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IMPORTANCE OF X-RAY FLASHES IN THE GAMMA-RAY BURSTS POPULATION.

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Abstract. Gamma-Ray Bursts constitute the most powerful explosions in the Universe and seem to be, for most of them, associated with the death of massive stars. Using the data collected during the 6-year mission of the High Energy Transient Explorer II satellite on a complete sample of 82 GRBs, we study the intrinsic energetic properties of these transient events.

The results obtained lead to a discussion on X-ray flashes, which is a GRB sub-population softer than the average population. We show that the HETE-2 XRFs are not soft due to their high redshift and that half of them are not classified as XRFs anymore if we compute their energetics' properties in the source frame, confirming the results of previous studies. We also derive the rate of GRBs occuring in the Local Universe and obtain a higher rate than previous studies. In particular, the study of the intrinsic properties shows the predominence of the XRFs in the GRBs population, that we link with the higher local rate we found.

1 Introduction

Long Gamma-Ray Bursts (GRBs) are brief (> 2 seconds) and intense flashes of high-energy photons occuring randomly in the sky at a rate of one to several per day. They are produced in distant galaxies and are the results of ultra-relativistic outflows generated by newborn black holes or magnetars.
Several recent observations confirm the association of GRBs with Type Ic Supernovae (SNeIc), which is coherent with what we have learned in the recent years, i.e the link between GRBs and the death of massive stars ($M > 20$-$30\ M_{\rm sun}$). Consequently, for all GRBs occuring in the Local Universe, we should observe the emergence of an associated supernova. However this scheme is not so simple: some recent observations of nearby long GRBs did not reveal any supernova. Therefore, the comprehension of GRB progenitors is currently stimulated and constitute an important debated theme in the community.
To make a contribution, we propose to use the GRBs detected by the satellite HETE-2. Thanks to its broad energy coverage (2-400 keV) and particularly its detection capacity down to a few keV, both 'classical' GRBs and soft GRBs (X-ray flashes) were detected during its mission.
Taking advantage of the forthcoming HETE-2 GRBs Catalog (Vanderspek et al., in prep.) we investigate the importance of XRFs in the GRBs global population.
Reminding first some important results of the HETE-2 mission dealing with the connection between GRBs/XRFs and GRBs/SNe (Section 2) we present our study on the intrinsic properties of a complete sample of HETE-2 bursts (Section 3). We finally show in Section 4 the place of the XRFs in the GRBs population from several points: distance-scale, energetics and rate of GRBs in the Local Universe.

2 Two important results of the HETE-2 mission: GRBs/XRFs and GRBs/SNe connections

The satellite HETE-2 (Ricker et al. 2001) was launched in October 2000 for a mission entirely dedicated to the detection of high energy transient sources such as Soft Gamma Repeaters (SGRs), X-ray Bursters (XRBs) and Gamma-Ray Bursts (GRBs). Three instruments are on-board: the FREnch GAmma TElescope (FREGATE)

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with a 6-400 keV energy range (Atteia et al. 2003) and two X-ray cameras: the Soft X-ray Camera (SXC, Villasenor et al. 2003) and the Wide-field X-ray Monitor (WXM, Shirasaki et al. 2003) permitting the bursts' localization. The mission is over since the end of 2006 and if we had to draw up a balance sheet we would for sure state that HETE-2 was very useful for the science of GRBs.

2.1 X-ray flashes: 'An increase of their knowledge'

With an energy range going down to the hard X-ray, soft events are detected and spectrally analyzed by HETE-2. From an observational point of view, X-ray flashes spectra are identical to classical GRBs spectra. In a νF_ν representation, they are fitted by a phenomenological model composed of two power-laws smoothly connected at an energy – noted E_{peak} – corresponding to the maximum of emitted flux. The power-laws are similar for the two sub-classes. Only the E_{peak} and the flux are different: for XRFs the E_{peak} is only a few keV (against several hundreds of keV for GRBs) and the flux emitted in X-ray is higher than in γ-ray. HETE-2 has detected some of these soft events and has considerably improved their knowledge. A strong example is XRF 020903, for which an upper limit $E_{peak}^{obs} < 5$ keV (99.7% c.l.) was obtained (Sakamoto et al. 2004), giving this burst the rank of softest event localized by HETE-2. The analysis of the observed properties of a sample of HETE-2 GRBs/XRFs by Barraud et al. (2003) and of 42 HETE-2 X-ray Rich (XRRs) and XRFs by Sakamoto et al. (2005) show that classical GRBS, XRRs and XRFs belong to the same population.

