Gamma-Ray Bursts: Learning about the Birth of Black Holes and Opening new Frontiers for Cosmology

Guido Chincarini[1,2]
Fabrizio Fiore[3]
Massimo Della Valle[4]
Angelo Antonelli[3]
Sergio Campana[2]
Stefano Covino[2]
Giancarlo Cusumano[5]
Paolo Giommi[6]
Daniele Malesani[7]
Felix Mirabel[8]
Alberto Moretti[2,9]
Patrizia Romano[2,9]
Luigi Stella[3]
Gianpiero Tagliaferri[2]

[1] Università degli Studi di Milano-Bicocca, Italy
[2] INAF – Osservatorio Astronomico di Brera, Italy
[3] INAF – Osservatorio Astronomico di Roma, Italy
[4] INAF – Osservatorio Astrofisico di Arcetri, Italy
[5] INAF/IASF Palermo, Italy
[6] ASI Science Data Center
[7] International School for Advanced Studies (SISSA), Trieste, Italy
[8] ESO
[9] Supported by the Italian Space Agency (ASI)

Swift, a satellite devoted to the study of cosmic gamma-ray bursts (GRBs), is now fully operational and detects about 100 GRBs per year, as the first year of operation demonstrated. Since its launch (20 November 2004), Swift has monitored with the narrow-field X-Ray Telescope (XRT) 75 afterglows (out of 97 GRBs), starting just a few minutes after the GRB onset. Together with the events detected by HETE-II and INTEGRAL, Swift gives us a unique position to unveil the details of these enigmatic events, which likely identify the birth of black holes. GRBs are also useful cosmological tools, and can be used as powerful, distant beacons to trace the history and evolution of the early Universe. All of this can be accomplished by the use of Swift, coupled to large ground-based telescopes. In this article we describe some of the fresh, exciting results obtained in the field.

Zwicky used to say that Nature manifests itself in any form we may think of and has far more ways than we can possibly imagine. Indeed every time we increase the sensitivity of our instruments or develop the technology to open a new window in the electromagnetic spectrum, we discover new phenomena that in most cases were not predicted or even expected.

The Swift mission is no exception, its strength being the mission concept itself based on: multi-wavelength coverage with the on-board instrumentation, fast pointing capabilities of the satellite, tight international collaboration with team members permanently on duty, and worldwide networks with robotic and very large telescopes ready to respond in a matter of minutes. Facilities like the VLT, Keck, Gemini, Subaru, and many others, play a fundamental role with their fast response and high sensitivity. The fundamental discoveries made in the past year were made possible by the excellent level of coordination between Swift team members, ground-based telescopes and the GRB community at large. The key elements in this scientific enterprise, i.e. speed and coordination, were discussed and carefully planned over the years; they are now working very efficiently.

Back in 1963 Hoyle and Fowler pointed out that the energy source of a quasar or AGN could arise from a collapsed object or black hole. A flow chart originally due to Martin Rees illustrates different channels possibly leading to the formation of black holes, on a variety of scale lengths, always with gravity as the main player. We do not know the quantitative aspect of various processes but we are making important theoretical progress in the field. The energy that black holes irradiate can be produced in different ways, for instance via extraction of black hole rotational energy through the Blandford and Znajek mechanism, or via the more generally accepted mechanism involving the release of gravitational energy from matter inflowing through an accretion disc. Both mechanisms can be made to work on a sufficiently short time and with high enough efficiency to power GRBs, provided that nuclear density matter, possibly in the form of a torus, surrounds the innermost regions around the event horizon of the black hole.

The collapse of a massive star towards a black hole occurs in a very short time and releases a very large amount of energy. Woosley, Paczyński and coworkers proposed the collapsar/hypernova model: the fast rotating iron core of a very massive star collapses and forms a rotating black hole surrounded by a very high-density accretion ring. This scenario was illustrated by the simulations of Zhang, Woosley and MacFadyen. Powerful relativistic jets along the polar axis are formed by extracting the potential energy and rotational energy via neutrinos or magnetic fields. Contrary to ordinary core-collapse supernovae (SNe), a collapsar/hypernova is also expected to expel matter at relativistic speed. This model envisages that long GRBs should go off mainly in star forming regions.

