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GRB 090423 and the high-z GRBs as a New Tool to study the Reionization Epoch

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Abstract. The observation of the very early stages of the Universe represents one of the main challenges of modern cosmology. The direct investigation of the early Universe has been usually accomplished by observing distant quasars, but a new fundamental tool is now at hand thanks to Gamma-ray Bursts (GRBs). Indeed, the observation of GRB 090423 at a redshift of $z = 8.2$ has shown that GRBs can be detected at redshift higher than any other astrophysical objects. We will discuss here the possible use of high-z GRBs as a fundamental new tool to study the Universe at those early epochs.

Key words. gamma-ray sources; gamma-ray bursts; observational cosmology

1. Introduction

GRB 090423 was detected by NASA's *Swift* satellite on 23 April 2009 at 07:55:19 UT as a double-peaked burst of duration $T_{90} = 10.3 \pm 1.1$ s. As observed by the *Swift*/BAT, it had a 15–150 keV fluence $F = (5.9 \pm 0.4) \times 10^{-7}$ erg cm^{-2} and a peak energy $E_p = 48^{+6}_{-5}$ keV (errors at 90% confidence level). We used the 3.6m Italian Telescopio Nazionale Galileo (TNG) with the Near Infrared Camera Spectrometer (NICS) and the Amici prism to obtain a low-resolution ($R \approx 50$) spectrum of GRB 090423 $\sim$ 14 hrs after the trigger Salvaterra et al. (2009b). The spectrum reveals a clear break at 1.1 μm (fig. 1). Interpreting the break as Lyα absorption in the IGM, we derive a spectroscopic redshift of the GRB of $z = 8.1^{+0.1}_{-0.3}$ Salvaterra et al. (2009b), consistent with the later measurement with VLT Tanvir et al. (2009). At $z \sim 8.1$, GRB 090423 has a prompt-emission rest-frame duration of only $T_{90,rf} = 1.13 \pm 0.12$ s in the redshifted 15-150 keV energy band, an isotropic equivalent energy $E_{iso} = 1.0 \pm 0.3 \times 10^{53}$ erg in the redshifted 8-1000 keV energy band and a peak energy $E_{p,rf} = 437 \pm 55$ keV. The short duration and the high peak energy are consistent both with the distribution of long and short bursts, but the fact that GRB 090423 matches within 0.5σ the $E_{iso} - E_{p,rf}$ correlation Amati et al. (2008) argues in favor of a long GRB.

The rest-frame $\gamma-$ and X-ray light curve of GRB 090423 is remarkably akin to those of long GRBs at low, intermediate and high redshifts, suggesting similar physics and interaction with the circum-burst medium. Thus, it is unlikely that GRB 090423 arises from the explosion of a very massive, metal-free PopIII star. Instead we believe that the progenitor of GRB 090423 should belong to a second stellar generation, formed in a region enriched

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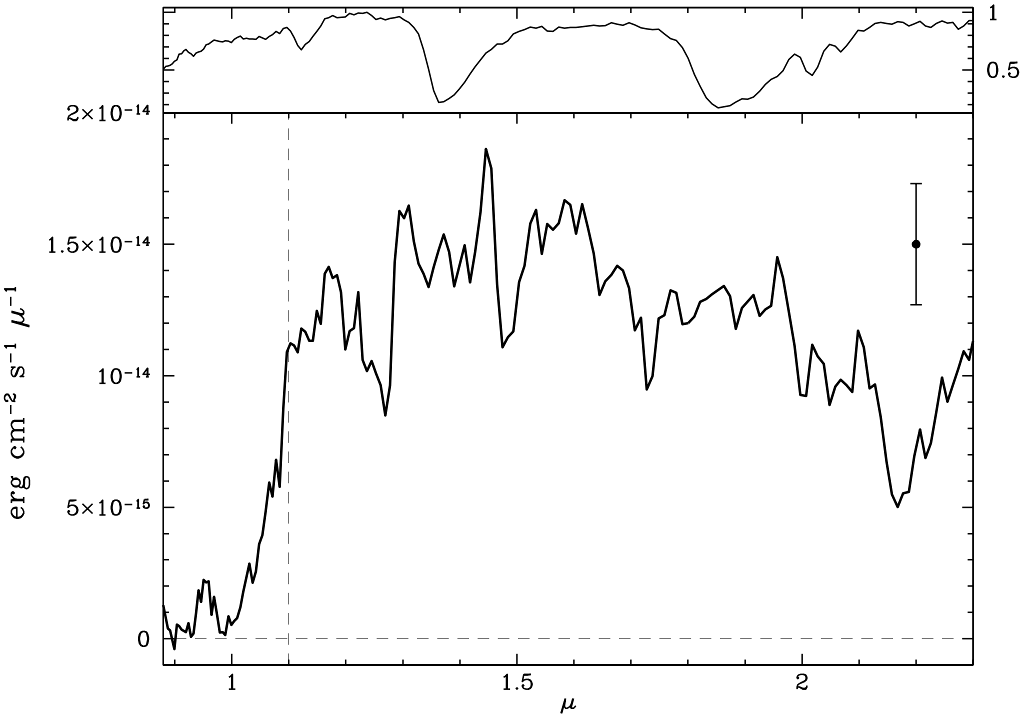

