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Exploring the Cosmic Chemical Enrichment at $z \gtrsim 2$ via GRB Afterglow Spectroscopy

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There are more than 60 GRBs at $z \gtrsim 1.5$ for which has been possible to measure the neutral hydrogen content along their line of sight using absorption spectroscopic technique. We present the largest sample of GRB-DLAs to date and the metallicity of their hosts in order to understand if this particular subset of hosts can be the key to understand the role of metallicity in GRB formation as well as star-formation rate. We compare this sample with DLAs along quasars and demonstrated that GRB-DLAs live in a metal enriched environment, especially at $z \gtrsim 4$. We also derive that our metallicity measurements are broadly consistent with a mild metallicity bias for the GRB formation.

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1. Introduction

Thanks to the *Swift* satellite [1], hundreds of GRBs have been discovered, even up to $z \approx 8$ [2, 3, 4]. These high-z GRBs can be used to test cosmic star-formation rate models as well as the cosmological chemical enrichment [5, 6]. GRB progenitor models require massive, fast-rotating, and low-metallicity objects, [7, 8, 9], although the discovery of few GRBs that might have occurred in a solar or even super solar metallicity environment challenges this paradigm, e.g. [10, 11, 12].

Afterglow absorption spectroscopy of $z \gtrsim 1.5$ GRBs provides a unique tool to determine the constituents of the GRB environment, in particular the amount of metals produced by past and on-going star-formation in the vicinity of the GRB explosion. This has important consequences for our understanding of the progenitor itself as well as the galaxies hosting GRBs throughout cosmic time. GRBs are identified, at first, based only on their high energy emission, therefore their hosts can be studied in great detail after the afterglow emission disappears, representing a sample of star-forming galaxies unbiased with respect to their intrinsic luminosity. In fact, it is possible to use GRBs and their hosts to trace cosmic star-formation in an independent way compared to magnitude limited Lyman-break galaxy surveys, although the effects of dust and metallicity biases are still under investigation [13, 14, 15].

Similar to GRBs, quasars (QSO) have also been used for decades to study the effects of re-ionization, the conversion of neutral hydrogen into stars, and the cosmic metal enrichment. In fact QSOs, like GRB optical afterglows, are very bright and can be seen up to very high redshift. The spectra of QSOs often show the presence of intervening absorbers (at redshifts lower than the QSOs), some of which are associated with large reservoirs of neutral hydrogen along their lines of sights. In particular, Damped Lyman-α systems (DLAs), by definition, have column density of neutral hydrogen $N_{\rm HI} \geq 2\times10^{20}\,{\rm cm}^{-2}$, while sub-DLAs are defined as absorbers with column density $10^{19} < N_{\rm HI} < 2\times10^{20}\,{\rm cm}^{-2}$ (other types of subdivisions have been made, but they are not relevant for the purpose of this work). These absorbers, which often trace galaxies along the QSO lines of sight, e.g., [16, **?**], are the best laboratories to investigate the ISM, its evolution, and cosmic star-formation at high redshift, providing important constraints on galaxy evolution models, e.g. [18, 16, 19, 20, 21, 22, 23].

Recently, [24] (R14 from now on) have extended QSO-DLA studies up to $z \sim 5$: they show that the overall cosmological mean metallicity[1] slowly decreases from $z \approx 1$ up to $z \approx 4.7$ and then it appears to drop rapidly below the extrapolated linear metallicity evolution, as if a sudden metallicity enrichment in DLAs occurs shortly after the end of re-ionization. GRB-DLAs, in which the DLA is inside the GRB host, have been sparsely studied [25, 11, 26, 27], mainly due to the small sample size, the different data quality, and incompleteness. Nevertheless, [28] have derived a higher metal content at $z \gtrsim 2$ for a set of GRB-DLAs with respect to a large sample of QSO-DLAs, suggesting that GRBs probe denser, more dust depleted, and metal rich regions then the QSO-DLAs population (see also [29]).

