

THE X-SHOOTER GTO SAMPLE OF GRB AFTERGLOW AND HOST GALAXY SPECTRA

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Draft version September 29, 2016

ABSTRACT

The *Swift* satellite allows us to use gamma-ray bursts (GRBs) to peer into the hearts of star forming galaxies through cosmic time. Our open collaboration, representing most of the active ESO member researchers in this field, seeks to build a public legacy sample of GRB X-shooter spectroscopy while *Swift* continues to fly. We propose to continue our programme to target all suitably observable GRB afterglows (up to 15 bursts per semester), with the primary goal of producing a well-defined, homogeneous, statistically useful sample. To date, our spectroscopy covers a redshift range from 0.059 to about 8, with more than 20 robust metallicity measurements from absorption lines (over the redshift range 1.7–5.9) and 4 secure detections of H₂ or CH molecular absorption. Such information is extremely difficult to obtain by other means. In terms of studying the spread and redshift evolution in gas-phase properties, the sample is still limited by low-number statistics.

Keywords: Gamma-ray burst: individual: GRB 120815A — galaxies: high-redshift — ISM: molecules — dust, extinction

1. INTRODUCTION

Only after observing more than 12000 damped Lyman- α absorbers (DLAs) towards about 10⁵ QSOs have 5 systems with $\log(N_{\text{HI}}/\text{cm}^{-2}) > 22$ been identified (Noterdaeme et al.

2012, A&A, 547, L1). Long GRB afterglow spectra, by contrast, reveal such systems in the majority of cases (e.g., Jakobsson et al. 2006, A&A, 460, L13; Fynbo et al. 2009, ApJS, 185, 526). Whereas DLAs towards QSOs are mostly limited to $1.8 \lesssim z \lesssim 5$ due to the atmospheric UV-cutoff and increasing Lyman-blanketing at increasing redshifts (e.g., Rafelski et al. 2014, ApJL, 782, L29), GRBs allow us to see into the hearts of star-forming galaxies over the full history of cosmic star formation from $z \approx 0$ to $z > 8$ (e.g., Tanvir et al. 2009, Nature, 461, 1254; Salvaterra et al. 2009, Nature, 461, 1258; Jakobsson et al. 2012, ApJ, 752, 62). With afterglow spectroscopy (throughout the electromagnetic spectrum from X-rays to the sub-mm) we can hence characterize the properties of star-forming galaxies over cosmic history in terms of redshifts, metallicities, molecular contents, ISM temperatures, UV-flux densities, etc.. This is, however, only possible as long as there are satellites in orbit that rapidly and accurately locate GRBs. The currently operating *Swift* satellite, launched in 2004 and still fully-functioning, allows for very efficient follow-up observations of GRBs due to its unprecedented rate, speed and precision of localisations.

The case for a large sample of GRBs with X-shooter spectroscopy.

There are several unanswered but fundamental questions that must be addressed in order to exploit the full potential of GRBs as cosmological probes. More than 50% of the *Swift* bursts with measured redshift are at $z > 2$, and 5–10% are expected to be above $z = 5$ (Salvaterra et al. 2008, MNRAS, 380, L45; Salvaterra et al. 2012, ApJ, 749, 68; Jakobsson et al. 2012, ApJ, 752, 62; Perley et al. 2016, ApJ, 817, 7). A high redshift completeness is crucial for our understanding of the link between the number density of GRBs per unit redshift and the global star-formation history of the Universe, as measured by other means (UV, FIR, sub-mm, see Robertson & Ellis 2011, ApJ, 744, 95). The detection of GRBs at $z > 6$ shows that GRBs have become competitive as a tool to identifying galaxies at the highest redshifts and unsurpassed in providing detailed abundance information via absorption line spectroscopy (Tanvir et al. 2012, ApJ, 754, 46, McGuire

[†] Based on observations collected at the European Southern Observatory, Paranal, Chile, Program ID: 084.A-0260, 085.A-009, 086.A-0073, 087.A-0055.

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et al. 2016, ApJ submitted, arxiv:1512.07808).

From March 2005 to March 2016 there have been about 350 *Swift* bursts complying with our sample selection criteria (see “Immediate objective”), and about half of them have measured redshifts. Among the latter subset, the team proposing these observations has measured about two thirds of the redshifts, mainly with FORS1/2 and X-shooter (see Fynbo et al. 2009, ApJS, 185, 526; Jakobsson et al. 2012, ApJ, 752, 62; Krühler et al. 2012, ApJ, 758, 46). Our current aim is to build a sample superior to our previous low-resolution survey (Fynbo et al. 2009, ApJS, 185, 526), both in terms of quantity and quality of the spectra. Our program started as guaranteed time observations during periods 84-91, and we have continued in open time since then.

