GRB Afterglows: Illuminating the Star-Forming Universe[1]

Gamma-Ray Burst (GRB) afterglows are distant powerhouses that can be extremely bright. Therefore, they can be used as a tool to study intervening matter along the line of sight, in exactly the same way that quasars have been used for decades, with two important differences: First, GRB afterglows fade away, thereby in time opening up their lines of sight for deep searches for the counterparts of the absorption systems. Secondly, a subclass of GRBs is related to the deaths of massive stars, and hence their afterglows provide sightlines directly into the very cores of star-forming regions, illuminating the line of sight all the way down to their immediate surroundings.

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Seven years after the discovery of the first afterglow in 1997, several dozen have been discovered by an active and growing community. The distances, or redshifts, range from $z = 0.0085$ to $z = 4.5$, with a mean redshift of 1.4. The left panel of Fig. 1 shows the redshift distribution until August 2004. Afterglows can be spectacularly bright at early times: the afterglow of GRB 990123 (i.e. the burst that happened on 23rd of January 1999) was detected by the ROTSE robotic telescope at 50s after the burst at 9th magnitude (Akerlof et al. 1999). For a source whose distance was determined to be at $z = 1.6$, this is quite amazing. One comparison to visualise this brightness is the following: if this burst would have happened in the Andromeda galaxy, still some three million light years away, for a short moment it would have been as bright as the full moon. The right panel in Fig. 1 shows the light curve of GRB 990123 and those of all other afterglows whose redshifts have been determined.

Although the afterglow can be extremely bright, it fades away rapidly. Observations of GRBs therefore require fast response and quick decision making, and there is no chance to return to get the "missing observation". After it has faded, there is then plenty of time to explore the clear, undisturbed view of its place of birth. Deep observations performed several months after the GRB have shown that for almost every afterglow a host galaxy is detected at the afterglow position. The host-galaxy magnitudes range from roughly $V = 22$ to $V = 30$. GRB hosts show prominent emission lines, they are sub-luminous, under-massive and blue (e.g.

