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Gamma Ray Bursts : Probing Burst Environments in High Redshift Galaxies

by

Paul Anthony Ward

A thesis submitted to
the University of Dublin
for the degree of

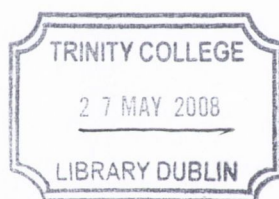
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Thesis
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Declaration

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Summary

First discovered in the late 1960s, Gamma Ray Bursts have remained something of a cosmic mystery for almost four decades. It has only been quite recently that the nature of these phenomena is beginning to be understood. It was not until the late 1990s that GRBs were confirmed to occur at cosmological distances. This makes GRBs the most energetic explosion known in the Universe, thought to arise from the cataclysmic core collapse of a massive star or through the interaction of two compact objects, such as the merger of two neutron stars. Not only do GRBs themselves pose an interesting astrophysical problem, but they offer a superb opportunity to act as bright beacons, illuminating the Universe between them and the observer.

In this thesis I present the work I have undertaken since September 2003 in GRB research. The work covers a broad range of observationally driven projects, with the largest emphasis being on high resolution spectroscopy of GRB environments.

One of the keys to obtaining observations of GRBs is speed. During the course of my thesis work, I have worked extensively with the Robotic Eye Mount telescope (REM), situated at La Silla, Chile. This telescope was purpose built to observe GRBs, and is capable of beginning observations tens of seconds after the first alert. Such prompt observations allow not only for detailed photometric observations of the early afterglow, but can also give a greater accuracy for the position of the burst, thus alerting larger ground based telescopes, which can then begin follow-up observations. One of the main aims of the REM project was to detect the early afterglow of GRBs. To date this has been achieved with two bursts, GRB060418 and GRB060607, for which detailed light curves were obtained. On analysing these, peaks were found in both the afterglows, occurring before the GRB began a power law decay. The initial Lorentz factor, Γ_0 , found for both bursts was ~ 400 . My main involvement with REM was as duty scientist. As duty scientist (DS) for the telescope, my responsibilities included managing the observation schedule, monitoring the performance of the telescope and notifying relevant persons in the case of a system error. In the case of a GRB, the DS is required to react immediately, ensuring the telescoping is operating properly and beginning observations. This work is presented in Chapter 3 of this thesis.

Chapters 4, 5 and 6 of this thesis focus on my involvement with a collaboration, the principal investigator of which is Fabrizio Fiore, to obtain high resolution spectra of GRB environments, in particular the study of their host environments through UVES (Ultra-violet Visible Echelle Spectrograph) observations. This work not only involves the reduction of data and identification of absorption features, but also the disentangling and interpretation of the various spectral compo-

nents. The data reduction is done using the UVES Pipeline, part of the MIDAS software package, and the analysis of the spectra is done using FITLYMAN, again part of MIDAS. To date I have worked with UVES data of three GRBS, GRB021004 (Chapter 4), GRB 050922C (Chapter 5) and GRB060607A (Chapter 6). The results of the analysis on GRB021004 showed for the first time the highly complex nature of the GRB circumburst environment, with multiple spectral components spanning a velocity range of ~ 3000 km / s. The results of GRB050922C furthered this with the identification of multiple fine structure transitions, which allowed for a constraint on the ionisation mechanisms involved. Also for the first time we could identify which components were associated with the medium surrounding the burst and those associated with the host galaxy. In addition, through the detection of MgI, we can determine which components are closest to the GRB site. Finally, GRB060607 showed once again the unpredictable nature of GRBs, as the spectra of the host galaxy showed little detail, while the intervening absorption systems (probably due to Galaxies along the line of sight) showed far more detail. One possible reason for the uncomplicated nature of the absorption systems of the host is the ejection of the progenitor from the rich starforming region in which it was born.

Finally in Chapter 7 I explore the idea of Supernova (SN) contributions to GRB light curves, which manifest as late time rebrightenings. By superimposing template SN lights curve over these bumps we can determine which SN types may be associated with the GRB. In general these bumps are best fitted by Hypernovae, a type of SN type Ic core collapse SN which has lost its hydrogen envelope. But in some cases other SN types are possible, such as SN Ia. This is possibly due to a high amount of nickel being produced in the SN explosion, giving an extremely luminous light curve similar to a SN Ia. I have developed a method to measure the K-correction for various SN types, in order to give a more correct correlation between the peak of the SN light curve and the bump which occurs in the GRB light curve. K-correction is a purely observational effect, due to the measurement of an object through a fixed bandpass. The effective rest frame wavelengths the band will cover will differ depending on the redshift of the object.

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Over the past four years I've learned a great deal about astronomy research, but also (and maybe more importantly) I've learned it's impossible to work well as a scientist, and as a person, without being surrounded by really great people, be it friends or colleagues. I'm lucky to have been surrounded by some of the best; here's some of them....

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REM observations of GRB 060418 and GRB 060607A: the onset of the afterglow and the initial fireball Lorentz factor determination, *E. Molinari, et al., 2007, A&A, 469L, 13M*

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UVES/VLT High Resolution Spectroscopy of GRB050922C, *S. Piranomonte, P. Ward, F. Fiore, et al.*

UVES/VLT High Resolution Spectroscopy of GRB060607, *P. Ward et al.*

Cosmological K-corrections for Supernovae, *P. Ward et al.*

Supernova Contributions to GRB Lightcurves, *P. Ward, M.C.A. Rebelo, et al.*

¹There are a number of publications for which I am co-author where the results are not presented in this thesis. In these cases the work was carried out as part of a larger collaboration and my input into these publications was nominal.

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1

Introduction

1.1 Gamma Ray Bursts - A Mystery Being Solved

1.1.1 Discovery

For a few hours after their onset, Gamma Ray Bursts (GRBs) are the brightest beacons in the far Universe. GRBs were first encountered, by accident, in 1967. However, it has not been until recently that the physics of these phenomena is being understood. Initially GRBs were the cause of much debate, manifesting as seemingly random bursts of gamma radiation; it has only been ten years since their cosmological origin was confirmed with the first detection of an afterglow.

VELA, an American cold war satellite was built to detect the gamma-radiation pulses emitted by possible secret nuclear weapons tests in space by the USSR after the signing of the Nuclear Test Ban Treaty in 1963. VELA did not detect any traces of gamma-radiation due to nuclear testing. However the satellites did detect unusual flashes of γ radiation looking nothing like a nuclear weapons signature, but coming rather from seemingly random directions in deep space (see figure 1-1). This discovery was not known to the scientific community until the early 70's. The results

were not published, and therefore not seen by the worldwide astronomy community, until 1973 (Klebesadel et al. 1973).

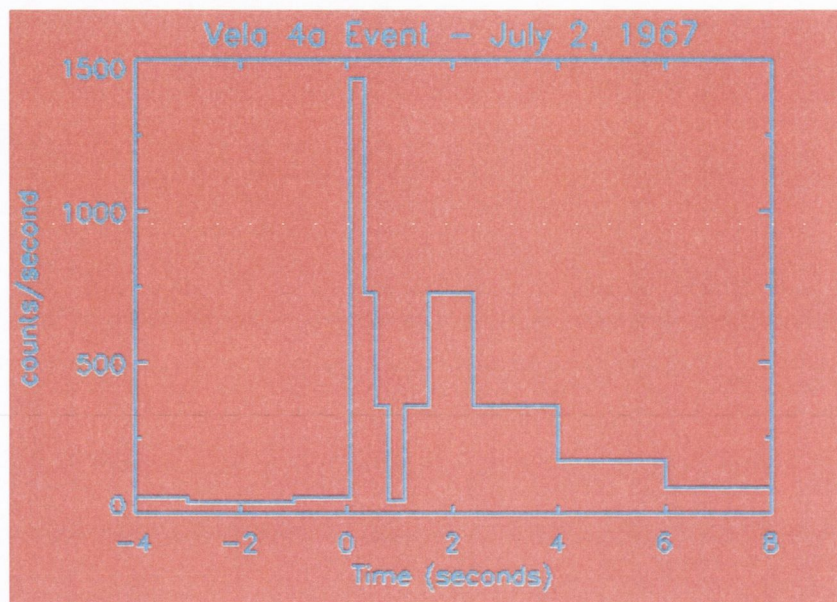


Figure 1-1: *The first observed Gamma Ray Burst by Vela (Klebesadel et al. 1973).*

The initial discovery of GRBs caused quite a stir and with it came a lot of unanswered questions. Most importantly: what was causing them and were they local to our galaxy or cosmological in nature? As GRBs were such bright sources, if they were indeed cosmological then the energy released in the explosion would have to be huge.

As a result several space based missions were planned to shed some light on these phenomenon. The most successful of these earlier missions was the BATSE (Burst and Transient Source Explorer) detector aboard the Compton Gamma Ray Observatory.