X-shooter is in many ways the ideal GRB follow-up instrument and indeed GRB follow-up was one of the primary science cases behind the instrument design and implementation. Our program secures general purpose GRB afterglow spectroscopic follow-up that adds strong legacy value to the *Swift* GRB sample. Due to the wide wavelength range of X-shooter with the same observation cover molecular H_2 absorption near the atmospheric cut-off and all the strong emission lines from the host in the NIR arm (e.g., Friis et al., 2015, MNRAS, 451, 167). In general, the wide wavelength coverage ensures that we always have features on which to base a redshift measurement as long as the afterglow is brighter than about 23 mag in either the *R*- or *z*-band. Frequently, emission lines are also detected from the underlying host, which also provide further information such as SFR and metallicity (the top right panel in Fig. 1 shows an example). Only for 7 out of more than 70 secured spectra could we not measure a redshift. With the X-shooter survey we provide **metallicity measurements** for about 30% (Voigt-profile fits) of the $z > 1.7$ events. So far we have measured metallicities for more than 20 GRB afterglows with X-shooter. With the wide wavelength coverage of X-shooter we can study important chemical species as Zn II, Cr II and α elements over a much wider redshift range than what is possible with other instruments. As an example, we have measured a metallicity of $0.1Z_{\odot}$ for GRB 100219A at $z = 4.669$ (Thöne et al. 2013, MNRAS, 428, 3590), $0.02Z_{\odot}$ for GRB 111008A at $z = 4.991$ (Sparre et al. 2014, ApJ, 785, 150) and $0.05Z_{\odot}$ for the $z = 5.9125$ GRB 130606A (Hartoog et al. 2015, A&A, 580, 139). Reconciling the abundance patterns of GRB absorbers, other types of absorbers, QSO DLAs in particular, and old stars in the Local Group is an important long-term goal (see also Sparre et al. 2014, ApJ, 785, 150). Metallicities are also measured from host emission lines (Krühler et al. 2015, A&A, 581, A125). GRB spectroscopy also allows us to determine the dust content of their environments, both through analysis of the depletion pattern and through measurement of the associated extinction (Japelj et al. 2015, A&A, 451, 2050). This allows us to quantify the dust-to-metals ratio and its evolution with redshift (e.g., De Cia et al. 2013, A&A, 560, 88; Zafar & Watson 2013, A&A, 560, 26).

We will also determine the frequency and properties of **molecular absorption** towards GRB absorbers. Molecular gas is a key element to catalyze the process of star formation, but prior to our program H_2 had been detected just in two cases (tentatively in Fynbo et al. 2006, A&A, 451, L47; securely in Prochaska et al. 2009, ApJ, 691, L27). With our X-shooter program we have found three more systems (Krühler et al. 2013, A&A, 557, 18; D’Elia et al. 2014, A&A, 564,

38; Friis et al. 2015, MNRAS, 451, 167). We are currently analysing more of our spectra for less obvious molecular absorption and we expect to find more (a dedicated sample paper is addressing this issue).

A natural question to ask is: **how long should this work continue?** Our view is that we need to keep observing the afterglows as long as we have *Swift* in operation. Also note that the program is still producing many papers and provides data for many theses (Box 9 and 10). *Swift* is currently funded until 2018, but is likely to get more extensions given its overwhelming success. As mentioned above GRBs allow us to probe star-forming galaxies that are almost impossible to study in other ways both in terms of redshifts, galaxy luminosity function, and regions within galaxies. After 7 periods we have secured seven spectra of $z > 4$ GRBs, of which three were of sufficient quality to allow abundance measurements (Thöne et al. 2013, Sparre et al. 2014, Hartoog et al. 2015). GRBs offer the only way to derive chemical abundances for the gas phase of central, actively star-forming regions of high- z galaxies. The program also maintains a very high discovery potential where we occasionally find something completely unexpected that provides interesting clues to puzzles in other fields, e.g. extinction of type Ia supernovae (Fynbo et al. 2014, A&A, 572, 12). Each of these spectra are like precious jewels – it is a type of observation that can never be repeated and a class of sightlines that can only be studied while we have operating GRB satellites.

It is also worth adding that we have build up a rather unique team spread over Europe from Granada to Reykjavik, which by now has reached a point where the distribution of night shifts, the scientific exploitation of the data is efficient and where we are open to all new members who wish to participate. As mentioned all data are public immediately.

For all of these reasons, we need to keep building up the sample of GRB afterglow spectra now as we may have to wait many years before a mission like *Swift* becomes available again.

A significant proportion of GRBs lack a bright optical afterglow (“**dark bursts**”, e.g., Jakobsson et al. 2004, ApJ, 617, L21; Melandri et al. 2012, MNRAS, 421, 1265). Some of these are at the highest redshifts ($z > 6$) and their observer-frame optical emission is absorbed by the IGM. The majority, however, suffer from large dust obscuration (e.g., Perley et al. 2009, AJ, 138, 1690; Greiner et al. 2011, A&A, 526, 30). Identifying such GRBs is important for constraining the fraction of obscured star formation. In both cases, NIR emission is expected. X-shooter can adequately study these objects, provided that a NIR counterpart is timely identified, for which we have the dedicated HAWKI run D.

The detection of **absorption line variability** can reveal the burst influence on the surrounding medium and in turn the absorber distance from the burst and its metallicity (Vreeswijk et al. 2007, A&A 468, 83; D’Elia et al. 2009, ApJ, 694, 332; Thöne et al. 2011, MNRAS, 414, 479; De Cia et al. 2012, A&A, 545, 64; Hartoog et al. 2013). **Short GRBs** originate in a substantially different environment compared to long GRBs. Short GRBs may be related to the merging of compact binaries and the coalescence time can be long enough to allow the progenitor system to move far away from the star formation site (Belczynski et al. 2002, ApJ, 571, 147). Up to now, however, no spectrum with a sufficient signal-to-noise ratio of a short GRB afterglow has been secured. A knowledge of the redshift distribution of short bursts is of key importance for

the next generation of gravitational wave experiments, as they are the likely EM counterparts to their primary targets.

