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Review

High redshift Gamma-Ray Bursts

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ABSTRACT

Ten years of operations of the *Swift* satellite have allowed us to collect a small sample of long Gamma-Ray Bursts (GRBs) at redshift larger than 6. I will review here the present status of this research field and discuss the possible use of GRBs as a fundamental new tool to explore the early Universe, complementary to quasar and galaxy surveys.

1. Introduction

In the standard ΛCDM scenario, the first stars, the so-called Population III (PopIII) stars, are predicted to form in dark matter minihalos of typical mass $\sim 10^6$ $M_\odot$ at $z \sim 20$–30 out of a gas of pristine composition (see Ciardi and Ferrara, 2005; Bromm and Yoshida, 2011, for recent reviews). Because of their peculiar chemical composition, they are expected to be more massive than the subsequent stellar populations with typical mass of ~ 40 $M_\odot$ (Hosokawa et al., 2011), possibly extending up to hundred solar masses (Hirano et al., 2014). The formation of these stars mark the fundamental transition from a simple, very homogeneous Universe to the complex and structured one we see already in place a billion years after the Big Bang. During this period of time two fundamental transitions are expected to occur: (i) a change in the SFR mode, i.e. from massive PopIII to solar-size PopII/I stars and (ii) the cosmic reionization, i.e. the change of the inter-galactic medium (IGM) from a neutral to a fully ionized state. There is a general consensus that the first transition is driven by the so-called chemical feedback (Schneider et al., 2002), i.e. the enrichment of star forming clouds by the first supernova explosions above a critical threshold of $Z_{\rm crit} = 10^{5\pm1}$ $Z_\odot$ (Schneider et al., 2003). As the chemical feedback is essentially a local effect, on cosmological scale the two populations should be coeval for a long period of time (Schneider et al., 2006; Tornatore et al., 2007; Maio et al., 2010). Understanding how and when the change in the SFR mode happened is one of the main goals for current studies of galaxy formation in the early Universe and the detection of PopIII stars one of the main challenges of the next generation of space and ground facilities (see Bromm and Yoshida, 2011, for a review). The cosmic reionization of the IGM has been extensively studied in the last years both from a theoretical and observational point of view (see Loeb and Furlanetto, 2013, for a recent review). While many steps towards our understanding of reionization process have been done, still many fundamental details are missed: In which way does it proceed? How gradual and how prolonged was the process? Was radiation from early stars sufficient to sustain this phase transition? Do PopIII stars or quasars have a major role in driving the process? Is some other more exotic process at work? etc.

Historically, the exploration of the distant Universe has been carried out following two main pathways: the observations of bright quasars detected in wide shallow surveys (Fan, 2012), and of distant galaxies identified through the drop-out technique in small fields (Bouwens et al., 2014). Because of their extreme brightness Gamma-Ray Bursts (GRBs) represent an alternative way to access those early epochs. As demonstrated by GRB 090423 at $z = 8.2$ (Salvaterra et al., 2009a; Tanvir et al., 2009), they can be detected even at distances much larger than any other cosmic object. In principle, their afterglow emission can be observed up to $z \sim 20$ (Ciardi and Loeb, 2000; Gou et al., 2004) providing useful information about the ionization and metal enrichment history of the early Universe. Here, I will review the present observational status of this research field and discuss the possible role of GRBs in the exploration of the Universe during and before the reionization epoch.

This paper is organized as follows. In Section 2, a brief summary of the observations of the GRBs at $z > 6$ and of their host galaxies is given. Section 3 presents the expected rate of high-z GRBs both from PopII and PopIII stars and the expected proper-

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Table 1
List of the GRBs at $z > 6$ detected by *Swift* and of their observed properties: peak energy (E_p), isotropic equivalent energy in the 1–10 000 keV range (E_iso), hydrogen column density in the host (N_HI), X-ray equivalent hydrogen column density ($N_\mathrm{H,X}$), host metallicity (Z) and dust extinction (A_V). The last two columns report the limits on the host galaxy luminosity ($M_\mathrm{UV,host}$) and SFR. See text for references.

GRB	z	E_p [erg]	E_iso [erg]	$\log(N_\mathrm{HI})$ [cm^{-2}]	$\log(N_\mathrm{H,X})$ [10^{21} cm^{-2}]	Z [$Z_\odot$]	A_V	$M_\mathrm{UV,host}$ [AB]	SFR$_\mathrm{host}$ [$M_\odot$ yr^{-1}]
050904	6.3	3178	1.24×10^{54}	21.6	63^{+34}_{-29}	-1.6 ± 0.3	0.15 ± 0.07	> -19.95	< 4.1
080913	6.7	1008	7×10^{52}	19.84	95^{+89}_{-77}	–	0.12 ± 0.03	> -19.00	< 1.3
090423	8.2	746	1.88×10^{53}	–	102^{+49}_{-54}	–	< 0.1	> -16.95	< 0.38
130606A	5.9	2028	2.7×10^{53}	19.93	< 30	-1.35 ± 0.15	< 0.05	–	–
140515A	6.3	376	5.1×10^{52}	18.62	< 226	< -0.8	0.11 ± 0.02	–	–
090429B	9.4	437	4.31×10^{52}	–	140 ± 10	–	0.10 ± 0.02	> -19.65	< 2.4
120521C	6.0	–	1.9×10^{53}	–	< 60	–	< 0.05	–	–
120923A	8.5	376	5.1×10^{52}	–	< 720	–	–	–	–

ties of the relative host galaxies. In Section 4, the use of GRBs as a probe of the early Universe is reviewed. Finally in Section 5 I present some ideas for the future of this research field. The conclusions are drawn in Section 6.