1.1.2 BATSE

With BATSE came a number of revolutionary discoveries about GRBs it was the first instrument to shed light on the distance problem. BATSE detected 2704 bursts from 1991-2000. The first major discovery by this instrument was that gamma-ray bursts are isotropic (see figure 1-2) i.e. they appear to occur in every direction. This was certainly a good indication that GRBs were cosmological as there was no preferred origin of the BATSE sources along the galactic plane.

The next big discovery by BATSE was that GRBs seemed to have a bimodal distribution i.e. they fell into two distinct categories, short-duration, hard-spectrum bursts (“short burst”) and long-duration, soft-spectrum bursts (“long bursts”) (Kouveliotou et al. 1993). Short bursts are typically

2704 BATSE Gamma-Ray Bursts

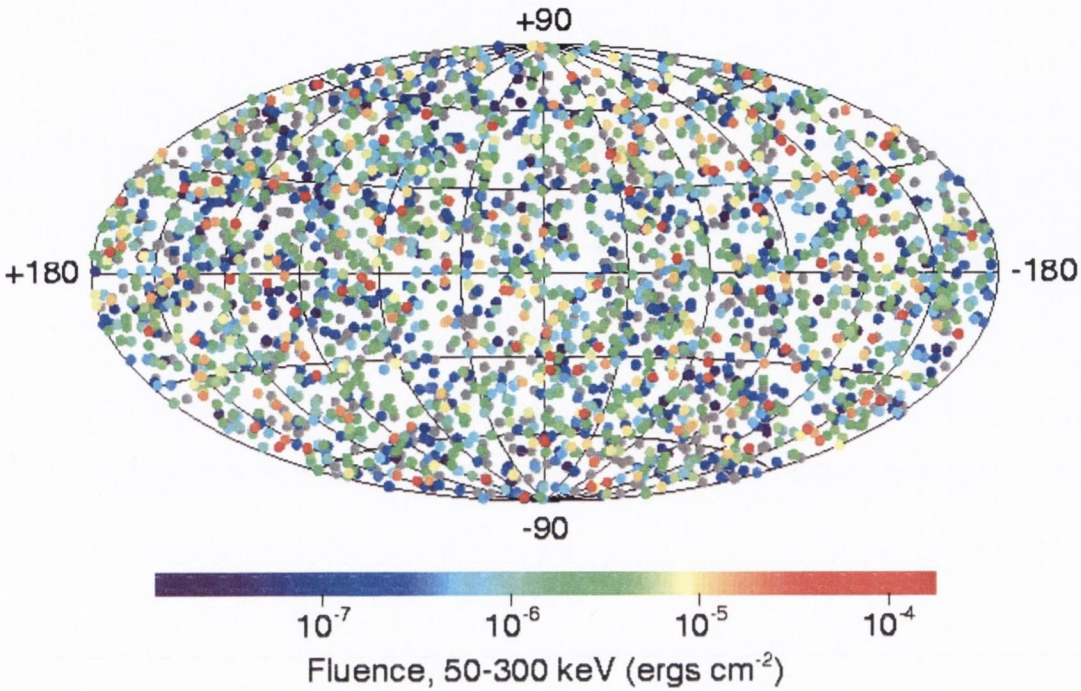


Figure 1-2: *Batse detected 2704 GRBs showing they are isotropic in the sky (<http://coss.c.gsfc.nasa.gov/docs/cgro/coss/batse/>).*

less than two seconds in duration and are dominated by higher-energy photons (hard); long bursts are typically more than two seconds in duration and dominated by lower-energy photons (soft). The ratio of the energy output measured by two BATSE channels covering different energy bands (Meegan et al. 1992)(see figure 1-3) gave this hardness ratio. The separation is not absolute and the populations do overlap observationally, but the distinction suggested at least two different classes of progenitors.

The only way to prove GRBs were originating in a distant galaxy was by finding fainter, fading emission, an “afterglow” (Fishman et al. 1995), at longer wavelengths following the initial “prompt emission” burst. However, because of the poor spacial resolution (on the order of tens of arc mins) of the early gamma-ray detectors, it was impossible to accurately determine the position of the GRB before it ceased.

1.1.3 BeppoSAX and the afterglow era

The first afterglow was not discovered until 1997, when the Dutch/Italian satellite BeppoSAX detected GRB970228. The burst was localised within a few hours, with an error box of a few arcmin-

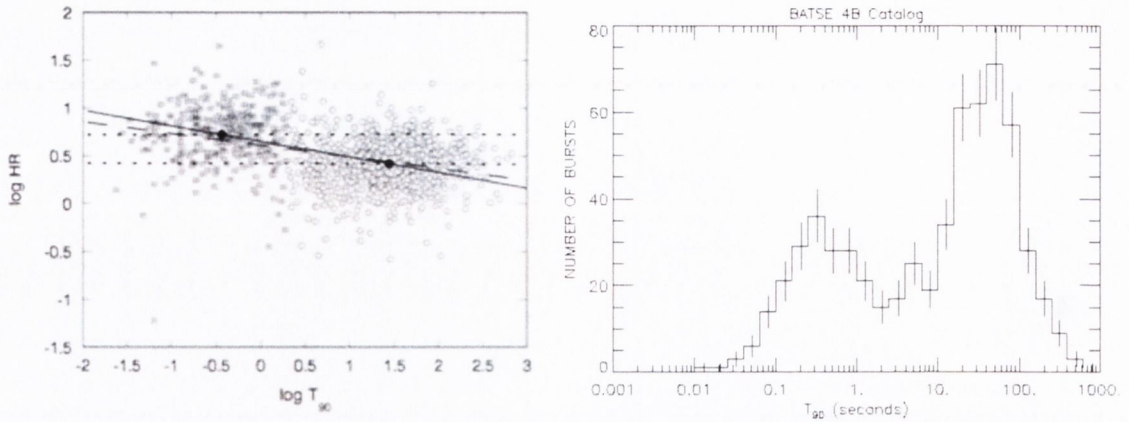


Figure 1-3: *Hardness ratios(left) and the number of bursts observed, by BATSE, with duration T_{90} (right) shows two distinct categories of GRBs; short-hard bursts and long-soft bursts.*

utes. BeppoSAX pointed its X-ray camera at the direction from which the burst had originated, and detected fading X-ray emission (see figure 1-4). Additional follow-up from ground-based telescopes identified a fading optical counterpart as well (van Paradijs et al. 1997). With the position of this event now known precisely, once the GRB faded away, deep imaging was able to identify a faint, very distant host galaxy at the GRB location. Not long after this another GRB, GRB970508 was localised. Optical spectroscopy of the host galaxy found the redshift of this burst to be $z=0.835$. The cosmological nature of GRBs was well and truly established. This discovery revolutionized the study of GRBs, and opened up the field to a whole host of observational and theoretical programs (Frontrera et al. 1998).

Since the GRB-dedicated Swift satellite (Gehrels et al. 2004), with the ability to slew on-board X-ray and optical telescopes to the direction of a new burst in under one minute, was launched in 2004, GRB research has undergone another revolution. Since Swift, observational data has increased substantially to a point where realistic models of progenitors are within reach. With Swift has come the advent of early time observations of GRB, with localisations of under a minute, being relayed to larger ground based telescopes to begin followup observations.

1.2 Short vs. Long Bursts

First suggested by BATSE observations, it is now widely accepted that there are at least two classes of GRB progenitors. To date this sub-classification has been limited to short and long burst. GRBs (the prompt emission) themselves show an extraordinary degree of diversity in their properties, lasting anywhere from a fraction of a second to many minutes in duration. Most studies of GRB

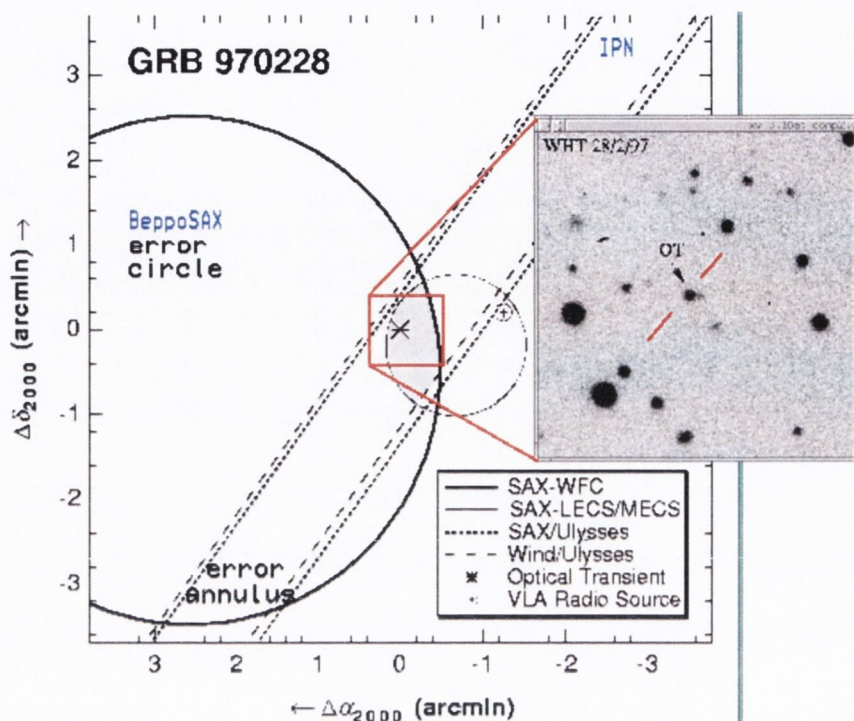


Figure 1-4: The discovery of the first afterglow of GRB970228. The X-ray transient was discovered within the BeppoSAX error circle.

afterglows have been limited to long bursts as there is a longer period in which to localise the burst and identify the host galaxy.