[1] The cosmic mean metallicity is defined as $\langle Z\rangle = \log\,(\sum_i 10^{[M/H]_i} N({\rm HI})_i)/\sum_i N({\rm HI})_i$, where i is the redshift bin of DLAs as a function of redshift

2. Data Collection

We select our GRB-DLAs sample from all the GRB afterglows observed during the 2000-2014 time span for which HI and metallicity measurements can be obtained. In order to detect the Lyα absorption line (1216 Å rest-frame) with most of the current spectrographs, a GRB has to be at least at $z \sim 1.8$ in order for the line to be redshifted out of the atmospheric blue cut-off (which usually means a minimum observed wavelength limit of ~3400 Å). GRB-DLA absorbers are unambiguously associated with the GRB host galaxies, since often fine-structure transitions (e.g. Fe II* λ2316) or the termination of Lyα forest are identified at the same redshift of the Lyα feature [30, 31]. The presented sample includes spectra obtained with different instrument resolutions: from low resolution (resolving power $R \sim 400$) spectra obtained with the AlFOSC camera, to high resolution ($R \sim 55000$) obtained with the UVES instrument. Due to the transient nature of GRB afterglows, some spectra were obtained when the afterglow was quite faint and the resulting signal-to-noise of the acquired spectra is not uniform within the sample. We therefore exclude GRBs with $S/N \leq 3$ (at usually 6000 Å), due to the unreliable detection of metal lines. All the data obtained with the Very Large Telescope (VLT) instruments were retrieved from the ESO Archive[2] or were available within our collaboration. In few other cases we cannot obtain the raw data and we include the results from abundance analysis as they appear in the literature (e.g. GRB 050904 obtained with the FOCAS camera on the Subaru telescope).

Our sample includes 13 GRB afterglow spectra obtained with the X-Shooter instrument mounted on the VLT. In order to analyze these data we primarily use our own customized pipeline written in `IDL` (Becker et al., private comm.) as it is optimized for point sources and has an improved sky subtraction procedure. Additionally, we used the official pipeline (version 2.5, within the `REFLEX` workflow [32, 33] to verify the output of our custom pipeline.

We measured ionic abundances using the Apparent Optical Depth method [34], which relies on the identification of several unsaturated lines of the same species and provides accurate measurements with no assumptions on the features Doppler parameter as other methods (Curve-of-Growth analyses, [35]).

3. Results and Conlcusions

3.1 Metallicity Evolution

Our findings are shown in Figure 1, where the QSO-DLAs (in gray) and GRB-DLAs (in red) metallicities are plotted. We perform a linear fit of the metallicity measurements (and limits) with redshift using a survival analysis technique [17], which takes into account upper and lower limits. In particular we used the `statistics.schmittbin` package within the `IRAF`[3] distribution. We also used a bootstrap sampling in order to determine the 1-sigma error in the fit (with 500 iterations).

Ideally, we would like to use our metallicity measurements to investigate the cosmic metal budget at different epochs: this is usually done weighting the average metallicity over a specific

[2] Based on data obtained from the ESO Science Archive Facility

[3] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy (AURA) under cooperative agreement with the National Science Foundation.

PoS(SWIFT 10)023

redshift bin with the total neutral hydrogen column density in the same redshift interval. Unfortunately, because the large number of limits present in the GRB-DLA sample we simply fit the metallicity of the single systems, which still provide useful insight on the DLA populations metal content.

For the GRB-DLA sample, we derive $[X/H]_{GRB} = (-0.07 \pm 0.06)z - (0.75 \pm 0.25)$ (thick red dashed line), which is also consistent with no-evolution (at the 1σ confidence level). For the QSO-DLA sample we derive a linear trend between redshift and DLA metallicity given by $[X/H] = (-0.20 \pm 0.03)z - (0.68 \pm 0.09)$ (thick black dashed line in Figure 1).

To test the reliability of our fit and how much this is sensitive to the small number of abundance measurements (with respecting the limits) we ran a series of Monte Carlo simulations: we created 1000 mock samples of GRB-DLAs metallicity measurements and limits (with values within the typical GRB-DLA high-resolution points RMS) and we repeated the survival analysis fit. Assuming an intrinsic true slope from the QSO-DLA distribution of -0.2 we obtained a slope > -0.07 or less only in 7% of the cases, which means that it is unlikely that our results are affected by low number statistics. Similar tests with different intrinsic distribution (from flat to very steep metallicity evolution) provide similar results and reassure us that, despite the small number statistics, we can recover the input slopes to within the reported 1σ confidence interval.

