Gamma-Ray Bursts as Cosmological Probes: from Concept to Reality

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We describe the current status and recent results from our ongoing programme at the VLT aimed at performing target-of-opportunity follow-up spectroscopy of gamma-ray burst (GRB) afterglows. Our primary goal is to secure redshifts for a complete sample of GRBs, thereby allowing the use of GRBs as probes of the cosmic star-formation history, chemical evolution and the luminosity functions of the GRBs themselves as well as their host galaxies. Contrary to earlier expectations, most optical afterglows are already faint a few hours after the bursts and 8–10-m telescopes are therefore crucial to determine redshifts for most GRBs.

GRBs as unique probes at all redshifts

It is fundamental to know the distance to an astronomical object. The majority of physical parameters depend on it, such as the luminosity and the size. The same holds true for γ-ray bursts and their afterglows. About ten years ago it was still controversial whether these brief flashes of γ-rays detected by satellites were located in our own Galaxy, or at cosmological distances. It was only after the first distance determination, or redshift, in 1997 that this debate was settled in favour of GRBs originating from the very distant Universe, implying that their energy output is enormous. We here describe our efforts to determine redshifts for a complete sample of GRBs.

One of the most interesting aspects of GRB research is that it sheds new light on a very broad range of astrophysics – from stellar evolution and the formation of compact objects, through ISM studies, dust formation, extinction curves, chemical evolution, intervening absorption systems, high-z galaxies at the faint end of the luminosity function, and all the way to probing the reionisation epoch. During the last ten years GRB research has seen enormous progress thanks to intensive global campaigns to identify and follow-up GRB afterglows and their host galaxies. Hence, while GRB research is challenging in using target-of-opportunity time at very large telescopes, it is an investment that certainly pays off. This is reflected in the high citation rates for GRB papers – a consequence of the broad range of astrophysics on which GRB results have implications. However, the full potential for advances based on GRB observations in all of these fields has not yet been exploited.

The idea to use GRBs as probes goes back to the beginning of the so-called afterglow era (e.g. Wijers et al. 1998). So far the main obstacle to using GRBs as probes of the luminosity function of star-forming galaxies, the cosmic star-formation history and the fraction of obscured star formation (to mention just three examples) has been the very incomplete and heterogeneous nature of the small sample of GRBs with measured redshifts. The currently operating *Swift* satellite (Gehrels et al. 2004) is changing this. *Swift* was specifically designed for GRB studies and offers a unique chance to build a sample of GRBs that is sufficiently large and complete to address very fundamental questions that cannot adequately be addressed in other ways. This is a golden opportunity that we simply cannot afford to miss.

Our complete sample of *Swift* GRBs

The *Swift* satellite has been operating for about three years and is far superior to previous GRB missions. The reason for this is the combination of several factors: (1) it detects GRBs at a *rate* of about two bursts per week – about an order of magnitude larger than the previous successful BeppoSAX and HETE-2 missions; (2) with its X-ray Telescope (XRT) it *localises* the bursts with a precision of about 5 arcsec – also orders of magnitude better than previous missions; (3) it has a much shorter *reaction time*, allowing the study of the evolution of the afterglows literally seconds after the burst, sometimes during the prompt γ-ray emission itself. The *Swift* mission is funded at least until 2010. Our primary objective is to secure a large sample, as complete as possible, of GRB afterglows while *Swift* is still operating. More concretely, rather than including all *Swift* detected GRBs, our group is concentrating on those GRB afterglows with favourable observing conditions, which fulfil the following criteria:

(1) XRT afterglow detected within 12 hr
(2) Small foreground Galactic extinction: $A_V < 0.5$ mag
(3) Favourable declination: $-70° < \text{dec} < 70°$
(4) Sun distance larger than 55°.

By introducing these constraints, we are not biasing the sample towards optically bright afterglows, but we select a sample for which useful follow-up observations are likely to be secured. About 50 % of all

Swift GRBs do not fulfil these criteria, primarily because *Swift*, for technical reasons, has to point close to the Sun a significant fraction of the time. For bursts fulfilling the above criteria, we make every possible effort to detect optical and near-infrared afterglows and to measure their redshifts.