The mechanism responsible for both classes are thought to be quite different. The progenitors of long GRBs are believed to be massive, low-metallicity stars exploding due to the collapse of their cores (MacFadyen et al. 2001), while the progenitors of short GRBs, though still unknown, are thought to be as a result of mergers of neutron stars (Blinnikov et al. 1984).

1.2.1 Long Bursts - Collapsar Model

The last ten years have seen large advances in theories and observations of long GRBs. It is now almost widely agreed that this class of GRB is the result of the cataclysmic death of a massive star (probably at least 40 Solar masses on the main sequence). The best model to support this theory is known as the collapsar model.

Theoretical and computational modelling have shown scenarios whereby the core of massive star collapse can reproduce the observed results (MacFadyen et al. 2001). Very massive stars are able to fuse material in their centers all the way to iron, at which point a star cannot continue to

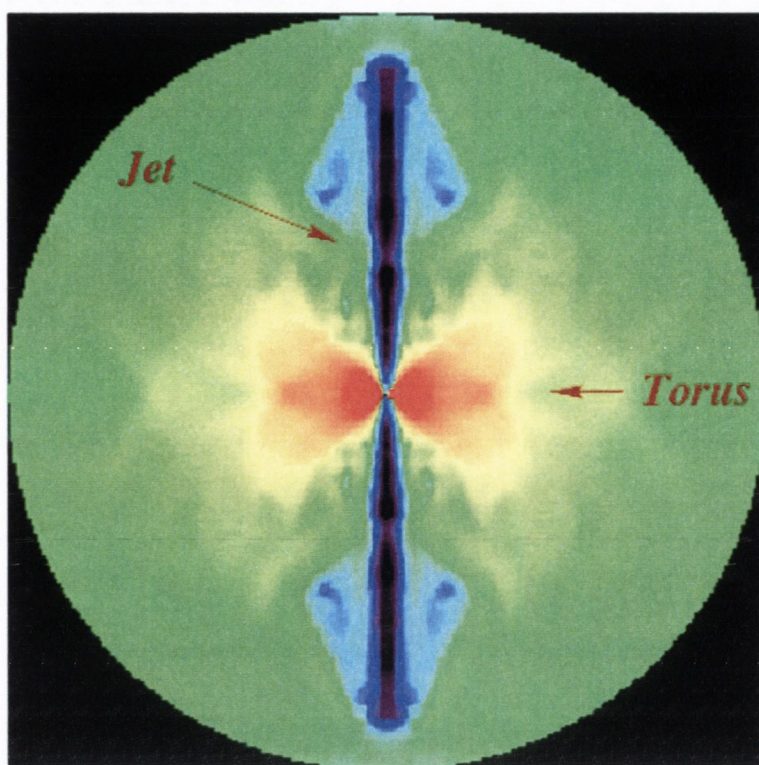


Figure 1-5: *Illustration of the Collapsar model. The core collapses creating a torus of accreting matter from which the jets are produced (MacFadyen et al. 1999).*

generate energy by fusion and immediately collapses, in this case, to a black hole. This scenario is similar to certain types of supernova explosions called core collapse supernovae.

This scenario involves the influx of matter from inside the rapidly rotating star towards the core onto an accretion disc. The infall of this material into the black hole drives out a pair of jets, to conserve momentum, along the rotation axis towards the poles of the star at velocities approaching the speed of light, creating a relativistic shock wave at the front (see figure 1-5) (Blandford & McKee 1976).

The model also requires an evolved star which has lost its diffuse hydrogen envelope at some point prior to the collapse of the core. If the star has not lost its hydrogen envelope the jets will not be able to escape the surface of the star, as too much baryonic matter will be swept up. It is also required that the star have low metallicity, otherwise too much angular momentum would be lost driving the stellar wind. By the time the jet reaches the surface of the star it may be traveling with a Lorentz factor of 100 or higher (that is, a velocity of 0.9999 times the speed of light). Recent observational evidence has shown this may even be higher (see Chapter 3).

When the jet reaches the surface of the collapsing star, internal shocks within the relativistic jet convert most of the energy of the jet into gamma rays; the external shock sweeping up the external medium creates the afterglow (see section 1.3 for an expanded explanation of the emission processes).

There is growing observational evidence for this scenario. Observations of GRB host galaxies have shown that they occur in star-forming regions, such as in irregular galaxies and in the spiral arms of spiral galaxies (Bloom et al. 2002). Massive stars capable of creating a GRB occur exclusively in regions of galaxies undergoing strong formation.

Second, there are now several observed cases where a supernova has immediately followed a GRB. While most GRBs occur too far away for current instruments to have any chance of detecting the relatively faint emission from a supernova at that distance, for lower-redshift systems there are several well-documented cases where a GRB was followed within a few days by the appearance of a supernova (GRB060218 (Sollerman et al. 2006), GRB030329 (Hjorth et al. 2003; Stanek et al. 2003) and GRB980425 (Galama et al. 1998)).

All such supernovae that have been successfully classified have been of type Ib/c i.e. due to core collapse but lack hydrogen absorption lines, consistent with the theoretical prediction of association with stars that have lost their hydrogen envelope. Chapter 8 deals further with the association between GRBs and SNa_e.

1.2.2 Short Bursts

Until the GRB-dedicated Swift satellite only a handful of these events had been localized to a definite galactic host; all of which were at low redshift (Prochaska et al. 2006). Now there is a larger number of short GRBs for which hosts have been identified, not all of which are at low redshift (Berger et al. 2007). Those that have been localized appear to show significant differences from the long-burst population. While one has been associated with star-forming regions there are others which seem to be occurring in outer regions of galaxies, perhaps in galactic halos and in regions of galaxies where there is little or no star formation.

Several scenarios have been put forward to describe the mechanism by which short bursts are created. The generally preferred model is the merger of two compact objects as a result of gravitational collapse (see figure 1-6) i.e. two neutron stars (Blinnikov et al. 1984), or a neutron star and a black hole (Lattimer & Schramm 1976). The process evolves whereby the two companions gradually lose energy due to gravitational radiation as their orbital stability degenerates. Eventually

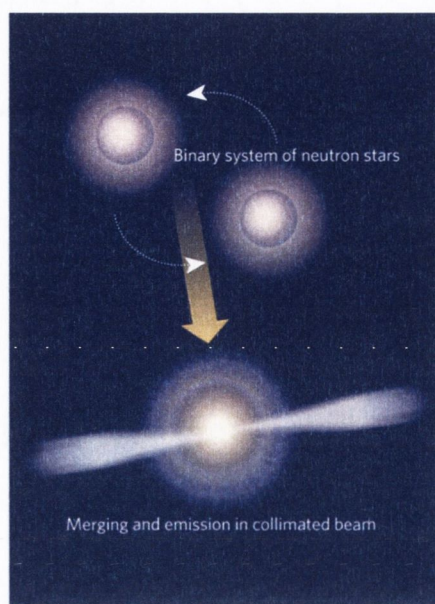


Figure 1-6: *Illustration of two compact objects (NS-NS) merging to form a short GRB. Piro et al. 2005*

the two coalesce and tidal forces rip the neutron star (or stars) apart and an immense amount of energy is liberated before the matter plunges into a single black hole. This process is believed to occur in a matter of seconds, fitting quite well with what is observed for short bursts.

Another possible model to explain short bursts is a highly magnetised neutron star known as a “magnetar”, which are capable of producing brief but enormous outbursts of high-energy photons. One such event in our galaxy, which occurred in 2004, was strong enough to disrupt the Earth’s ionosphere (Hurley et al. 2005).

1.3 GRB Energetics

The most popular model for the emission of radiation in a GRB involves shocks in the expanding relativistic shells of matter from a newly forming black hole after the death of a star. The GRB and afterglows are produced by internal (collisions within the shells) and external shocks (interaction with circumburst medium) respectively (Rees and Meszaros 1992; Rees and Meszaros 1994; Sari and Piran 1997) (see figure 1-7).