2. SAMPLE SELECTION CRITERIA

Being of transient nature, it is difficult to impose strong sample selection criteria on GRBs, without hampering the follow-up effort. Many natural follow-up restrictions exists from already, being it weather conditions, pointing restrictions of the telescope or poorly localized bursts as reported by the *Swift*-telescope. To maximize the return of the follow-up campaign we have chosen a few selection criteria that attempts to provide an unbiased selection of bursts, while allowing for a high success-rate

²²

1. GRB triggered onboard by Swift.
2. Galactic $A_V \lesssim 0.5$ mag.
3. XRT started observing within 10 minutes since the GRB; an XRT position must be distributed within 12 hr.
4. The target must be visible for at least 60 min at least 30 above horizon, with the Sun below -12.
5. No bright closeby stars.

²²Note that in the P84 proposal the criteria have been stated a bit differently, the visibility constraint being replaced by a declination + Sun angle constraint. The above criteria are however those defining the sample.

3. OBSERVATIONS

3.1. *RRM observations*

The rapid-response mode is

4. REDUCTION SCHEME

Table 1

The full sample of afterglows or hosts observed in the program. We here list the burst names and details of the spectroscopic observations. The exposure times and slit widths are given in the order UVB/VIS/NIR. The column Δt shows the time after trigger when the spectroscopic observation was started. Mag_{acq} gives the approximate magnitude (typically in the *R*-band) of the afterglow in the acquisition image.