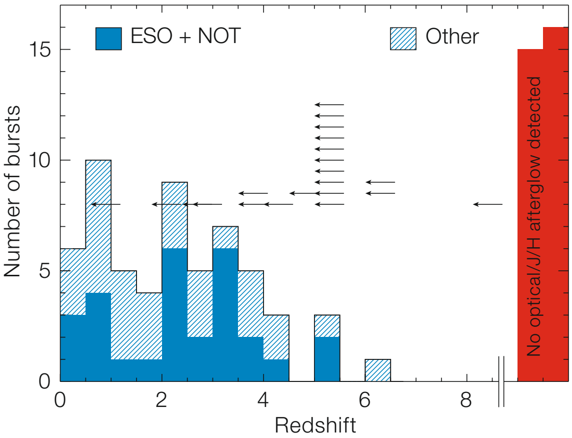

Figure 1: Redshift distribution (up to October 2007) of 109 long *Swift* GRBs localised with the X-ray telescope and with low foreground extinction $A_V \leq 0.5$. Of the 58 measured redshifts, our group has measured nearly half (25, shown in blue). As shown, the VLT is the dominant source of redshifts in the Swift era (four of the blue bursts in the histogram are also from the Nordic Optical Telescope). Bursts, for which only an upper limit on the redshift could be established so far, are indicated by arrows. Note that it is also difficult to secure redshifts for GRBs in the desert between $z = 1$ and $z = 2$. The red histogram at the right indicates the 27 bursts for which no optical/J/H afterglow was detected and hence no redshift constraint could be inferred (see Ruiz-Velasco et al. 2007 for a full discussion).

As shown below, we have been very successful in this effort, using the ESO VLT. Redshifts, or more generally spectroscopic observations, are crucial for almost all GRB-related science. The most important science cases for which spectroscopy is critical are listed below:

(1) Determining the luminosity function for GRBs (prompt emission as well as afterglows)
(2) Determining the redshift distribution of GRBs and using GRBs as tracers for the cosmic star-formation history (Jakobsson et al. 2006; Fiore et al. 2007)
(3) Studying the host galaxies, in particular those faint, high-redshift galaxies that are unlikely to be found and studied with other methods (e.g. Vreeswijk et al. 2003)
(4) Studying GRB-selected absorption-line systems (e.g. Prochter et al. 2006)
(5) Characterising the dust extinction curves of high-z galaxies (see Figure 5 for example)
(6) Spotting very high redshift GRBs (e.g. Kawai et al. 2006; see also Figure 2)
(7) Probing cosmic chemical evolution wth GRBs (e.g. Fynbo et al. 2006; see also Figure 4)
(8) Studying if GRBs can be used for cosmography (e.g. Ghirlanda et al. 2004).

The need for 8–10-m telescopes

Since the launch of *Swift*, we have had programmes running at the VLT with the aim of securing redshifts for *Swift* GRBs (PIs Fynbo and Vreeswijk). The status at the time of writing is that 109 *Swift* GRBs fulfilled our selection criteria. For 57 of these a redshift measurement has been secured (see Figure 1). The VLT has been the dominant single contributor in all GRB redshift measurements, providing around 40 % of the secure redshifts to date. The second highest redshift was also measured by our group with the VLT (Figure 2). The redshift of the most distant known GRB 050904 at $z = 6.295$ was measured with the SUBARU telescope (Kawai et al. 2006). Most of the other redshifts have been measured using other 6–10-m telescopes (Keck, GEMINI, SUBARU, Magellan). This is contrary to the expectations prior to the launch of *Swift*, where it was suspected that *Swift* itself, or at least 2–4-m telescopes, would be able to measure most of the redshifts. However, optical afterglows turned out to be much fainter at early times than anticipated. As we show in Figure 3, the majority of the afterglows are fainter than R = 20 when a slit can be placed on them. R = 20 is, in our experience, the limit for spectroscopic redshift determination using 2–4-m telescopes (typically, no more than 1–2-hr exposure time is available for observing GRB afterglows). Several optical afterglows are already fainter than R = 22 a few hours after the burst. Hence, 6–10-m telescopes are crucial for securing redshifts for the majority of *Swift* GRBs.

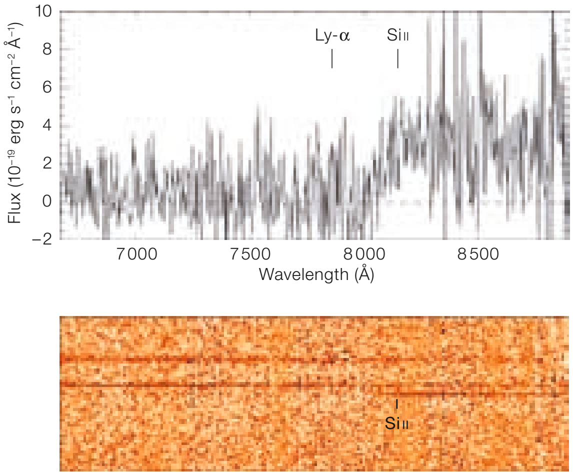

Figure 2: The spectrum of GRB 060927 obtained with FORS2 about 12.5 hr after the burst (from Ruiz-Velasco et al. 2007). A clear cut-off in the afterglow trace is observed at $\lambda = 8100$ Å, due to the onset of the Lyα forest at $z \approx 5.5$, making this the second most distant *Swift* GRB so far for which the redshift has been measured. The probable Si II line (shown more clear in the 2-dimensional spectrum below) allows a precise redshift determination of $z = 5.47$.