GRB FIREBALL MODEL

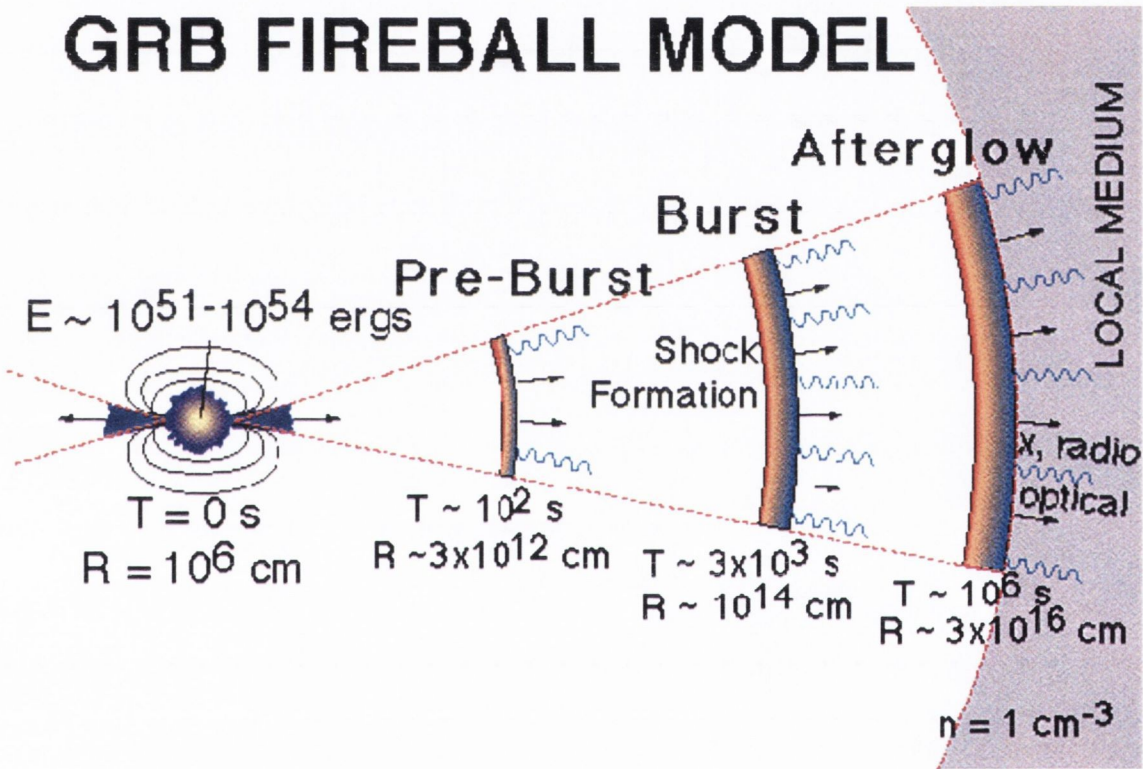


Figure 1-7: The “fireball model” is currently the best supported model to explain the prompt emission and subsequent afterglow. Taken from <http://www.swift.ac.uk/grb.shtml>

1.3.1 Prompt Emission - Internal Shocks

The prompt emission of the GRB lasts typically from tens to thousands of seconds, showing rapid variability on scales of ms (see figure 1-8). This rapid variability was initially cause for much debate due to the fact that variability on such short timescales must come from a very small region, or else the time delay due to the finite speed of light would "smear" the emission out in time, wiping out any short-timescale behavior. This is commonly known as the "the compactness problem". Assuming that the initial energy is released in a volume $R < c\delta t$, the resulting size of the emitting region is too small to be a source capable of emitting enough energy. However if we take into account the relativistic motion, the compactness problem becomes $R < c\Gamma^2\delta t$, where Γ is the Lorentz factor of the fireball.

Another problem imposed by the variability is the relative scale of the various components compared to the length of the total burst. Often this variability timescale is far shorter than the total burst length. In bursts as long as 100 seconds, the majority of the energy can be released in short episodes less than 1 second long. If the GRB were due to matter moving towards us, the central engine would have to be changing in activity on these time-scales to release its energy in such brief intervals (Rees & Meszaros 1994).

However, if we consider that the emission is due to internal shocks within the jet itself, whereby multiple shells moving at different velocities collide, the collision of two thin shells flash-heats the matter, converting enormous amounts of kinetic energy into radiation.

There is currently no theory that has successfully described the spectrum of all gamma-ray bursts. However, the so-called Band function has been fairly successful at fitting, empirically, the spectra of most gamma-ray bursts (see Chapter 2, section 2.5.1 for more details).

The most commonly used measurement of the duration of GRBs is T_{90} , which is defined as the time interval over which 90% of the total background-subtracted counts are observed, with the interval starting when 5% of the total counts have been observed.

1.3.2 The Afterglow - External Shocks

While the GRB prompt emission is thought to arise from internal shocks arising from collisions within the outflow, the longer-lasting afterglow (Mezsaros & Rees 1997) is thought to arise from external shocks (Rees & Mezsaros) as the outflow sweeps up the interstellar medium surrounding the burst.

Once the central engine has ceased activity, the various shells will eventually coalesce into a

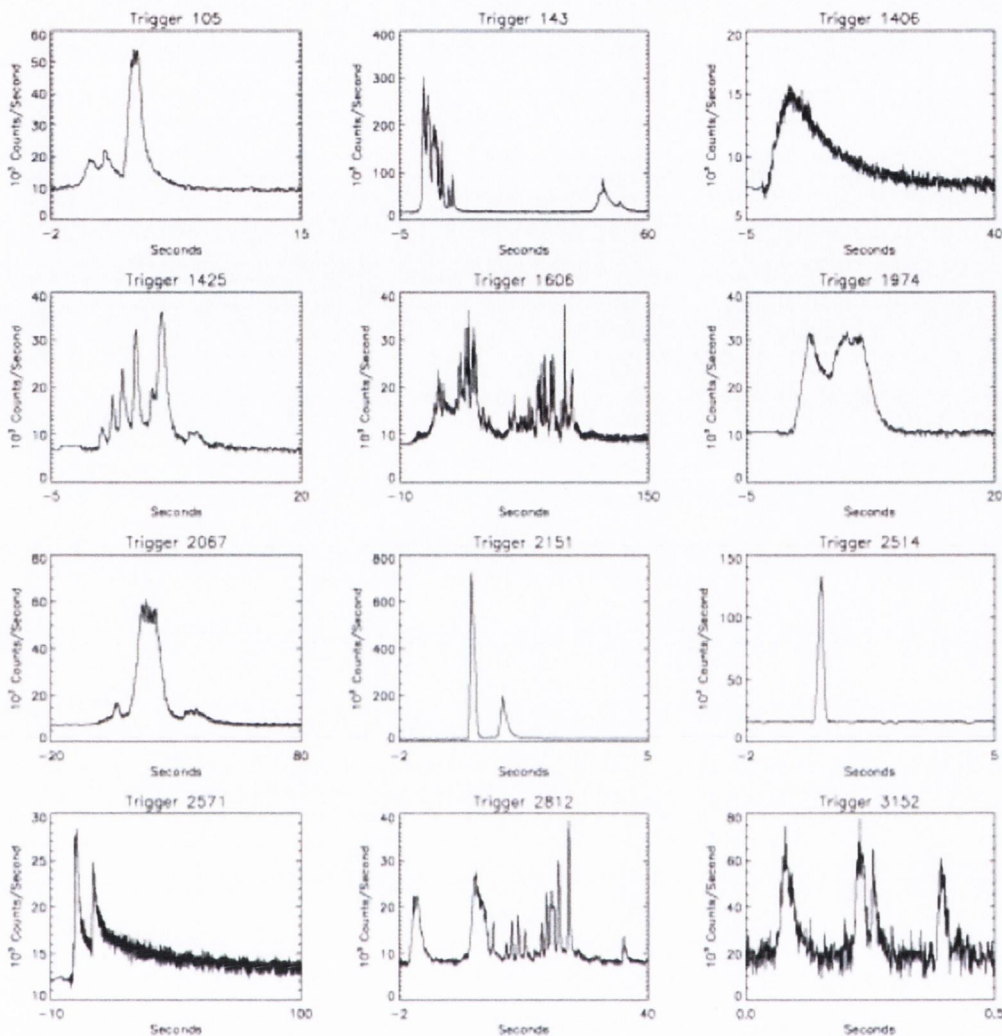


Figure 1-8: *The initial prompt emission shows strong variation on short timescales (from BATSE). Each GRB is unique.*

single shell traveling outward into the interstellar medium. At this stage the outflow is still moving at relativistic speeds and at the front is a shock wave, the so called “external shock”. As the interstellar matter moves across the shock, it is immediately heated to extreme temperatures. These relativistic particles moving within a magnetic field radiate their energy via synchrotron radiation (Sari, Piran & Narayan 1998).