Finally, we point out that GRB-DLAs and QSO-DLAs have a similar metallicity distribution at $z \sim 2-3$, suggesting that there is no difference among the two populations of absorbers in terms of metal content. We performed a two-sample Kolmogorov-Smirnov test among these subsamples using the IRAF `stsdas.analysis.statistics.twosampt` task and we can rule out the null hypothesis that the two distributions are drawn from the same parent population at the 90% confidence level.

3.2 Characterizing these DLA populations

We will now try to understand the different metallicity evolution between the GRB- and QSO-DLA samples. For example, if GRB-DLAs trace the general host galaxies ISM, this gas ionization state may show the effect of whatever local ionization field is in the vicinity of the GRB or along the line of sight.

[28] argued that the size of such molecular cloud would exceed the largest molecular cloud in the local group, so the GRB-DLAs are tracing material as far as at least 100pc from the GRB (and even out to ≈ 2 kpc in the case of GRB 060418, [31]). The fact that in the $z = 3.5-6$ redshift range the metallicity of the gas is, on average 10% of the solar value suggests that a substantial amount of metals are already present at high redshift.

These estimates are in agreement with the most recent GRB progenitor models (e.g. [36, 37]): if the GRB host galaxy is metal rich, then a large amount of metals have been produced by SNe or, in the highest redshift bin observed, by a late population of PopIII stars (or more likely early PopII). Nevertheless, in order to be able to produce a GRB explosion from Wolf-Rayet type stars, the amount of metal injected into the ISM and mixed throughout the host galaxy has to be below a certain threshold to retain enough angular momentum and minimize the stellar mass loss of the progenitor [38, 36, 37]. Clearly more data need to be acquired, in particular at high-z to confirm the existence of such limits, also in light of the high-metallicity hosts observed (e.g [39, 12, 11]).

PoS(SWIFT 10)023

On the other hand, DLAs identified in QSO spectra are cross-section dependent, and therefore they might not trace the denser part of the galaxies (like for GRB-DLAs). Also, it has been proposed that a combined large sample of GRB- and QSO-DLAs may represent a complete census of $z \approx 3$ star-forming galaxies that could be missed by magnitude limited surveys [25].

The GRB-DLA metallicity declines suggests that, in particular at $z \gtrsim 3$, GRB-DLA environment is more metal enriched than in QSO-DLAs, likely by active star-formation episodes. These metals may have been ejected by supernova explosions or mass losses and polluted the GRB progenitor's neighborhood before the GRB occurred [41, 42]. If this is true, the inferred metallicity may not reflect the overall metal content of such high-z GRB host galaxies, although we know that the gas intercepted by GRB afterglow spectra may lie up to few kpc from the GRB explosion site (see next section).

Finally, as R14 pointed out, the observed metallicity decrement at $z \gtrsim 4.7$ suggests an increase in the covering fraction of neutral gas: similar behavior in fact can be produced by the combination of increased density of the Universe and lower background radiation field, which allows the hydrogen gas to be self-shielded at the lower density as function of redshift [**?**]. In this picture, the denser region would reside in the halo of the galaxies or in the IGM where the star-formation, and therefore metal enrichment, is lower.

3.3 GRB-DLA metallicity in context

A long standing debate exists as to the degree to which GRBs faithfully trace the cosmic star formation rate. Although GRBs have been associated with broad lined supernovae at low redshift and regions of active star formation in their host galaxies, spectroscopic observations have shown that GRB host galaxies tend to be relatively metal poor compared to SNe Ibc hosts [43]. This observed preference for low metallicity environments may impart a redshift dependent bias in the type of star forming regions that can produce a GRB [44, 13].

In particular, at low redshifts ($z \lesssim 1$), a preference for low metallicity environments would limit GRBs to low mass spirals and dwarf galaxies [45], due to the well established relationship between mass and metallicity [15, 46]. At higher redshifts, the mass range of galaxies capable of hosting a GRB would increase to include more massive, star forming galaxies, since the average metallicity of all galaxies in the Universe falls. Recent unbiased searches of GRB host galaxies like the *THOUGH* survey [47] or of the host galaxies of the "dark" GRB population [**?**] largely support this trend. These surveys find that bursts at intermediate redshifts tend to be drawn from star forming galaxies with a greater diversity of mass, morphology, and dust content, suggesting that high redshift GRBs may serve as more faithful tracers of cosmic star-formation compared to their low redshift counterparts.