The fact that, in particular, the VLT, but also other 6–10-m telescopes, have made tremendous efforts to secure redshifts means that we now have a much higher redshift completion than for pre-*Swift* samples. But it is clear that we will not get redshifts for all bursts from spectroscopy of the afterglows for multiple reasons. In about 20–30 % of the triggers we are not able to measure the redshift, either due to lack of lines (probably bursts at redshifts between 1 and 2 – see Figure 1), bad weather or because the afterglow has faded too much before it is observable from Paranal. For these bursts our only chance of measuring the redshift is via spectroscopy of the host galaxy. We have also pursued this route ex-

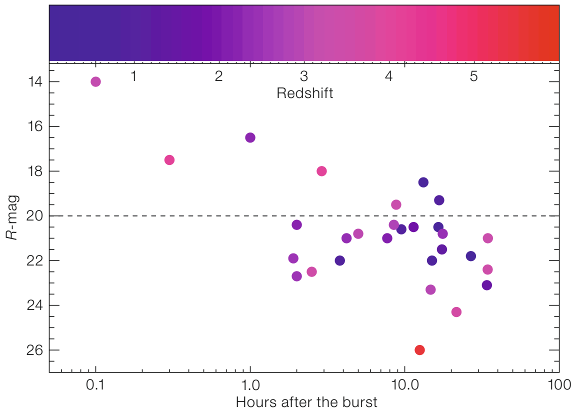

Figure 3: The *R*-band magnitude of the optical afterglows as a function of the time after the burst at which the spectroscopic observations were obtained. Only included are *Swift* bursts for which we have measured the redshift (using primarily the VLT, but also NOT, WHT and GEMINI). The colour bar at the top indicates the colour code for the measured redshifts. The dashed line marks a magnitude of R = 20 which is roughly the spectroscopic limit for 2–4-m telescopes for detecting absorption lines. As seen, most afterglows are fainter than this limit when observable.

tensively in an ESO large programme (PI Hjorth). This is a challenging task due to the faintness of these systems, and the analysis of these data is still ongoing, but we have already determined a number of redshifts (included in Figure 1).

The redshift distribution of *Swift* GRBs: current status

The first conclusion from Figure 1 is that *Swift* GRBs are very distant. *Swift* GRBs are more distant than GRBs from previous missions due to its higher sensitivity to the lower energies prevalent in the more distant events (Fiore et al. 2007). The median and mean redshift are now both 2.3, while for previous missions it was closer to 1 (Jakobsson et al. 2006). The record holder is $z = 6.295$ (Kawai et al. 2006) compared to the former $z = 4.50$ measured at the VLT. It is striking how events at redshifts as large as 6 can be detected within such a small sample. For comparison, only a few QSOs are detected at similar distances out of a sample of a hundred thousand QSOs. Remarkably, the redshift distribution, measured for just over 50 % of all bursts, is consistent with the redshift distribution predicted if GRBs are unbiased tracers of star formation (see e.g. Jakobsson et al. 2006 and *http://www.dark-cosmology.dk/~pallja/GRBsample.html* for a regularly updated analysis).

Additional science derived from afterglow spectroscopy

It is currently debated if and how GRBs may be biased towards a special subset of massive stars, in particular those with low metallicity. This issue is not resolved, but there is evidence that, if it exists, such bias cannot be strong. Afterglow spectroscopy often allows us to measure the metallicity of the line of sight in the host galaxy. In Figure 4 we plot the metallicities along GRB sightlines together with metallicities derived from QSO absorbers and emission-selected galaxies. Here it can be seen that GRBs are more metal-rich than QSO-DLAs at similar redshifts and almost as metal rich as the Lyman-break galaxies. The shift in metallicity relative to QSO-DLAs can be understood from the different selection functions of the (star-formation selected) GRB-DLAs and the (H I cross-section selected) QSO-DLAs (Fynbo et al., in preparation). Hence, most likely, GRBs will be unbiased tracers of star-forming galaxies, at least at $z > 2$ (Fynbo et al. 2006). This further adds to the value of GRB afterglow spectra: they provide redshifts and information on ISM properties such as metallicity and kinematics of the inner, intensively star-forming regions of distant starbursts.