2. Observations

2.1. The Swift high-z GRB sample

In ten years of operations *Swift* has detected a handful of bursts with spectroscopically confirmed redshift larger than 6. In addition, other three GRBs have well constrained photometric redshift above this limit. The observed high-z sample represents $\sim 1\%$ of all *Swift* bursts, $\sim 2.5\%$ of those with known z. The main properties of the $z > 6$ GRB sample are given in Table 1.

- **GRB 050904** at $z = 6.3$ (Kawai et al., 2006)
  This burst was firstly imagined by the 25-cm telescope TAROT (Klotz et al., 2005). Its high-z nature was recognized by multi-wavelength photometric data (Haislip et al., 2006; Tagliaferri et al., 2005) and firmly confirmed spectrocopically three days after the *Swift* trigger by the Subaru telescope (Kawai et al., 2006). The afterglow spectrum provided a upper limit on the neutral hydrogen fraction at the GRB redshift of $x_\mathrm{HI} < 0.17$ at 1σ confidence (Totani et al., 2006) and a measure of the metallicity at the level of $\sim 0.1\ Z_\odot$ (Kawai et al., 2006). Recently, Thöne et al. (2013) revised this value, inferring a slightly lower metallicity from the S II λ1243 equivalent width, resulting in $\log(Z/Z_\odot) = -1.6 \pm 0.3$. The afterglow spectral energy distribution (SED) requires the presence of SMC or supernova (SN) type dust at a level of $A_V = 0.15 \pm 0.07$ (Stratta et al., 2011, but see Zafar et al., 2011b). The modeling of afterglow data from X-ray to radio suggests GRB 050904 to be an energetic burst blowing up in a dense medium with $n \simeq 680$ cm^{-3} (Frail et al., 2006; Laskar et al., 2014).
- **GRB 080913** at $z = 6.7$ (Greiner et al., 2009)
  The high-z nature of this burst was recognized via the detection of a spectral break between the i' and z' bands of the GROND instrument and then confirmed spectroscopically by VLT observations. The analysis of the red damping wing constrained $x_\mathrm{HI} < 0.73$ at 90% confidence level (Patel et al., 2010). In spite of the rapid follow-up campaign, the faintness of the afterglow prevented the detection of any metal absorption line, but the $\mathrm{S_{II}}+\mathrm{Si_{II}}$ at 2.9σ level (Patel et al., 2010). Dust absorption of $A_V = 0.12 \pm 0.03$ is found from SED fitting (Zafar et al., 2011a).
- **GRB 090423** at $z = 8.2$ (Salvaterra et al., 2009a; Tanvir et al., 2009)
  The spectroscopic redshift of this burst was secured by TNG (Salvaterra et al., 2009a) and by VLT (Tanvir et al., 2009), and still represents the distance record for a cosmic object. Radio observations by VLA were reported by Chandra et al. (2010). The analysis of the multi-wavelength dataset shows that the afterglow is reminiscent of many other lower redshift bursts, suggesting that in spite of its extreme redshift, its progenitor and the medium in which it blowed up were not peculiar. Indeed, its detection is consistent with the high-z tail of PopII/I GRB redshift distribution (Salvaterra et al., 2009a). From the X-ray to optical SED no absorption by dust is evident with $A_V < 0.1$ (Salvaterra et al., 2009a; Tanvir et al., 2009, but see Laskar et al., 2014).
- **GRB 130606A** at $z = 5.9$ (Chornock et al., 2013; Castro-Tirado et al., 2013; Totani et al., 2014; Hartoog et al., 2014)
  The redshift of this burst was obtained by Gemini-North (Chornock et al., 2013), GTC (Castro-Tirado et al., 2013), Subaru (Totani et al., 2014) and VLT (Hartoog et al., 2014). In particular, the superior resolution and wavelength coverage of the VLT/X-shooter instrument showed the potentiality of GRBs as tool to study in great details the metal enrichment of star forming region inside high-z galaxies (Hartoog et al., 2014). Precise column densities of H, Al, Si and Fe are reported together with limit on C, O, S and Ni. The host metallicity is constrained to be in the range of 0.03–0.06 solar and the high [Si/Fe] in the host suggests the presence of dust depletion (though $A_V < 0.05$ from SED fitting). The best fit of the Lyα absorption line is obtained for $\log(N_\mathrm{HI}) = 19.94 \pm 0.01$ and negligible neutral hydrogen in the external medium, with $x_\mathrm{HI} < 0.03$ at 3σ significance.
- **GRB 140515A** (Chornock et al., 2014; Melandri et al., in preparation)
  The redshift of this burst has been secured by Gemini-North (Chornock et al., 2014), GTC and VLT (Melandri et al., in preparation). Chornock et al. (2014) analyzed the Gemini-North spectra finding no evidence of narrow absorption lines, indicating a host metallicity $Z < 0.15\ Z_\odot$. However, Melandri et al. (in preparation) by modeling the X-ray to optical SED found evidence for dust absorption to the level of $A_V \sim 0.1$ indicating some metal enrichment. The red damping wing of Lyman-α can be fitted equally well by a single host galaxy absorber with $\log(N_\mathrm{HI}) = 18.62 \pm 0.08$ or a pure IGM absorption with neutral hydrogen fraction $x_\mathrm{HI} \sim 0.06$ (Chornock et al., 2014).

Other three GRBs have accurate photometric redshift measurement that place in the $z > 6$ sample:

- **GRB 090429B** at $z \sim 9.4$ (Cucchiara et al., 2011)
  Cucchiara et al. (2011) collected the afterglow data obtained with Gemini-North, VLT and GROND. In the best fit model these data are all consistent with a photometric redshift of $z = 9.4$ and low extinction $A_V = 0.10 \pm 0.02$. A secondary solution at very low redshift is still allowed by the SED fitting, but it seems unlikely due to the lack of any detection of the GRB host galaxy (see next section).