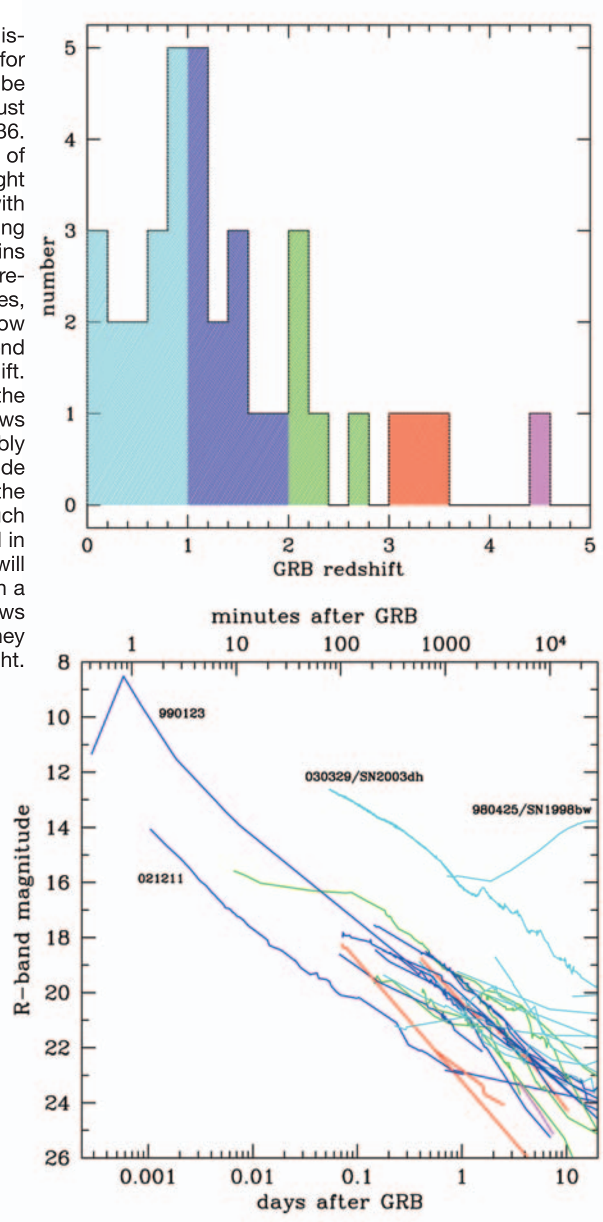

Figure 1: *Top:* Redshift histogram of all GRBs for which the distance could be determined up to August 2004; a total of 36. *Bottom:* The collection of available *R*-band light curves of the GRBs with redshifts. The colour coding of the different redshift bins matches that of the corresponding light curves, showing that the afterglow brightness does not depend very much on the redshift. Back-extrapolation of the late-time afterglows shows that all were probably brighter than 18th magnitude after 10 minutes. With the latest satellite missions such as *Swift* (launched in November 2004), it will become possible to catch a large sample of afterglows at early times, when they are still bright.

[1]Most of the observations that we use to illustrate this article were obtained by the GRB Afterglow Collaboration at ESO (GRACE); see the Messenger article by Kaper et al. 2002 and the GRACE webpage: http://www.gammaraybursts.org/grace/index.php.

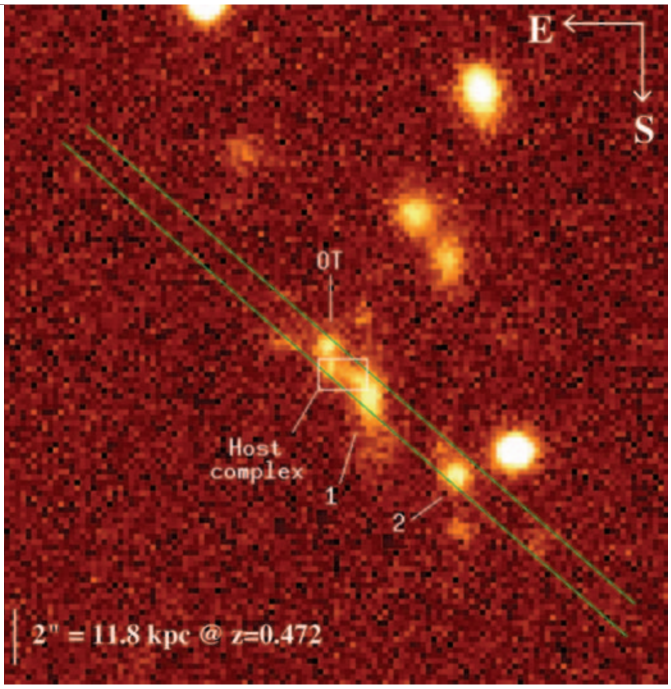

Figure 2: The afterglow (or optical transient - OT) of GRB 020405 and its environment, as imaged in the *R*-band by the VLT. The VLT/FORS1 afterglow spectrum (with the slit shown on the image) contains two absorption systems: one at $z = 0.691$, the redshift of the host galaxy, and a foreground system at $z = 0.472$. Objects “1” and “2” show emisssion lines that are measured to be at the same redshift as the foreground absorber: $z = 0.472$. Therefore, the likely counterpart of the absorption system is object “1”, at an impact parameter of about 2″ (12kpc). From Masetti, Palazzi, Pian & GRACE (2003)

Le Floc’h et al. 2003), and their morphology is sometimes very disturbed. But in a few cases, a very large star-formation rate (hundreds of $M_\odot$ per year) has been inferred from radio and/or sub-mm observations (e.g. Frail et al. 2002). Overall, the emission properties of most GRB host galaxies seem to be very similar to those of a population of young starburst galaxies (Christensen et al. 2004).

Apart from their distance, the most important thing that we have learned from GRB afterglow studies so far, is the following clue to their origin. For at least two GRBs that were relatively nearby (GRB 980425 and GRB 030329 - see the labels in Fig. 1), the GRB afterglow lightcurve and spectrum are very similar to a supernova of type Ic (Galama et al. 1998, Hjorth et al. 2003), i.e. a core-collapse explosion of a massive star at the end of its lifetime, after having shed its hydrogen and helium layers. So apparently, at least some GRBs are produced in a special type of supernova event, and therefore their progenitors are massive stars.