The coalescence of two relativistic stars (double neutron star or black hole/neutron star binary mergers) is the end result of 0.1–1 Gyr of orbital decay caused by the emission of gravitational waves. This paroxysmal event should also give rise to a black hole surrounded by a torus of matter at nuclear densities, possibly producing relativistic jets that are less energetic and shorter lived than those of collapsars and originating short GRBs. These merger events should, in general, be associated with galaxies having an older stellar population and take place, in a fraction of the cases, in the outskirts of (or even outside) the galaxy.

These are the two main models invoked to explain the two flavours in which GRBs manifest themselves: long and short. Gathering evidence in favour of this overall scenario is certainly among main results so far obtained by Swift, in conjunction with large ground-based telescopes, the ESO VLT facility in particular, where, thanks to the MISTICI and GRACE collaborations, most of the bursts visible from the southern hemisphere have been monitored. The deep significance of the ongoing research is not only that of putting together a complicated mosaic, but also trying to match at an unprecedented level the observational results with the predictions of the models. This is what Swift can do in conjunction with ground-based telescopes: witnessing the birth of black holes surrounded by very dense matter, and extracting crucial new information from these events.

In the following we will refer in particular to the data obtained with the X-ray telescope onboard Swift and to the fast follow-up observations carried out especially with the ESO VLT. These are indeed the two facilities that allowed us to gather most of the information. Needless to say, none of this would have been possible without the Burst Alert Telescope (BAT) on board Swift, the instrument that detects the bursts. The sequence of events is led by the Swift satellite so that in this paper we will follow the same outline dictated by the Swift observations.

X-ray light curves and optical observations

Thanks to the remarkable theoretical progress achieved in recent years, we now have a reasonably good understanding of the afterglow light curves observed in the soft X-ray band by Swift (Figure 1). Most of them are characterised by a steep early decline, followed by a milder one after a few hundred seconds, which breaks again to a faster decline generally in less than 10 000 seconds. The spectral shape does not change much in time, even in correspondence of the light curve breaks. The first break seems to mark the transition between the GRB tail and the long-lasting afterglow emission, which is continuously energised by the central engine (thus the decay is slow). The end of this energy input is marked by the second break. A further break is often visible due to the collimation of the ejecta. Such a break has been observed in long GRBs, while it has not yet been detected unambiguously in short bursts (a low significance indication has been reported by Fox and co-authors in GRB 050709). A minority of bursts do not display the early steep decline. The afterglow emission is produced by the so-called 'forward shock', produced in the impact between the GRB ejecta and the surrounding medium. There is additional emission from the 'reverse shock', produced inside the shocked ejecta themselves. This emission lasts for a rather short time and is mainly in the optical and infrared bands. However, depending on the distribution of matter in the ejecta, the emission can be long lasting. The phenomenon is quite complex and depends on the regime of synchrotron emission, the hydrodynamics of the jet and the interaction with the surrounding medium (that could be different in the various shocks) and the behaviour of the energy injection during the evolution of the afterglow. This is why observations in the optical and near infrared are very important and their potential is to a large extent still to be exploited. There are still a number of unresolved issues: an especially important one is that in some cases an optical/NIR afterglow is not detected.

The observations of GRB 050721 (Figure 2) provide an excellent example of what is needed. The VLT rapid response mode allowed these early observations to be compared with the XRT light curve from the earliest stages, showing that both the X-ray and the R-filter light curves

