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The farthest GRBs similar to the closest

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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 and galaxies, but a new fundamental tool is now at hand thanks to Gamma-Ray Bursts (GRBs). Here we review the status of the observations of GRBs at $z > 6$ and show that they exhibit properties similar to those at low/intermediate redshifts. Finally, we discuss these results in the light of up-to-date model predictions.

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

1. Introduction

Gamma-ray bursts (GRBs) are powerful flashes of high-energy photons occurring at an average rate of a few per day throughout the universe. Thanks to their luminosity, GRBs can be detected up to very high redshifts and can be used to study the first stages of structure formation. In particular, at those early epochs we expect two fundamental transitions to have occurred: the change in the star-formation mode (from massive, metal-free PopIII stars to normal PopII stars) and the reionization of the inter-galactic medium. It is believed that the transition from PopIII to PopII stars is driven by the change in the metal content of the gas from which the two populations arise. In particular, it has been shown that there exists a critical metallicity, $Z_{\rm crit} = 10^{-5\pm1}\ Z_{\odot}$, below which massive PopIII stars are expected to form (Schneider et al. 2003). On cosmic scale, this process depends on the strength of the so-called chemical feedback (Schneider et al. 2006). PopIII stars are powerful source of ionizing photons (Schaerer 2002) and, thus, may play a major role in the reionization process (see Ciardi & Ferrara (2005) for a review).

High-z GRBs may provide important new information about these processes. Here, we review the status of observations of GRBs at $z > 6$ and compare them with up-to-date model predictions.

2. High-z GRB observations

At the time of writing, four GRBs at $z > 6$ has been detected by *Swift*: GRB 050904 (Kawai et al. 2006), GRB 080913 (Greiner et al. 2009), GRB 090423 (Salvaterra et al. 2009b; Tanvir et al. 2009), and GRB 090429B (Cucchiara et al. 2011).

The only high-quality spectra burst at $z > 6$ available so far, GRB 050904 at $z = 6.3$, shows the expected metal absorption features, witnessing the presence of metals at the same redshift of the GRBs (Kawai et al. 2006). From this data, and with the further assumption that the measured sulfur ([S/H]=-1.3 ± 0.3) is a

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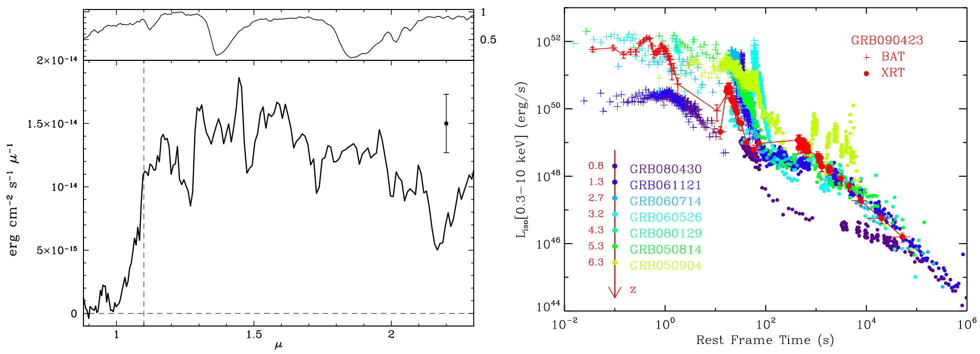

Fig. 1. GRB 090423. Left panel: Spectrum of the NIR afterglow of GRB 090423 obtained with TNG (Salvaterra et al. 2009b). The sharp break at $\lambda \approx 1.1$ μm, due to the HI absorption in the intergalactic medium at the wavelength of the Lyα line, implies $z = 8.1^{+0.1}_{-0.3}$. The plot in the top panel represents the atmospheric trasparency convolved with the instrumental response. Right panel: BAT and XRT light curve of GRB 090423 (red data) in the source rest-frame compared with seven GRBs at low/intermediate redshifts.

good proxy for metallicity, one can determine the metal content of the host galaxy. This measurement indicates that GRB 050904 exploded in a galaxy already enriched at the level of $\sim 0.05\ Z_{\odot}$, which is in line with the measure metallicity of GRB host at lower redshift (Savaglio et al. 2009). We will further discuss this point in Sect. 4.

GRB 080913 was identified by GROND as a good high-z candidate and confirmed to lie at $z = 6.7$ by spectroscopic observations with VLT (Greiner et al. 2009). The low signal-to-noise ratio of the spectrum prevents the identification of any metal feature, although the detection of SII+SiII absorption at 2.9σ level has been tentatively reported by Patel et al. (2010).