Fig. 1. Bottom Panel. Spectrum of GRB 090423 obtained with TNG. Top Panel. The plot represents the atmospheric transparency convolved with the instrumental response.

above the *critical metallicity* of $Z \sim 10^{-4}\ Z_{\odot}$ Schneider et al. (2003). So, GRB 090423 supports empirically the cosmological scenarios in which stars and galaxies, already enriched by metals, are in place at these redshifts. Long GRBs are mostly associated with star forming dwarf galaxies that are thought to be the dominant population of galaxies in the early Universe Choudhury et al. (2008). The fact that GRB 090423 appears to have exploded in an environment similar to that of low-z GRB hosts Fruchter et al. (2006) is in agreement with this.

2. Expected rate of extremely high-z GRBs

The occurrence of a GRB at $z \sim 8$ has important implications for the cosmic history of these objects Salvaterra & Chincarini (2007); Salvaterra et al. (2009a). In a first simple approach, we can assume that: i) GRBs trace the cosmic star formation history, given the well-known link of the long GRBs with the deaths of massive stars, and ii) GRBs are well described by a universal luminosity function. However, under these assumptions, the expected number of bursts at $z \geq 8$ with an observed photon peak flux larger than or equal to that of GRB 090423 is extremely low, $\sim 4 \times 10^{-4}$ in ~ 4 yrs of *Swift* operation. Hence, one or both above assumptions may be oversimplified Salvaterra & Chincarini (2007); Salvaterra et al. (2009a). The detection of a very high-z burst such as GRB 090423 could be accomodated if the GRB luminosity function were shifted towards higher luminosity according to $(1+z)^{\delta}$ with $\delta \gtrsim 1.5$ or if the GRB formation rate were strongly enhanced in galaxies with $Z \lesssim 0.2 Z_{\odot}$. Similar results can be obtained by considering both the large number of *Swift* detections at $z > 2.5$ Salvaterra & Chincarini (2007) and the number of bursts with peak luminosities

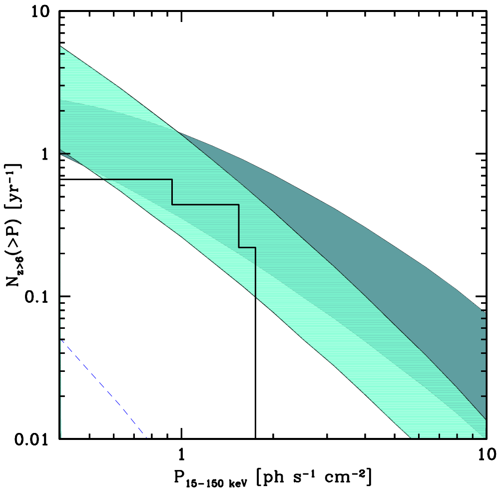

Fig. 2. Expected rate of GRBs at $z > 6$ as a function of the photon flux P in the *Swift* 15-150 keV band. No evolution model is shown with the dashed line. The dark (light) shaded area shows luminosity (density) evolution models. The solid histogram reports the distribution of the three observed GRBs at $z > 6$.

in excess of 10^{53} erg s^{-1} Salvaterra et al. (2009a).