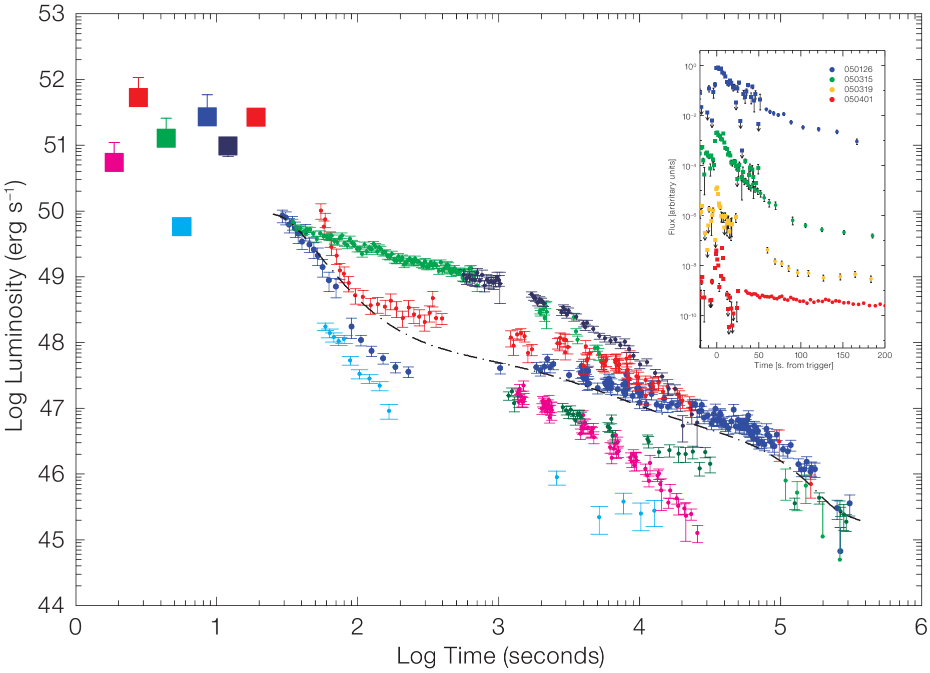


Figure 1: Rest frame 0.2–10 keV light curves of GRB 050126 (light blue), GRB 050315 (blue), GRB 050318 (violet), GRB 050319 (red) GRB 050401 (green), GRB 050408 (dark green), GRB 050505 (dark blue). The dot-dashed line is a mean curve of the type-I (steep, shallow, steep) light curve. The squares on the top left of the figures represent the mean luminosity of the prompt emission detected by BAT and converted to the XRT band pass. The inset shows four representative light curves, combining BAT and XRT data. There is a clear continuity between the two instruments. The light curve of GRB 050401 does not show the steep early decay.

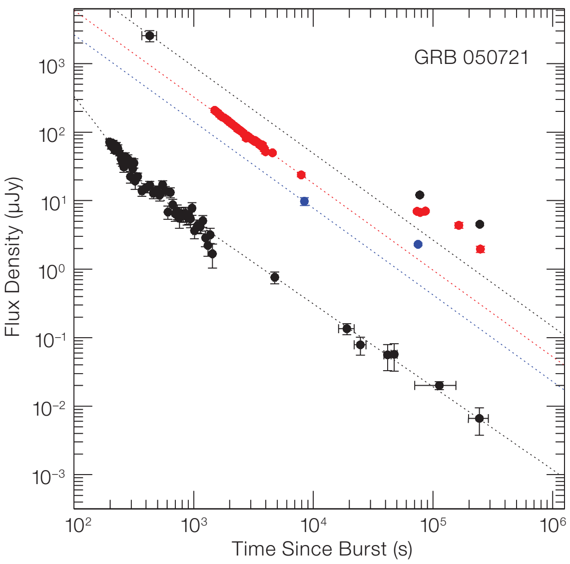
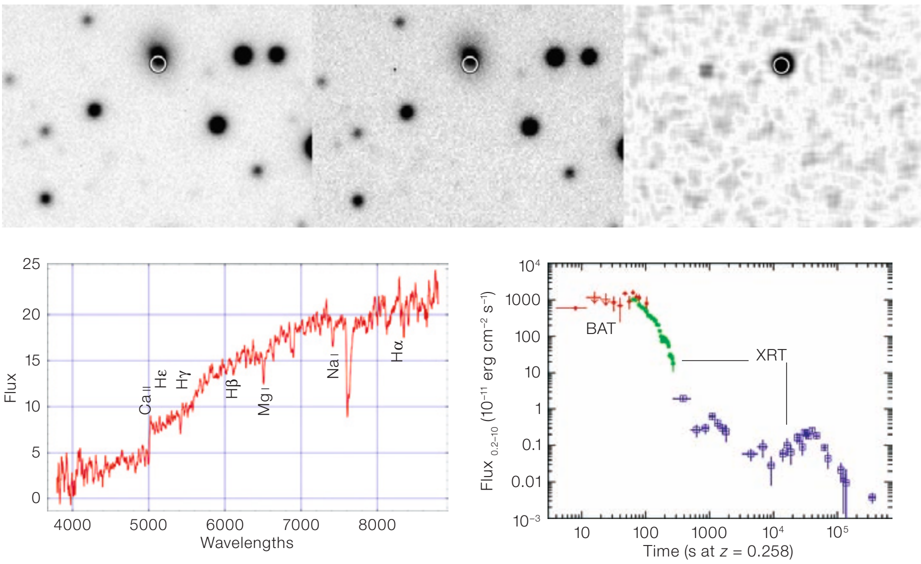