In general, the GRB spectrum assumes the form of a power-law with three break points (and therefore four different power-law segments). The lowest break point, ν_a , corresponds to the frequency below which the GRB is opaque to radiation and so the spectrum attains the form of the Rayleigh-Jeans tail of blackbody radiation. The two other break points, ν_m and ν_c , are related to the minimum energy acquired by an electron after it crosses the shock wave and the time it takes an

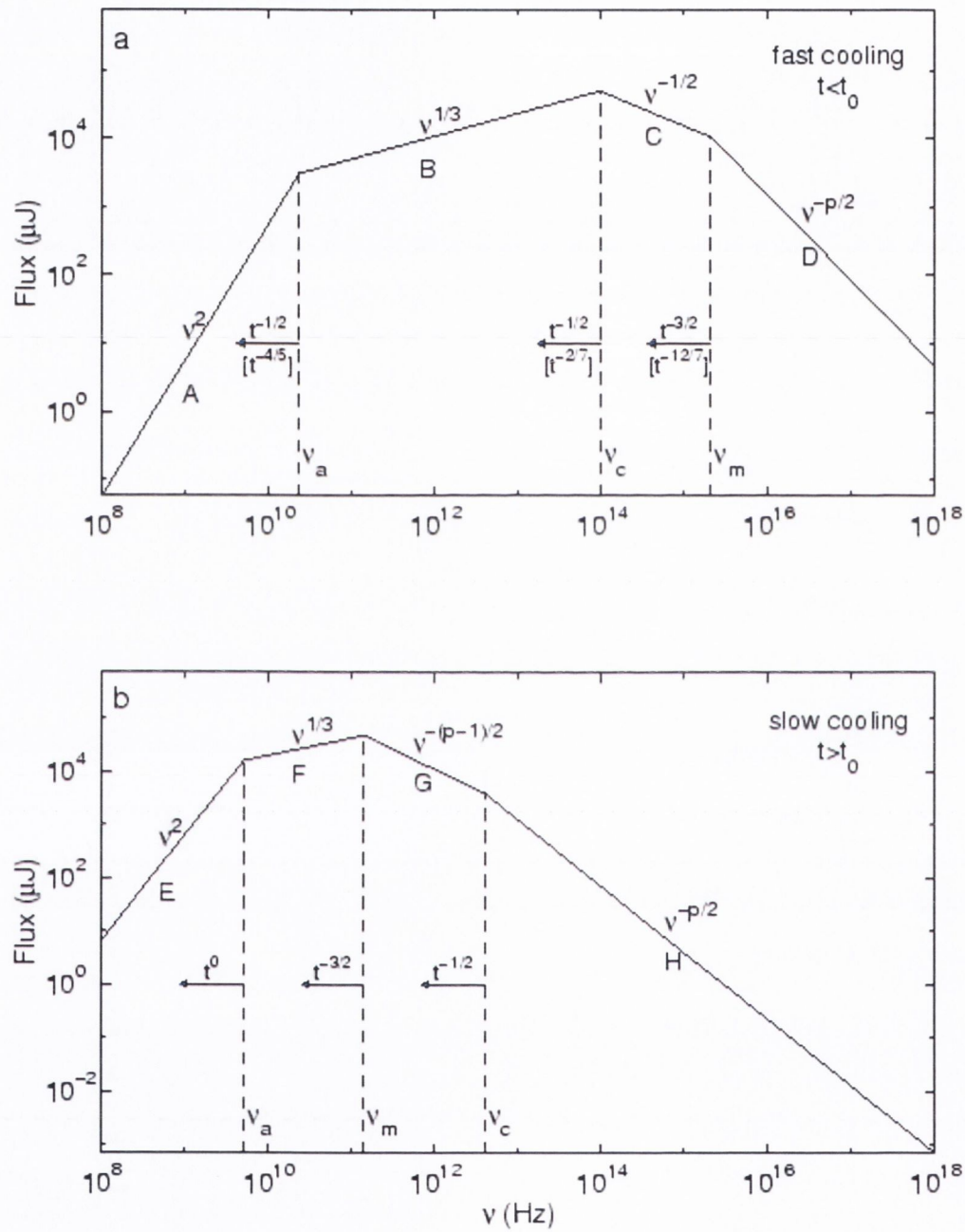


Figure 1-9: Predicted synchrotron emission spectra of the afterglow for fast cooling (top) and slow cooling(bottom). From Sari, Piran & Narayan (1998).

electron to radiate most of its energy, respectively. Depending on which of these two frequencies is higher, two different regimes are possible:

Fast cooling ($\nu_m > \nu_c$) - Shortly after the GRB, the shock wave imparts immense energy to the electrons and the minimum electron Lorentz factor is very high. In this case, the spectrum looks like figure 1-9 (top).

Slow cooling ($\nu_m < \nu_c$) - Later after the GRB, the shock wave has slowed down and the minimum electron Lorentz factor is much lower. In this case, the spectrum looks like figure 1-9 (bottom).

1.3.3 Reverse shocks and the optical flash

There can be “reverse shocks”, which propagate back into the shocked matter once it begins to encounter the interstellar medium (Sari & Piran 1999). The twice-shocked material can produce a bright optical/UV flash, which has been seen in a few GRBs (Akerlof et al. 1999), though it appears not to be a common phenomenon.

1.3.4 Refreshed shocks and late-time flares

There can be “refreshed” shocks if the central engine continues to release fast-moving matter in small amounts even out to late times; these new shocks will catch up with the external shock to produce something like a late-time internal shock. This explanation has been invoked to explain the frequent flares seen in X-rays and at other wavelengths in many bursts, though some theorists are uncomfortable with the apparent demand that the progenitor continues to remain active for very long.

1.3.5 Beaming

In recent years there has been both observational and theoretical evidence to suggest that GRB emission is released as jets as opposed to spherical shells (Rhoads 1997; Sari, Piran & Halpern 1999). This finding has major implications on GRB energetics and models for progenitors. In the next Chapter I will review this topic in more detail, outlining some potential implications and applications of this process.

1.4 GRBs as probes of the high redshift universe

The main purpose of this thesis is to use GRBs as probes of the high redshift universe and, by utilising spectroscopic and photometric observations, gain a better understanding of the progenitor and medium surrounding the GRB. The structure of the thesis is outlined as follows.

- **CHAPTER 2: Review of GRB distance determinations, estimations and applications**

Here we review the methods by which distances to GRBs were estimated and determined both prior to the discovery of the afterglow and in the post afterglow era. Further to this some of the observational evidence for jets is reviewed, with some implications for GRB energetics. Finally we explore the possibility of using GRBs as cosmological tools and some recent work on developing distance estimators based on observations.

- **CHAPTER 3: The REM Telescope**

One major aspect of successful GRB research is the speed at which observations can be performed. REM is a purpose built robotic telescope designed to observe the early time behaviour of the light curve. Over the course of the last four years I have been involved with many aspects of this telescope. In this Chapter I will explain these involvements, and review some of the results REM has obtained since the beginning of its operations.

- **CHAPTER 4/5/6: High Resolution Spectroscopy of GRB Environments**

In the following three Chapter I will describe observations made of three GRBs with the UVES instrument, GRB021004 (Chapter 4), GRB050922C (Chapter 5) and GRB060607 (Chapter 6). The observations of GRB021004 and GRB050922C were work as part of a larger collaboration, the PI of which is Fabrizio Fiore at Rome Observatory. The work on GRB060607 was done individually due the data being publicly available immediately after the observations.

- **CHAPTER 7: Supernova / GRB connections**

In the final Chapter I will examine the nature of Supernova / GRB connections through a study of SN signatures in GRB lightcurves. The main focus of this work is to measure the cosmological K-correction for various SN types in order to superimpose template SN lightcurves on those of GRBs, with accurate corrections for cosmological effects.

2

A Review of GRB Distance Determinations, Estimations and Applications

2.1 Introduction

Prior to the discovery by BATSE that GRBs are isotropic, and the discovery of the first afterglow by BeppoSax, the distance scale to GRBs was completely unknown. There were two main possibilities that were explored, first that GRBs were local to our galaxy and second that they were cosmological, residing in distant galaxies.

The discovery that they were isotropic in the sky strongly favoured the cosmological models, but some advocates of galactic models still suggested the possibility of a class of objects known as soft gamma repeaters (SGRs), highly magnetized galactic neutron stars that periodically erupt in bright flares at gamma-ray and other wavelengths, as prospective candidates. One further point in favour of the galactic model was the enormous energy budget involved if GRBs were originating in distant galaxies.

