A cosmological independent calibration of the $E_{p,i}$-$E_{iso}$ correlation for Gamma Ray Bursts

S. Capozziello\textsuperscript{1} and L. Izzo\textsuperscript{1,2,3}

\textsuperscript{1} Dipartimento di Scienze Fisiche, Università di Napoli "Federico II" and INFN Sez. di Napoli, Compl. Univ. Monte S. Angelo, Ed. N, Via Cinthia, I-80126 Napoli, Italy
\textsuperscript{2} ICRA Net and ICRA, Piazzale della Repubblica 10, I-65122 Pescara, Italy.
\textsuperscript{3} Dip. di Fisica, Università di Roma "La Sapienza", Piazzale Aldo Moro 5, I-00185 Roma, Italy.

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\section*{ABSTRACT}

\textbf{Aims.} The relation connecting the emitted isotropic energy and the rest-frame peak energy of the \nuFnu spectra of Gamma-Ray Bursts (the Amati relation), strictly depends on the cosmological model, so we need a method to obtain an independent calibration of it.

\textbf{Methods.} Using the Union Supernovae Ia catalog, we obtain a cosmographic luminosity distance in the $y$-redshift and demonstrate that this parametrization approximates very well the fiducial standard cosmological model $\Lambda$CDM. Furthermore, by this cosmographic luminosity distance $d$, it is possible to achieve the Amati relation independent of the cosmological model.

\textbf{Results.} The cosmographic Amati relation that we obtain agrees, in the errors, with other cosmological-independent calibrations proposed in the literature.

\textbf{Conclusions.} This could be considered a good indication in view to obtain standard candles by Gamma-Ray Bursts.

\textbf{Key words.} Gamma rays : bursts - Cosmology : cosmological parameters - Cosmology : distance scale

1. Introduction

Supernovae Ia (SNeIa) are considered accurate and reliable standard candles, (Phillips et al.). In recent years, their use as cosmological distance indicators have led to the puzzling discovery that the Universe is in a phase of accelerated expansion, (Riess et al. 1998; Perlmutter et al. 1999). This feature has also led to the revision of the standard cosmological model, leading to what is known today as the $\Lambda$CDM concordance model, see e.g. (Ostriker and Steinhardt 1995). However it is not possible to observe these objects very far in the Universe. The most distant Supernova Ia was observed at a redshift of $z \sim 1.7$ (Benitez et al. 2002). For this reason, several cosmological analysis made by using the various compiled sample of SNeIa, like the Union Catalog, (Kowalski et al. 2008), are not able to investigate higher redshift regions of the Universe. If we had distance indicators at higher redshifts, then we could extend our knowledge at these unexplored regions.

One of the possible solutions to this problem could come from the Gamma-Ray Bursts (GRBs) assumed as cosmological indicators (Piran 2005; Meszaros 2006). GRBs are the most powerful explosions in the Universe: this feature allows them to be observed at extremely high redshift. The most distant GRB observed up to now is at a redshift of $\sim 8.1$ (Tanvir et al. 2003; Salvaterra et al. 2009). However, GRBs are not standard candles, since they have no known and well-defined luminosity relation. Due to this lack, we have to find another way to use GRBs as cosmological beacons. A possible solution could consist in finding correlations between photometric and/or spectroscopic properties of GRBs themselves. In the scientific literature there are several of these relations, (Schaefter 2006). One of these is the Amati relation, (Amati 2002), which relates the isotropic energy emitted by a GRB with the peak energy in the rest-frame of the \nuFnu electromagnetic spectrum of a GRB. This relation has already been widely used to constraining the cosmological density parameter ($\Omega$), with quite remarkable results. However, there is still not a physical link between this correlation and the mechanisms underlying the production and the emission of a GRB. The basic emission process of a GRB is very likely not unique, so it is not easy to explain, from a physical point of view, such a relation. Recently it has been suggested that the Amati relation could depend strongly on the satellite measurements used for detection and the observation of each GRB (Butler et al. 2007). However this hypothesis has been rejected recently, (Amati et al. 2008), since the relation seems to be verified regardless of the satellite considered for the observations and detection.