Figure 2: On the bottom of the figure the light curve obtained with the XRT in the 0.5–10 keV band. The black filled circle on the top of the figure represents the first optical observation in the *I*-band obtained by a Japanese robotic telescope. The other black filled circles are the *I*-band observations obtained at ESO. Always at ESO we observed in the R pass-band, red filled circles and in the blue passband, blue filled circles. The optical re-brightening of $\Delta R = 1.8$ magnitudes is not present in the XRT observations at the bottom of the figure.

were decaying at a comparable rate. In this case, both the optical and X-ray emissions likely arise from a single component and it is not yet clear whether there is a reverse shock component. On the contrary, when an early rapid X-ray decay phase (e.g. the case of GRB 050713A) is present, the optical and XRT light curves differ significantly, indicating a different origin of the X-ray emission, which perhaps represents the soft tail of the prompt emission. A good coincidence between the optical and X-ray light curves has been observed also in GRB 050525A and GRB 050801. The VLT rapid response mode is a fundamental tool to build the statistics needed to discrimate amongst different models. In addition, detailed monitoring of the light curve might reveal short-timescale variability that may arise from the injection of energy from a highly variable central engine, the newly born black hole.

Figure 3: **Left top panel:** The image of the GRB 050724 plus the host galaxy obtained on the night of 24 July. **Top centre panel:** The image of the host galaxy plus GRB obtained on 29 July. **Right top panel:** The image obtained subtracting the two previous images (24 July – 29 July) showing the detection of the short GRB. **Bottom left panel:** the VLT FORS spectrum of the host galaxy showing the characteristics of a rather old stellar population. **Bottom right panel:** the XRT light curve showing the presence of flares and the continuity between the BAT and XRT light curves.



Short gamma-ray bursts

The typical duration of a short burst is about 0.2 s. These bursts are spectrally harder than the long ones and comprise about 30 % of the BATSE (25–350 keV) sample, and about 10 % of the Swift sample. The rapid response of the Swift spacecraft yielded the first unambiguous detection of the X-ray emission from a short GRB, GRB 050509, in turn measuring the sky position of the event accurately enough to pinpoint the most likely host galaxy, an elliptical galaxy at $z = 0.22$. Excellent images were obtained with VLT, Subaru, HST, and other telescopes. Two months later HETE-II detected GRB 050709 and ESO telescopes were able to discover the optical counterpart and observe the host galaxy at a redshift of $z = 0.16$. About two weeks later Swift detected and observed GRB 050724 (Figure 3), and a few other short GRBs in the following months. After many years of chasing, the mystery of the counterparts to short GRB was finally solved.

These observations showed that the host galaxies of short GRBs are either of early type, as in the case of GRB 050509B, or harbour a reasonably old stellar population, as in the case of GRB 050709. This is much at variance with respect to long GRBs, which appear to be associated with dwarf galaxies with intense star-forming activity.

The relatively low redshift observed for these objects implies an energy output that is about a factor 100–1000 smaller than that observed for long bursts. For several of the short GRBs with accurate positions detected so far no optical after-glow could be found. In some other cases even the soft X-ray emission was not detected. A continuing programme of fast response observation by ground-based telescopes is essential in order to determine whether short GRBs comprise different subclasses. On the other hand, both long and short bursts are consistent so far with the same general scenario in which the GRB is generated by a newly formed black hole-torus system, resulting however from much different paths in the evolution of massive stars. It should be said that important alternatives exist. In Usov's model, the relativistic flow is mostly Poynting flux and is driven by the magnetic and rotational energies of a rapidly rotating neutron star.

