Absorption spectroscopy of gamma-ray burst afterglows: probing the GRB line of sight

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GRB absorption spectroscopy opened up a new window in the study of the high redshift Universe, especially with the launch of the Swift satellite and the quick and precise localization of the afterglow. Eight-meter class telescopes can be repointed within a few hours from the GRB, enabling the acquisition of high signal-to-noise ratio and high resolution afterglow spectra. In this paper I will give a short review of what we learned through this technique, and I will present some of the first results obtained with the X-shooter spectrograph.

1 Introduction

Since the discovery of their afterglow emission, it soon became evident that gamma-ray burst (GRB) spectroscopy could greatly improve our knowledge of these exciting sources and contribute to unveil the high redshift Universe. More than ten years later, thanks to the launch of the Swift satellite, which disseminates GRB coordinates in a few tens of seconds, and the implementation of Rapid Response Mode (RRM) in several facilities, we are able to point eight-meter class telescopes equipped with high resolution spectrographs in just a few minutes from the GRB explosion.

Spectroscopy of the GRB line of sight is demonstrating all its diagnostic power in the following scientific issues: i) to find GRB redshifts and build the GRB luminosity function; ii) to estimate the metal content in high redshift galaxies; iii) to characterize the circumburst environment and to explore the interaction between the GRB and the surrounding medium; iv) to study the intervening absorbers along GRB sightlines.

I refer the reader to Fynbo (2011) and Vergani et al. (2009) for details on items i) and iv), respectively, and I will concentrate on the other topics, to which the following sections are devoted. The last section will instead present some of the first results obtained with the new X-shooter spectrograph.

2 Metal content in high redshift galaxies

The study of the metal content of the interstellar medium (ISM) gives us precious information on the metal enrichment history of the galaxies. This quantity is in turn linked to the galactic mass function evolution.

In the past, the study of the metal content in high redshift galaxies has traditionally relied upon Lyman-break galaxies (LBGs) at $z = 3 - 4$ (see e.g. Steidel et al. 1999) and galaxies that happen to be along the lines of sight to bright background quasars (or QSOs). However, both classes present selection effects. LBGs can not be representative of the true galaxy population, since they are obviously biased toward high luminosities. Concerning QSOs, their light preferentially probes the outskirts of the intervening galaxies for a cross section effect.

In this framework, GRBs are a new class of sources whose absorption spectroscopy provides an independent way to study the metal enrichment of galaxies at $z > 1$. In addition, using GRBs as torchlights, we are sure that we are probing the central regions of the galaxies, since their birthplace are the star-forming regions. Moreover, galaxies are not selected according to their luminosity, since the probing light comes from the GRB. Finally, QSOs need at least several hundreds of million years to form, so in principle GRBs can probe the ISM up to higher redshifts, as confirmed by the $z = 8.2$ GRB 090423 (Salvaterra et al. 2009, Tanvir et al. 2009).

Metallicities measured in GRB host galaxies are on average higher than those found along QSO sightlines (see e.g., Prochaska et al. 2007). However, the metallicity values are subsolar, varying from less than $10^{-2}$ to nearly solar values (Savaglio 2010).

3 The circumburst environment and the need for high resolution spectroscopy

Redshift determination and metallicities of GRBs and their host galaxies can be derived using ordinary low resolution spectroscopy, despite a higher resolution is more adequate
in order to obtain more precise column densities and to correctly control the possible saturation of strong absorption lines.

On the contrary, in order to provide a correct description of the ISM in general, and the circumburst environment in particular, high resolution spectroscopy is mandatory. This happens because of several reasons. First of all, the GRB surrounding medium is complex, with many components contributing to the total absorption; these components can be separated only using high resolution spectroscopy: this is the only way to perform an accurate study of the composition, density, kinematics and physics of the absorbing gas. Fig. 1 (adapted from Fiore et al. 2005) illustrates this concept by comparing FORS1 low resolution ($R \sim 1000$) and UVES high resolution ($R \sim 40000$) spectra of the same source, GRB 021004. It is evident how what appears as a single absorber in the FORS1 spectrum shows instead a more complex structure when observed at higher resolutions. This information allows us also to discriminate between progenitor models, since in this specific example, the high velocity dispersion and the constant ionization parameter prefer a Wolf-Rayet wind rather than a supernova remnant as responsible for the absorption (Fiore et al. 2005).

