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GAMMA-RAY BURSTS AS COSMOLOGICAL PROBES

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Abstract.
Gamma-ray bursts (GRBs) are short, intense bursts of gamma-rays which during seconds to minutes outshine all other sources of gamma-ray emission in the sky. Following the prompt gamma-ray emission, an 'afterglow' of emission from the X-ray range to radio wavelengths persists up to months after the initial burst. The association of the class of long GRBs with the explosion of broad-line type Ic SNe hence with the death of massive stars, makes this class of GRBs a tracer of star formation across the observable Universe up to the highest redshifts. They can be used to probe the reionization and the first stars.

GRBs allow galaxies to be selected independently of their emission properties (independently of dust obscuration and, uniquely, independently of their brightnesses at any wavelength) and they also permit the study of the gas in the interstellar medium (ISM) systematically and at any redshift by the absorption lines present in the afterglow spectra. Moreover, the fading nature of GRBs and the precise localization of the afterglow allow a detailed investigation of the emission properties of the GRB host galaxy once the afterglow has vanished. GRBs therefore constitute a unique tool to understand the link between the properties of the ISM in the galaxy and the star formation activity, and this at any redshift. This is a unique way to reveal the physical processes that trigger galaxy formation.

The *SVOM* space mission project is designed to improve the use GRBs as cosmological probes.

Keywords: Gamma-ray burst: general, Cosmology: observations, early Universe, dark ages, reionization, first stars, Galaxies: evolution, Galaxies: ISM

1 Introduction

Gamma-ray bursts (GRBs) are the most extreme cosmic explosions. They are detected from space thanks to the flash of high-energy photons released within a transient relativistic jet, which signals the explosion. This short lasting *prompt emission* is followed by an *afterglow*, detectable from the X-ray to the radio wavelengths for hours to months, depending on the frequency domain and on its intrinsic brightness. The production of the ultra-relativistic jet is associated with the formation of a black hole by the explosion of a massive star or by the merger of two compact objects.

The study of GRBs impacts several branches of physics and astrophysics. In fact, GRBs can be used to study the physics of jets, of relativistic shocks and radiative processes. Moreover they constitute excellent candidate sources for multi-messenger astrophysics (high-energy neutrinos and gravitational waves). Being connected with the last phases of stars, they are of great interest also for the stellar physics and evolution domain. Thanks to their exceptional brightness GRB afterglows can be used as powerful extragalactic background sources. They behave like distant lighthouses capable of unveiling the properties of the universe at different redshifts. Furthermore the class of long GRBs (LGRBs; see Kouveliotou et al. 1993 for a definition) is associated with the deaths of the most massive stars, making LGRBs especially suitable as tools to investigate star formation in the early Universe.

The following sections are focused on the use of LGRBs as cosmological probes (see also Petitjean & Vergani 2011) and on the future perspective that the *SVOM* satellite could fulfill.

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2 Advantages and disadvantages of using LGRBs as cosmological probes

There are at least four factors that make LGRBs potentially very powerful for the study of galaxy evolution and of the very high redshift universe up to the reionization epoch. First of all GRBs are extremely bright at all redshift and even their afterglow brightness is only marginally decreasing with redshift (Lamb & Reichart 2000). This, combined with the association of LGRBs with the death of massive stars, makes LGRBs observable in principle up to $z > 15$ with present day instruments, and therefore tools to probe the early universe, the epoch of reionization, the first stars and the chemical enrichment of the universe. A further help in this direction comes from the power-law shape of the afterglow continuum, that makes the study of the absorbing gas easier compared to quasars (QSOs). Another advantage is that the afterglow emission is fading quite rapidly with time, allowing the study of the GRB host galaxies. These last form a sample of star forming galaxies selected independently of their emission properties (independently of dust obscuration and, uniquely, independently of their brightnesses at any wavelength), therefore complementary to the galaxy survey samples. Furthermore GRBs offer the unique opportunity to investigate systematically both the neutral gas using the afterglow spectra absorption lines AND the ionized gas by the emission lines of the host galaxy spectra. GRBs therefore constitute a unique tool to understand the link between the properties of the interstellar medium of galaxies and their star formation activity, and this at any redshift. This is a unique way to reveal the physical processes that trigger galaxy formation.