Flares

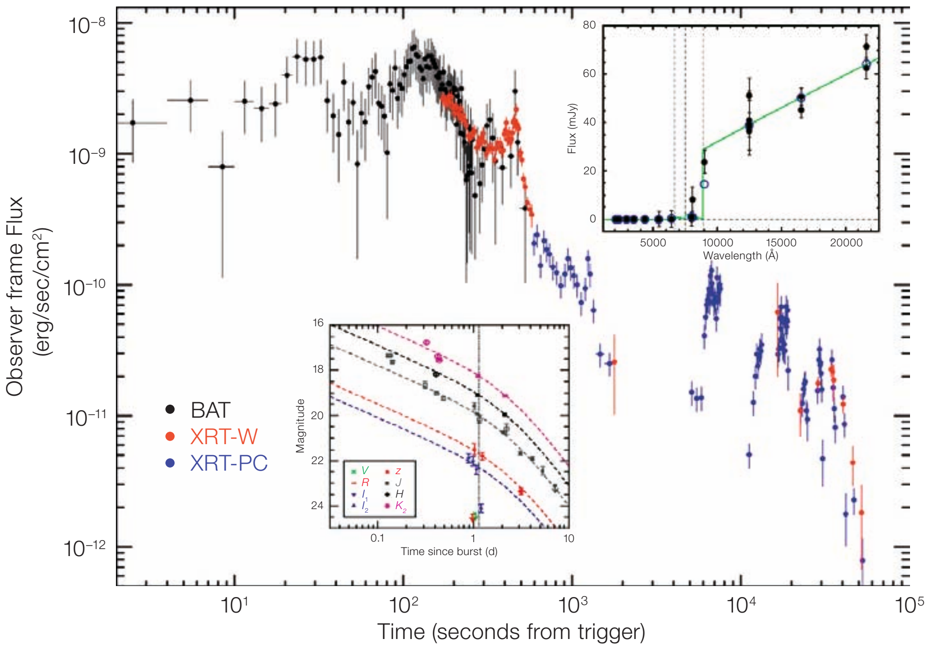
Flares were detected superimposed on the 'basic' X-ray light curves (Figure 1) in about 40 % of the bursts, during both the GRB tail (the steep decay phase) and in the early afterglow, in both GRB flavours (long and short), and at small as well as high redshift (as in GRB 050724, GRB 050730, and GRB 050904; Figure 4). The energy emitted during a flare is sometimes comparable to the energy emitted during the entire X-ray afterglow, as in the case of GRB 050502B. This is a fundamental discovery made by the Swift mission and provides additional clues about the central engine. Flares might well be due to internal shocks resulting from new energy injection into the jet caused by an active central engine (as opposed to internal shock from the catching-up of shells emitted at different speeds).

No very large flare has been observed yet in the optical band; extensive optical coverage of the light curve during the early stages is essential to address this issue.

Gamma-ray bursts and supernovae

The first suggestion of a possible connection between SNe and GRBs dates back to Colgate (1968). This prediction was confirmed in recent years, thanks to intensive optical and near-infrared follow-up observations of GRB afterglows discovered by BeppoSAX. These studies firmly established that long-duration GRBs (or at least a large fraction of them) are connected with the death of massive stars. The most persuasive evidence arises from observations of supernova features in the spectra of a few GRB after-

Figure 4: The BAT + XRT light curve of the long GRB 050904 at $z = 6.3$. The continuity between BAT (after conversion of the emission to the band pass of XRT) and XRT is perfect and the light curve shows the presence of flares. The top-right inset shows the optical observations (mainly from VLT) used to estimate the photometric redshift. The light curve in various optical and near-infrared bands has been plotted in the inset on the bottom of the figure.



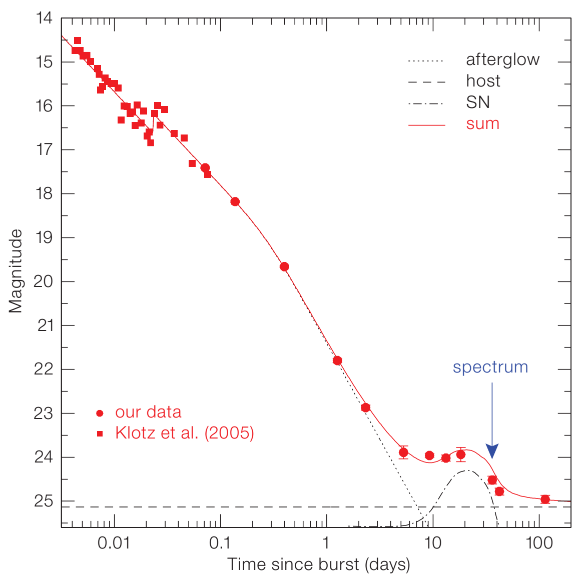


Figure 5: The photometric evolution of the afterglow of GRB 050525A, obtained at early stages with TNG and at later epochs with VLT-UT1 + FORS2, shows a flattening in the light curve starting about five days after the gamma event, followed by a sharp dimming. The magnitude and the duration of the flattening suggest the presence of a SN component (dot-dashed line), which is marginally fainter than SN 1998bw (Della Valle et al. 2006, ApJ, submitted).