Although not supported by self-consistent physical motivations, it is a phenomenological relation which could be extremely useful for cosmological considerations. However, a problem related with such a relation is that it must be calibrated independently of the considered cosmological model. In order to compute the energy emitted from an astrophysical object at a certain redshift $z$, we need, as a matter of fact, a measurement of the bolometric flux and the distance of the same object. For the first quantity, we follow the idea outlined by (Schaefter 2006): one can obtain a very precise measurement of the bolometric fluence emitted by a GRB from the observed fluence, the integrated flux in the observation time and the spectral model that best fits the spectral energy distribution of each GRB. However, the distance depends on the considered cosmological model. People usually adopt the standard $\Lambda$CDM model, with fixed values of the density parameter $\Omega$. This procedure leads to the so-called complexity problem when the Amati relation is used to standardize GRBs. For this reason we need a cosmology-independent calibration of the relation.
Recently, it was released a calibration with SNeIa data by using different numerical interpolation methods (Liang et al. 2008); the results seem very reliable to address cosmological issues by GRBs. In this work we shall take into account a similar analysis: by taking into account SNeIa data from the cosmographic point of view (for a detailed description see e.g. (Weinberg 1972; Visser 2004)), it could be possible to obtain a calibration of the Amati relation. We will use results obtained from a cosmographic fit of a sample of SNeIa extended up to very high redshift with the GRBs. The use of the cosmography to deduce the cosmological parameters from SNeIa was widely discussed in the literature. (Visser 2007a), and the results are very close to that attained by other and more accurate analysis. Recently applications of cosmographic methods have been taken into account galaxy clusters (Capozziello et al. 2004) and GRB, (Capozziello & Izzo 2008; Vitagliano et al. 2010) but their reliability drastically fails at high redshifts. Indeed, the estimates of the deceleration parameter $q_0$ and of the jerk parameter $j_0$ are usually achieved only at very low redshift and then any extrapolation could lead to shortcomings and misleading results as soon as they are extended. However by an appropriate parameterization of the redshift parameter, one can circumvent the problem introducing a new redshift variable ranging from 0 and 1 (Visser 2004). Let us consider the following quantity as the new redshift variable:

$$y = \frac{z}{1 + z},$$

we obtain that the range of variation is between 0 and 1. In this way, we can derive a luminosity distance by which we can obtain the Amati relation suitable for cosmography.

The layout of the paper is the following: in Sect. 2 we tackle the cosmographic analysis considering the SNeIa Union sample. Results will be used to derive the luminosity distance for each GRB and then we will fit the cosmographic Amati relation. In Sect. 3 a discussion on how to extend the same relation is reported. We add further 13 GRBs (as of December 2009), computing the bolometric fluence and the peak energy for each of them and after we calculate the cosmographic parameters using the new relation. Finally, we calculate the isotropic energy for each GRB and then compute the best fit for the considered sample of data (Sect. 4). Discussion and conclusions are reported in Sect. 5.

### Table 1. SNeIa cosmographic fit obtained by both the redshift variables $z$ and $y$.

| Parameter | value $z$-redshift | Parameter | value $y$-redshift |
|-----------|---------------------|-----------|---------------------|
| $a$       | $4242 \pm 1.76$     | $a$       | $4213 \pm 2.16$     |
| $b$       | $0.959 \pm 0.2447$  | $b$       | $2.248 \pm 0.863$  |
| $c$       | $-0.8201 \pm 0.4290$| $c$       | $-0.894 \pm 3.576$ |
| $d$       | $0.2722 \pm 0.2119$ | $d$       | $1.784 \pm 4.057$  |