As GRB afterglows are bright and distant, they can be used to perform detailed studies of any matter that is located along the line of sight, which will reveal itself through absorption lines in the spectrum of the afterglow. The systems that can be explored in this way range from the immediate environment of the GRB explosion (e.g. the stellar wind from the massive progenitor star) and the star-forming region in which it exploded, to more distant systems, either inside the host galaxy, or at lower redshift in the inter-galactic medium. Once the afterglow has faded, the absorption properties of these systems can be complemented with studies in emission, to obtain a more complete picture of the processes governing star formation.

The counterparts of foreground absorption-line systems

To use a bright background source to trace matter along the line of sight is a well-known technique in astronomy. The prime analog is that of the study of foreground absorption-line systems along QSO lines of sight (see the Messenger article by Max Pettini, 2003, which includes a very nice illustration of the technique of absorption-line spectroscopy). Through high-resolution spectroscopy of distant QSOs, one can probe inside the absorption systems, and determine detailed characteristics such as the metallicity, dust and H_2 content, and kinematics. Moreover, the physical conditions of the gas, such as density, temperature, and the local UV flux can be measured. Our knowledge of the chemical evolution of the universe has also greatly improved through such QSO absorption-line studies.

Several types of foreground absorbers are distinguished based on their neutral hydrogen (H I) column density. In order of increasing column density: the Ly-α forest, Lyman-limit systems (LLSs) and damped Ly-α absorbers (DLAs). The DLAs, with $N(\text{H I}) > 2\ 10^{20}$ atoms cm^{-2}, have received considerable attention among the absorption-line systems, as they contain most of the neutral gas in the early universe, from which the stars that we see around us today must have formed. Therefore, DLAs play an important role in the study of the global star-formation evolution of the universe.

Detection of the counterparts of these absorption-line systems is extremely interesting, as it allows identification of the type of galaxy in which the absorption takes place, and determination of its internal characteristics. However, the counterpart identification is made very difficult by the glare of the bright QSO, which greatly complicates detection of faint systems close to the line-of-sight. After decades of QSO absorption-line studies, counterparts of only a handful of high-redshift DLAs have been identified. At lower redshifts, the searches have been more successful with the counterparts being brighter: about a dozen $z < 1$ DLA galaxy counterparts have been discovered, with one as close as 1.2″ from the line-of-sight. However, the inner 1″ is practically impossible to probe, so the possibility remains that some counterparts are hiding very close to the QSO sightline.

In order to use GRB afterglows for the same purpose, one has to be extremely quick to obtain a useful high-resolution spectrum (see Fig. 1). With a QSO of constant brightness one can integrate at leisure, obtaining a spectrum with the desired signal-to-noise. However, the transient nature of GRB afterglows harbours an advantage as well: as the afterglow fades away, its line of sight is opened up for deep searches for the counterparts of the absorption-line systems discovered in the spectrum. Although the background host galaxy may still present some contamination, its brightness is negligible compared to that of a QSO. And if needed, it may be separated from the counterparts of the foreground absorbers through the use of narrow-band filters, as outlined in Vreeswijk, Møller & Fynbo (2003), allowing detection of the absorber even when it is located exactly along the line of sight.

The accumulated redshift path covered by GRB afterglows is still fairly small, so it is not surprising that none of the rare foreground DLAs have been detected so far. However, several lower column density metal absorbers (or Lyman limit systems) have been detected, of which a couple of counterparts have been identified: the $z = 0.47$ system along the line of sight toward GRB 020405 (Masetti et al. 2003, see Fig. 2), and the foreground system at $z = 0.84$ toward GRB 030429 (Jakobsson et al. 2004). Both absorbers are located at a small impact parameter (i.e. the projected distance of the absorber to the line of sight at the absorber redshift): 12kpc for galaxy “1” of Fig. 2 in the 020405 sightline, and only 9 kpc (1.2″) for the 030429 foreground absorber. This is lower than the typical range of impact parameters measured for metal absorbers at similar redshifts along QSO lines of sight. For example, Guillemin & Bergeron (1997) find an impact parameter range of 2–23″ (12–127 kpc), for a few dozen Mg II counterparts at $0.15 < z < 1.3$.