GRB	Exptime (ks)	Slit width (arcsec)	Airmass	Seeing (arcsec)	Δt (hr)	Mag_{acq}	Redshift	Ref
GRB090313 ¹	6.9/6.9/6.9	1.0/0.9/0.9	1.2–1.4	1.0	45	21.6	3.3736	(1)
GRB090530 ¹	4.8/4.8/4.8	1.0/1.2/1.2	1.6–2.2	1.5	20	22	1.266	(2)
GRB090809 ¹	7.2/7.2/7.2	1.0/0.9/0.9	1.2–1.1	0.9	10.2	21	2.737	(2,3)
GRB090926 ¹	7.2/7.2/7.2	1.0/0.9/0.9	1.4–1.5	0.9	22	17.9	2.1062	(4)
GRB091018	2.4/2.4/2.4	1.0/0.9/0.9	2.1–1.8	0.8	3.5	19.1	0.9710	(5)
GRB091127	6.0/6.0/6.0	1.0/0.9/0.9	1.1–1.2	1.0	101	21.2	0.490	(6)
GRB100205A	10.8/10.8/10.8	1.0/0.9/0.9	1.9–1.8	1.0	71	–	–	(2)
GRB100219A	4.8/4.8/4.8	1.0/0.9/0.9	1.3–1.1	0.7	12.5	23	4.667	(7)
GRB100316B	2.4/2.4/2.4	1.0/0.9/0.9	2.0–2.4	0.7	0.7	18.2	1.18	(2)
GRB100316D-1 ²	3.6/3.6/1.8	1.0/0.9/0.9	1.2–1.3	1.0	10	21.5	0.059	(8)
GRB100316D-2	2.4/2.4/2.4	1.0/0.9/0.9	1.1–1.2	1.0	58	20.2	0.059	(8)
GRB100316D-3	2.6/2.6/3.2	1.0/0.9/0.9	1.1–1.2	1.1	79	19.9	0.059	(8)
GRB100316D-4	2.6/2.6/3.2	1.0/0.9/0.9	1.1–1.2	1.2	101	19.9	0.059	(8)
GRB100418A-1	4.8/4.8/4.8	1.0/0.9/0.9	1.6–1.3	0.7	8.4	18.1	0.6235	(9)
GRB100418A-2	4.8/4.8/4.8	1.0/0.9/0.9	1.2–1.3	0.6	34	19.2	0.6235	(9)
GRB100418A-3	4.8/4.8/4.8	1.0/0.9/0.9	1.2–1.4	0.7	58	–	0.6235	(9)
GRB100424A ³	4.8/4.8/4.8	1.0/0.9/0.9	1.1–1.2	0.8	–	–	2.465	(2)
GRB100425A	2.4/2.4/2.4	1.0/0.9/0.9	1.5–1.3	0.7	4.0	20.6	1.755	(2,3)
GRB100615A ³	4.8/4.8/4.8	1.0/0.9/0.9	1.0–1.1	0.8	–	–	1.398	(2)
GRB100621A	2.4/2.4/2.4	1.0/0.9/0.9	1.3–1.4	1.0	7.1	–	0.542	(2)
GRB100625A ³	4.8/4.8/4.8	1.0/0.9/0.9	1.1–1.0	0.8	13	–	0.452	(2)
GRB100724A ⁴	4.2/4.2/4.2	1.0/0.9/0.9	1.5–2.3	0.7	0.2	–	1.288	(2)
GRB100728B ⁵	7.2/7.2/7.2	1.0/0.9/0.9	1.5–1.1	0.5	22	23	2.106	(2)
GRB100814A-1 ⁴	0.9/0.9/0.9	1.0/0.9/0.9	1.9–1.7	0.5	0.9	19	1.439	(2)
GRB100814A-2	4.8/4.8/2.4	1.0/0.9/0.9	1.5–1.2	0.6	2.1	19	1.439	(2)
GRB100814A-3	4.8/4.8/2.4	1.0/0.9/0.9	1.2–1.0	0.6	98	20	1.439	(2)
GRB100816A ⁶	4.8/4.8/2.4	1.0/0.9/0.9	1.8–1.6	0.8	28.4	–	0.805	(2)
GRB100901A	2.4/2.4/2.4	1.0/0.9/0.9	1.5–1.5	1.5	66	–	1.408	(10)
GRB101219A	7.2/7.2/7.2	1.0/0.9/0.9	1.1–1.7	2.0	3.7	–	0.718	(2)
GRB101219B-1	4.8/4.8/4.8	1.0/0.9/0.9	1.6–2.6	1.3	11.6	20	0.5519	(11)
GRB101219B-2	7.2/7.2/7.2	1.0/0.9/0.9	1.2–2.0	0.8	394	22.7	0.5519	(11)
GRB101219B-3	7.2/7.2/7.2	1.0/0.9/0.9	1.4–2.1	0.9	886	–	0.5519	(11)
GRB110128A	7.2/7.2/7.2	1.0/0.9/0.9	2.0–1.6	0.9	5.5	22.5	2.339	(2)
GRB110407A	9.6/9.6/9.6	1.0/0.9/0.9	1.4–1.3	2.0	12.4	23	–	(2)
GRB110709B ^{1, 3}	7.2/7.2/7.2	1.0/0.9/0.9	1.6–1.1	1.0	–	–	–	(2)
GRB110715A	0.6/0.6/0.6	1.0/0.9/0.9	1.1–1.1	1.7	12.3	18.5	0.82	(2)
GRBGRB110808A	2.4/2.4/2.4	1.0/0.9/0.9	1.2–1.1	1.1	3.0	21.2	1.3488	(2)
GRB110818A	4.8/4.8/4.8	1.0/0.9/0.9	1.3–1.3	1.0	6.2	22.3	3.36	(2)
GRB111005A ³	1.2/1.2/1.2	1.0/0.9/0.9	1.3–1.3	0.7	–	–	0.013?	(2)
GRB111008A-1	8.8/8.8/8.4	1.0/0.9/0.9	1.1–1.0	1.2	8.5	21?	4.9898	(12)
GRB111008A-2	8.0/8.0/7.2	1.0/0.9/0.9	1.3–1.0	1.0	20.1	22?	4.9898	(12)
GRB111107A	4.8/4.8/4.8	1.0/0.9/0.9	1.8–1.5	0.7	5.3	21.5	2.893	(2)
GRB111117A ⁶	4.8/4.8/4.8	1.0/0.9/0.9	1.5–1.4	0.6	38	–	1.3?	(2)
GRB111123A-1	6.2/6.6/6.6	1.0/0.9/0.9	1.6–1.1	1.0	12.2	>24	3.1516	(2)
GRB111123A-2 ³	2.4/2.4/2.4	1.0/0.9/0.9	1.0–1.0	0.5	–	–	3.1516	(2)
GRB111129A	3.6/3.6/3.6	1.0/0.9/0.9	1.6–2.1	1.7	–	–	–	(2)
GRB111209A-1	4.8/4.8/4.8	1.0/0.9/0.9	1.1–1.2	0.8	17.7	20.1	0.677	(13)
GRB111209A-2	9.6/9.6/9.6	1.0/0.9/0.9	1.2–2.0	0.8	497	23	0.677	(13)
GRB111211A ¹	2.4/2.4/2.4	1.0/0.9/0.9	1.4–1.6	0.6	31	19.5	0.478	(2)
GRB111228A	2.4/2.4/2.4	1.0/0.9/0.9	1.4–1.4	0.9	15.9	20.1	0.716	(2)
GRB120118B ³	3.6/3.6/3.6	1.0/0.9/0.9	1.1–1.0	1.0	–	–	2.943	(2)
GRB120119A-1	2.4/2.4/2.4	1.0/0.9/0.9	1.1–1.1	0.6	1.4	17	1.728	(2)
GRB120119A-2	1.2/1.2/1.2	1.0/0.9/0.9	1.8–1.9	0.6	4.5	20	1.728	(2)
GRB120119A-3 ³	4.8/4.8/4.8	1.0/0.9/0.6JH	1.0–1.1	1.1	–	–	1.728	(2)
GRB120211	–	–	–	–	–	–	2.346	(2)
GRB120224A	2.4/2.4/2.4	1.0/0.9/0.9	1.7–2.1	1.4	19.8	22.3	–	(2)
GRB120311A	2.4/2.4/2.4	1.0/0.9/0.9	1.6–1.4	0.6	3.7	21.6	–	(2)
GRB120327A-1	2.4/2.4/2.4	1.0/0.9/0.9	1.6–1.4	0.5	2.1	18.8	2.815	(14)
GRB120327A-2	4.2/4.2/4.2	1.0/0.9/0.9	1.0–1.1	1.0	29	22.5	2.815	(14)
GRB120404A	9.6/9.6/9.6	1.0/0.9/0.9JH	1.7–1.3	1.3	15.7	21.3	2.876	(2)
GRB120422A-1	4.8/4.8/4.8	1.0/0.9/0.9	1.3–1.3	0.6	17.2	22.0	0.283	(15)
GRB120422A-2	4.8/4.8/4.8	1.0/0.9/0.9	1.3–1.4	0.9	113	–	0.283	(15)