$$d_H(z) = d_H \{1 + \frac{1}{2} \{1 - q_0\} z - \frac{1}{6} \{1 - q_0 - 3q_0^2 + j_0 + \frac{k d_H^2}{a_0^2}\} z^2 + \frac{1}{24} \{2 - 2q_0 - 15q_0^2 - 15q_0^3 + 5j_0(1 + 2q_0) + s_0 + 2k d_H^2 (1 + 3q_0)\} z^3 + \mathcal{O}(z^4)\}\}.$$ (2)

where $d_H = c/H_0$ and $H_0$, $q_0$, $j_0$ and $s_0$ are known as the Hubble constant, the deceleration, the jerk and the snap parameters respectively. In order to obtain accurate measurements of the cosmographic parameters, we need to go up to large values of the redshift. This goal can be achieved by considering large data sample as SNeIa (Visser 2004) and, eventually, GRBs.

Here, we are interested in reconstructing the relation $d_H(z)$ by cosmetic methods in order to test correlations for GRBs. In order to achieve this goal, we will use the data sample of SNeIa Union, (Kowalski et al. 2008) consisting of 307 supernovae up to redshift $z \sim 1.7$. By this data sample, it is possible to perform a non-linear least-squares fit considering the empirical equation given by the distance modulus obtained from the expanded $d_H(z)$, that is:

$$\mu(z) = 25 + \frac{5}{\log 10} \log \left\{d_H \{1 + \frac{1}{2} \{1 - q_0\} z^2 - \frac{1}{6} \{1 + j_0 + \frac{c^2 k}{a^2 H_0^2}\} - q_0 - 3q_0^2\} z^3 + \frac{1}{24} \{2 + 5j_0 - 2q_0 - 15q_0^2 + 3c^2 k(1 + 3q_0)\} a^2 H_0^2 z^4 + 10j_0 q_0 - 15q_0^2 + s_0\} z^5 + \mathcal{O}(z^6)\}\}.$$ (3)

In this work we are not interested in the estimate of the cosmographic parameters but in using cosmography to constrain a GRB-energy relation. To this aim, we will use a custom equation for the fit of the type

$$\mu(z) = 25 + (5/\log 10) \log (az + bz^2 + cz^3 + dz^4),$$ (4)

so we will compute only the parameters $a, b, c, d$. Once we have an estimate of these parameters, we could easily obtain the values of the related cosmographic parameters. To obtain a better analysis, we can use a robust interpolation method of Levenberg-Marquardt type. The results of our data fitting are shown in Table I.

The test of reliability of the fit has been done with a $R_2$-test, (Bevington et al. 2002), whose value is 0.9914. However the extension up to high redshift of this function $\mu(z)$ shows a serious problem: for redshifts greater than $\sim 2$ the curve grows...
rapidly, see Fig[1] This steep departure is due to the higher-order term, i.e. \( d \), which has a decisive influence at high redshift. This fact rules out \textit{a priori} a possible supernova-calibrated \( \mu(z) \) at high redshift. Such problems can be eliminated if we consider a new variable for the redshift. It has been shown \cite{Visser2007a} that the coordinates transformation \( y = z/(1+z) \) and, consequently, the power series of the luminosity distance provides a better extrapolation at high redshift, as well as better results for the parameters of the fit. Due to this fact, we can perform a cosmographic analysis for the new distance modulus \( \mu(y) \), in analogy with what has been already done for the \( \mu(z) \). The new expression for the distance modulus, which takes into account the new redshift parameterization, becomes \cite{Vitagliano2010}:

\[
\mu(y) = 25 + \frac{5}{\log 10} \left\{ \log d_L + \log y - \frac{1}{2}(q_0 - 3)y \right. \\
+ \frac{1}{24} \left( 21 - 4(j_0 + \frac{c^2k}{a^2H_0^2}) + q_0(9q_0 - 2) \right)y^2 \\
+ \frac{1}{24} \left( 15 + 4 \frac{c^2k}{a^2H_0^2}(q_0 - 1) + j_0(8q_0 - 1) - 5q_0 \right)y^3 \\
- 2q_0^2 - 9q_0^3 + 8q_0 \right\} (5)
\]

so we will consider a custom equation for the fit similar to the previous one, used for the estimate of the \( \mu(z) \) parameters. The results obtained with a non-linear fit are shown in Table[1] while in Figure[1] it is shown the trend of the distance modulus for both the redshift variables considered.