Our sample of GRB-DLAs, although not a complete host sample, covers a much greater redshift range than the emission line derived measurements in these studies and, more importantly, does not depend on strong observational biases (e.g. brightness of the host, intensity of the emission lines), although we may miss some dusty (therefore metal rich) events. Based on the arguments outlined above, even as metallicity biased tracers of star formation, the GRB-DLA results presented in Figure 1 should become more representative of the metallicity evolution of the general star forming galaxy population with increasing redshift. However, a better understanding of both observational biases [40, 25] and the effect of metallicity in GRB production [48] are required before we can fully address the connection between the environments which are capable of producing GRBs and the conditions of star forming regions in the early Universe.

From a theoretical standpoint, recent simulations by [13] have been suggesting that two combined channels of GRB populations exist: one, the "collapsar" mode, which strictly depends on the host metallicity, and a second one, the "binary stars" mode, which is metallicity independent. Assuming these two modes coexist and the known mass-metallicity relation of star forming galaxies, these authors predict GRB host galaxies metallicity redshift evolution with different combinations of these two channels (from strong metallicity bias to an almost negligible one). Unfortunately, metallicity measurements from emission line diagnostics are not yet available for $z \gtrsim 1$ host galaxies, but our sample represents the best opportunity to test these models.

In Figure 2 we present our metallicity results in comparison the predicted metallicity for the upper 95%, the median, and the bottom 20% of the GRB host galaxies distribution, assuming an absent (dotted lines) and a moderate (solid lines) metallicity bias (adapted from [13] using a value of $p = 0.04$).

These models essentially predict that in any given redshift bin, for example, 20% of the hosts that produce a GRB have metallicity below the lower solid line. Indeed, focusing on the redshift $z = 2-3$ range, 5 over 27 hosts have metallicity below the line. On the other hand the "no-metallicity bias" model does not agree with the data. Overall, it seems that at least at $z \lesssim 4$ a moderate metallicity bias is required in order to reconcile theory and observations [49], although a more detailed analysis of these models and the implications on the metallicity cut-off in the GRB host masses is needed, in particular to understand the role of such metallicity bias, if indeed exists, at higher redshift.

Overall, our findings confirm the idea that moving towards higher redshifts, GRBs continue tracing preferentially a denser metal rich environment within galaxies, while the QSO-DLA population may be progressively dominated by neutral regions with minor star formation. This can be due to the fact that larger, metal poor, haloes at high redshift are likely to be intersected by QSO lines of sight. In other words, considering valid the mass-metallicity relation the absence of metal poor ($[X/H]_{GRB} \lesssim -1.5$) GRB-DLAs at high-$z$ seems to indicate that such GRB-DLA hosts are at the low-end of the luminosity (or mass) distribution and do not present high star-formation (and maybe not even GRB progenitors). Another possibility is that these GRBs occurred in a completely different environments (galactic haloes). Deep imaging, with 8-10 meter telescopes or with *HST*, is needed in order to fully characterize these hosts.

Our GRB-DLA host galaxies represent the largest sample available to date and, although not complete, it is suitable for multi band follow-up, in particular for the current and upcoming near-infrared spectroscopic instruments, which will allow to determine SFR and metallicities directly using emission line diagnostics. Also, the determination of the hosts properties, like mass and rest-frame UV star formation, will help in better characterizing the overall high-z GRB host population, and their capability to harbor GRB progenitors. Furthermore, we will be able to better understand the observational biases that might affect our results, especially at high-z, where few lines of sights are observed (including dust extinction and/or cosmic metallicity trend).