In addition to H I column densities, metal and molecular abundances and kinematics, the afterglow spectra also provide information on the extinction curves. The intrinsic spectrum of the afterglow from theory is predicted to be a power law and therefore any curvature or other broad features in the spectrum can be interpreted as being due to features in the extinction curve. So far, almost all the extinction curves we have derived for GRB host galaxy sightlines have been consistent with an extinction curve similar to that of the SMC. Recently we obtained the clearest detection yet of the 2 175 Å bump, known from the Milky Way extinction curve, in a $z = 2.45$ GRB (Elíasdóttir et al., in preparation and Figure 5). This GRB absorber also has unusually strong metal lines suggesting that the presence of the 2 175 Å extinction bump is related to a high metallicity. However, we have examples of GRBs with nearly solar metallicity for which the bump is not seen so it seems that metallicity is not the only parameter controlling the presence of the 2 175 Å extinction bump.

Finally, the VLT rapid response mode (RRM) has now started to deliver the first very interesting discoveries. The first time that the RRM was used fully automatically, without any human intervention from the *Swift* satellite GRB alert to the preset of the VLT, was when we triggered UVES

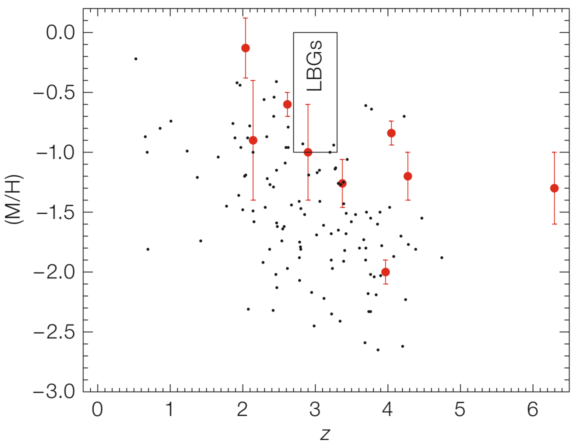

Figure 4: The logarithmic abundance with respect to hydrogen, expressed as a fraction of the Solar abundance, is plotted for various probes. Red circles represent the measurements for GRB metallicities (taken from the compilation of Fynbo et al. 2006). The small dots with no error-bars are the measurements for 121 QSO-DLAs taken from Prochaska et al. (2003). For comparison the range of metallicities for bright Lyman-break galaxies (LBGs) found by Pettini et al. (2001) is also shown. It is clear that GRBs in this small sample are more metal-rich than the QSO-DLAs and almost as metal-rich as the LBGs. Whereas the QSO-DLAs are cross-section selected, and the LBGs represent the most luminous (and hence rare) starbursts, the GRB hosts are presumably close to being purely star-formation selected.

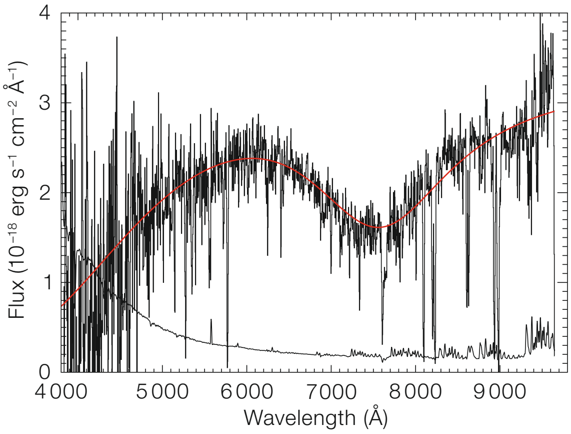

Figure 5: The spectrum of the afterglow of GRB0 70802 obtained with FORS2 (from Elíasdóttir et al., in preparation). The flux calibrated spectrum (upper curve) and the observed error spectrum (lower) are shown. From the unusually strong metal lines we derive a redshift of $z = 2.45$. A broad absorption bump peaking around 7500 Å is clearly apparent. The spectrum is well fitted (red line) with a power-law spectrum and an extinction curve containing the 2175 Å extinction bump, known from our Galaxy and the LMC. This is the clearest detection of the 2175 Å extinction bump for any sightline outside the Local Group.

observations of GRB 060418. The afterglow happened to be bright, and the resulting sequence of spectra is truly unique due to the spectacular combination of response time (10 min), spectral resolution (45 000), time resolution (a succession of pairs of exposures with durations of 3, 5, 10, 20, 40 and 80 minutes) and signal-to-noise ratio (10–15 per pixel for each spectrum). This response time of only 10 minutes represented the fastest spectroscopic follow-up of any GRB by an optical facility at that time, let alone at this resolution (this record was later broken by another trigger from our team, for GRB0 60607, which was started a mere 7.5 minutes after the GRB).