In the following we will consider the formulation for the distance modulus in terms of the \( y \)-redshift in order to derive a cosmographic Amati relation.

3. The data sample

As said in Introduction, in recent years the interest of astrophysicists and cosmologists has been attracted by the possibility of using GRBs as potential distance indicators. This interest is due to the fact that most of the GRBs satisfy some correlations between photometrical and spectroscopical observable quantities. Among the various existing correlations (for a review of these see e.g. \cite{Amati2002}), the Amati relation seems very attractive \cite{Schafer2006}. It relates the cosmological rest-frame \( \nu F(\nu) \) spectrum peak energy \( E_{p,i} \) with the equivalent isotropic radiated energy \( E_{iso} \). It was discovered based on BeppoSAX data and then confirmed also for the X-ray flashes (XRFs) \cite{Band1993}. It seems that it does not work for short GRBs. For this reason the relation could be used to discriminate among different GRB classes.

The possible origin of this correlation as due to detector selection effects seems not consistent, nevertheless the large scatter in the normalization and the shift toward the Swift detection threshold \cite{Butler2007}. A recent study \cite{Amati2009} has shown that the different \( E_{p,i} - E_{iso} \) correlations, obtained independently from the detectors considered for the observations, are fully consistent each other, so the hypothesis of a strumental-dependent Amati relation seems to fail.

Here we are going to expand the sample of GRBs reported in \cite{Amati2009} adding 13 GRBs and obtaining a sample consisting of 108 GRBs. Substantially we need to know the redshift \( z \), the observed peak energy \( E_{p,obs} \) of the \( \nu F(\nu) \) spectrum and an estimate of the bolometric fluence \( S_{bol} \), for each GRB in the sample. To derive the bolometric fluence \( S_{bol} \), we can use the method outlined in \cite{Schafer2006}, where from the observed fluence and the spectral model, we can obtain an estimation of \( S_{bol} \) via the following formula:

\[
S_{bol} = S_{obs} \frac{\int_{0}^{10^{4(z+1)}} \phi \, dE \, dE \, dE}{\int_{0}^{E_{max}} \phi \, dE \, dE} (6)
\]

where \( \phi \) is the spectral model considered for the spectral data fit and \( S_{obs} \) is the fluence observed for each GRB in the respective detection band \( (E_{min}, E_{max}) \). In particular, for 6 of the 13 GRBs added, we consider a cut-off power-law spectral model while for the remaining 7 we use a band model \cite{Band1993}. In the Table[2] the spectral data for the 13 GRBs are shown. \( E_p \) column refers to the measured peak energy. To obtain the peak energy in the rest frame, we have to take into account the redshift of the GRB, then \( E_{p,i} = E_p(1+z) \). Once we have obtained the estimate of \( S_{bol} \) for each GRB in the sample, the next step is to estimate the isotropic energy from the well-known formula which relates the luminosity distance and the fluence, that is

\[
E_{iso} = 4 \pi d_L^2 S_{bol} (1+z)^{-1}. (7)
\]

Note that the quantity \( (1+z) \) to obtain the value of an observable quantity in the rest-frame is equivalent, in the new redshift parameterization, to use, instead, the correction \( 1/(1-y) \). The value of the luminosity distance which must enter in Eq[2] is what we got previously from the cosmographic fit of the SNeIa. From this fit, we obtained an estimate of the function \( \mu(y) \); to go back to the luminosity distance, we can use the following formula:

\[
d_L(y) = 10^{-\frac{\mu(y)}{5}} (8)
\]

by which it is possible to compute the value of \( d_L(y) \) for each GRB in the sample.

