IL NUOVO CIMENTO Vol. 28 C, N. 4-5 Luglio-Ottobre 2005
DOI 10.1393/ncc/i2005-10120-7

Redshift indicators for Gamma-Ray Bursts(*)

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(ricevuto il 23 Maggio 2005; pubblicato online il 14 Ottobre 2005)

Summary. — The measure of the distances and luminosities of Gamma-Ray Bursts (GRBs) led to the discovery that many GRB properties are strongly correlated with their intrinsic luminosity, leading to the construction of reliable luminosity indicators. These GRB luminosity indicators have quickly found applications, like the construction of "pseudo-redshifts", or the measure of luminosity distances, which can be computed independently of the measure of the redshift. In this contribution I discuss various issues connected with the construction of luminosity-redshift indicators for gamma-ray bursts.

PACS 98.70.Rz – γ-ray sources; γ-ray bursts.
PACS 98.62.Py – Distances, redshifts, radial velocities; spatial distribution of galaxies.

1. – Introduction

Measuring the cosmological redshifts of gamma-ray bursts of all types (GRBs, XRFs, short-hard bursts) is crucial for our understanding of these events. The measure of redshifts tells us the energy output of the source, it allows the measure of the burst intrinsic parameters (duration, peak energy, etc. . .), and determines the position of the burster in the history of the universe. Unfortunately, the obtention of spectroscopic redshifts requires a succession of non trivial observing steps: reliable localization of the prompt emission in X-rays or gamma-rays, quick distribution of the alert to the ground, identification of the afterglow at optical, radio or X-ray wavelenths, and measure of the redshift of the host galaxy in absorption (when the afterglow is bright) or in emission (when the afterglow has faded). This complex sequence of events explains why in February 2005, 8 years after the discovery of the first afterglow, the web page of Jochen Greiner([1]) contains only 40 spectroscopic redshifts among 263 localized GRBs (of which about 100 have an optical, X-ray or radio afterglow). The statistics is similar for HETE-2 GRBs [31], which has localized 75 events, from which 25 afterglows have been found, and 14 redshifts measured.

(*) Paper presented at the "4th Workshop on Gamma-Ray Burst in the Afterglow Era", Rome, October 18-22, 2004.
([1]) http://www.mpe.mpg.de/ jcg/grbgen.html

The fact that we are currently measuring the redshift of one out of six localized GRBs implies strong biases in the observed redshift distribution. For instance GRBs at high redshift are very difficult to detect in the optical range, and the lack of GRBs with $z > 5$ in the current sample may be the consequence of selection effects. The intrinsic faintness of XRFs makes them difficult to detect beyond $z = 1$, again biasing their observed redshift distribution. It is precisely this small fraction of GRBs with a redshift and the likely existence of biases in the observed redshift distribution which constitute the rationale for the construction of "redshift indicators". In order to complement spectroscopic redshifts usefully, "redshift indicators" must provide redshift estimates for most GRBs detected at high energies([2]). The construction of such indicators is considered in sect. **2**. Section **3** addresses some open issues in the construction of redshift indicators. Possible applications of these indicators are presented in sect. **4**.

2. – Building redshift indicators

2˙1. *Searching standard candles.* – Gamma-ray bursts have a broad dispersion in peak luminosity (by a factor 10^4 at least), which prevents using them as standard candles straightforwardly. After the the measure of a dozen GRB redshifts, much work has been devoted to the search of luminosity estimators with an intrinsic dispersion smaller than the peak luminosity. This work brought two complementary results:

- $E_{\rm rad}$, the energy radiated by GRBs when the beaming factor of the emission is taken into account([3]), appears to be significantly less scattered than the peak luminosity ($L_{\rm iso}$) or the energy radiated ($E_{\rm iso}$) measured assuming an isotropic emission [12,8]. The standard deviation of the logarithm of $E_{\rm rad}$ is 0.35 dex [8], providing a measure of luminosity which approaches a standard candle.
- Many temporal and spectral GRB properties are strongly correlated with the radiated energy (either $E_{\rm iso}$ or $E_{\rm rad}$). These correlations permit to use these temporal or spectral properties as luminosity indicators, and as redshift indicators by assuming a cosmology([4]). Even if the theoretical justification of these correlations is not fully understood yet, they are currently providing interesting luminosity indicators with typical standard deviations of the order of 0.1 dex [15,3]. Aditional details on these luminosity indicators are given in subsect. **2**˙2 below.