Second, some absorbers are close to the explosion site and are strongly influenced by the GRB output, while others are located far away. This is evident in absorption components in which high ionization lines and excited levels are totally absent, reflecting the scarce influence of the GRB on such absorbers (see e.g. Piranomonte et al. 2008). The disentangling of these absorbers is only possible using high resolution spectrographs.

Finally, the level structure of an atom or ion is characterized by a principal quantum number $n$, which defines the atomic level, and by the spin-orbit coupling (described by the quantum number $j$), which splits these levels into fine structure sub-levels. In GRB absorption spectra, several excited features are detected at the GRB redshift, due to the population of both $n > 1$ and/or $n = 1$ fine structure levels. These transitions are extremely important to gather information on the interaction between the GRB and the circumburst environment (see next subsection). To separate these features from the ground state ones is only possible using high resolution spectroscopy.

Of course, high resolution is suitable for high luminosity GRBs only, and a fast reaction to the trigger (now possible thanks to Swift and RRM) is needed. In the next subsection I will illustrate two scientific topics that can be addressed using high resolution, namely, the excited features and the high ionization lines in GRB absorption spectra.

### 3.1 Excited absorption features

As mentioned before, fine structure and other excited levels are commonly observed in GRB afterglow spectra. There is conspicuous literature on the population of excited states in GRB surrounding medium and their detection in these spectra (see e.g. Prochaska, Chen & Bloom 2006, Vreeswijk et al. 2007 and reference therein). There is general consensus that these features are produced by indirect UV pumping by the afterglow, i.e., through the population of higher levels followed by the depopulation into the states responsible for the absorption features. This has been proven both by the detection of variability of fine structure lines in multi-epoch spectroscopy (Vreeswijk et al. 2007, D’Elia et al. 2009a), and through the column density ratios of different excited levels when multiple spectra were not available (Ledoux et al. 2009, D’Elia et al. 2009b).

Assuming UV pumping as the excitation mechanism, the distance between the GRB and the absorber can be estimated, because the closer is the gas to the GRB, the higher are the column densities of the excited levels. In order to quantify this, a comparison of the observed column densities with those predicted by a time-dependent, photo-excitation code is required. This kind of analysis has been performed for 4 GRBs, and the distance of the absorbers from the burst is in the range $d = 0.3–6\,\text{kpc}$ (Vreeswijk et al. 2007, D’Elia et al. 2009a,b, Ledoux et al. 2009). This striking result sug-
gests that the power of a GRB affects a region of gas that is at least a few hundreds pc in size.

### 3.2 High ionization lines

High ionization transitions in GRB spectra are though to be excited very close to the GRB explosion site. In particular, the column densities of NV in GRB host galaxies appear to be higher than along QSO sightlines. This, together with the high ionization potential of this species, makes the GRB UV flux a privileged candidate for the production of this ion (Prochaska et al. 2008). If this were the case, the nitrogen should be located at \( \sim 10 \) pc from the GRB, a distance close enough to photo-ionize the NIV and not too high to allow the photo-production of NVI through the destruction of NV.

In this scenario, a strong variability of these lines is predicted, just like that of the excited and fine structure levels. On the other hand, Fox et al. (2008) shows that SIV must be at least at \( 400 \) pc from GRB 050730, since its fine structure level is not observed in the afterglow spectrum. In order to firmly assess if NV is close to the GRB, a multi-epoch spectroscopy of a \( z > 2 \) GRB is needed to search for variability of high ionization lines. If this picture will be confirmed, this will mean that we have access to a region of ISM very close to the GRB.

### 4 X-shooter spectroscopy of GRB 090926A

Within this context, X-shooter represents an excellent trade-off between limiting magnitude accessible for spectroscopy (Mag\(_R\) \( \sim 21 - 22 \)) and achievable spectral resolution (\( R \sim 4000 - 14000 \)). In the framework of the science verification phase program, the afterglow of GRB090926A was observed with X-shooter \( \sim 22 \) hr post burst. The observations consist of 4 different exposures of 600 s each. The resolution is \( R \sim 10000 \) and the achieved spectral range is \( 3000 - 24800 \)\( \AA \). The four spectra were co-added after searching for variability in the absorption features.

In the next subsections I summarize the results obtained analyzing this spectrum. More details on this work can be found in D’Elia et al. (2010).

