Gamma-ray Bursts as Dark Energy Probes

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Abstract. We discuss the prospects of using Gamma Ray Bursts (GRBs) as high-redshift distance estimators, and consider their use in the study of two dark energy models, the Generalized Chaplygin Gas (GCG), a model for the unification of dark energy and dark matter, and the XCDM model, a model where a generic dark energy fluid like component is described by the equation of state, \( p = \omega \rho \). We find that this test yields rather disappointing results for the GCG model, being mainly sensitive to the total amount of matter present in the Universe in the case of the XCDM model. We also find that, within the framework of the XCDM model, a large sample of GRBs (\( \geq 200 \)) may turn out to be quite useful to improve the forthcoming type Ia supernovae data.

Keywords: Cosmology, Luminosity Distance, Gamma-ray Bursts, Dark Energy, Dark Matter

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INTRODUCTION

Recently, there has been a great deal of activity on attempts of using GRBs as cosmological probes \([1]\). In the original proposal \([2]\), it has been suggested that the magnitude versus redshift plot could be extended to redshifts up to \( z \approx 4.5 \), via correlations found between the isotropic equivalent luminosity, \( L_{\text{iso}} \), and two GRB observables, namely the time lag (\( \tau_{\text{lag}} \)) \([3]\) and variability (\( V \)) \([4]\). The isotropic equivalent luminosity is the inferred luminosity (energy emitted per unit of time) of a GRB if all its energy is radiated isotropically, the time lag measures the time offset between high- and low-energy arriving GRB photons, while the variability is a measure of the complexity of the GRB light curve. Using these correlations, one can infer two estimates of the absolute isotropic equivalent luminosity, which are combined through a weighted average. Knowing the absolute isotropic equivalent luminosity together with the observed fluence yields an estimate of the luminosity distance to the GRB.

Unfortunately, these correlations are affected by a large statistical (or intrinsic) scatter. This statistical spread affects not only the cosmological precision via its direct statistical contribution to the distance modulus uncertainty, \( \sigma_d \), but also through the calibration uncertainty given that the suitable GRB sample with known redshift is rather small. In what follows we show that a relatively small sample of GRBs with low redshifts is sufficient to greatly reduce the systematic uncertainty thanks to a more robust and precise calibration.

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1 Talk presented by O.B. at The Dark Side of the Universe International Workshop, Madrid, Spain, 20–24 June 2006.
More recently, a new correlation has been suggested [5], which is subjected to a much smaller statistical scatter. The so-called Ghirlanda relation is a correlation between the peak energy of the gamma-ray spectrum, $E_{\text{peak}}$ (in the $\nu$ – $\nu F_{\nu}$ plot), and the collimation-corrected energy emitted in gamma-rays, $E_{\gamma}$. This collimation-corrected energy is a measure of the energy released by a GRB taking into account that it is beamed into a narrow jet. Unlike the $L_{\text{iso}} – \tau$ and $L_{\text{iso}} – V$ relations, the Ghirlanda relation is not affected by large statistical uncertainties, however, it depends on poorly constrained quantities related to the properties of the medium around the burst. Indeed, to infer $E_{\gamma}$ one must estimate the angular opening of the jet, which can be performed assuming a density profile for the medium around the burst (or circum-burst medium for short), where a fraction $\eta_{\gamma}$ of the fireball kinetic energy is emitted in the prompt gamma-ray phase, and where one has measured the jet break time, $t_{\text{jet}}$ [6]. Assuming that the circum-burst medium has a constant density, the simplest possible assumption, requires one additional parameter. This constant density has been measured for a few bursts [5], and it exhibits a wide variation from burst to burst.

Another difficulty involving GRBs is that they tend to occur at rather large distances, which makes it impossible to calibrate any relationship between the relevant variables in a way that is independent from the cosmological model. The method that is usually employed consist in fitting both, the cosmological and the calibration parameters, and then use statistical techniques to remove the undesired parameters. In here, we follow a different procedure [1, 7]. We consider that the luminosity distance for $z < 1.5$ was previously measured using type Ia supernovae, and divide the GRBs sample in two sets; the low redshift sample, with $z < 1.5$, and the high redshift one, with $z > 1.5$. Since the luminosity distance of GRBs in the range $z < 1.5$ is already known, one can calibrate the luminosity estimators independently of the cosmological parameters and use the high redshift sample as a probe to dark energy and dark matter models. This method also allows us to verify whether the larger redshift range probed by GRBs can compensate for the larger uncertainty associated with the distance estimates thus obtained.