Table 1 — *Continued*

GRB	Exptime (ks)	Slit width (arcsec)	Airmass	Seeing (arcsec)	Δt (hr)	Mag _{acq}	Redshift	Ref
GRB120422A-3	4.8/4.8/4.8	1.0/0.9/0.9	1.4–1.7	1.0	210	–	0.283	(15)
GRB120422A-4	4.8/4.8/4.8	1.0/0.9/0.9JH	1.3–1.4	0.6	449	–	0.283	(15)
GRB120422A-5	4.8/4.8/4.8	1.0/0.9/0.9JH	1.3–1.6	0.8	593	–	0.283	(15)
GRB120422A-6	4.8/4.8/4.8	1.0/0.9/0.9JH	1.7–2.4	2.5	882	–	0.283	(15)
GRB120422A-7	4.8/4.8/4.8	1.0/0.9/0.9JH	1.5–1.9	1.3	906	–	0.283	(15)
GRB120712A	4.8/4.8/4.8	1.0/0.9/0.9	1.5–2.5	1.3	10.4	21.5	4.175	(2)
GRB120714B	4.8/4.8/4.8	1.0/0.9/0.9JH	1.5–1.2	1.2	7.8	22.1	0.398	(2)
GRB120716A ¹	3.6/3.6/3.6	1.0/0.9/0.9JH	1.8–2.6	1.0	62	20.9	2.486	(2)
GRB120722A ²	4.8/4.8/4.8	1.0/0.9/0.9	1.3–1.3	1.1	10.3	23.6	0.959	(2)
GRB120805A ²	3.6/3.6/3.6	1.0/0.9/0.9JH	1.3–1.7	0.9	218	–	2.8?	(2)
GRB120815A	2.4/2.4/2.4	1.0/0.9/0.9	1.3–1.4	0.6	1.7	20	2.358	(16)
GRB120909A	1.2/1.2/1.2	1.0/0.9/0.9	1.6–1.6	1.4	1.7	21	3.929	(2)
GRB120923A	9.6/9.6/9.6	1.0/0.9/0.9JH	1.2–1.4	1.0	18.5	–	≥ 8	(2)
GRB121024A	2.4/2.4/2.4	1.0/0.9/0.9	1.2–1.1	0.6	1.8	20	2.300	(17)
GRB121027A	8.4/8.4/8.4	1.0/0.9/0.9	1.3–1.3	0.9	69	21.1	1.773	(2)
GRB121201A	4.8/4.8/4.8	1.0/0.9/0.9JH	1.1–1.1	0.9	12.9	23	3.385	(2)
GRB121229A	4.8/4.8/4.8	1.0/0.9/0.9JH	1.4–1.2	1.4	2.0	21.5	2.707	(2)
GRB130131B ³	7.2/7.2/7.2	1.0/0.9/0.9JH	1.3–1.6	0.8	–	–	2.539	(2)
GRB130408A	1.2/1.2/1.2	1.0/0.9/0.9	1.0–1.0	1.0	1.9	20	3.758	(2)
GRB130418A	1.2/1.2/1.2	1.0/0.9/0.9	1.4–1.3	1.3	4.6	18.5	1.218	(2)
GRB130427A	1.2/1.2/1.2	1.0/0.9/0.9JH	1.8–1.8	0.8	16.5	19	0.340	(18)
GRB130427B	1.2/1.2/1.2	1.0/0.9/0.9JH	1.2–1.0	0.8	20.3	22.7	2.78	(2)
GRB130603B ⁶	2.4/2.4/2.4	1.0/0.9/0.9	1.4–1.4	1.1	8.2	21.5	0.356	(19)
GRB130606A	4.2/4.2/4.2	1.0/0.9/0.9JH	1.7–1.9	1.1	7.1	19	5.91	(20)
GRB130612A	1.2/1.2/1.2	1.0/0.9/0.9	1.3–1.3	1.4	1.1	21.5	2.006	(2)
GRB130615A	1.2/1.2/1.2	1.0/0.9/0.9	2.1–2.2	1.0	0.8	21	3?	(2)
GRB130701A	1.2/1.2/1.2	1.0/0.9/0.9JH	2.0–2.0	1.6	5.5	19.9	1.155	(2)

Friis et al. (2015)

References. — (1) de Ugarte Postigo et al. (2010); (2) This work ; (3) Skuladottir (2010); (4) D’Elia et al. (2010); (5) Wiersema et al. (2012); (6) Vergani et al. (2011); Cobb et al. (2010); (7) Thone et al. (2013); (8) Bufano et al. (2012) ; (9) De Ugarte Postigo et al. (2011) ; (10) Hartoog et al. (2013); (11) Sparre et al. (2011); (12) Sparre et al. (2014); (13) Levan et al. (2014); (14) D’Elia et al. (2014); (15) Schulze et al. (2014); (16) Krühler et al. (2013); (17)