2.2 The GRBs/SNe connection: 'A confirmation by HETE-2'

The detection and localization of GRB 030329 has highly confirmed the GRB/SN connection. This burst is peculiar for several points: it is among the brightest GRB ever seen, its optical afterglow is several magnitudes brighter than the ones usually observed and its host galaxy lies very nearby at a redshift z=0.167, whereas the typical population occurs at z$\sim$2-3. There was consequently only a very low probability that HETE-like missions had detected such an event, and will detect such an other burst in the near future. This 'Rosetta Stone' has permitted to see the spectral signature of a Type Ic supernova emerging about ten days after the GRB, hence confirming the previous observation of a connection between a GRB and a supernova five years earlier (GRB 980425/SN 1998bw: Galama et al. 1998; Kulkarni et al. 1998).

3 Unbiased distributions of intrinsic HETE-2 GRBs' properties

Observed properties of GRBs have been largely studied thanks to missions like BATSE (1990-2000) that have detected thousands of these events. However, for a better knowledge of the mechanisms at work in these astrophysical sources, physical parameters such as their duration or their luminosity in the source frame are necessary. Experimentally, this is not evident because it requires to have both well constrained measures of the bursts' observed parameters and their distance-scale. We present in this Section how we have realized such a study with the HETE-2 mission.

3.1 What do we need to perform this study?

- a/ a complete sample of bursts
- b/ the properties of each burst measured in the observer frame
- c/ a distance-scale to the source

a/-b/ It is of prime importance for our study to construct a GRB sample containing all the events not only detected but also localized by HETE-2, and selected with uniform criteria (angle of incident beam, detection threshold, signal-to-noise ratio). Our complete sample contains 82 events (see Pélangeon et al., in prep., for a complete description of the selected sample).
For the observed properties we have considered the results referenced in the HETE-2 Catalog (Vanderspek et al., in prep.).

c/ If now one wants to derive the same properties in the source frame, one must know the distance-scale of the source. This is possible observationally by measuring a spectroscopic redshift, which requires a non trivial chain of detections: a quick transmission of the burst detection to the ground, a follow-up by telescopes at different wavelengths of the X-ray, optical or radio counterpart, and finally the measure of the redshift obtained by the emission lines of the host-galaxy or the absorption lines of the afterglow. Hence, considering all the missions, only about one fourth of the GRB have a spectroscopic redshift. For our sample, 19 GRBs have a measured redshift. For the remaining 63 we have used the redshift-estimates (pseudo-redshifts) based on the redshift indicator of Pélangeon et al. (2006).

3.2 Results

Deriving 'true intrinsic' properties requires to correct the observed properties for two main effects:

- the cosmological effects: the redshift reduces the energy of the photon reaching the Earth and dilates the duration of the events.
- the true rate of occurence of each type of GRB.

For each burst contained in the sample we first compute its properties in the source frame –for instance E_{peak}^{source} and E_{iso}– by correcting the observed properties from the effect of the redshift (or at least the pseudo-redshift). In a second step we compute the 'distance of detectability' (D) of each burst, i.e the distance at which the S/N of the GRB reaches the threshold of detectability used to construct our studied sample. Each GRB is finally given a weight (W) inversely proportional to its 'volume of detectability' (V), i.e the volume of universe enclosed in the distance of detectability: W= 1/V [Gpc^{-3}].
Two examples of unbiased distributions of the intrinsic parameters dealing with bursts' energetics are shown in Figure 1, where we clearly show the predominance of the X-ray flashes (lowest E_{peak}^{source} and E_{iso}) in the GRBs population.