The transient nature of GRBs is, on the other hand, also the main disadvantage of the use of these sources as cosmological probes. The optical/near-infrared afterglow observations, necessary for a precise localization allowing the observation of the afterglow spectrum and the association with the host galaxy, have to take place as early as possible after the GRB prompt emission detection. Moreover it is not possible to carry out observation over long integration time so as to obtain high signal-to-noise spectra for all GRBs. To date, less than 30% of GRBs have a measured redshift*. More than 1100 GRBs have been detected, but the afterglow spectra are about 300 and the sample of host galaxies detected at least in one optical band is formed by less than 200 galaxies.

3 Afterglow spectroscopy

Thanks to their exceptional brightness, GRB afterglows can be used as powerful extragalactic background sources. The gas in front of the GRB selectively absorb part of the light and consequently is revealed by spectroscopic observations. The afterglow spectrum shows the signatures of the gas associated with the GRB host, with the IGM and with other galaxies present along the GRB line of sight.

Many are the gas properties that can be measured through the absorption lines present in the afterglow spectra, mainly for GRBs at $z > 2$. In fact, at those redshift the damped Lyman-α absorption (DLA) of the neutral hydrogen associated with the GRB host galaxy is in the frequency range covered by the optical-NIR spectrographs, together with the metal lines. It is possible to determine directly the neutral hydrogen and metals column densities and hence the metallicity of the gas. The H_2 and CO absorption features can also be present (Prochaska et al. 2009; Krühler et al. 2013).

3.1 Chemical Enrichment

The metallicity and abundance measurements can be use to add information on the chemical enrichment of the Universe. Differently from QSOs that probes random lines of sight of the foreground galaxies, GRBs mostly probes the gas associated with the star forming regions of their host. As shown in Figure 1 (left panel; see Sparre et al. 2013 and references therein), LGRBs are playing a fundamental role to add information at $z > 4.5$, and testify of an interstellar gas already quite enriched even at high redshift.

3.2 Reionization and PopIII stars

It is possible to probe the reionization epoch using the absorption signatures imprinted by neutral hydrogen in the intergalactic medium in the spectrum of GRB afterglows at high redshift (see Fig. 1, right panel). When the Universe is neutral, a broad and extended absorption trough with a red damping wing will be seen in the

*http://www.mpe.mpg.de/~jcg/grbgen.html

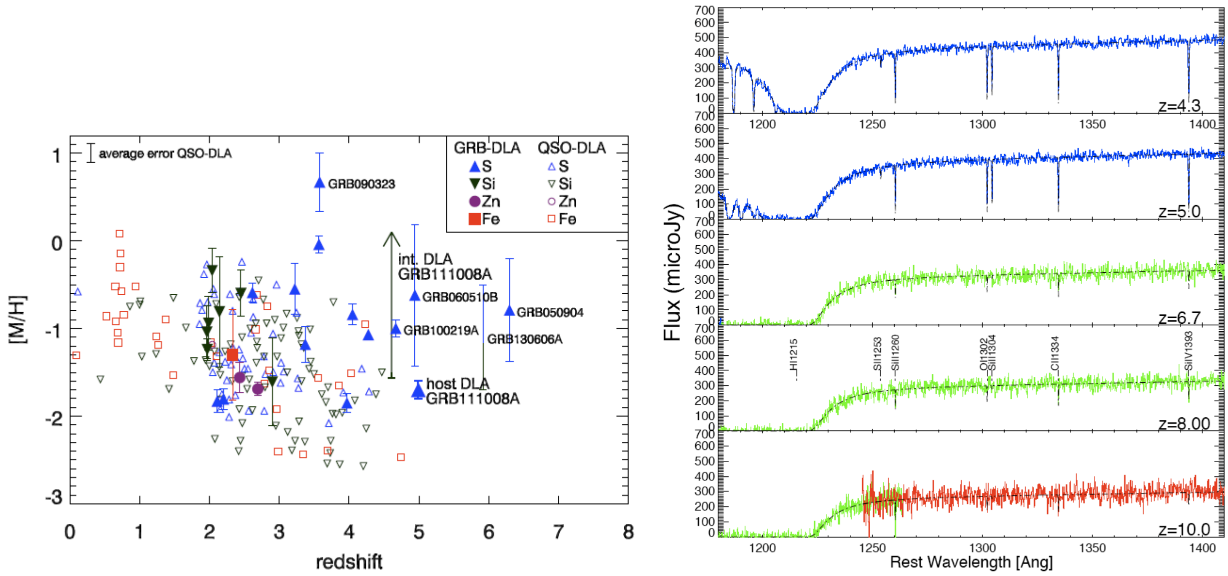

Fig. 1. Left: From Sparre et al. (2013). Metallicities as a function of redshift for GRB-DLAs (filled symbols) and QSO-DLAs (open symbols). **Right:** From McQuinn et al. (2009). Simulation of high-z GRB afterglow optical and near infrared spectra at $R \sim 3000$. The impact of the IGM on the spectrum is apparent in the left-side of the spectra.