¹ Not part of the statistical sample

² Spectrum dominated by light from the host galaxy

³ Spectrum of the host galaxy taken long after the burst

⁴ RRM observation

⁵ ADC malfunction during observation

⁶ Short burst

5. RESULTS

5.1. Spectral resolution

The afterglow spectra described in this paper are obtained in Target-of-Opportunity (override) mode. In most cases there is therefore little possibility to tweak slit widths to the seeing at the time of observations (i.e. to optimise spectral resolution and signal to noise), and almost all our data is therefore taken with a fixed set of slit widths and binning, described above. In a fair number of cases, the seeing full width at half maximum (FWHM) is considerably smaller than the slit width, and the delivered spectral resolution will then be determined by the seeing rather than slit width, as afterglows are point sources (this is evidently not the case for extended sources, e.g for host galaxies). The delivered resolution for slit width dominated spectra post-reduction and extraction can easily be determined from the bright sky emission lines. For afterglow spectra with very high signal to noise, the delivered spectral resolution can at times be determined from the science data themselves. However, in the presence of multiple velocity components in absorption, other forms of line broadening, and a lack of lines at some redshifts, this is difficult to do at poorer signal to noise ratios (the majority of

spectra in our sample). A broad starting value for the expect resolution will help fitting of these spectra, and can be important in upper limit determination, and for this reason we construct a aim to construct a crude relation between the seeing and the delivered resolution at our slit width, binning, and reduction pipeline settings. To this end we use observations of telluric standard stars that are taken with identical instrument settings as our afterglow spectra, usually just after the science data, as part of the ESO X-shooter calibration plan. These spectra have been reduced together with the afterglow spectra, using identical pipeline settings with the same version of the pipeline. First we fit a Gaussian function in the spatial direction of the trace of the standard star at 792 nm (i.e. in the VIS arm). After this, we fit a series of 20 telluric absorption lines in the telluric standard star spectra with Gaussians, taking care to select transitions that are not almost-resolved multiples, should be intrinsically unresolved, and are in areas with well defined continuum flux. We pick 34 telluric standard stars spanning a range of DIMM seeing values, with the majority between 0.5–1.5 *arcsec*. The resulting distribution of spectral FWHM (km/s) as a function of spatial FWHM at 792 nm is fairly well described by a linear relation $a + b * x$, with x the spatial FWHM in pixels (with 0.15 arc sec per pixel), $a = 21.4 \pm 1.3$ km/s, $b = 1.4 \pm 0.2$. We use this linear relation as a way to estimate the spectral resolution for medium to poor signal to noise afterglow spectra in the VIS arm. To extend this to the UVB and NIR arm, we measured a series of lines in NIR arm spectra of a subset of 19 sources used for the VIS arm above, and find that the resulting distribution is consistent with a simple scaling of the VIS arm relation by the ratio of resolutions of the NIR and VIS arm for unresolved, slit filling, sources as given on the ESO instrument website. The UVB arm contains no suitable absorption lines to use, and we therefore use a scaled value as in the NIR arm. While this simple method is not terribly accurate (for one, the spa-

tial profile of the trace is not a perfect Gaussian), but it gives a sufficiently accurate estimate for the analysis of these poor signal to noise science spectra.

5.2. Correction for offsets in the wavelength calibration

X-shooter, being installed at the VLT Cassegrain focus is prone to flexures during operations. The flexures modify the projection of the slit on the detector with respect to the one obtained in daytime calibration. This requires a modification of the wavelength solution in order to process correctly the night-time data. Part of this correction is performed by the pipeline using the frames taken during X-shooter Active Flexure Compensation procedure²³ We corrected the remaining part using as a reference the sky emission lines present in the observed data.

For every afterglow observation we reduced one frame individually in STARE mode without sky subtraction obtaining ~ 100 sky spectra. The sky line list compiled at ESO for the E-ELT study²⁴ from the work of (Hanuschik, 2003, A&A, 407, 1157) and (Rousselot et al. (2000, A&A, 354, 1134), was used as a reference. From this list, we selected a subset of bright and isolated lines. In the case of the OH doublets, unresolved at X-shooter resolution, we took as line position the average between the blue and red components. To find the offsets of the spectra, we fitted gaussians near the expected positions under IDL using the MPFIT software (Markwardt, 2009, Astronomical Society of the Pacific Conference Series, Vol. 411, ADASS XVII, ed. D.A. Bohlender, D. Durand, & P. Dowler, 251) and we compared the result to the tabulated values. The resulting offsets, which were smaller than 0.1 Å in the UVB and VIS data and smaller than 0.5 Å in the NIR spectra, were applied to the corresponding spectra.

5.3. Redshifts

6. DISCUSSION

JPUF, BMJ and DX acknowledge support from the ERC-StG grant EGG-278202. The Dark Cosmology Centre is funded by the Danish National Research Foundation. TK acknowledges support by the European Commission under the

Marie Curie Intra-European Fellowship Programme in FP7. AdUP acknowledges support by the European Commission under the Marie Curie Career Integration Grant programme (FP7-PEOPLE-2012-CIG 322307). This work made use of data supplied by the UK *Swift* Science Data Centre at the University of Leicester. Finally, we acknowledge expert support from the ESO staff at the Paranal and La Silla observatories in obtaining these target of opportunity data.

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²³X-shooter User Manual available at <https://www.eso.org/sci/facilities/paranal/instruments/xshooter/doc.html>

²⁴http://www.eso.org/sci/facilities/eelt/science/drm/tech_data/data/optical_ir_sky_lines.dat

APPENDIX

A. NOTES ON INDIVIDUAL OBJECTS

A.1. *GRB090313*A.2. *GRB100205A*

Observed 3 days after the *Swift* trigger. No afterglow or host detected in 10.8 ks. GRB likely located at high redshift²⁵. The spectrum has not otherwise been published previously.