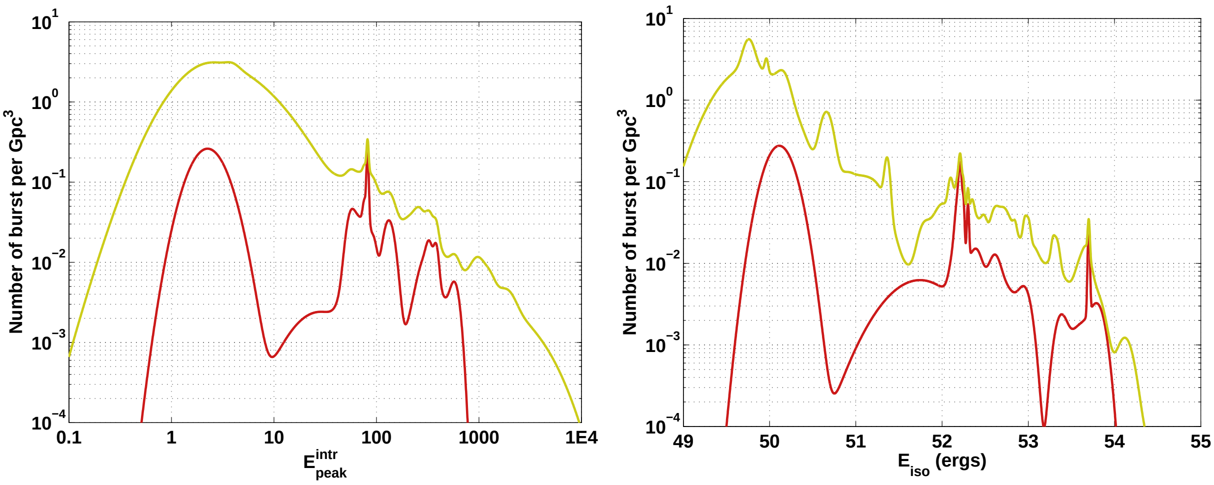

Fig. 1. Unbiased distributions for two main properties characterizing Gamma-Ray Bursts' energetics, computed in their source frame: E_{peak} (left panel) and E_{iso} (right panel). We have considered the complete sample of 82 bursts detected and localized by the satellite HETE-2 (see Section 3). For each parameter considered, the smoothed distribution based on the 19 bursts that have a measured redshift is in red. The same distribution for the complete sample is shown in dark yellow.

4 Discussion: 'The place of XRFs in the global GRBs population'

X-ray flashes are not trivial to detect due to their intrinsic faintness. In the observer frame, most of XRFs' photons are detected below ∼15 keV. As an example, the current mission *Swift* (Gehrels et al. 2004) which is very efficient in detecting GRBs (about 100 per year) is not able to detect a lot of XRFs, and when it happens its narrow energy range (15-150 keV) do not allow to measure the spectral parameters. Moreover, the study of the intrinsic properties requires the knowledge of the distance-scale, which also reduces the number of soft events available for such a study. In our complete HETE-2 sample of 82 bursts, the sub-sample of XRFs contains twenty or so XRFs, which constitute a quite important sample in regards to what can be obtained with the other missions.

As a consequence, it is interesting to compare this sub-sample of HETE-2 soft events with the classical GRBs in terms of distance-scale and energetics.

4.1 Are X-ray flashes occuring at very high redshift?

This hypothesis was proposed by Heise et al. (2001) to explain their observed faintness. We show in Fig.2 the cumulative distributions of the sub-sample of HETE-2 XRFs and the sub-sample of classical GRBs. We note that only 30% of the XRFs are situated at a redshift greater than z=1, whereas this rate is higher than 70% for classical GRBs. The faintness of XRFs is hence not due to their high-redshift, as have also shown e.g. Barraud et al. (2003); Gendre, Galli & Piro (2007).

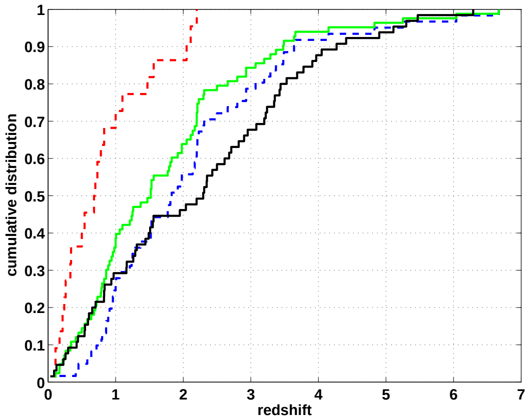

Fig. 2. Four redshift cumulative distribution functions (cdf) are plotted. The cdf of the HETE-2 complete sample is in green solid line. The cumulative distributions considering separately the 'classical' GRBs and the X-ray flashes are in dashed line: the XRFs' distribution is the leftmost one. There is no ambiguity concerning the distance-scale classification of the XRFs contained in our sample: 70% of them are at a redshift z<1. This strengthen the hypothesis that XRFs are not classical GRBs occuring at high-redshift, but are GRBs intrinsically faint.