In this Chapter I will review distance determinations of GRBs. Firstly I will examine the pre-

afterglow era, when the cosmological nature of GRBs was still in question and measuring of their distance was still a way off. Secondly I will look at the post afterglow era that started when the first GRB redshift was measured through observations of its afterglow.

Next I will give an introduction to the concept of beaming and some potential implications on distance measurements and GRB energetics, and more specifically on the more recent work attempting to utilize GRB as standard candles. Finally I will introduce an empirical distance estimator employing intrinsic burst properties.

2.2 Pre-Afterglow Distance Estimations

Prior to the age of GRB afterglow measurements the question remained as to whether or not GRBs are phenomena local to our galaxy or cosmological in nature. Distance estimations were based on the observable quantities available from the prompt GRB spectrum itself. As a result the building of a theoretical model was quite difficult. Methods for such distance determination involved comparisons between $\langle V/V_{max} \rangle$ statistics (Mao & Paczynski 1992) and time dilation (Wei & Lu 1997), as well as the log N - log P distribution and time dilation (Fenimore & Bloom 1995). Two methods are used in each case to obtain consistent estimates for the value of the redshift.

2.2.1 $\langle V/V_{max} \rangle$ statistics vs. Cosmological Time Dilation

According to Wei and Lu (1997) the expansion of the universe will have two main effects on GRBs at cosmological distances. Firstly it will stretch the temporal structure of the burst, making it appear that dimmer bursts are longer than brighter ones. The temporal structure of the burst will be stretched by a factor of $(1 + z)$, where z is the redshift. Therefore the temporal structure of the dimmest burst (farthest) will be stretched by a factor y greater than the brighter ones (nearer) such that

$$y = \frac{(1 + z_{dimmest})}{(1 + z_{bright})} \quad (2.1)$$

Such behaviour has been observed in the BATSE GRB catalog (Norris et al. 1994; Norris et al. 1994; Davis et al. 1994). Various methods give a dilation factor of about 2.

Secondly, the number of GRBs would decrease with distance due to redshift, causing the value of $\langle V/V_{max} \rangle$ to be less than 0.5 (the value expected for nearby homogenous sources), where V is the minimum volume of space the GRB can be in and V_{max} is the maximum volume accessible to the

detector. In practice it is the quantity $(C_{max}/C_{min})^{-3/2}$ that is measured (Mao and Paczynski 1992):

$$\frac{V}{V_{max}} = \left(\frac{C_{max}}{C_{min}}\right)^{-3/2} = \left\langle \frac{F_{min}}{F_{obs}(z)} \right\rangle^{3/2} \quad (2.2)$$

Here C_{max} is the maximum count rate, C_{min} is the minimum count rate required to trigger the instrument and F is the corresponding flux. It is found that $\langle V/V_{max} \rangle$ decreases monotonically with redshift and therefore z can be measured from the observed value of $\langle V/V_{max} \rangle$, see Figure 2.1.

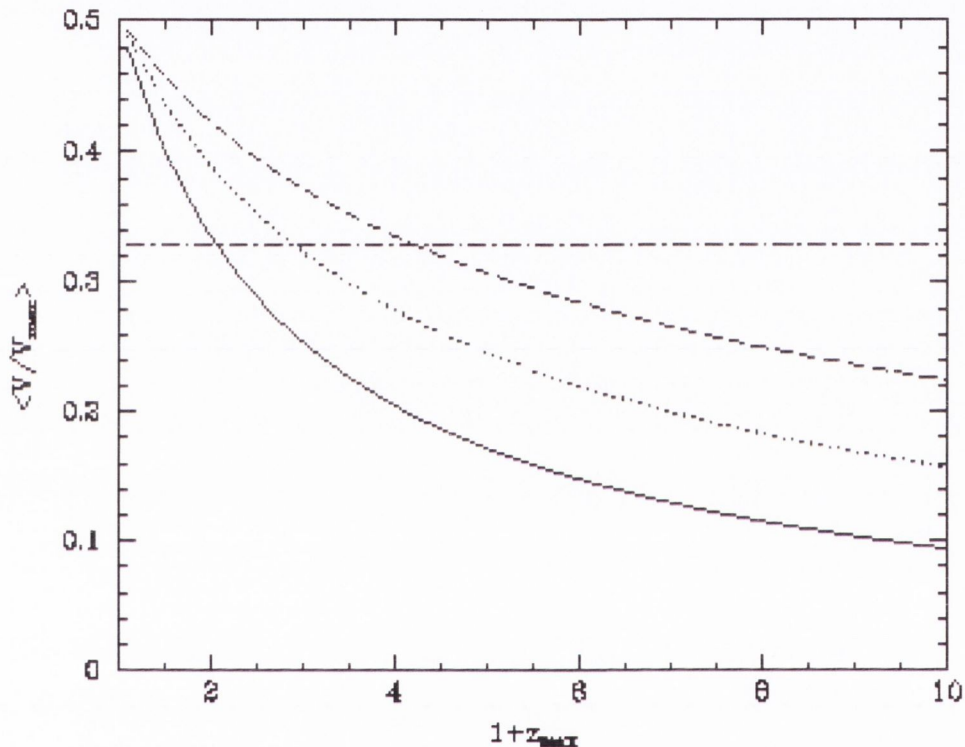


Figure 2-1: The variation of $\langle V/V_{max} \rangle$ with the maximum redshift $(1 + z_{max})$. The solid, dashed and dotted lines correspond to $\alpha = 0, 1, 1.5$ respectively. The horizontal line corresponds to the observed value $\langle V/V_{max} \rangle$. Taken from Wei and Lu (1997).

This method of $\langle V/V_{max} \rangle$ statistics is adopted by both Mao and Paczynski (1992) and Wei and Lu (1997). Both assume the bursts to be standard candles (each event releases the same amount of energy) with identical power law spectra. This adds in fact a free parameter α .

$$EL(E)dE = cE^\alpha dE \quad (2.3)$$

Where L is the luminosity of the burst. The relationship between time dilation and luminosity (also the redshift) is strongly dependent on α . In the case of $\alpha = 1.5$, the luminosity corresponding to

the observed time dilation of 2 is only about $4 \times 10^{51} \text{ergs}^{-1}$; the corresponding redshift z of the dimmest bursts in the case of $\alpha = 1$ and 1.5 are 2.0 and 3.4 respectively.

When values of 0 and 1 for α are used, the redshift obtained from the $\langle V/V_{max} \rangle$ statistics is much less than that for time dilation tests, while for $\alpha = 1.5$ the redshifts are consistent, namely z around 3.4 and $L_0 \ 4 \times 10^{50} \text{ergs}^{-1}$. From these two independent methods a consistent distance scale can be determined. This method gives substantial evidence in favour of the cosmological origin of GRBs.

2.2.2 log N - log P distribution vs. Cosmological Time Dilation

Fenimore and Bloom (1995) calculated the redshift according to observed time dilation and log N - log P distribution. A log N - log P distribution gives the number of events (N) with a peak intensity (P) above some value and is sensitive to the distribution of events in space.

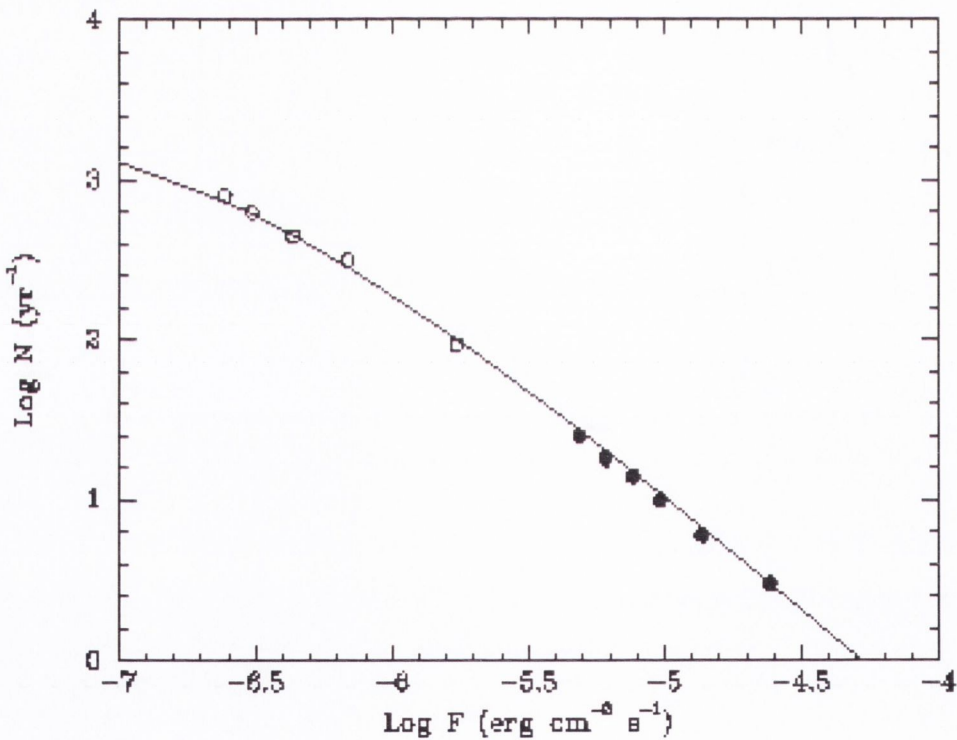


Figure 2-2: The calculated $\log N - \log F$ distribution with $L_0 = 4 \times 10^{50} \text{ergs}^{-1}$ compared with the observations. Taken from Fenimore and Bloom (1995). The open circles and the filled circles denote the data observed by PVO (Pioneer Venus Explorer) and BATSE respectively.