A.3. *GRB100219A* ($z = 4.667$)

The data presented here also formed the basis of GCN # 10441²⁶ and is published in Thone et al. (2013). Observations started 12.5 hours after the *Swift* trigger and has a total exposure time of 4.8 ks. Absorption features, including those of Ly α , from a multitude of ions are detected against the afterglow continuum at $z = 4.667$. Additionally, absorption from an intervening system is found at $z = 2.181$.

A.4. *GRB100316B* ($z = 1.180$)

The data presented here also formed the basis of GCN # 10495²⁷. The spectrum has not otherwise been published previously. Observations started 44 minutes after the *Swift* trigger and has a total exposure time of 2.4 ks. Absorption features from Fe II, Al II, Al III, Mg II and Mg I are well detected against the afterglow continuum at $z = 1.180$. Additionally, strong absorption lines from Fe II and Mg II from an intervening system are found at $z = 1.063$.

A.5. *GRB100316D* ($z = 0.059$)

The data presented here also formed the basis of GCN # 10512²⁸, GCN # 10513²⁹, GCN # 10543³⁰ and is published in Bufano et al. (2012) and Starling et al. (2011). This GRB is very close by and has an associated SN and has therefore undergone intense follow-up. The data presented here consists of a subset of the entire VLT/X-shooter campaign, covering the four first observing days while the afterglow still contributes significantly to the total emission. The first observations started 10 hours after the burst, before the SN was discovered, and targeted the star-forming 'A'-region(Starling et al. 2011), not the GRB. A very rich spectrum containing a multitude of emission lines puts the host at $z = 0.059$. For three consecutive nights, 58, 79 and 101 hours after the *Swift* trigger, the afterglow was observed as it transitioned into the spectrum of a high-velocity Ic-BL SN. The observations taken 79 and 101 hours after the burst are taken under programme 084.D-0265(A) (PI: Benetti), but with a similar setup to first two observations.

A.6. *GRB100418A* ($z=0.624$)

The data presented here also formed the basis of GCN # 10620³¹ and GCN # 10631³² and is published in De Ugarte Postigo et al. (2011). The burst have been followed up in three epochs of observations, 0.4, 1.4, and 2.4 days after the burst, each lasting 4.8 ks. The unambiguous redshift of the host, $z = 0.624$, is found from the simultaneous detection of emission features belonging to nebular lines, including H I, [O II] λ 3727, [O III] λ 5007, [Ne III], [N II], [S II], [S III], and [He I] as well as absorption features due to the presence of Zn II, Cr II, Fe II, Mn II, Mg II, Mg I, Ti II, and Ca II, all at a consistent redshift. Temporal evolution of the fine-structure lines belonging to Fe II* is found between the epochs.

A.7. *GRB100424A* ($z=2.465$)

The data presented here also formed the basis of GCN # 14291³³. The spectrum has not otherwise been published previously. Observations carried out, long after the burst has faded. Emission lines from the host are detected at $z = 2.465$.

A.8. *GRB100425A* ($z=1.1755$)

The data presented here also formed the basis of GCN # 10684³⁴ and is used in ?, but not published elsewhere. Observations started 4 hours after the *Swift* trigger, totaling 2.4 ks. Absorption features from Mg II and Fe II in the afterglow continuum are detected at $z = 1.1755$.

A.9. *GRB100615A* ($z=1.398$)

The data presented here also formed the basis of GCN # 14264³⁵, but not published elsewhere. Host observation of a dark burst(D'Elia & Stratta 2011) taken long after the afterglow has faded. Emission lines from the host belonging to [O II] λ 3727, [Ne III], [O III] λ 5007 and H α are detected at a common redshift of $z = 1.398$.

²⁵<http://gcn.gsfc.nasa.gov/gcn3/10399.gcn3>

²⁶<http://gcn.gsfc.nasa.gov/gcn3/10441.gcn3>

²⁷<http://gcn.gsfc.nasa.gov/gcn3/10495.gcn3>

²⁸<http://gcn.gsfc.nasa.gov/gcn3/10512.gcn3>

²⁹<http://gcn.gsfc.nasa.gov/gcn3/10513.gcn3>

³⁰<http://gcn.gsfc.nasa.gov/gcn3/10543.gcn3>

³¹<http://gcn.gsfc.nasa.gov/gcn3/10620.gcn3>

³²<http://gcn.gsfc.nasa.gov/gcn3/10631.gcn3>

³³<http://gcn.gsfc.nasa.gov/gcn3/14291.gcn3>

³⁴<http://gcn.gsfc.nasa.gov/gcn3/10684.gcn3>

³⁵<http://gcn.gsfc.nasa.gov/gcn3/14264.gcn3>

A.10. *GRB100621A* ($z=0.542$)

The data presented here also formed the basis of GCN # 10876³⁶, but not published elsewhere. Beginning 7.1 hours after the GRB, 2.4 ks observations reveal emission lines from [O II] λ 3727, H β and [O III] λ 5007 at a common redshift of $z = 0.542$ and a very weak afterglow continuum.