glows. In a number of other cases, the evidence for a SN is based on a late time photometric hump emerging out of the decaying optical afterglows. Outstanding examples of this SN/GRB connection include SN 1998bw/GRB 980425, SN 2003dh/GRB 030329, and SN 2003lw/GRB 031203. The average redshift of Swift GRBs is quite large ($<z> \sim 2$), making the search for an associated SN difficult. GRB 050525A at $z = 0.606$ is the first supernova detected in a GRB discovered by Swift. The photometric evolution (Figure 5), obtained at early stages with TNG and NTT, and at later epochs with VLT, allowed us to discover a flattening in the light curve starting about five days after the GRB explosion, followed by a sharp dimming. The magnitude and duration of the flattening suggest the presence of a SN component, marginally fainter than the prototypical SN 1998bw, and characterised by a faster rise to maximum light. An early spectrum obtained by Foley and collaborators with Gemini North and GMOS indicates that GRB 050525A occurred in a star-forming galaxy. A spectrum obtained with VLT UT1 + FORS2, during the flattening, shows strong similarities with the spectrum exhibited by SN 1998bw at about five days after the maximum. Therefore in this case we have also discovered a connection between a SN and a GRB. With a frequency of about $4\ 10^{-6}$ GRB per galaxy per year accounting for a jet angle, $<\theta> \sim 10°$, we have a frequency of $\sim 4\ 10^{-4}$ GRB per galaxy per year $\sim 1/30$ the rate of Ibc supernovae.

While the discovery of a clear SN/GRB connection represented a major step in the study of GRBs, it also posed a number of new questions. Whether the association is restricted to bright SNe, as the cases with spectroscopic confirmation seem to indicate so far, or is open also to fainter type-Ibc SNe, remains to be established through forthcoming observations. Based on a reasonably large sample, we may finally track down the physical mechanism of the association and understand how the explosions evolve in time. There is no indication at all in the short GRBs 050709 and 050724 of the signature of a supernova, although they are quite nearby.

Cosmology and the new frontiers

It is fascinating to consider the possibilities opened in cosmology by GRBs. Indeed, after the detection of GRB 050904 and the measurement of its redshift ($z = 6.3$) by the VLT and the SUBARU telescopes, our wildest hopes became reality. We can now likely trace the star-formation rate and its evolution. Furthermore, since for a few hours after their onset, GRB afterglows are the brightest beacons in the far Universe, they offer a superb opportunity to investigate the environment in which they go off in very young galaxies, determine the properties of the interstellar medium and determine cosmic abundances up to the re-ionisation epoch. The GRACE and MISTICI collaborations achieved milestone discoveries in this field. Here we can only touch upon this fascinating research briefly.

One of the straightforward discoveries of UVES high resolution spectroscopy of GRB afterglows is that the ISM of GRB host galaxies is complex, with many components resolved down to a width of a few tens of km/s, contributing to each main absorption system, and spanning a total velocity range of up to thousands of km/s. The absorption systems can be divided into three broad categories. First, those associated with the GRB surrounding medium; second, those associated with the ISM of the host galaxy along the line of sight, which is far enough so that it is not affected by the GRB emission; last, the intergalactic matter along the line of sight. Strong 'fine structure' lines have been detected in GRB 050922C and in GRB 050730 (previously these were also detected in GRB 020813, GRB 030323 and in GRB 021004). The presence of strong fine structure lines of several ions, C II*, Si II*, O I*, O I**, Fe II*, is at odds with QSO absorption systems, where, despite more than 30 years of investigation, only sparse detections of fine structure lines are available. Strong fine structure lines in GRB sightlines are most likely due to the dense environment of the star-forming regions hosting GRBs. Furthermore, GRB afterglows provide a new, independent tool to study the ISM of high-redshift galaxies. Figure 6 illustrates the UVES spectrum of GRB050922C, but a very similar situation is also present in the spectrum of GRB050730 About six absorption systems of relatively high ionisation are detected, likely associated with the GRB surrounding medium. On the other hand, we also observe a Si II λ1304 component (marked HG in Figure 6) that is not present in either the Si IV or Si II* transitions. This is an indication that the gas of this component is much less dense and ionised than that of the other six components, suggesting that this component is not part of the cloud surrounding the GRB but rather belongs to the ISM of the host galaxy.