The construction of reliable luminosity indicators has started only recently, with the measure of the first GRB redshifts, and significant improvements are to be expected in the coming years. In order to facilitate the comparison of existing and future luminosity indicators, we suggest the use a common measure of their quality. We propose to use $\sigma_{\rm DL}$, the dispersion of $\log(D_L^{\rm pred.}/D_L^{\rm meas.})$, where $D_L^{\rm pred.}$ is the luminosity distance predicted

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([2]) In the following, we call "pseudo-redshifts" these redshift estimates.

([3]) The beaming factor of the emission is usually derived from the time at which the light curve of the afterglow shows a break [27]. The measure of the fluence of a GRB and of its redshift can be used to derive $E_{\rm iso}$, the isotropic-equivalent radiated energy. The identification of a jet-break allows the determination of the opening angle of the jet, giving the beaming factor and the energy radiated, $E_{\rm rad}$.

([4]) In the following the terms luminosity indicators and redshift indicators are used indifferently. The reader should nevertheless keep in mind that redshift indicators are constructed from luminosity indicators, assuming a cosmology.

by the luminosity indicator, and $D_L^{\rm meas.}$ is the luminosity distance which is measured. Using this measure, the pseudo-redshifts proposed by Atteia [2] have $\sigma_{\rm DL} = 0.15$ dex, for 24 GRBs with a redshift, and $\sigma_{\rm DL} = 0.11$ dex, for the subsample of 13 HETE GRBs.

2·2. *Practical luminosity-redshift indicators.* – From a general point of view, good redshift indicators require combinations of GRB parameters which have a small intrinsic scatter and, as possible, a strong dependence on redshift. Concerning light curves, the two most publicized correlations are the lag-luminosity correlation [24], and the variability-luminosity correlation [26]. The construction of luminosity indicators based on these relations requires light curves with a large number of counts, which can only be provided by instruments having large effective area. Luminosity indicators based on GRB spectra demand the measure of the three parameters of the Band function usually adopted to fit GRB spectra [5]. They are based on the so-called $E_{\rm peak}$-$E_{\rm iso}$ relation [1, 2, 18], on the $E_{\rm peak}$-$L_{\rm iso}$ relation [33], or on the $E_{\rm peak}$-$E_{\rm rad}$ relation [15](5). These indicators require instruments having a broad spectral range (at least two decades), and, in the case of the $E_{\rm peak}$-$E_{\rm rad}$ relation, a good sampling of the afterglow light curve. These studies have shown that useful luminosity indicators can be constructed for GRBs, even if they depend on the details of each GRB detector (effective area, spectral range, time and energy resolution), and must be adapted for each mission. Recently, the consistency of redshift indicators obtained from the light curves and from the spectra has been demonstrated [16, 25]. Despite the rapid progress of the last years, some open issues remain, which are presented in the next section.

3. – Open issues

3·1. *Validity of luminosity indicators.* – The importance of the empirical relations used in the definition of luminosity indicators, and the fact that they are based on a small number of GRBs with redshifts, raised questions on their overall validity and on their applicability to the entire GRB population. Various authors attempted to check the validity of the $E_{\rm peak}$-$E_{\rm iso}$, and of the $E_{\rm peak}$-$E_{\rm rad}$ relations by verifying if, for every GRB in the BATSE sample, one can find a redshift which puts it along the correlations observed for the GRBs with a redshift. The conclusions of these efforts are diverse: while Lloyd *et al.* [20] actually *predicted* the $E_{\rm peak}$-$E_{\rm iso}$ relation, Nakar and Piran [23], and Band and Preece [6] found that the majority of BATSE GRBs cannot follow this relation, but this conclusion was later contradicted by Ghirlanda *et al.* [16], and Bosnjak *et al.* [9]. These contradictory results may reflect the difficulty of properly accounting for the uncertainties in the measure of individual $E_{\rm peak}$ for all GRBs, or the existence of a class of outliers (see below), treated differently in these studies.