The time dilation tests typically use averages from the count rate time history of the bursts as a function of brightness, whereas the log N - log P distribution test uses the number of detected

events. If these two rather independent tests are consistent, it would be strong evidence in favour of the cosmological explanation of the origin of GRBs.

Unlike Wei and Lu (1997) however, the results they found showed that the redshifts obtained from these two different methods are quite different. From the observed time dilation factor of about 2 they obtained a redshift of $z > 6$, while for the $\log N$ - $\log P$ distribution a value of about 0.8 was obtained (see Figure 2-2, in this Figure P is given in terms of the flux F). This clearly shows an inconsistency. It was concluded that either a large fraction of the observed dilation was intrinsic to each burst or there was a strong luminosity evolution.

2.3 Distance Estimations-post afterglow

The measurement of GRB distances was finally made possible by the precise location capability of the wide field camera of the Beppo-SAX satellite, which allowed the detection of X-ray afterglow emission (Costa et al. 1997) and the optical follow up (van Paradijs et al. 1997).

With the advent of optical observations it was therefore possible to obtain spectroscopic information about the afterglow. This is ideal for the measurement of their distances by using emission and absorption features and calculating their redshift. Such redshift estimates have several different sources, e.g. absorption lines in the optical afterglow, absorption/emission lines of the presumed host galaxy, or Fe emission lines in the afterglow X-ray spectra.

2.3.1 GRB970228 and GRB970508: Optical Spectra

The first GRB for which an afterglow was observed was GRB970228. The X-ray afterglow was detected and quickly positioned by the Beppo-SAX satellite on the 28th of February 1997. The X-ray source was detected with the X-ray telescope aboard the same satellite about eight hours after the burst and faded away in a few days with a power law. This started a multiwavelength campaign that led to the identification of a fading optical source at the same position. However, no distance determination was successfully made at the time.

GRB970508 was the second such GRB for which the optical afterglow was detected. However it was the first for which a redshift measurement was successfully made. This was done using emission and absorption features in the spectra of the optical afterglow.

Spectra were obtained using the Keck II 10-m telescope on May 11 (Metzger et al. 1997). A set of absorption features was identified between 430 and 514 nm that was associated with an Fe II triplet and Mg II (see Figure 2-3), which placed the system at $z = 0.835$. Several other absorption

features were also seen. Subsequently a 30-min spectrum was obtained on June 5 (Metzger et al. 1997) which revealed an emission line at 684.0 nm that was identified as [O II] 372.8-nm emission at $z = 0.835$, the same redshift as the previous spectra. The line fluxes also suggested that emission may be due to nebular emission from a coincident host galaxy.

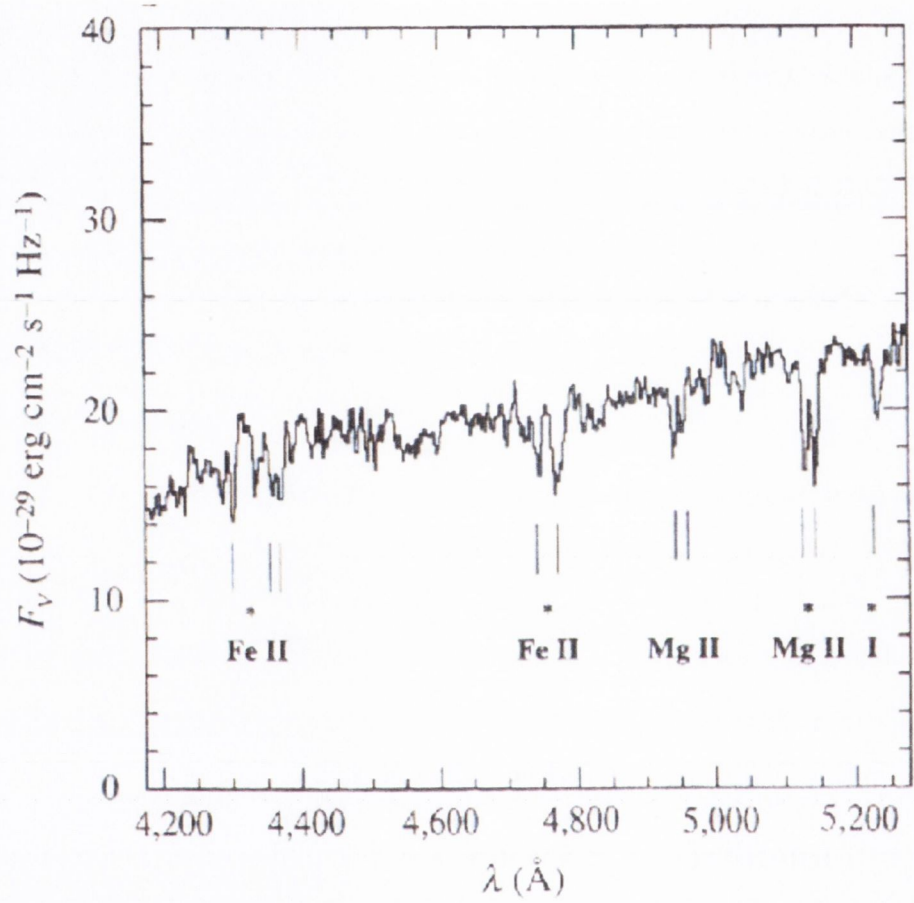


Figure 2-3: Spectrum of GRB970508 showing the identification of FeII and MgII absorption features which led to the first GRB redshift measurement. Metzger et al. (1997)

To date the most reliable method for determining the redshift of a GRB is through spectroscopy. This method has, to a certain degree, limitations. To detect absorption features, such as Lyman α , at very high redshifts ($z \geq 7$) would require IR spectroscopy. At these redshifts absorption due to hydrogen may render detection of absorption lines in the UV/optical impossible.

2.3.2 GRB980425: Association with Supernova

The discovery of GRB980425 raised many questions on the nature of GRB progenitors due to its unusual coincidence with a supernova (Galama et al. 1998). The source was observed in the spiral

arm of a relatively nearby galaxy at $z = 0.0085$. However an optical transient was discovered which occurred within a day of the event. Its light curve, spectrum and location showed that the transient was a very luminous type Ic Supernova, SN 1998bw (Galama et al. 1998).

Modeling of the optical light curve of SN 1998bw shows that it can be reproduced with the core collapse of a massive CO progenitor star; and the time of collapse coincides with that of the GRB to within a day. The notion that GRB980425 and SN 1998bw have no physical connection is difficult to agree with (Galama et al. 1998).

In Chapter 7 I will explore further the SN / GRB connection and its implications on potential progenitors for GRBs. Since SN 1998bw several GRBs have been shown to have a coincident SN event (see Chapter 7), or in some cases a late time rebrightening of the light curve that can be interpreted as a Supernova emerging from the decaying GRB light curve.

2.3.3 GRB970828: Association With Host Galaxy

Unlike previous afterglows GRB970828 had no optical afterglow. This made determining its redshift from optical spectroscopy impossible. X-ray observations, however, showed what appeared to be a hump at $\sim 5\text{keV}$ and an absorption column of $7.1 \times 10^{21} \text{cm}^{-2}$. This was interpreted as a redshifted Fe $K\alpha$ line. Hence, it suggests a relatively small redshift of $z = 0.33$ for this GRB. This would have been the first GRB with its redshift determined only by the X-ray observation if this interpretation were true.

However this was withdrawn when the probable host galaxy was discovered for GRB970828 (Djorgovski et al. 2001). A series of VLA observations detected a weak radio flare 3.5 days after the burst within the BeppoSax error region. It suggests that the GRB occurred in a dust lane at an interface between two interacting galaxies. A subsequent spectroscopic study by the Keck telescope on one of the galaxies clearly showed two emission lines, giving a redshift of $z=0.9578$ for the galaxy which is the likely host (Djorgovski et al. 2001).

Reanalysis of the X-ray data (Yoshida et al. 1999) led to a new interpretation of the spectral feature as being a radiative recombination edge of iron in the vicinity of the source, taking into account the redshift of the likely host galaxy.

