{E_y}{E_0} \right)^\eta.$$  

Note that $E_0$ is an arbitrary constant and that by putting $E_0 \propto h^{-3/2}$, the best-fit $\kappa$ and $\eta$ will be independent of the value of the Hubble parameter. Thus, marginalizing over $\kappa$ and $\eta$ is similar to marginalizing over $\mathcal{M}$ for SNe Ia (e.g., Hannestad & Mörtsell 2002).

There have been several suggestions on how to include the information from the $E_{\text{peak}} - E_y$ fit in the cosmology fit. Dai et al. (2004) basically ignored this complication. This was quickly noted and remedied by Ghirlanda et al. (2004b), who refitted the relation for each cosmology. Ghirlanda et al. (2004b) and Xu et al. (2005) have also used a simple, but rather unrealistic, approach in assuming that $\kappa$ and $\eta$ can be exactly determined using a sample of low redshift GRBs, or by theoretical considerations, and does not need to be recalibrated. Friedman & Bloom (2005) also refits the $E_{\text{peak}} - E_y$ power-law and obtains a new set of $\kappa$ and $\eta$ with corresponding errors for each cosmology. These errors are then propagated to the error in the derived luminosity distance. This approach has the drawback of giving smaller $\chi^2$-values for cosmologies where the $E_{\text{peak}} - E_y$ relation is badly fit since the luminosity distance errors are larger. Xu (2005) discuss a method where cosmologies with a good fit of the $E_{\text{peak}} - E_y$ relation are favored (their Method III). This method is similar to adding the $\chi^2$-values from the cosmology fit and the power-law fit for each cosmology.

In this paper, we treat $\kappa$ and $\eta$ as unknown parameters that should be marginalized over. This means that we do not use the $\kappa$ and $\eta$ that gives the best fit to the $E_{\text{peak}} - E_y$ relation for each cosmology, but instead use the $\kappa$ and $\eta$ that minimizes the cosmology $\chi^2$-value, in analogy with marginalizing over $\mathcal{M}$ for SNe Ia. We have noted that our constraints on the cosmological parameters does not depend sensitively on the specific method used, as long as $\kappa$ and $\eta$ are not assumed to be fixed.

2.2. The GRB sample

The aim of this paper is to investigate the future potential of GRB cosmology by simulating a larger sample of GRBs. For supernova cosmology, many such investigations have been performed, in particular in conjunction with the planned SNAP mission (e.g., Goliath et al. 2004; Wang et al. 2004).
For a true SWIFT sample we should distribute the $E_{\text{peak}}$ in a smaller range, since the BAT instrument is sensitive only in the relatively narrow 15-150 keV range. We have, for the sake of simplicity, ignored this matter, but note that it has been used as an argument to continue the efforts for HETE II and Integral (Friedman & Bloom 2003; Gorosabel et al. 2004).

Lamb (2002) argued that even for the most distant GRBs, follow-up observations will be possible. Redshift determinations will indeed be feasible up to $z \approx 10$ with instruments such as X-shooter (D’Odorico et al. 2004). While optical follow-up of very distant bursts may not be good enough to probe the jet break in detail, also X-ray and near-IR facilities are available for this. Gorosabel et al. (2004) estimate that a near-IR afterglow can be followed up to $z = 9$ even with modest exposure times on a 10-m class telescope. The very late occurrences of jet-breaks will of course be difficult to detect for the dimmest targets, which may bias the sample.

The narrow energy range for SWIFT means that 200 GRBs with measurements of all relevant observables is probably a too optimistic assumption for this mission. This is also supported by the fact that the SWIFT bursts detected so far appears to be faint and has therefore not been successfully characterised (Berger et al. 2005). The sample we use for our simulations should therefore be regarded as a rather optimistic guess that has been influenced by the SWIFT mission, but may have to await future missions to be accomplished. This optimistic assumption will only strengthen our conclusions given below.

2.3. The SN sample

To compare the constraints on the cosmological parameters obtained from our GRB simulation we have also simulated a future set of SN Ia data using the publicly available SNOC package (Goobar et al. 2003). Just as the constructed GRB sample was motivated by the SWIFT mission, which is already ongoing, we base the constructed SN Ia sample on the available Gold sample (Riess et al. 2004) as well as two ongoing supernova surveys, the ESSENCE project and the Supernova Factory.

The ESSENCE project (e.g., Matheson et al. 2005) is an ongoing survey aimed to measure 200 SNe Ia in the redshift domain $z = [0.2 − 0.8]$. The goal is to derive tight constraints on the equation of state, $w$, of the dark energy. In constructing the sample for our simulations we have used the redshift distribution of the hitherto discovered 109 SNe Ia, but increased the number of SN Ia to 200, as planned for ESSENCE (Miknaitis et al. 2004). We have adopted an intrinsic photometric error for an individual supernova of 0.14 mag. Binning 200 SNe into $\Delta m = 0.1$ redshift bins gives a statistical uncertainty (Garnavich et al. 2002; Miknaitis et al. 2005) close to the systematic floor expected from e.g., uncertainties in the k-corrections.