3·2. *Calibration.* – Luminosity indicators are not well calibrated, essentially due to the small number of GRBs with a spectroscopic redshift, and to the restricted range of redshifts measured ($z = 0.1$ to 4.5). The number of GRBs available for calibration is further reduced by the fact that many GRBs have their light curves, spectra or afterglows known with insufficient accuracy to compute luminosity indicators reliably. With these restrictions in mind, the accuracy of present-day luminosity indicators is not too bad since the best of them have a standard deviation smaller than 0.1 dex.

(5) Here $E_{\rm peak}$ designates the energy of the maximum of the $\nu F\nu$ spectrum of the prompt emission. $E_{\rm iso}$ and $E_{\rm rad}$ have been defined in the footnote in subsect. **2**·1.

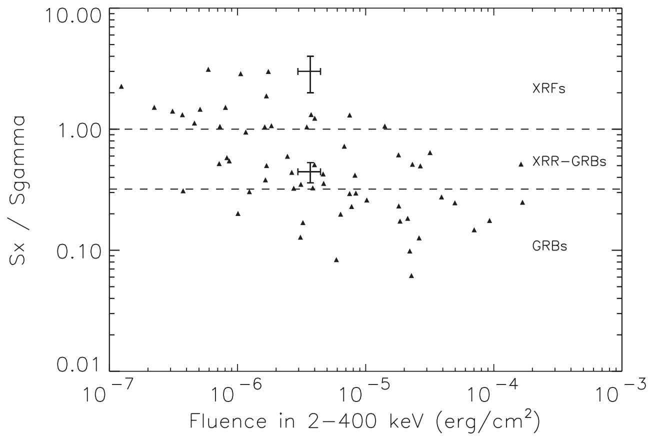

Fig. 1. – Position of GRB 031203 (crosses) in a fluence-softness plot, among 63 GRBs detected and localized by HETE-2 [7]. The low (respectively high) softness point reflects the numbers given by [28] (respectively [32]). This figure shows that sensitivity considerations cannot be invoked to resolve the contradiction raised by GRB 031203: the only GRB with a redshift detected with INTEGRAL is an outlier to the E_{peak}-E_{iso} relation, while the 14 GRBs with a redshift detected with HETE follow this relation.

3˙3. *Outliers.* – The association of GRB 980425 with the energetic supernova 1998bw at $z = 0.0085$ revealed a sub-energetic burst, whose radiated energy is one thousand times smaller than other GRBs with a redshift. As a consequence this burst does not fit the empirical relations used to define luminosity indicators. The nature of the link between GRB 980425 and the bulk of the classical GRB population has not been elucidated yet, and we should wait the detection of additional events of this type to clarify the nature of the outliers. Recently, GRB 031203 has also been considered has a potential outlier to the E_{peak}-E_{iso} and to the lag-luminosity relations [28]. The case of this burst is, however, much less clear than the case of GRB 980425 because its E_{peak} has not been measured. Figure 1 illustrates the contradiction raised by this burst: From the point of view of its prompt gamma-ray emission, GRB 031203 appears fully comparable with the GRBs detected with HETE-2; On the other hand, this burst, the only INTEGRAL GRB with a redshift, does not follow the E_{peak}-E_{iso} relation, while all the 14 HETE GRBs with a redshift follow this relation. In our opinion, the situation of GRB 031203 with respect to the empirical E_{peak}-E_{iso}, and lag-luminosity relations remains unclear.