A possible explanation for this difference is exemplified in Fig. 2. If the absorbing galaxies are members of pairs or groups, then a companion to a QSO absorber further away from the line-of-sight is much easier to identify than the absorber itself. In the case of GRB 020405, the two objects “1” and “2” have the same redshift as that of the absorption system. Hence, object “1”, at a impact parameter of about 2″ (12kpc) is the probable counterpart of the absorption system. Note that even if “1” would have been on top of the afterglow, its redshift would still have been obtained. Placing a bright quasar at the position of the GRB afterglow (marked “OT” in Fig. 2) would render “1” very difficult to detect, and could result in the obvious identification of “2” (at 6″, or 36 kpc) as the absorber, i.e. as a small galaxy with an extended halo of absorbing gas. The implication is that some of the counterparts of absorbers toward QSOs may have been misidentified. Rapid spectroscopic follow-up observations of GRBs and later studies of their host sightlines will uniquely resolve this question.

Massive star-forming regions inside the host galaxy

As GRB afterglows are caused by the deaths of massive stars, they lead us directly to regions of massive-star formation. Star formation is an important ingredient in our understanding of galaxy evolution, and has therefore been extensively studied, mostly through emission properties of star forming regions in the ultra-violet, optical, infra-red, sub-mm and radio wavelengths. GRB afterglow spectroscopy will now in addition allow measurements of the internal proporties of star-forming regions, in the same way as for the foreground absorbers. The combination of both absorption and emission properties will provide additional insight in the understanding of the process of star formation.

Our study of the afterglow of GRB 030323 is a nice example of what can be done with GRB afterglows. VLT/FORS2 spectroscopy of the GRB 030323 afterglow (see Fig. 3), obtained by the GRACE collaboration, show several interesting properties of the host galaxy, even though the resolution of the spectrum is fairly low. First, a heavily damped Ly-α line (shown in green in the figure) is detected at the redshift of the GRB: z=3.37. The redshift of the GRB cannot be higher, as in that case Ly-α forest lines (shown in blue) would also be visible to the right of the Ly-α line, which is not the case. A fit to the DLA line (see the figure inset) implies a neutral hydrogen (HI) column density of log N(H I)=21.90±0.07. The H I column density of the z=3.37 DLA in GRB 030323 is larger than that of any intervening DLA observed along a QSO line of sight. In fact, several other GRB afterglows have shown evidence for a DLA at the GRB redshift (all of which have been discovered by the GRACE collaboration). All the GRBs for which the neutral hydrogen column could be measured (7 so far) are shown in Fig. 4. Most of the GRB absorbers have very high values for the H I column compared to the QSO distribution, but two are below the DLA definition. The sample is still too small to allow any firm conclusions, but it does show that there is a wide spread in the GRB