A.11. *GRB100625A* ($z=0.452$)

The data presented here is of the candidate host galaxy, taken long after the burst has faded and have not previously been published. 4.8 ks of exposure reveals a weak continuum present in all arms, but an absence of emission lines. This could indicate that the host primarily contains a older stellar population. The redshift, $z = 0.452$, is taken from Fong et al. (2013).

A.12. *GRB100724A** ($z = 1.288$)

The data presented here also formed the basis of GCN # 10971³⁷. The spectrum has not otherwise been published previously. The observations were carried out in RRM starting 11 min after the GRB trigger. See section 3.1, for a description of the RRM scheme. Absorption lines from several ionic species are detected in the afterglow continuum at a common redshift of $z = 1.288$. This is not a part of the statistical sample.

A.13. *GRB100728B* ($z=2.106$)

The data presented here also formed the basis of GCN # 11317³⁸. The spectrum has not otherwise been published previously. Starting 22 hours after the burst trigger, 7.2 ks of observations reveals a faint afterglow continuum with Ly α - and Mg II-absorption at $z = 2.106$. Due to a malfunctioning ADC, the sensitivity of X-shooter is depressed with respect to normal operations, resulting in a poorer throughput. Additionally, the position of the trace on the slit moves due to atmospheric differential refraction.

A.14. *GRB100814A* ($z=1.439$)

The spectra presented here has not been published previously. The observations consists of three visits, the first beginning only 0.9 hours after the *Swift* trigger, the other two visits were 2.13 and 98.40 hours after the trigger, respectively. A bright afterglow continuum is present in all visits, allowing identification of absorption features belonging to a wide range of ions at $z = 1.439$. A complex velocity structure in the absorption features belonging to Mg II, shows several components, separated by as much as 500km/s, pointing to a likely merger scenario in the host.

A.15. *GRB100816A* ($z=0.805$)

The data presented here also formed the basis of GCN # 11123³⁹. The spectrum has not otherwise been published previously. This short GRB was observed 28.4 hours after the GRB trigger. 4 x 1200 s of exposure reveals two distinct sets of emission lines, spatially offset $\lesssim 1''$, very close in redshift space, $z = 0.8034$ and $z = 0.8049$, indicating either an interacting host or some complex velocity structure of the host. Faint underlying continua are present under both sets of lines.

A.16. *GRB100901A* ($z=1.408$)

The data presented here has been published in Hartoog et al. (2013). Because of the unusual lingering brightness of this GRB, 2.4s of observations taken 65.98 hours after the GRB trigger still reveals an afterglow continuum visible across the entire spectral coverage of X-shooter. Absorption lines from a wide range ion put the redshift at $z = 1.408$, with intervening absorption systems at $z = 1.3147$ and $z = 1.3179$.

A.17. *GRB120327A* ($z = 2.813$)

The data presented here also formed the basis of GCN # 13134⁴⁰ and is published in D'Elia et al. (2014). The observation consists of two visits, 2.13 hrs and 29.98 hrs after the burst, with an afterglow continuum visible in all arms for both visits. We detect absorption features from Ly-limit, Ly α , C II/C II*, Si II/Si II*, Al I, Fe II and Mg II are detected at a consistent redshift, $z = 2.813$.

A.18. *GRB130408A* ($z = 3.758$)

The data presented here also formed the basis of GCN # 14365⁴¹. The spectrum has not otherwise been published previously. The observations consists of two 600sec spectra taken 1.9hrs after the burst. We detect absorption features from a wide range of ions. We also detect intervening absorption at $z = 1.255$ and $z = 3.248$.

A.19. *GRB130606A* ($z = 5.913$)

The data presented here also formed the basis of GCN # 14816⁴² and is published in ?. The observations consists of three 2x600sec visits starting 7.1 hrs after the burst at fairly high airmass. We detect absorption features from a wide range of ions at $z = 5.913$ as well as intervening absorption at $z = 2.3103, 2.5207, 3.4515, 4.4660, 4.5309, 4.5427, 4.6497$ and 4.7244 .

³⁶<http://gcn.gsfc.nasa.gov/gcn3/10876.gcn3>

³⁷<http://gcn.gsfc.nasa.gov/gcn3/10971.gcn3>

³⁸<http://gcn.gsfc.nasa.gov/gcn3/11317.gcn3>

³⁹<http://gcn.gsfc.nasa.gov/gcn3/11123.gcn3>

⁴⁰<http://gcn.gsfc.nasa.gov/gcn3/13134.gcn3>

⁴¹<http://gcn.gsfc.nasa.gov/gcn3/14365.gcn3>

⁴²<http://gcn.gsfc.nasa.gov/gcn3/14816.gcn3>

A.20. *GRB151021A* ($z = 2.330$)

The data presented here also formed the basis of GCN # 18426⁴³ and is not published elsewhere. The observation was carried out in RRM starting 44 minutes after the GRB trigger. We detect absorption features from a wide range of ions at $z = 2.330$ as well as intervening absorption at $z = 1.49$.

A.21. *GRB160203A* ($z = 3.517$)

The data presented here also formed the basis of GCN # 18982⁴⁴ and is not published elsewhere. The observation was carried out in RRM starting 18 minutes after the GRB trigger. We detect absorption features from a wide range of ions at $z = 3.517$ as well as intervening absorption at $z = 2.203$.

⁴³<http://gcn.gsfc.nasa.gov/gcn3/18982.gcn3>

⁴⁴<http://gcn.gsfc.nasa.gov/gcn3/18982.gcn3>