The Supernova factory is an ongoing effort to measure 300 nearby, $z = [0.03 − 0.08]$, SNe Ia (e.g., Aldering et al. 2002). We have assumed an uniform redshift distribution in this range, and again an individual error of 0.14 mag per supernova. Note that our approach only includes statistical errors.

3. Results and discussion

In Fig. 2 we provide the results of our simulations. All simulations have been made assuming a flat universe ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$) dominated by a cosmological constant ($w = -1$).

In Fig. 2 we show the probability contours for the 200 GRBs (dashed lines) and the combined (Gold sample+ESSENCE+SN factory) SN Ia sample (solid lines). Combined results are showed using yellow (filled contours). The four contours correspond to 68.3 %, 90 %, 95 % and 99 % confidence, respectively.

From the top row in Fig. 2 it can be seen that the GRB sample (dashed lines) in itself is not very efficient in constraining $\Omega_\Lambda$. This is true for both adopted redshift distributions. The interesting aspect is that the constraints are rather complementary to the SN Ia constraints, which makes the combination of these two datasets relatively fruitful. That the GRB cosmology is predominantly sensitive to $\Omega_M$, and rather insensitive to the value of the cosmological constant, reflects the higher redshift distribution of this sample. At these epochs, the dark energy contribution to the energy density was still relatively unimportant and we lack a set of low-$z$ GRBs that would provide the necessary leverage in the Hubble diagram to constrain the dark energy.

Clearly, a good prior on $\Omega_M$ from large scale structure (LSS) surveys, such as 2df (Percival et al. 2001) or SDSS (Tegmark et al. 2004) are more helpful in constraining the SN Ia contours, but we find it noteworthy that the same thing can be achieved using only standard candle techniques.

The lower row in Fig. 2 shows constraints derived for a constant equation of state parameter, $w = w_0$, for the dark energy. When fitting $w_0$, we have assumed a flat universe, i.e., $\Omega_M + \Omega_X = 1$. The solid contours correspond to the SN constraints and the dashed contours to GRB constraints. From this exercise it can be seen that GRB cosmology can not be expected to give very useful constraints on the equation of state parameter. It has been suggested (e.g., Friedman & Bloom 2005) that the GRBs could be useful to constrain any potential evolution of $w$. We believe that, given the large uncertainties in even constraining a constant value for the equation of state parameter, such efforts will be in vain. It is interesting to note that combined with a good prior on $\Omega_M$ from, e.g., LSS surveys, SN Ia data alone will provide very powerful constraints on a constant equation of state parameter within a few years.

Our main conclusion is thus that GRBs are not likely to contribute significantly to constraints on the cosmological parameters in the near future. This is similar to the wordings in Friedman & Bloom (2005) and also to the results of Xu et al. (2005) when not assuming an artificially fixed $E_{\text{peak}} - E_X$ relation but at odds with other investigations (e.g., Ghisellini et al. 2005; Lazzati et al. 2005). The main reasons for the limited use of GRBs, apart from the huge inherent uncertainties in trying to standardize these candles (e.g., Friedman & Bloom 2005), is their redshift distribution. Probing $\Omega_X$ and its equation of state benefits from a wide redshift distribution, with good coverage at the epochs where $\Omega_X$ dominates the energy density and a set of low-$z$ events to constrain the normalization of the GRB luminosity. By
artificially including a large number of low-z bursts into the sample, we were indeed able to considerably shrink the confidence regions for the cosmological parameters. The point is that the calculations used for the future GRB redshift distributions used in this work predict that very few of these rare bursts will be available within the limited volume spanned by these low redshifts.

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Fig. 1. The redshift distributions used for our simulated GRB sample. The dashed line is the predicted redshift distribution available to SWIFT according to Gorosabel et al. (2004), while the solid line shows the distribution of GRBs according to the calculations by Bromm & Loeb (2002).

Fig. 2. Upper left: $\Omega_\Lambda$ versus $\Omega_M$ for the GRB sample based on the Gorosabel et al. (2004) redshift distribution (dashed lines) and the SN sample (solid lines). Combined results are showed in yellow (filled contours). Upper right: $\Omega_\Lambda$ versus $\Omega_M$ for the GRB sample based on the Bromm & Loeb (2002) redshift distribution. Lower left: $w_0$ versus $\Omega_M$ assuming a flat universe for the GRB sample based on the Gorosabel et al. (2004) redshift distribution (dashed lines) and the SN sample (solid lines). Combined results are showed in yellow (filled contours). Lower right: $w_0$ versus $\Omega_M$ for the GRB sample based on the Bromm & Loeb (2002) redshift distribution.