Finally, GRB afterglows can be used to probe the Lyα forest and the high-redshift intergalactic medium (Figure 7). An accurate determination of the number of absorption systems per unit redshift dn/dz at high redshift has strong implications for any investigation of the reionisation epoch, since the optical depth due to Lyα line blanketing is evaluated by extrapolating the Lyα dn/dz measured at lower redshifts. Using GRBs as remote beacons opens up the opportunity of highlighting any deviation from what is already known from quasar forests. For example the so-called 'proximity effect' should be much reduced for GRB. By using GRBs as very remote beacons, carbon, silicon, oxygen and iron ions, as well as Lyα, can be studied with UVES up to $z \sim 6$–6.5 and with ISAAC up to the reionisation epoch, thus yielding the first metal abundance measurements at epochs when the Universe was less than 1 Gyr old.

Conclusions

It is by now evident that GRBs provide us with a new fascinating perspective in relativistic astrophysics and Cosmology. The central engine of GRBs must be capable of producing, in a matter of seconds, energies of the order 10^{49}–10^{52} erg, which result in the acceleration of a planetary-mass jet of plasma to ultrarelativistic speed. The energy and duration of the prompt emission and the characteristics of the parent galaxies, including their locations inside them, suggest that both GRB types, long and short, may well end up in the same configuration, consisting a of newborn black hole surrounded by an ultradense torus. However the two GRB types would be the final outcome of two extremely different evolutionary paths: the long bursts may arise in the collapse of the iron nucleus of a very massive star, while the short bursts might originate from the merging process of a relativistic binary. GRB afterglows can be used to probe the IGM during the reionisation epoch, through the detection of metal systems associated with early starburst winds. High-resolution UVES observations are already giving us precious information on the kinematics, ionisation and metallicity of the interstellar matter of GRB host galaxies up to a redshift of $z \sim 4$. Further optical and near-infrared spectroscopy will allow us to extend further the redshift range, possibly up to the reionisation epoch. These were amongst the main motivations for building the REM telescope, a robotic, fast-slewing facility capable of observing the early optical and near-infrared GRB afterglows. However, Swift has shown that most GRB counterparts are fainter than expected in the optical and NIR, so that we must work even more with medium and very large telescopes.

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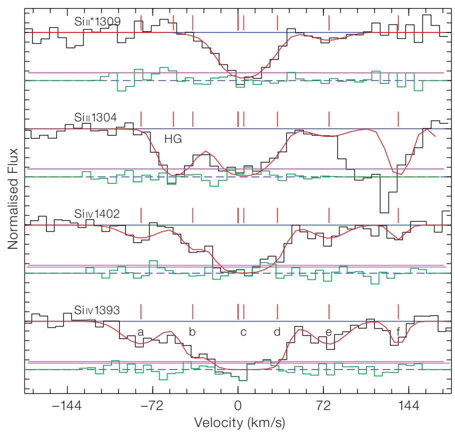

Figure 6: The UVES spectrum of GRB 050922C around the the Si IV λ1393, Si IV λ1402, Si II λ1304 and Si II* λ1309 lines. The zero of the velocity scale refers to the redshift of the host galaxy, $z = 2.199$. Six components, labelled from 'a' to 'f', are identified for the Si IV λ1393 and Si IV λ1402 lines, spanning a velocity range from −75 to +140 km/s. Each component has a width from 10 to 25 km/s. The main component 'c' has nearly zero velocity shift.

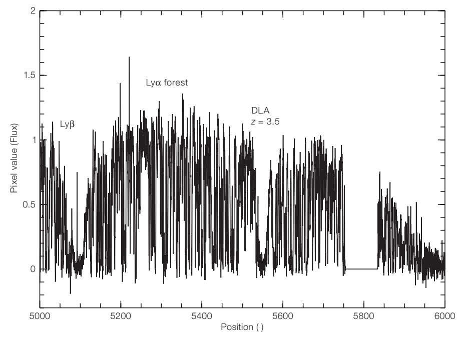

Figure 7: UVES spectrum of the Lyα forest of GRB 050730. Note the strong Lyα absorption at the redshift of the GRB host galaxy (log N_H in the range 21.2–22.2). Taken at face value the [C/H], [O/H], [S/H] and [Si/H] ratios imply a metal abundance between 1/10 and 1/100 of the solar value.