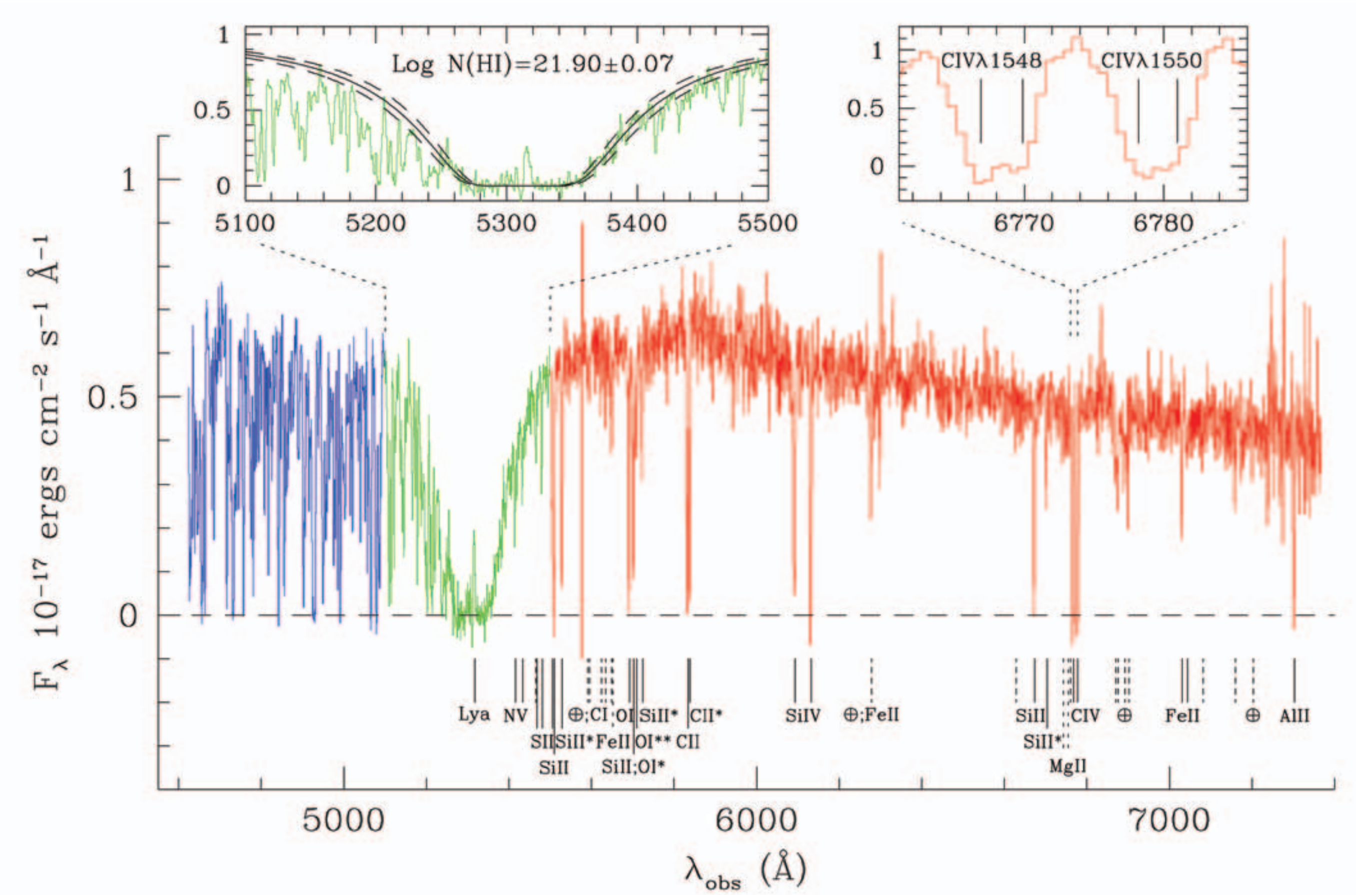

Figure 3: This VLT/FORS2 spectrum of the afterglow of GRB 030323 shows the imprint on the afterglow flux of numerous metal-absorption features in the red part, a strong damped Ly-α line (green), and the Ly-α forest (blue). The metal lines and the DLA are both caused by absorption in the interstellar medium of the GRB host galaxy, at z = 3.37. From a fit to the damping wings of Ly-α (see the inset) we measure a neutral hydrogen (H I) column density of log N(H I) = 21.9. As can be seen in Fig. 4, this column is larger than seen in any QSO-DLA. In the Ly-α trough, we also detect Ly-α in emission, which corresponds to a host-galaxy star-formation rate of about 1 $M_\odot$ per year. Interestingly, fine-structure lines of Si II (indicated with the *) are also detected, which have never been clearly seen in QSO-DLAs. This could imply that these lines are produced very close to the site of the GRB explosion. From Vreeswijk, Ellison, Ledoux & GRACE (2004)