The GRB 060418 spectra allowed us to measure the column density variability of various Fe II fine-structure levels and metastable levels of Fe II as well as Ni II (see Figure 6). Both the observed variability and the detection of metastable levels of Fe II and Ni II had never been seen before in GRB host galaxies. Modelling the time evolution of the excited level population unambiguously shows that UV pumping from afterglow photons is the dominant excitation mechanism, and that the distance from the GRB to the cloud of excited atoms is unexpectedly large: 1.7 kpc (Vreeswijk et al. 2007). Applying this method to a sample of bursts will provide the radial distribution of neutral gas clouds around GRBs, and therefore around massive star-forming regions in faint distant galaxies.

Prospects

Spectroscopy of GRB afterglows provides redshifts and information on the ISM properties for the population of galaxies possibly responsible for the bulk of the high-redshift star formation. We are currently working on securing this information for a complete sample of *Swift* GRBs. The current sample of 109 GRBs is 53 % complete and we wish to increase both the sample size and the completion. Such a large and complete sample of GRBs constitutes a powerful tool to study the star-formation history of the Universe, complementary to studies based on either deep galaxy surveys or QSO absorbers. The spectra also allow a broad range of additional science, most importantly the study of the ISM of the galaxies hosting the GRBs. As stressed, *Swift* makes it possible to build such a sample. With the VLT we are finally moving GRBs as probes from concept to reality

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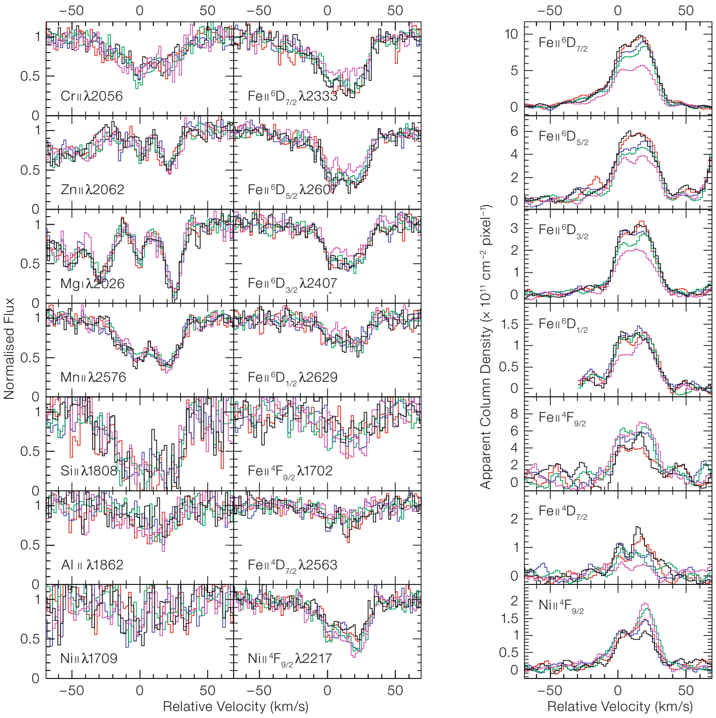

Figure 6: The UVES spectra of GRB 060418 obtained in RRM (from Vreeswijk et al. 2007). The five epochs of spectra, beginning 10 min after the burst, are plotted with the colours black, red, blue, green and magenta, respectively. In the left panel individual lines are shown: typical resonance lines on the left; the lines arising from the excited levels of Fe II and Ni II on the right. The latter show evidence for a varying equivalent width as a function of time. To make this variability clearer, we have combined various lines that arise from the same level and constructed apparent column density profiles, smoothed with a boxcar of 5 pixels; these are shown in the right panel.

The Long Night of Science outside ESO Headquarters: a group of young people being shown around the constellations by Andreas Wicenec (at left).

The Long Night of Science inside ESO Headquarters: Jochen Liske explaining the ELT to a group of attentive visitors. (See article on page 59.)

Photos: H. H. Heyer, ESO