It is worth noticing that for values of \( y \) greater than ~ 2.5, the curve \( \mu(y) \) begins to increase slightly. This fact could lead to improper estimates of the isotropic energies emitted by GRBs at high redshift. If we consider an analogous curve referred to a fiducial standard \( \Lambda \)CDM cosmological model, we can quantitatively evaluate this deviation. In Figure[4] it is shown the deviation of the curve \( \mu(y) \), obtained by the cosmographic fit of the SNeIa and the one obtained by considering a \( \Lambda \)CDM model with values of the density parameters given by \( \Omega_m = 0.27 \) and \( \Omega_L = 0.73 \). The discrepancy from the fiducial \( \Lambda \)CDM model seems quite small, but it has to be taken into account when we will compute the cosmographic Amati relation.

4. The Cosmographic Amati relation

At this point we can calculate the parameters of the Amati relation for the sample that we constructed previously. This relation is a correlation of type \( E_{iso} = a E_{p}^{\gamma} \); however if we report it in a logarithmic basis, it reduces to the form:

\[
\log_{10} E_{iso} = A + \gamma \log_{10} E_{p,i} \quad (9)
\]

so we can report our sample in a diagram \( \log_{10} E_{iso} - \log_{10} E_{p,i} \) and perform a linear fit of the data, with weights given by the
account the corrections due to physical parameters as traced by SNeIa, while the cosmographic analysis takes into the calibration in (Liang et al. 2008). It depends on the trend between the parameters of the relation. This fact could be due to the interpolation methods (Liang et al. 2008) shows a slight discrepancy for the cut-off power law spectral model, the corresponding covariance matrix are:

\[ \sigma_{\text{fit}} = 3.0 \text{ in } (\text{Liang et al. } 2008), \]

that in (Liang et al. 2008), where the authors adopted the catalog of 192 SNeIa discussed in (Wood-vasey et al. 2007). This means that the slight difference in the results could be due to the different samples used for the calibration.

\[ \text{(1)} \ (\text{GRB}) \ \text{spec} \text{ model} \ \text{z} \ E_{\text{p,iso}} \ (\text{keV}) \ \alpha \ \beta (\gamma) \ S_{\text{obs}} (10^{\text{53}} \text{ ergs/cm}^2) \ \text{band} (\text{keV}) \ GCN \]