We can use the above results to compute the expected rate of GRB detection at $z > 6$. Assuming a *Swift* photon flux limit of $P_{lim} \sim 0.4$ ph s^{-1} cm^{-2}, we find that 1-7% of all GRBs detected by the satellite should lie at $z > 6$ depending on the assumed evolution model. This is consistent with the three GRBs detected up-to-now (fig. 2). Future missions (e.g. EXIST, SVOM, JANUS, XENIA) will rapidly increase the number of detections. In particular, EXIST Grindlay et al. (2009) is expected to collect several tens of GRBs at $z > 6$ every year Salvaterra et al. (2008).

3. GRBs as a tool to study the reionization epoch

High-z GRBs can be used to address many fundamental open questions about the epoch in which the reionization process should have been completed (see Mc Quinn et al. (2009) for a brief review). In particular, GRBs can be use to select and study those faint galaxies that provide the bulk of the ionization photons and to constrain the reionzation redshift.

3.1. GRBs as signpost of reionization sources

At low-z, GRBs are typically found in blue, low-metallicity dwarf galaxies with stellar masses $M_* \sim 10^{8-9}\ M_\odot$ and high specific star formation rates Savaglio et al. (2009). These objects closely resemble the properties of high-z galaxies identified in recent cosmological simulations Salvaterra et al. (2010), suggesting that high-z GRBs can be used as signpost of these objects that are the main source of ionizing photons at $z > 6$. Moreover, the study of their afterglows can provide new hints about the metal (and dust) content of these objects Salvaterra et al. (2010) offering a unique way to study the metal enrichment history of the source of re-ionization. In particular, EXIST, thanks to its 1.1m optical-NIR telescope, will be able to take the GRB afterglow spectrum only 300 s after the trigger, allowing an on-board direct measure of the redshift and the identification of metal absorption lines when the afterglow is still sufficiently bright even for high-z bursts Grindlay et al. (2009).

3.2. Studying the reionization history with GRBs

GRBs consituite a powerful way, complementary to quasar, to study the reionization process. The spectra of a high-z GRB afterglows bluewards of the Lyα are characterized by dark portions (gaps) produced by intervening neutral hydrogen along the line of sight, interspersed with peaks of transmitted flux from ionized regions. The statistics of gaps and peaks can provide strong constraints on the ionization fraction along the line of sight. In particular, the size of the largest of these dark gaps can be used to discriminate among different reionization scenarios Gallerani et al. (2008). As a test, we applied the above method to GRB 050904 at $z = 6.3$ whose largest dark gap is $\sim$ 63 Å(see fig. 3), indicating a net preference of an early reionization model (i.e.

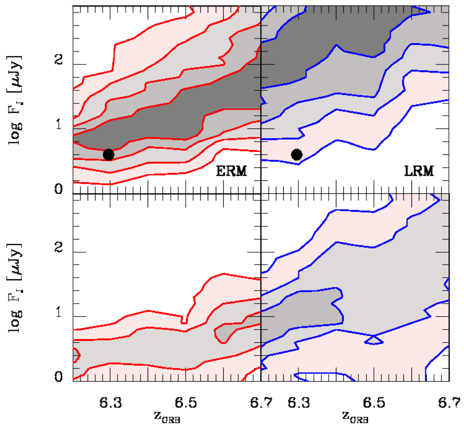

Fig. 3. Isocontours of the probability that the afterglow spectrum of J-band flux F_J associated with a GRB at redshift z_{GRB}, contains a largest gap in the range 40–80 Å (top panels) and in the range 80–120 Å (bottom panel). The left (right) panel shows the results for the ERM (LRM). The isocontours correspond to probability of 15%, 30%, 45%, and 60%. The black point indicates the position in the (z_{GRB}, F_J) plane of GRB 050904.

$z_{reion} \geq 7$) over a late reionization model (i.e. $z_{reion} \sim 6$). Spectroscopic observations of a few tens of GRBs in the redshift range $6 < z < 7.5$ with EXIST will enable us to constrain the epoch of reionization.

4. Conclusions

The observation of GRB 090423 at $z = 8.2$ has shown that GRBs do exist at very high redshift and are detectable with available facilities. Thanks to their brightness, GRBs appear to be a fundamental tool to study the early Universe as they are expected to highlight the position of those faint galaxies that provide the bulk of ionizing photons. Spectroscopy of their optical-NIR afterglows will provide the measure of the metallicity of these galaxies allowing to extend the study of the mass-metallicity relation and its evolution well beyond current limits. Moreover, the study of the gaps distribution between Lyα and Lyβ for GRBs at $6 < z < 7$ can be used to give important constraints on the reionization history.

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