spectrum. GRBs have the advantage compared to QSOs to be able to probe higher redshifts ($z > 8$). They also do not produce the large-scale proximity effect of QSOs that ionize the IGM to a distance of several Mpc. The neutral gas from the host galaxy located in front of the GRB already produces a damping wing (upper panel of the figure) but the additional signature of the IGM is much stronger (other panels) and can be detected even at intermediate spectral resolution.

The formation of the first objects in the Universe is a vividly debated issue and numerous models have been proposed (see Bromm 2013 for a review). These objects have an important impact on the first stages of structure formation and on the reionization history of the IGM, as they provide the first sources of light, heat and metals in the Universe (Ciardi & Ferrara 2005). LGRBs represent the most promising way to directly experience the explosion of the first stars. Indeed, the high mass expected for these stars (between 100 and 200 solar masses) strongly suggests that they will end their life producing a GRB. The spectroscopic observation of only one of the afterglow of such an explosion would correspond to a tremendous breakthrough by revealing the physical state of the gas in the surrounding of such remote objects. Recently, simulations of the expected afterglow spectral features of a GRB in a PopIII environment have been performed (Wang et al. 2012) showing that they can be detectable with future spectrographs, and confirming that GRBs may open one of the few direct windows into the crucial epoch of the first stars.

4 Observations of the GRB host galaxies

Once the afterglow vanished, it is possible to carry out photometrical and spectroscopical campaigns to study the properties of the GRB host. Using the emission lines present in the spectra it is possible to determine the dust extiction (by the Balmer decrement), the star formation rate (SFR, by the H-α or [OII] lines) and the metallicity mainly through indirect indicators (R_{23}, N2, etc...). Thanks to the spectral energy distribution (SED) built using multi-band photometry of the host it is possible to estimate also the stellar mass of the galaxy and the age of the stellar population (e.g.: Savaglio et al. 2009).

Most exciting is the combination of the gas properties obtained by the afterglow spectroscopy and those retrieved by the host observations. A systematical study in this sense can bring important informations on the physical processes that trigger galaxy formation. The kinematics and geometry of the gas can be assessed as well. First attempts in this way have been performed by Vergani et al. (2011b) and Chen (2012).

5 X-shooter

One of the best instrument available to carry out both afterglow spectroscopy and host galaxy studies is the ESO (European Southern Observatory) X-shooter spectrograph (Vernet et al. 2011) installed at the VLT (Very Large Telescope) in Paranal (Chile). This first ESO new generation instrument has the unique capability to produce intermediate resolution spectra from the UV to the near-infrared (NIR), covering simultaneously a spectral range from 300 to 2400nm. Two modes of observations are possible: the classical slit mode and the integral field unit (IFU) mode (see Vergani et al. 2011a for an example of the use of both modes applied to GRBs). The X-shooter large spectral range and sensitivity allow for the first time detailed studies of faint objects even at high redshift.

The French GEPI and APC laboratories were part of the consortium that built the instrument and participated to two X-shooter Guarantee Time Observation (GTO) programs dedicated to GRBs, ended in 2013: 1. The French-Italian GTO to observe LGRB host galaxy (40 host galaxies up to $z = 3$); 2. The GTO to observe the spectra of GRB afterglows ($\sim$ 40 afterglow spectra). Thanks to the large wavelength coverage it has been possible to use the X-shooter afterglow spectra to determine abundances and metallicities of the gas associated with the GRB hosts up to $z \sim 6$, bringing new information for chemical enrichment studies at $z > 4$ (see Fig. 1). Furthermore, the first detections of the emission lines of the host galaxies at $z > 1.5$ have been obtained, adding important information on the properties of the LGRB host galaxy population and its evolution with redshift (e.g.: Krühler et al. 2012; see Sect. 6).