The spectroscopic measure of the redshift of GRB 090423 at $z = 8.2$ (see left panel of Fig. 1) pushes the limit of detection of GRBs well inside the so-called reionization epoch, indicating that GRBs are detectable with present-day facilities at extreme high redshifts. Let us now consider more in details the observed properties of GRB 090423 and compare them with those of lower redshift bursts. At $z = 8.2$, GRB 090423 has 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, making it consistent within 0.5σ the $E_{iso} - E_{p,rf}$ correlation (Amati et al. 2008) that holds for lower redshift bursts. Moreover, 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 (see right panel of Fig. 1). These facts suggest that the progenitor and the circum-burst medium of GRB 090423 are similar to those of bursts exploding at lower redshift. This is also confirmed by the data at radio wavelengths (Chandra et al. 2010). Similar conclusions have been reached in the case of GRB 090429B for which a photometric redshift of $z \sim 9.4$ has been measured (Cucchiara et al. 2011) . Thus, it is unlikely that GRB 090423 and GRB 090429B, in spite of their extreme high redshift, arise from the explosion of a very massive, metal-free PopIII star. Instead we believe that their progenitors should belong to a second stellar generation, formed in a region enriched above the critical metallicity. Indeed, this is in line with what expected in up-to-date simulations of structure formation and evolution in the early Universe (Tornatore et al. 2007; Maio et al. 2010) that take into account the effect of the chemical feedback. Using these results, we compute a conservative upper limit on the rate of GRBs from PopIII progenitors that can be detected by

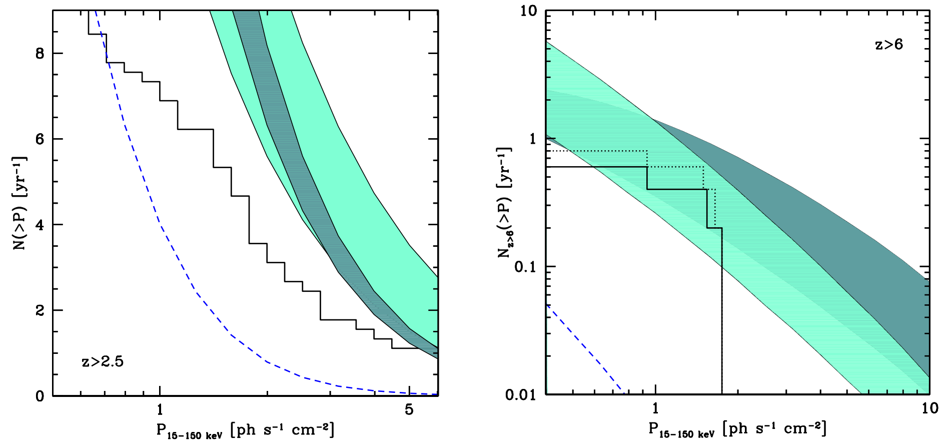

Fig. 2. Model predictions. Left panel: expected rate of GRBs at $z > 2.5$ as a function of the photon flux P in the *Swift* 15-150 keV band. The histogram report the observed distribution of GRBs with $z > 2.5$. Note that the histogram has to be considered as a strong lower limit on the real rate since many $z > 2.5$ GRBs can be hidden among those bursts lacking redshift measurements ($\sim 60 - 70\%$ of all *Swift* GRBs). No evolution model is shown with the dashed line. The dark (light) shaded area shows luminosity (density) evolution models. Right panel: same as in the left panel but for $z > 6$. Solid histogram reports the three spectroscopic confirmed GRBs at $z > 6$ whereas the dotted one takes into account also the detection of GRB 090429B with a photometric redshift of $z \sim 9.4$.

Swift (Campisi et al. 2011a). We find that less than 20% of *Swift* GRBs at $z > 8$ should arise from PopIII stars even assuming that PopIII GRBs were much more luminous than PopII/I GRBs.

3. High-z GRB model predictions

In order to compute the expected rate of GRBs at very high redshift, we have to follow their formation and evolution through cosmic times (Salvaterra & Chincarini 2007; Salvaterra et al. 2009a). In a first simple approach (no evolution model), 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. Model results has been compare with the lower limits on the rate of GRBs at $z > 2.5$ obtained by the number of *Swift* bursts with known redshift (see dashed line in Fig. 2). It is clear that this simple model fails to reproduce available data and, hence, one or both above assumptions may be oversimplified (Salvaterra & Chincarini 2007; Salvaterra et al. 2009a). Indeed, the large number of *Swift* detections at $z > 2.5$ (Salvaterra & Chincarini 2007) and also the number of bursts with peak luminosities in excess of 10^{53} erg s^{-1} (Salvaterra et al. 2009a) can be explained assuming the existence of some evolution in luminosity and/or in density of long GRBs. For example, in Fig. 2 we show the results obtained assuming that the GRB luminosity function is shifted towards higher luminosity according to $(1 + z)^{\delta}$ with $\delta \gtrsim 1.5$ (dark shaded area) or that the GRB formation rate were strongly enhanced in galaxies with $Z \lesssim 0.3 Z_{\odot}$ (light shaded area). In both cases, evolutionary models can account easely for the observed rate of $z > 2.5$ bursts.