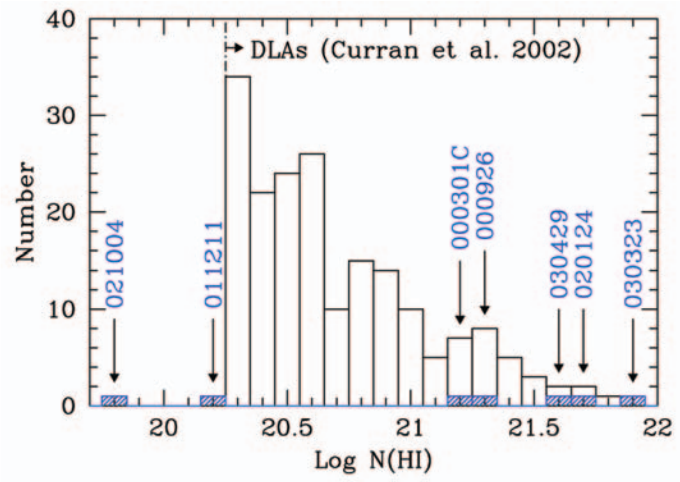

Figure 4: Histogram of the column densities of DLA systems measured through the damping wings of Ly-α discovered in the spectrum of a background QSO (compilation taken from Curran et al. 2002). The blue histogram shows measurements in GRBs for which the redshift was large enough to detect Ly-α. Out of 7 GRBs, 5 show neutral hydrogen column densities above the DLA definition of 2 10^{20} atoms cm^{-2} (log N(H I)=20.3). The host of GRB 030323 contains a column density larger than in any observed (GRB- or QSO-) DLA system. From Vreeswijk, Ellison, Ledoux & GRACE (2004)

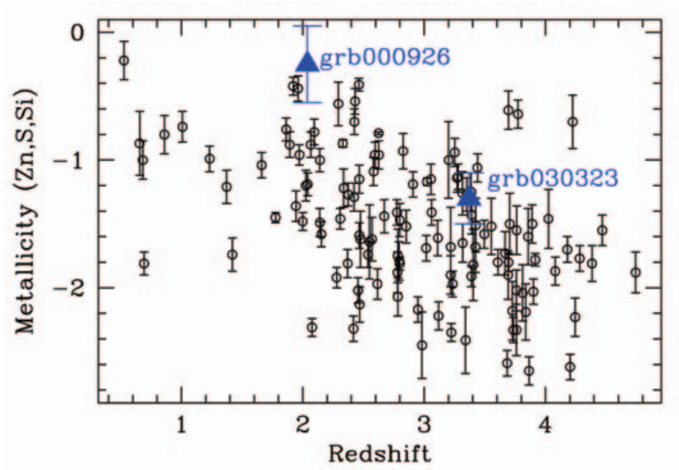

Figure 5: Comparison of the metallicities of a sample of QSO-DLAs (open circles) with the two GRBs for which a metallicity has been determined (solid triangles): GRBs 000926 and 030323 (this paper). The two GRB hosts are located at the metal-rich end of the QSO-DLA distribution. From Vreeswijk, Ellison, Ledoux & GRACE (2004)

H I column density distribution. It will be interesting to see how this plot will develop as the sample of GRB afterglow H I measurements increases, as it will tell us about the distribution of H I gas in high-redshift galaxies and their star-forming regions.

Several metal-absorption lines are detected redward of Ly-α (shown in red in Fig. 3). Even though most are saturated, we are able to obtain the abundance of iron and sulphur with respect to hydrogen: [Fe/H]=–1.5 and [S/H]=–1.3, where [X/H]=log (X/H)–log $(X/H)_{\odot}$, with X and H denoting the element and hydrogen abundance, respectively. So far metallicities have been determined this way for only two GRB afterglows: GRBs 030323 and 000926. Both are shown in Fig. 5, and are again compared to a sample of intervening QSO-DLAs. The GRB values seem to end up in the upper regime of the QSO-DLA metallicity distribution, but the sample is still very small. Higher values for GRB-DLAs is what one would expect, as GRBs probe star-forming regions, where the metallicity should be larger than along random sight lines through foreground galaxies, as probed by the QSOs.

Possibly the most surprising fact in the spectrum of 030323, is the discovery of fine-structure lines of singly-ionised Silicon: Si II*. These lines have never been clearly detected in QSO-DLAs, which suggests that either the lines have an origin related to the GRB, or it could be due to the very high column density observed. The population of fine-structure levels can be caused by collisions between several particles in the interstellar medium, direct photo-excitation by infra-red photons, or fluorescence, and thus depends either on the density of the absorbing medium or the ambient photon-flux intensity. If we assume that the Si II* levels in the case of 030323 are caused by collisions (and neglecting direct excitation), we estimate that the volume density is 100-10,000 cm^{-3}, which is much higher than the density inferred for QSO-DLAs. Combined with the column density, we can then estimate the size of the Si II* absorption region to be 0.5–50pc. However, the population of these levels may well have been caused by the ionising radiation from the GRB afterglow. A larger sample of GRB spectra, taken at different epochs, will be able to discriminate between these two possibilities, and constrain either the volume density, or the strength of the ionising GRB flux in the surroundings of the GRB.