6 The population of LGRB hosts

The study of the population of LGRB hosts is of particular interest in the perspective of using LGRBs as star formation tracers up to the highest redshifts. In the last few years an increasing number of works have tackled this issue (e.g.: Kistler et al. 2013, see Fig. 2). The main problem here is to know if LGRB hosts can be used as proxy of star forming galaxies at any redshift.

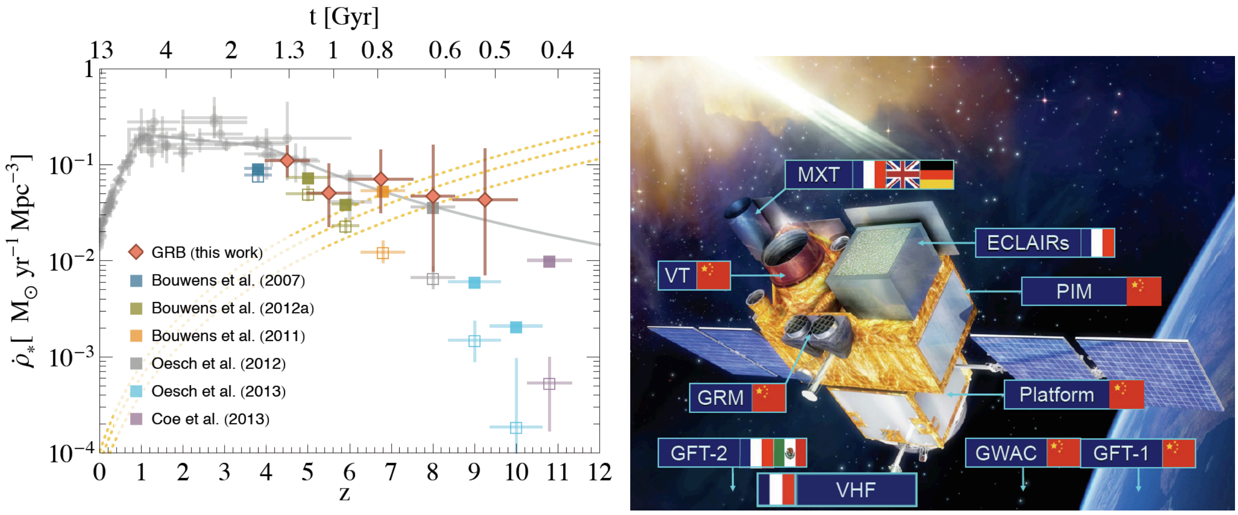

Fig. 2. Left: From Kistler et al. (2013). The cosmic rate of star formation in the first Gyr of galaxy formation is still highly debated, and the few GRBs so far detected at $z > 5$ may suggest a much higher activity of massive star formation than was derived from deep surveys. **Right:** The *SVOM* mission satellite and instruments.

Studies of LGRB host galaxies carried out mainly at $z < 1$ have shown that they have a lower metallicity compared to other galaxies at similar masses (e.g.: Levesque et al. 2010), tracing an environment younger and richer in gas than the galaxies selected by other techniques. On the other hand Mannucci et al. (2011) demonstrate that at $z < 1$ LGRB hosts are found to be consistent with the Fundamental Metallicity Relation, and there are more and more evidences that at higher redshift several LGRB hosts are not metal poor (e.g.: Krühler et al. 2012). Very recently, Boissier et al. (2013) highlighted the presence of a bias in the distribution of GRB host properties with respect to the star-forming galaxy population. It is important to note that the observations of GRB hosts are very sparse and inhomogeneous, so that they can not be used for statistical analysis. All the results listed above are based on GRB host samples that are far from being complete and that are likely biased. For example, since the hosts are generally identified only for those bursts for which an accurate (optical) position is available, bursts exploding in dusty environments (i.e. part of the so-called *dark burst* population) have been likely under-represented. Current researches are now able to cover the hosts of these event as well, mainly thanks to the X-shooter, GROND[†] and Herschel[‡] facilities or to dedicated campaigns (Hjorth et al. 2012; Perley et al. 2013).

To overcome these problems and have an unbiased picture of the properties of GRB hosts, complete samples of GRBs are necessary. Two complete samples have become available in 2012: the BAT6 sample presented in Salvaterra et al. (2012), and the TOUGH sample (Hjorth et al. 2012), larger in number, but less complete in redshift. These samples offer the opportunity to study the population of LGRB hosts in a statistical unbiased way. The availability of large LGRB samples complete in redshift is of capital importance to study the LGRB redshift distribution and luminosity function (see Salvaterra et al. 2012).