4.2 X-ray flashes in the $E_{\rm peak}^{\rm source}$-$E_{\rm iso}$ correlation

At the end of the 90s, the first redshift measures for GRBs have led to the search of intrinsic correlations between physical quantities derived in their source frame. One of the most intriguing correlation that was firmly found by Amati et al. (2002) links the source peak energy ($\mathrm{E}_{\rm peak}^{\rm source}$) with the total isotropic-equivalent radiated energy ($\mathrm{E}_{\rm iso}$). Despite a clear correlation, recently confirmed with 53 GRBs/XRFs from several satellites by Amati (2006), the physics that could explain it is still not well understood. Thanks to XRF 020903 localized by HETE-2 and occuring at a redshift z=0.25 (Soderberg et al. 2004) this correlation is extended over five decades (Sakamoto et al. 2004). Two others XRFs detected by Swift are situated in the gap between XRF 020903 and the classical GRBs: XRF 050416 (Sakamoto et al. 2006) and XRF 060218 (Amati et al. 2007). Some other events classified as XRF in the observer frame due to their low measured $\mathrm{E}_{\rm peak}$ (<30 keV) and to their ratio $\mathrm{S}_x/\mathrm{S}_\gamma > 1$ are in fact situated in the cluster of classical GRBs when correcting these values for the redshift (or pseudo-redshift), as noted by Stratta et al. (2007) with the following X-ray flashes: XRF 021104, XRF 030823 and XRF 040912. Consequently, the following questions are still unsolved:

'Are most of the XRFs in the observer frame belonging in fact to the softest part of the classical GRBs in their rest frame?' 'Are intrinsic XRFs (i-XRFS) such as XRF 020903 and the classical GRBs forming two distinct population, indicating a different population of very soft bursts?

The number of events (particularly the number of XRFs) considered so far is not important enough to make any clear conclusion. However, if we put our bursts in the (E_{peak}^{source}-E_{iso}) plane (see Fig.3) we note that half of our bursts classified as XRFs are in fact intrinsic classical GRBs; the others are situated in the gap between XRF 020903 and the classical GRBs. Consequently, i-XRFs do not seem to form a distinct population but are the extension down to the low energies of the Amati correlation (Amati et al. 2002).

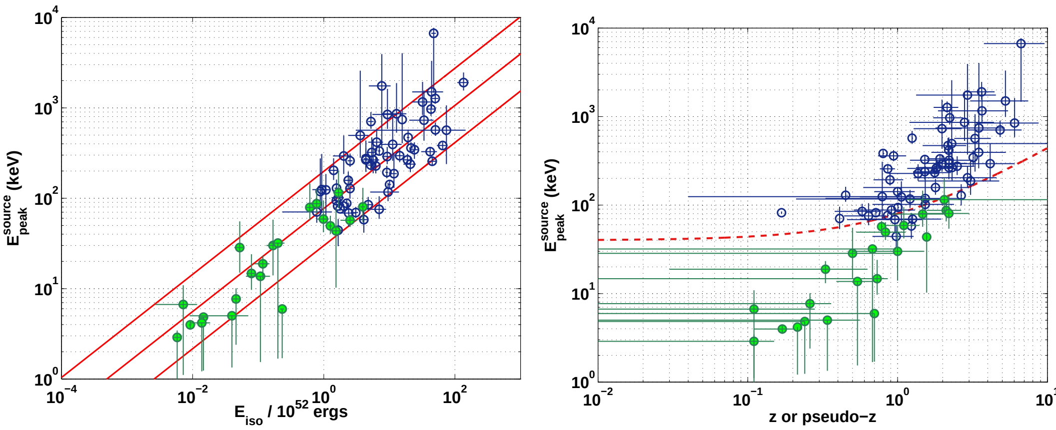

Fig. 3. In the left panel we have represented the 82 bursts of our sample in the E_{peak}^{source}-E_{iso} plane. We note that the HETE-GRBs are in agreement with the 'Amati correlation' (Amati et al. 2002), as it is imaged by the best-fit power-law found by Amati (2006) and that we have superimosed to our sample: $E_{peak}^{source} = 77 \times E_{iso}^{0.57}$ (with E_{peak}^{source} in keV and E_{iso} in units of 10^{52}erg) delimitated by a logarithmic deviation of 0.4. In the right panel the bursts are represented in the E_{peak}^{source}-z plane. The error bars on the pseudo-z reaching z=10 are for values having only a lower limit. The ones going down to z=0.1 are for pseudo-z with only an upper limit. The red dashed curve marks the redshift evolution of the E_{peak}, assuming a burst with $E_{peak}^{(z=0)}$=40 keV (see Stratta et al. 2007).