Only the lucky combination of a GRB occuring in this galaxy, and our ability to rapidly follow it up via the very efficient ESO ToO (Target-of-Opportunity) programme of GRACE, which is superbly supported by the Paranal and La Silla observatories, allowed us to study it in detail. Figure 6 shows a Hubble Space Telescope (HST) image of the field of the host, which is measured to be around $V = 28$. With conventional techniques one would have very little to say about this galaxy: basically its Ly-α star-formation rate and its color, nothing more. This shows the enormous power of GRB afterglows as a tool to study high-redshift star-forming galaxies.

Stellar wind from the GRB progenitor

Absorption systems along QSO lines of sight can roughly be divided into three different types according to their origin: Intervening systems (unrelated to the QSO), local systems (in the environment surrounding the QSO host galaxy or galaxy cluster), and intrinsic systems (created close to the central engine of the QSO). The GRB analogy to QSOs would then suggest that maybe there could also be spectroscopic signatures of the third kind in GRB spectra. Such signatures of the progenitor itself could then provide detailed information on events prior to the actual burst of gamma rays. If, for example, the progenitor would have been in active wind phases at earlier times, then those winds could still be present as expanding shells at the time when the spectrum was obtained, and would tell us of the past history of the star leading up to its collapse.

In the low resolution spectrum of GRB 021004 obtained with the Nordic Optical Telescope (NOT) on La Palma (Møller et al. 2002), spectral signatures were seen which in a very curious way resembled intrinsic absorption systems seen in QSO spectra. One particular resemblance was the fact that some of the absorbers had relative velocities which exactly shifted one line of the strongly absorbing CIV-doublet into the other line of the same doublet. This is known as "line-locking" and had until then only been observed in quasar spectra. The line-locking phenomenon is thought to arise from radiative acceleration of a wind. This observation therefore strongly supports the suggestion that progenitor winds may indeed be part of the "family" of GRB absorption systems. The same GRB was observed with the VLT using the UVES spectrograph and at the much higher resolution of UVES the GRB 021004 spectrum is a veritable treasure-trove of information revealing a whole series