3˙4. *Are redshift indicators applicable to X-ray flashes?* – X-Ray Flashes (XRFs) are soft GRBs with low E_{peak}, typically $E_{\mathrm{peak}} < 50$ keV. If they follow the E_{peak}-E_{iso} relation, they must be intrinsically faint and can only be seen at low redshifts. The redshifts of two XRFs have been measured to date: XRF 020903, at $z = 0.25$, and XRF 040701, at $z = 0.21$. These measures put these two bursts on the E_{peak}-E_{iso} relation, and suggest that luminosity indicators for GRBs could also be applicable to XRFs. The situation is however more complex than this simple picture since GRBs at high redshift ($z = 5 - 10$) will also appear as X-ray flashes. Due to the absence of GRBs with a measured redshift greater than 5, it is not clear if luminosity indicators can make the difference between XRFs from nearby intrinsically soft GRBs and classical hard GRBs at high redshift.

Another puzzle is connected with the lack of supernova light in several XRFs [19, 30]. Since all nearby GRBs seem to show SN light [34], this observation can be interpreted as an evidence that these XRFs lie at redshifts significantly larger than the values predicted by the redshift indicators (but other interpretations are also possible [19]). Until we know more about the distances of XRFs, it is difficult to affirm with certainty that GRB redshift indicators are also valid for XRFs.

3˙5. *Short-hard GRBs*. – The question of redshift indicators for short-hard GRBs is not addressed here since we have not yet measured the distance of a short-hard GRB. Furthermore, the recent observation of a very bright gamma-ray flare from the galactic magnetar SGR 1806-20, suggests that a significant fraction of the short-hard bursts could be due to extragalactic magnetars [17]. This could make short-hard GRBs fundamentally different from long GRBs for which luminosity indicators have been shown to work.

4. – Applications

We briefly present below some (not all) of the studies which have used luminosity-redshift indicators in the last years.

4˙1. *Quick redshift evaluation*. – The availability of redshift indicators exclusively based on the prompt emission opens the possibility to quickly distribute an evaluation of the distance of newly detected GRBs. This is especially important for GRBs at high redshifts ($z > 5$) which can only be identified with a rapid and specific follow-up [4]. In order to facilitate the follow-up strategy of ground observers, the HETE team has set up a program which performs the spectral analysis of GRBs automatically, as soon as the data become available (usually in the minutes following the burst), and evaluates a redshift indicator based on the $E_{\rm peak}$-$E_{\rm iso}$ relation.

4˙2. *Inferring the star formation rate*. – GRBs offer an unabsorbed view on the history of the Star Formation Rate (SFR). The distribution of the pseudo-redshifts of hundreds of BATSE GRBs has been computed by various authors (see [21, 22, 33] and reference therein). These studies show that GRBs offer an interesting alternative to constrain the SFR beyond $z \sim 3$–4, but we should keep in mind that redshift indicators have not yet been calibrated in this range of redshifts.

4˙3. *Testing the cosmology*. – The availability of accurate luminosity indicators for GRBs can be used to measure luminosity distances independent of the redshift, and to derive the cosmological parameters. Following [29, 14], various authors assessed the constraints that GRBs impose on the cosmological parameters. Whether or not current data are sufficient in number and accuracy to constrain the cosmological parameters is the subject of an on-going debate [10, 14, 13], but there is a strong consensus on the fact that GRBs will become a valuable tool in this field in the coming years.

5. – Conclusions and perspectives

Luminosity and redshift indicators for GRBs will certainly play an increasing role in the future. The growing number of redshifts is expected to bring several improvements to this field: a more accurate calibration of existing luminosity indicators, the construction of new indicators, a better understanding of systematic effects (*e.g.*, luminosity evolution) and of the issues discussed in sect. **3**. The progress in this field may be fast in the

SWIFT era thanks to the small error boxes provided by the XRT, which permit efficient afterglow searches, and raise the hope that a significant fraction of SWIFT GRBs will have spectroscopic redshifts. A recent good piece of news is that the luminosity indicator based on the variability of the light curve, which was developed for BATSE bursts [26], seems to be directly applicable to SWIFT GRBs [11].

We would like to conclude with strong incentive to observers to quickly follow-up at X-ray and NIR wavelengths, GRBs with high pseudo-redshifts. The identification of GRBs at high redshifts ($z > 5$) is a difficult task which requires deep, prompt observations with powerful instruments. This cannot be done for just any GRB, and the luminosity indicators discussed in this paper could be a decisive tool to ensure the success of future searches for high-redshift GRBs.

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