We have analyzed the use of these correlations in order to study of GCG, a model that unifies the dark energy and dark matter in a single fluid [8] through the equation of state $p_{ch} = -A/\rho_{ch}^\alpha$, where $A$ and $\alpha$ are positive constants. The case $\alpha = 1$ describes the Chaplygin gas, that arises in different theoretical scenarios. If the curvature is fixed, there are only two free variables, $A$ and $\alpha$, although it is more convenient to use the quantity $A_s \equiv A/\rho_{ch,0}^{1+\alpha}$ instead of $A$. Thus, we consider two free parameters, $\alpha$ and $A_s$. A great deal of effort has been recently devoted to constrain the GCG model parameters [9], which include, for instance, supernovae [10, 11], cosmic microwave background radiation [12, 13, 14], gravitational lensing [15] and cosmic topology [16].

In addition to the GCG model, we also study the more conventional flat XCDM model. Likewise the GCG model, the XCDM model is also described by two free parameters, the dark energy equation of state, $\omega \equiv p/\rho$, and the fraction of non-relativistic matter, $\Omega_m$. Testing these models is particularly relevant since they are degenerate for redshifts $z < 1$ [10, 11].
VARIABILITY AND TIME LAG AS LUMINOSITY ESTIMATORS

Let us describe here the approach based on the correlation between the isotropic luminosity, and the variability and time lag. The \( L_{iso} - \tau \) and \( L_{iso} - V \) correlations are written as

\[
L_{iso} = B_\tau \tau^{\beta_\tau}, \quad L_{iso} = B_v V^{\beta_v}.
\]

The parameters \( B_\tau/v \) and \( \beta_\tau/v \) are found through fitting of these relationships to the data points, that is, via calibration of the luminosity estimators. Given that the GRB sample with measured redshifts is rather small, at present the calibration is rather poor. To test what improvements one expects to achieve in the future, we assess the gain in calibrating these relationships with larger samples. Three mock, yet realistic, samples were generated, using the method detailed in Ref. [1]; these mock data sets were used to calibrate the luminosity estimators.

We find that a calibration performed with 40 GRBs greatly improves the previous results, decreasing \( \sigma_\mu \) by close to half, yielding \( \sigma_\mu = 0.68 \). However, by increasing the calibration sample to 100 GRBs the resulting improvement is just marginal, suggesting that very large calibration samples are not required. It is worth noting that a sample of about 40 GRBs may be available in the near future thanks to the Swift satellite. We also find that despite the large statistical scatter, due to improvements in calibration, the uncertainty for this estimator becomes quite close to that obtained with the Ghirlanda relation, \( \sigma_\mu = 0.5 \) (c.f. below). However, it is also evident that, due to this large statistical uncertainty, one cannot expect to significantly reduce the observational uncertainty of the variability and time lag method beyond about \( \sigma_\mu \approx 0.6 \). In a sense, one arrives at a minimum possible uncertainty plateau, beyond which any further improvement seems impossible.

Next, we examine how GRBs fare when used to constrain both models under consideration. The methodology is essentially the same of that used for type Ia supernovae [15]. One starts by defining a fiducial cosmological model, described by the parameters \( p_{fid} \), and then use the \( \chi^2 \) function, defined as

\[
\chi^2(p) = \sum_i \left[ \frac{5 \log D_L(z_i, p_{fid}) - 5 \log D_L(z_i, p)}{\sigma_\mu} \right]^2,
\]

where \( D_L \) is the dimensionless luminosity distance, to build confidence regions in parameter space. The dimensionless luminosity distance of the GRBs can be estimated using \( L_{iso} - \tau \) and \( L_{iso} - V \).

Somewhat against our expectation, we found that GRBs are not very suited to study the GCG model. The \( A_s \) parameter can be constrained, however no limit can be imposed on \( \alpha \), as shown in Figure [1]. Larger samples of GRBs decrease the area of the allowed parameter space, however there is no significant improvement on the constraints imposed on either parameter. We also find that using some low-redshift GRBs or the Ghirlanda relation does not alter these conclusions significantly.

The results for the XCDM model are, however, more promising. We find that GRBs are sensitive essentially to \( \Omega_m \), and very weakly sensitive to \( \omega \). The reason for this is the redshift range probed by GRBs. We have verified that when using a sample that includes...
FIGURE 1. Encountered confidence regions for the GCG model. The figure on the left shows the effect of increasing the number of GRBs in the sample. The curves show the 68% Confidence Level (CL) regions, from the outer to the inner curves, corresponding to 150, 500 and 1000 high-redshift GRBs. On the right, the solid line shows the 68% CL regions obtained through a sample of 100 low-redshift ($z < 1.5$) and 400 high-redshift ($z > 1.5$) GRBs, while the dashed line show the 68% CL constraints for a sample made up of 500 high-redshift GRBs only. On the left figure, the $\tau - L_{\text{iso}}$ and $V - L_{\text{iso}}$ relations have been used, while on the right one the Ghirlanda relation was employed. The degeneracy of the $\alpha$ parameter is quite evident.