While multiband surveys of this sample of GRB-DLA hosts will allow a better characterization of these galaxies, the advent of future missions like *JWST* and the new generation of 30-m

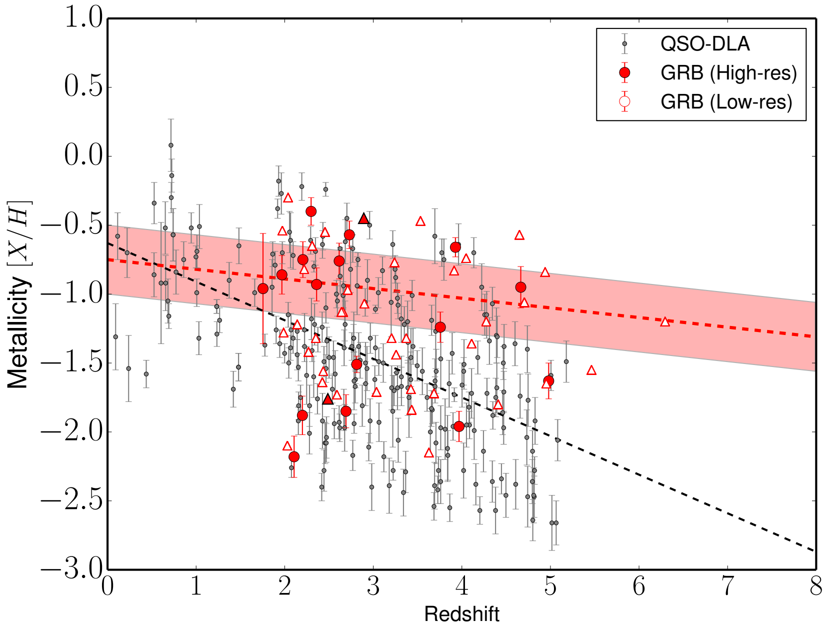

Figure 1: Metallicity evolution with redshift for the GRB (red) and the QSO (grey) samples. Lower limits are indicated by upward triangles, while filled/open symbols indicate if these values come from high/low resolving power instruments. We perform a linear regression fit of the GRB-DLA data using the Schmitt survival analysis method, which keeps into account the censoring within the dataset (red dashed line). The shaded area represents the 1σ error in the fitting parameters obtained using 500 bootstrap iterations. A linear fit of the QSO-DLAs metallicity is marked by the dashed black line (see text for details). The GRB sample, despite the large scatter in [X/H], seems to probe an environment which slowly declines across the $z = 1.8 - 6$ redshift range.

telescopes will be able to identify these faint hosts at the highest redshifts and spatially resolve the regions of star-formation traced by GRB-DLAs, which seem to hide the secrets of primordial star formation sites.

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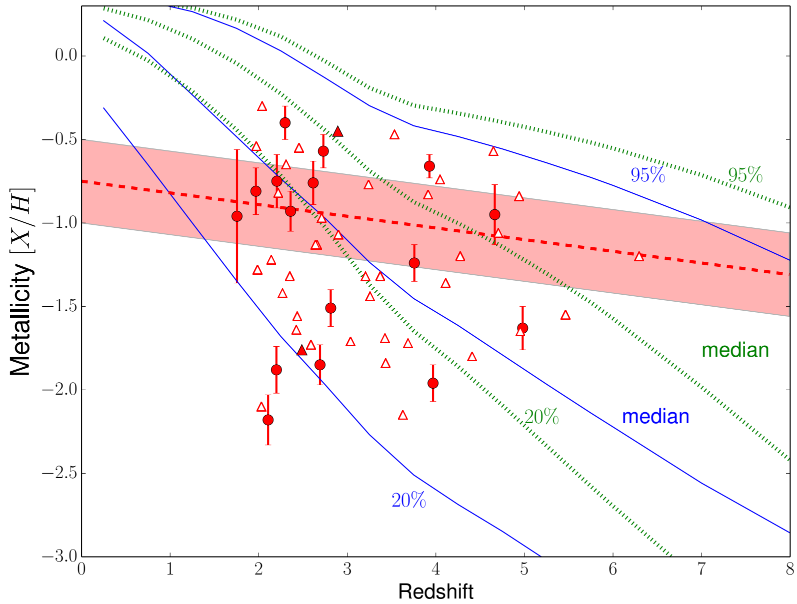

Figure 2: Adapted from [13]. The colored lines represent two particular model for GRB hosts metallicity assuming a mild metallicity bias ($p = 0.04$, solid blue) and no bias at all (dotted green). Lines also indicate the trends for the top 95%, the median, and lower 20% of the simulated GRB host population. The mild bias model is broadly capable to reproduce the observed metallicity distribution of our biased sample of GRB-DLAs at a specific redshift, while the "no bias" is largely inconsistence with the data.

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