#### 4.1 Host galaxy lines and redshift

The gas residing in the GRB host galaxy is responsible for many of the features observed in the GRB 090926A afterglow spectrum. Metallic features are apparent from neutral (OI, MgI, CaI), low-ionization (CII, MgII, AlII, AlIII, SiII, SiI, CaII, FeII, NiII), and high-ionization (CIV, NV, OVI, SiIV, SiV) species (see fig. 2). In addition, strong absorption from the fine structure levels of CII, OI, SII, FeII and from the metastable level of NiII is identified, suggesting that the intense radiation field from the GRB excites such features. The probed ISM of the host galaxy is resolved into two components separated by 48 km s\(^{-1}\), which contribute to the absorption system. The wealth of metal-line transitions enables to precisely determine the redshift of the GRB host galaxy. This yields a vacuum-heliocentric value of \( z = 2.1071 \pm 0.0001 \).

#### 4.2 Metallicities

The GRB 090926A redshift was high enough to allow the hydrogen Ly\( \alpha \) and Ly\( \beta \) lines to enter the X-shooter spectral window. The hydrogen column density has been constrained using these two features, and the resulting value is \( \log(N_H/cm^2) = 21.60 \pm 0.07 \). Comparing this value with the metallic column densities, the metallicities of the different species can be evaluated. Several transitions result to be saturated and were not taken into account. Despite this, very low metallicity values with respect to the solar ones, between \( 4.2 \times 10^3 \) and \( 1.4 \times 10^2 \), have been derived. These are among the lowest values ever observed for a GRB host galaxy.

#### 4.3 Distance between GRB and absorbers

Comparing the column densities of the ground state and excited lines of FeII and SiII, the distances between GRB 090926A and the two absorbers identified by the detected components can be derived. For the redmost component a distance of \( d = 2.6 \pm 0.3 \) kpc (using FeII) and \( d = 2.25 \pm 0.15 \) kpc (using SiII) is computed (see fig. 3). Our best value is then \( d = 2.4 \pm 0.15 \) kpc. The bluemost component is far away from the GRB, at a distance of \( \sim 5 \) kpc, but in this case the FeII could not be used because no excited levels were detected, so this value is computed using SiII only. The GRB 090926A/absorbers distances are compatible with what is found for the 4 other GRBs for which a similar analysis has been performed (See sect. 3.1). This is further confirmation that the power of a GRB affects a region of gas that is at least a few hundreds pc in size.
4.4 Other features at the host redshift

No emission lines were detected, but a Hα flux in emission of $9 \times 10^{18}$ erg s$^{-1}$ cm$^{-2}$ (i.e., a star-formation rate of $2 M_\odot$ yr$^{-1}$), which is typical of many GRB hosts, would have been detected in our spectra, and thus emission lines are well within the reach of X-shooter. Similarly, no molecules such as CO and H$_2$ were identified. The upper limit to the H molecular fraction of the host galaxy ISM is $f < 7 \times 10^{-7}$. Again, no diffuse interstellar bands are present in the X-shooter spectrum.

4.5 The host galaxy morphology

A powerful way to infer the nature and the age of objects whose morphology is unknown is with abundances and abundance ratios (see Matteucci 2001). This method is based on the fact that galaxies of different morphological type are characterized by different star formation histories, and these strongly influence the [X/Fe] versus [Fe/H] behavior (X being any chemical element). Therefore, if we compare the measured abundance ratios in the host of GRB 090926A with predictions from detailed chemical evolution models, we should be able to understand the nature of the host. These models show that the host of GRB 090926A is probably an irregular galaxy with baryonic mass $10^8 M_\odot$ and evolving with star formation rate (the inverse of the timescale of star formation) of 0.05 Gyr$^{-1}$.

4.6 The extinction curve shape

The X-shooter’s wide spectral coverage enables the search for dust through the spectral continuum analysis. The flux calibrated spectrum has been fitted assuming a power-law, with a spectral index of $\beta = 0.89 \pm 0.02$. The best fit does essentially not require any intrinsic extinction because $E_{BV} < 0.01$ mag adopting a SMC extinction curve.

4.7 Intervening systems

A detailed analysis of the data reveals that at least four intervening absorbers are present along the line of sight to GRB 090926A. Three of these systems, those with the highest redshifts ($z = 1.75 - 1.95$), show absorption from the CIV $\lambda\lambda 1548, 1550$ doublet, to which a well-defined HI $\lambda 1215$ line corresponds inside the Ly forest. The fourth system features instead the MgII $\lambda\lambda 2796, 2803$ doublet and (marginally) the MgI $\lambda 2852$ line, at the redshift of $z = 1.25$.

5 Conclusions

GRB absorption spectroscopy is a key tool to study both the GRB physics and the high redshift Universe. X-shooter is at the forefront in providing excellent datasets for these kind of science.

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