We can use the above results to compute the expected rate of GRB detection at $z > 6$. For the *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 four GRBs detected up-to-now (see the right panel of Fig. 2).

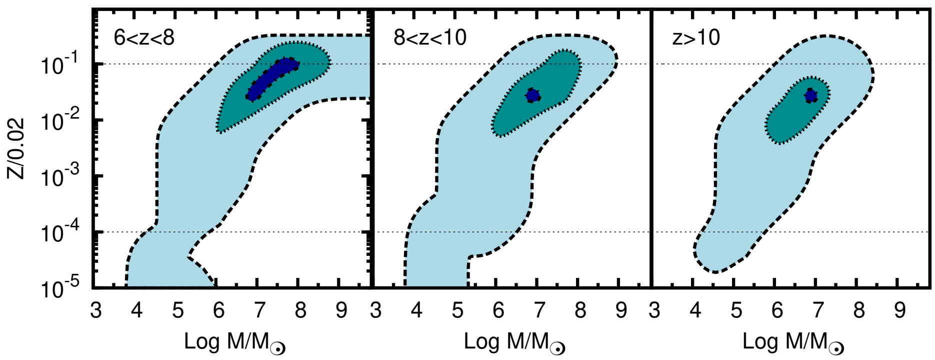

Fig. 3. Mass-metallicity relation for simulated GRB host galaxies at high redshift. The shaded areas represent the probability to find a GRB in a galaxy with stellar mass M and metallicity Z computed by weighting each galaxy for the number of GRBs hosted (see Campisi et al. (2011a,b) for the details of the procedure).

4. High-z GRB host galaxies

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; Mannucci et al. 2011). These objects closely resemble the properties of high-z galaxies identified in cosmological simulations (Salvaterra et al. 2011). In Fig. 3 we show the mass-metallicity relation of simulated GRB hosts at very high redshift. The shaded areas represent the probability contours to find a GRB in a galaxy with given stellar mass M and metallicity Z. These have been computed by weighting each galaxy for the number of GRBs hosted. At $6 < z < 8$ the highest probability is found for objects with stellar masses $3 \times 10^6 < M/M_\odot < 10^8$ and metallicity $0.02 < Z/Z_\odot < 0.2$. These objects are found to provide the bulk of the ionizing photons at these redshifts (Salvaterra et al. 2011).

As discussed above, absorption lines identified in the spectrum of GRB 050904 at $z = 6.3$ (Kawai et al. 2006) lead to an estimate of the metallicity of 0.05 $Z_\odot$. The metallicity of simulated GRB host galaxies is in agreement with this value. Interestingly enough, we find that GRB host galaxies are likely missed in current deep field survey even with HST/WFC3 (Salvaterra et al. 2011), showing that GRBs can be use as signposts of those faint galaxies that are now believed to be the sources that reionize the Universe (Salvaterra et al. 2011).

5. Conclusions

The detection of GRB 090423 at $z = 8.2$ and, more recently, of GRB 090429B at $z \sim 9.4$ have clearly shown that GRBs are detectable at extreme high redshift with present-day facilities. Future instruments (e.g. EXIST, JANUS, etc.) will detect a large number of high-z GRBs (Salvaterra et al. 2008). They will provide us fundamental information about the early Universe, shading light on the source that reionize the Universe (Salvaterra et al. 2011) and on the reionization process (Mc Quinn et al. 2009; Gallerani et al. 2008).

6. Discussion

JIM BEALL: What sort of stars and galaxies would one find in a PopIII epoch?

RUBEN SALVATERRA: With respect to normal PopII stars, massive metal-free stars are powerful sources of high energy photons, that can ionize both H and He. Thus, from an observational point of view, a PopIII galaxy would appear as a *dual emitter*, showing strong emission in both Lyman-α and HeII lines (Schaerer 2002). As discussed in the introduction, the transition from PopIII to PopII stars is govened by the so-called chemical feedback. This is essentially a local effect and therefore we expect that the two populations can coexist for a long period of time and PopIII galaxy may form even at relatively low redshift, i.e. $z \sim 5$ (see e.g. Schneider et al. (2006)). However, using recent cosmological numerical simulations including the effect of the chemical feedback, we found that the contribution of PopIII stars to the total luminosity of their parent galaxy is negligible ($< 5\%$) for all objects but the faintest ones, making their detection extremely difficult even with the next generation of space facilities (Salvaterra et al. 2011).

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