4.3 *Rate of GRBs in the Local Universe measured by HETE-2*

The method we employ to derive the unbiased distributions of the intrinsic GRBs' properties contained in our sample allows a renormalization of the global distribution by taking into account the true rate of occurence of each type of GRB. In other words, with the weight (W) applied to each burst (see Section 3), a GRB in a volume of visibility V=0.1 Gpc^3 has a weight 10 times more important (i.e. it is 10 times more frequent) than a GRB occuring in a volume of visibility V=1 Gpc^3. This also permits to derive the GRB rate, which is crucial to make a valuable comparison with the Type Ibc supernovae.

Since the last years, our increasing knowledge in GRBs has also lead to a complexification of the apparent population. The classical GRBs have appeared to be in fact the high-luminosity part (HL-GRBs) of the global population, which seems to contain, at the opposite, sub(low)-luminous bursts (LL-GRBs) such as GRB 980425 (Tinney et al. 1998) and GRB 060218 (Mirabal et al. 2006).

The rate of local GRBs obtained so far are always considering only one of this sub-population (HL- or LL-GRBs). The rate of HL-GRBs is generally derived by fitting a phenomenological luminosity function (LF) on known important catalogs of bursts (oftenly BATSE), and by assuming a theoretical model for the redshift evolution of the star formation rate (SFR). The HL-GRBs' rate is found to lie between 0.1 and 2 $Gpc^{-3}yr^{-1}$ (e.g. Schmidt 2001; Porciani & Madau 2001; Guetta et al. 2004, 2005; Liang et al. 2007). The rate derived considering the sub-luminous events is much higher, between 100 and 1000 $Gpc^{-3}yr^{-1}$ (Cobb et al. 2006; Pian et al. 2006; Soderberg et al. 2006; Liang et al. 2007; Guetta & Della Valle 2007), highlighting the fact that GRB 980425 or GRB 060218-like events are much more numerous than the 'classical bursts', but due to their extreme faintness they are much less detected. Therefore, we can argue that the GRBs usually detected by satellites are 'monsters', in comparison to the global population.

With the HETE-GRBs, we obtain a rate $\sim$17 $Gpc^{-3}yr^{-1}$. This is a lower limit because very faint events (E_{peak} $\sim$1 keV) are not detected by the satellite. We note that this rate is at least 1 order of magnitude higher than the expected HL-GRBs' rate and 1 order of magnitude lower than the expected LL-GRBs' rate obtained by the other studies mentioned above. This is explanable by the fact that we have not considered any phenomenological model (LF or SFR) but only measured observable parameters. Thus, the nature of the GRBs considered in the sample is predominant in the resulting rate. On the one hand, the HETE-GRBs' rate lower than the LL-GRBs' rate implies that no sub-luminous event such as GRB 980425 or GRB 060218 have been detected by HETE-2. On the other hand, we can argue that this rate higher than the HL-GRBs' one is the result of the important number of X-ray flashes detected by HETE-2. Indeed, these soft and faint events could not be detected by BATSE with its trigger energy range of 50-300 keV. However, as we have shown, their frequency is much higher than 'classical GRBs', that's why the local rate of HL-GRBs expected with BATSE bursts is at least ten times lower than the local rate measured with HETE-2 bursts.

X-ray flashes therefore constitute an intermediate class of occurence between the HL-GRBs and the LL-GRBs. Nevertheless, despite their softness, faintness and high frequency in the Local Universe, our study on the intrinsic parameters of HETE-2 bursts lets us bring closer the XRFs to the classical GRBs. Moreover, even if we take into account the X-ray Flashes, the measured rate of GRBs is far below the rate of SNe Ibc $R_0^{SNeIbc} = 9^{+3}_{-5} \times 10^3$ Gpc^{-3}yr^{-1} (Soderberg et al. 2006) measured by Cappellaro, Evans & Turatto (1999) and Dahlen et al. (2004) This low ratio images the fact that not all type Ib/c SNe are able to produce GRBs.

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