| GRB   | spec model | z        | $E_{\text{p,iso}}$ (keV) | $\alpha$ | $\beta (\gamma)$ | $S_{\text{obs}}$ (10$^{53}$ ergs/cm$^2$) | band (keV) | GCN |
|-------|------------|----------|---------------------------|----------|------------------|--------------------------------|-----------|-----|
| 090516 | CPL        | 4.109    | 190 ± 65                  | –        | -1.5 ± 0.3       | 15 ± 3                         | 20-1200   | 9422 |
| 090715B | CPL       | 3.00     | 134 ± 56                  | –        | -1.1 ± 0.4       | 9.3 ± 1.5                      | 20-2000   | 9679 |
| 090812 | CPL        | 2.452    | 580 ± 243                 | –        | -1.03 ± 0.07     | 26.1 ± 3.4                     | 15-1400   | 9821 |
| 090926B | CPL       | 1.24     | 91 ± 2                    | –        | -0.13 ± 0.06     | 8.7 ± 0.3                      | 10-1000   | 9957 |
| 091018 | CPL        | 0.971    | 28 ± 16                   | –        | -1.53 ± 0.59     | 1.44 ± 0.19                    | 10-1000   | 10045 |
| 091029 | CPL        | 2.752    | 61.4 ± 17.5               | –        | -1.46 ± 0.27     | 2.4 ± 0.1                      | 15-150    | 10103|
| 090618 | Band       | 0.54     | 155.5 ± 11                | -1.26 ± 0.06 | -2.50 ± 0.33 & 270 ± 6 & 8-1000 & 9335 |
| 090902B | Band      | 1.822    | 775 ± 11                  | -0.696 ± 0.012 | -3.85 ± 0.31 & 374 ± 3 & 50-1000 & 9866 |
| 090926 | Band       | 2.1062   | 314 ± 4                   | -0.75 ± 0.01 | -2.59 ± 0.05 & 145 ± 4 & 8-1000 & 9933 |
| 091003 | Band       | 0.8969   | 486.2 ± 23.6              | -1.13 ± 0.01 | -2.64 ± 0.24 & 37.6 ± 0.4 & 8-1000 & 9983 |
| 091020 | Band       | 1.71     | 103 ± 68                  | -0.93 ± 0.6 | -1.9 ± 0.8 & 10.4 ± 2.1 & 20-2000 & 10057 |
| 091127 | Band       | 0.49     | 36 ± 2                    | -1.27 ± 0.06 | -2.20 ± 0.02 & 18.7 ± 0.2 & 8-1000 & 10204 |
| 091208B | Band      | 1.0633   | 124 ± 20.1                | -1.44 ± 0.07 | -2.32 ± 0.47 & 5.8 ± 0.2 & 8-1000 & 10266 |

References: (Sakamoto et al. 2009), (McBreen 2009), (Golenetskii et al. 2009), (Sakamoto et al. 2009b), (Bissaldi & Connaughton 2009), (Bissaldi 2009), (Briggs 2009), (Rau 2009), (Golenetskii et al. 2009b), (Golenetskii et al. 2009c), (Barthelmy et al. 2009), (Wilson-Hodge & Preece 2009), (McBreen 2009b)

In Fig.3 it is shown the plot of the cosmographic Amati relation. The confidence level curves are calculated as the 3σ deviation from the best fit. Note how the 13 GRBs added to the old sample, marked with a circle, are distributed about the best-fit curve, indicating that the spectral analysis of these 13 GRBs is correct.

5. Discussion and Conclusions

The issue to extend the cosmic scale ladder up to medium-high redshift is an important questions of modern cosmology. A possible way to achieve this goal is to take into account GRBs, the most powerful explosions in the Universe. The energy emitted by these objects spans about six orders of magnitude. However, they cannot be assumed as standard candles in a proper sense. Dispite of this lack, the existence of several correlations between spectroscopic and photometric observable quantities of GRBs allow us to solve in part this problem. The fundamental prerequisite to obtain such relations is to estimate the emitted energy in a way independent of the cosmological model. In this pa-
per, we have considered a relation for the luminosity distance $d_l$ that is independent on the dynamics of the Universe, but, in principle, could work only at small redshift. Although we have use a parameterization for the redshift which allows to transform the variable $z$ in a new variable $y$, ranging in a limited interval, we have seen that the obtained luminosity distance at high-redshift differs slightly from the fiducial model $\Lambda$CDM at high redshift, see Fig. 3. Nevertheless, since we obtained the curve $d_l(y)$ by an analysis of the SNeIa Union survey, that extends up to a redshift of $\sim 1.7$, we achieved an independent estimate at slightly higher redshift. By the way using the $d_l(y)$ obtained with the cosmographic fit of the SNeIa, we have constrained a sample of GRBs in a cosmology-independent way so that we have fitted a cosmographic Amati relation for GRBs. The results are similar to those obtained from other analysis performed using other methods. (Schaefer 2006, Liang et al. 2008, Amati 2002). It is important to stress the independence from cosmology and the calibration obtained by SNeIa. In our opinion, this characteristic is relevant, from one side, to constrain cosmological models, in particular, dark energy models, and, from another side, to check the physical validity of the Amati relation.

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