Since LGRBs can happen at very high redshift, it is of great interest to use them to study the properties of high redshift galaxies. To date six LGRBs have a spectroscopically confirmed redshift at $z > 5$, including the record older GRB 080423 at $z = 8.2$ (Salvaterra et al. 2009; Tanvir et al. 2009). For five of them deep observations with the Hubble Space Telescope have been carried out and result in very deep limits on their magnitudes, even down to 30.3(AB) in H-band (Tanvir et al. 2012). Hence LGRBs pinpoint the extremely faint star forming galaxies belonging to the faint end of the luminosity function, that forms the bulk of the first galaxies population and that should significantly contribute to reionization (Salvaterra et al. 2011). High redshift LGRB host galaxies are the perfect target for the future JWST[§] and E-ELT[¶].

7 SVOM[‖]

In the next couple of decades the use of LGRBs as cosmological probes could experience a significant step forward thanks to the new facilities that will be available at different wavelength domains, such as JWST, SKA[**] and E-ELT (together with the new generation instruments on the VLT). Nonetheless, the success will depend on the availability of satellites triggering the GRB explosions and sending precise localizations to the Earth.

To date, most of the detections come from the *Swift* satellite (Gehrels et al. 2004) that is capable to observe both the prompt and afterglow emissions. The *FERMI* mission[††] is the second source of triggers of bursts, but its position errors are too big to allow an efficient follow up from ground-based instruments. *Swift* has been flying since 2005. On the chance that it will not be available anymore during next decade, the possibility of using LGRBs as cosmological probes will be lost. New GRB space missions are necessary.

The *SVOM* satellite is a Chinese mission with French participation whose launch should take please before 2020. On board of *SVOM* there will be a combination of multi-wavelength space payload (see Fig. 2). GRBs will be detected by the ECLAIRs wide-field camera working from 4 to 150 keV, whereas the Gamma-Ray Monitor (GRM) will enable to measure the spectral parameters of the prompt emission. The 0.3-10 keV Micro channel X-ray Telescope (MXT) and the Visible Telescope (VT) covering simultaneously the 400-900 nm range will detect the afterglow and refine the position of the GRBs from a few dozens of arcsecs to sub-arsec accuracy, respectively. The VT will also give information on the redshift of the GRBs, capital for the ground-based follow up strategy.

Another innovation of the *SVOM* mission will be the implementation of a dedicated ground segment in order to optimise the reactivity of the GRB follow-up, and hence to maximize the mission science return. The ground segment will consist of the Ground Wide Angle Camera (GWAC, in China) working in the V band and covering the ECLAIRs field of view, and of two robotic Ground Follow-up Telescopes (GFT) located in China and in Mexico. This French-Mexican one will extend its spectral coverage to the near IR (J & H) and be equipped with a spectrograph. Together, these two GFTs will be able to observe 40% of the ECLAIRs GRBs.

[†] `http://www.mpe.mpg.de/~jcg/GROND/`
[‡] `http://www.esa.int/Our_Activities/Space_Science/Herschel`
[§] `http://www.esa.int/Our_Activities/Space_Science/JWST`
[¶] `http://www.eso.org/sci/facilities/eelt/`
[‖] This Section is partly based on Godet et al. (2012) and on *SVOM science case*, SVOM collaboration internal report, 2013
[**] `http://www.skatelescope.org/`
[††] `http://fermi.gsfc.nasa.gov/`

SVOM will locate 70-80 GRBs/yr. Thanks to its unique features (the low-energy threshold of ECLAIRs, the sensitivity of the VT, a set of dedicated ground follow-up instruments, and a pointing strategy optimized for ground follow-up) it will possible to measure the redshift of more than 50% of the detected GRBs (compared to about 30% nowadays), to dramatically enhance the possibility to study the GRB line of sight, to identify quickly high-z GRBs candidates with their lack of visible emission in the VT, and to collect 15 GRBs at $z > 5$ during the nominal duration of the mission.

8 Conclusion

LGRBs can be unique tools to probe galaxy formation and evolution, and star formation at the highest redshift up to the first stars. Great progress can be achieved thanks to the facilities available for the GRB follow-up observations in the next decades (JWST, E-ELT, SKA,...). Nonetheless this will be possible only if *Swift*-like mission, as *SVOM*, will be operating.

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