100 GRBs with $z < 1.5$, the constraints on the XCDM model are substantially better, as depicted in Fig. 2. It should be pointed out that this redshift dependence is not found for the GCG fiducial model. These results were found using the minimal $\sigma_{\mu} = 0.66$. This uncertainty is essentially due to the statistical component, and hence it cannot be reduced by better calibration or data, only through larger GRB samples.

THE GHIRLANDA RELATION.

We discuss here the use of the Ghirlanda relation, which is known to be intrinsically more precise. A drawback of this relation is its dependence on more parameters, and on how the circum-burst medium is modeled [17]. The calibration testing procedure was not repeated, as the main sources of uncertainty in the Ghirlanda relation are the poorly constrained values of the peak energy, jet break time and circum-burst density [15].

As before, we find that the characteristic feature of GRBs of having rather high redshifts, makes them somewhat unsuitable to study dark energy models, even the GCG one. Despite the increased precision, the allowed parameter range for the GCG model is not greatly improved when one uses the Ghirlanda relation. As for the XCDM model, one finds that results are better if one uses the Ghirlanda relations, but not significantly in what concerns the dark energy component. However, this independence on the the nature and amount of the dark energy component means that GRBs can provide a estimate of $\Omega_m$ alone, something which is not possible when using type Ia supernovae.
FIGURE 2. Encountered confidence regions for the XCDM model. The solid lines show the 68% CL regions obtained through a sample of 100 low-redshift ($z < 1.5$) and 400 high-redshift ($z > 1.5$) GRBs, while the dashed lines show the 68% CL constraints for a sample made up of 500 high-redshift GRBs only. On the left figure, the $\tau - L_{iso}$ and $V - L_{iso}$ relations have been used, while on the right one the Ghirlanda relation was employed.

Thus, while an improvement in calibration should not greatly alter the above conclusions, it should be noted that data quality and statistics will greatly improve in the future thanks to Swift and HETE 2 experiments. Thus, as one expects significant improvements on the determinations of the peak energy, jet break time and circum-burst density, it is reasonable to assume that the distance modulus uncertainty for the Ghirlanda relation will decrease.

**FINAL REMARKS.**

The main conclusion of our study is that although GRBs are poor dark energy probes, for $z > 1.5$, their luminosity distance is quite sensitive to the dominating energy density component. For the XCDM model, this is dark matter, and we find that the amount of dark matter can be remarkably constrained. For the GCG model, on the other hand, it turns out that what arises is a combination of the $A_s$ and $\alpha$ parameters, and the data cannot lift the degeneracy on $\alpha$. Actually, if $z \gg 0$, the Hubble function for the GCG becomes

$$H_{ch}(z \gg 0) = \Omega_{ch}(1-A_s)^{1/(1+\alpha)}(1+z)^3,$$

and one can easily observe that the allowed parameter region predicted from GRBs does follow the line $\Omega_{ch}(1-A_s)^{1/(1+\alpha)} \approx 0.5$. This feature is also encountered in various phenomenological studies of the GCG, the only exception being on data from large scale structure formation\[18\]. Also, the transition into an accelerated expansion phase in a GCG universe is faster, and at a lower redshift, than for the XCDM model. This
explains why using some $z < 1.5$ GRBs improves the results for the latter model, while it does not have any impact on the former.

The sensitivity on the non-relativistic matter density in XCDM models means that GRBs may have a complementary role to play with respect to type Ia supernovae. To test the impact of such a joint use, we built joint confidence regions for GRBs and type Ia supernovae constraints that may be imposed by the SNAP satellite. It was found that GRBs may play an important role in the near future if a large GRB data set is built before the promised scientific bounty of SNAP becomes available (see Figure 3). However, GRBs should only marginally improve the constraints imposed by SNAP, unless the uncertainty is reduced by at least a factor of two by then.

It must be realized that these results did not take into account several other systematic sources of error, namely selection and gravitational lensing effects. While for a tentative study, such as the one considered in this contribution, these potential sources of uncertainty may be neglected, a more careful assessment must be performed if one aims to impose robust constraints on cosmological models. Furthermore, it is relevant to point out that the used correlations are purely phenomenological and lack, so far, a theoretical explanation.

It is interesting that a new correlation has been recently proposed [19] which does not require any assumptions with regards to the circum-burst medium or the gamma-ray production efficiency. We are currently in the process of assessing the potential of such a relationship and testing whether marginalization methods, such as those used for type Ia supernovae, can be advantageously employed [20].

**FIGURE 3.** Joint constraints from SNAP plus 500 high-redshift GRBs for the CGC (left) and XCDM (right) model. The dashed line corresponds only to SNAP constrains, while the solid region corresponds to the SNAP+GRBs ones. All curves correspond to 68% CL. Notice that an improvement, although marginal, is obtained.
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