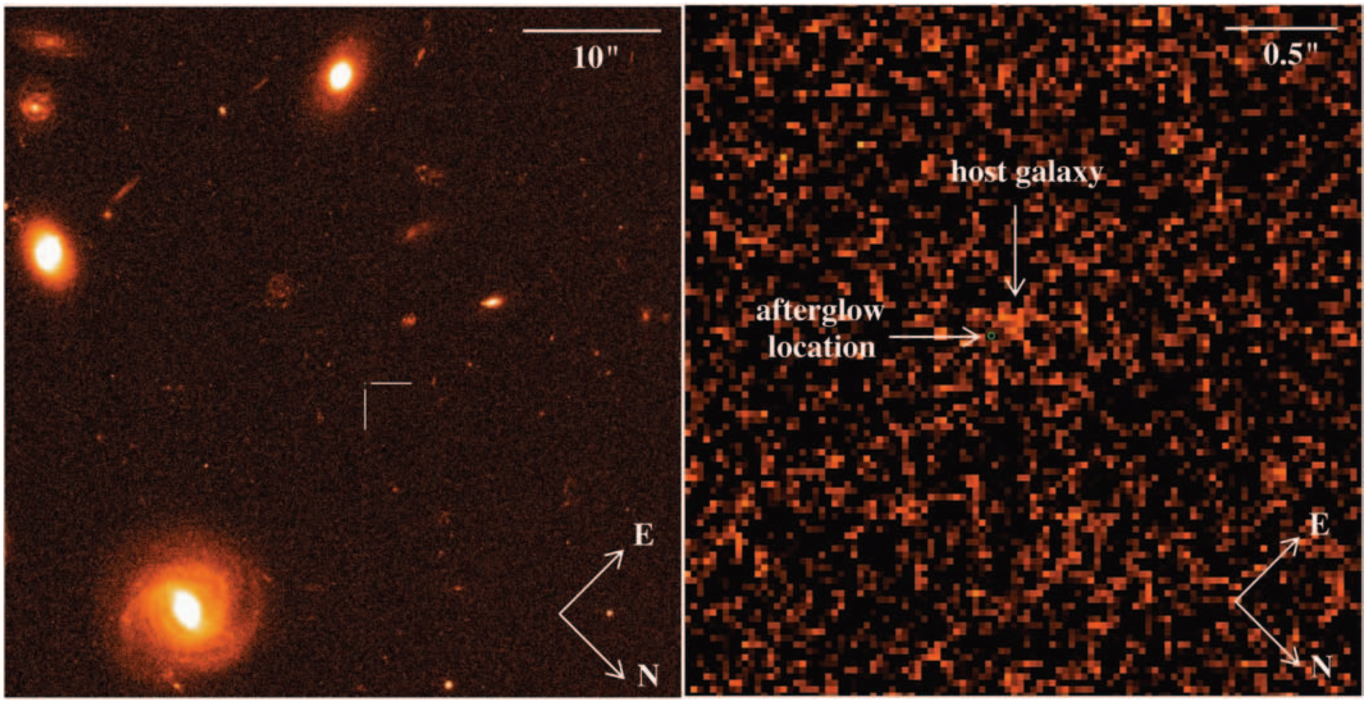

Figure 6: HST imaging in the F606W filter of the field of GRB 030323, obtained by the GOSH collaboration. On the left panel the 50″×50″ field surrounding the burst is shown, whose location is indicated by the cross hair. The right panel zooms in on the central region, where the green circle indicates the position of the early afterglow. The object next to it, with a magnitude of roughly *V* = 28, is the probable host galaxy of GRB 030323. From Vreeswijk, Ellison, Ledoux & GRACE (2004)

of absorption systems displaying ejection velocities from zero to more than 3,000 km/s (Castro-Tirado et al. 2004).

The bright future of GRB afterglows

The future of GRB afterglows literally looks bright. Figure 1 shows that in time the afterglow brightness fades very rapidly, and that most afterglows to date have been discovered around 20th magnitude. This is because, so far, the discovering satellite missions such as *BeppoSAX*, had a delay of at least a couple of hours between detection of the burst, and determination of the GRB error box. So the afterglows are usually faint at discovery, and before a spectrum can be taken, another couple of magnitudes are lost. For example, the spectra of GRB 030323, discussed in the previous section, were taken when the afterglow had a visual magnitude of about 21.5. At that magnitude, high-resolution spectroscopy is impossible, but this will change in the near future.

The *Swift* satellite, successfully launched on November 20, 2004, is expected to cause yet another revolution in the field of GRB afterglows. It is designed to chase roughly 100 bursts per year. For each GRB it will determine a 4′ radius error circle from the gamma-ray emission with its *Burst Alert Telescope* (BAT) after 20s, a 5″ accuracy with its X-ray Telescope (XRT) after 70s, and an optical sub-arcsecond localisation with its UV/Optical Telescope (UVOT) will be distributed after 4 minutes. This will allow extremely rapid follow-up observations from the ground, and telescopes of all sizes will play a role.

Many robotic telescope projects have popped up over the past several years, to chase GRB afterglows at very early times. Several clones of the successful ROTSE telescope, which detected the 9th magnitude flash of the afterglow of GRB 990123, have been spread around the world. At ESO's La Silla, both REM (Chincarini et al. 2003) and TAROT (Boer et al. 2003) are ready to chase Swift triggers in both the optical and near-infrared. The imaging data taken by this suite of robots will be unprecedented, and important to constrain the early light-curve evolution of GRB afterglows, of which very little is known at the moment.

However, for the science that we have been discussing in this article, what one would like is a world-class high-resolution spectrograph such as UVES at the VLT, to observe the afterglow only a few minutes after the GRB. For this to be possible, an ESO working group recommended implementation of the so-called Rapid-Response Mode (RRM) at the VLT, allowing semi-automatic observations. This mode has been installed for UVES at UT2 starting from Period 73, and will also be available for the FORSes and ISAAC from Period 74 onward. The typical delay time of the VLT with RRM will be around 5–10 minutes, and one can see from Fig. 1 that a large fraction of the afterglows will be brighter than 18th magnitude. Therefore, the powerful combination of VLT, UVES and RRM will allow high-quality spectroscopy of GRB afterglows of a large sample of Swift bursts, which will provide unique clues to the nature of foreground absorption systems and the process of star formation in high-redshift galaxies.

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