2.3.4 GRB990705: X-ray Spectra

From GRB970828 it was shown that not only the optical transient was a useful diagnostic for determining distance but also the X-ray equivalent was also. The X-ray afterglow of GRB990705

showed a transient absorption edge at ~ 3.8 keV (Amati et al. 2000). This can be explained by photoelectric absorption by a medium located at a redshift of ~ 0.86 .

The progressive photoionisation of the circumburst medium should produce a low-energy cut-off and K-edge absorption features in the burst’s X-ray spectrum. K-edge absorption features occur when the absorbed photons have an energy just above the binding energy of the K shell in the atom. This will be observed as a discontinuity in the X-ray absorption spectrum (see Figure 2-4).

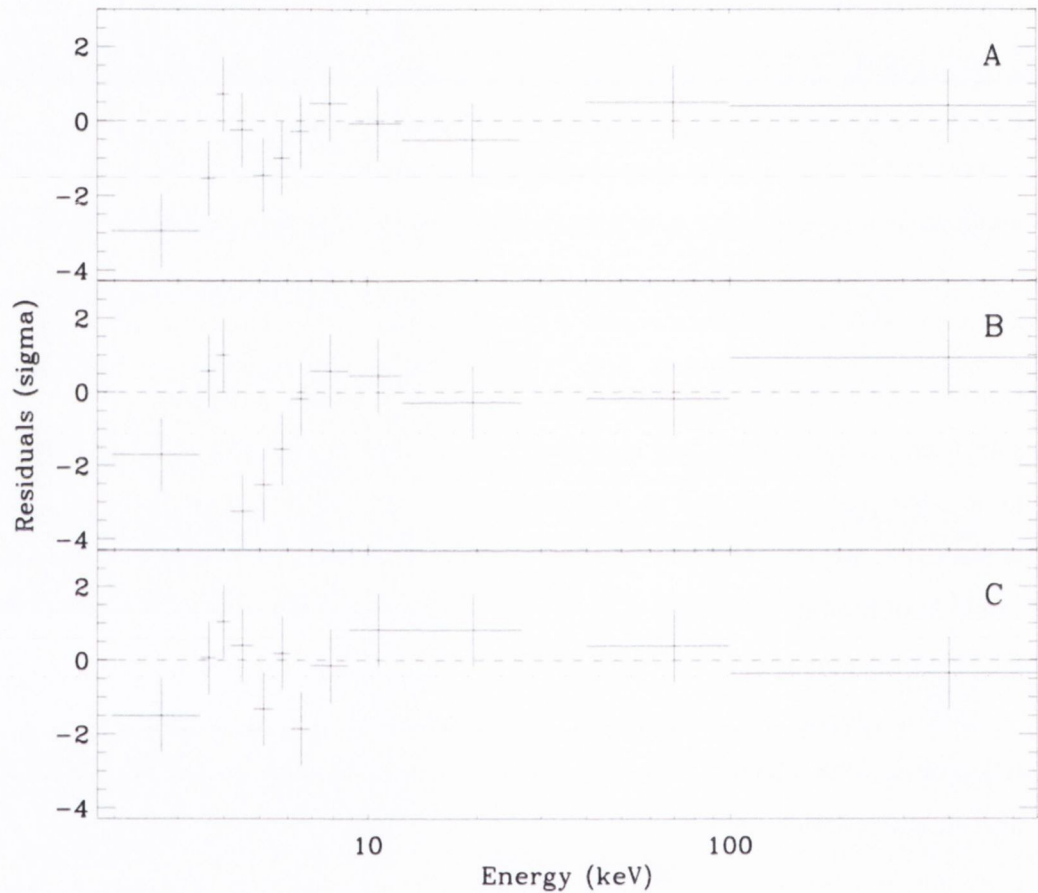


Figure 2-4: The X-ray absorption spectrum of GRB990705, taken at three time intervals after the burst. Taken from Amati et al. 2000.

2.4 GRB Energetics - Beaming

As the number of GRBs with accurate redshifts grows, a clearer picture of just how much energy is released in a GRB explosion emerges. One of the keys to understanding the progenitors of GRBs and the physics of their central engines lies in understanding the complexity of these energetics.

One of the most important discoveries in recent years is that, in all likelihood, GRB emission is beamed, meaning the emission is not isotropic but beamed into collimated jets. Indeed it has been suggested (Frail et al. 2001) that GRBs have a standard energy reservoir and that the observed distribution in emitted energy is in fact due to beaming.

2.4.1 So what is beaming?

Beaming involves a collimated jet-like structure in the GRB outflow. As a result the observed energy release would not necessarily be the true output. If the jet is pointed straight at the observer the GRB will appear brighter than if the GRB is observed off-axis. This also means the true energy output is significantly less than if the emission were isotropic.

The isotropic equivalent gamma-ray energy

$$E_{iso} = 4\pi F_{\gamma} d_L^2 (1+z)^{-1} \quad (2.4)$$

has been used as a surrogate for the energy released by the central engine, where F_{γ} is the fluence of the burst, z is the redshift and d_L is the luminosity distance.

However a conical jet-like GRB will not be isotropic but will instead light up a fraction, the so-called beaming fraction $f_b = (1 - \cos\theta_j)$ of the surrounding sphere, where θ_j is the opening angle of the jet. For small opening angles this becomes $f_b = \theta_j^2/2$ (Rhoads 1999; Sari et al. 1999). Thus the true energy release is much smaller than E_{iso} i.e. $E_{\gamma} = f_b E_{iso}$.

2.4.2 Spectral break

The signature of conical geometry manifests itself as a broadband break in the power-law decay of the afterglow emission (see Figure 2-5), which declines more rapidly to that of a spherical case (e.g. Rhoads 1997; Sari, Piran and Halpern 1999). This break happens for two reasons. First there is an edge effect that occurs at a time t_j when the bulk Lorentz factor of the blast wave (Γ) has slowed down to $\Gamma < \theta_j^{-1}$. The second effect is the lateral spreading of the jet when the ejecta decelerate faster as they encounter more circumburst material.

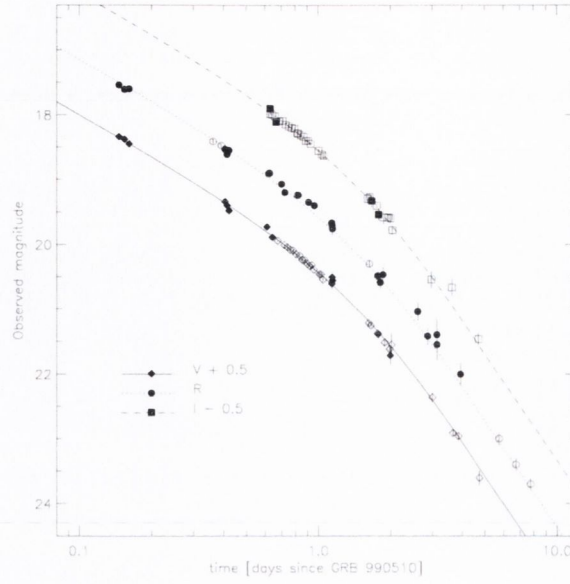


Figure 2-5: Break in the afterglow light curve of GRB990510. Harrison et al. (1999)

To convert the measured break times t_j to opening angles of the conical blast wave, the formulation of Sari et al. (1999) is used,

$$\theta_j = 0.057 \left(\frac{t_j}{1 \text{ day}} \right)^{-3/8} \left(\frac{1+z}{2} \right)^{-3/8} \left[\frac{E_{\text{iso}}(\gamma)}{10^{53} \text{ ergs}} \right]^{-1/8} \left(\frac{\eta_\gamma}{0.2} \right)^{1/8} \left(\frac{n}{0.1 \text{ cm}^{-3}} \right)^{1/8} \quad (2.5)$$

where η_γ is the efficiency of the fireball in converting the energy in the ejecta into gamma rays and n is the mean circumburst density.

Taking into account the geometry effects, the actual energy release of GRBs is in fact clustered around 5×10^{51} erg (see Figure 2-6), as found by Frail et al. (2001). This pointed towards a possible standard kinetic energy reservoir for GRBs.

2.4.3 The Gamma-Ray Burst Hubble Diagram

Using these temporal breaks and making several simplifying assumptions it is possible to arrive at the surprising result that the true energy release E_γ is strongly clustered. Frail et al. (2001) found that, allowing for beaming, E_γ is clustered around 5×10^{50} erg.

With nine new bursts available for E_γ measurement, Bloom et al. (2003) presented in a subsequent study a sample of 29 bursts with temporal breaks. In agreement with the previous results (Frail et al. 2001) the derived jet opening angles of those 16 bursts with redshift measurements result in a corrected energy value of about $E_\gamma = 1.33 \times 10^{51}$ erg.

Although the scatter is rather small, using GRBs for any real cosmographic purposes is still not

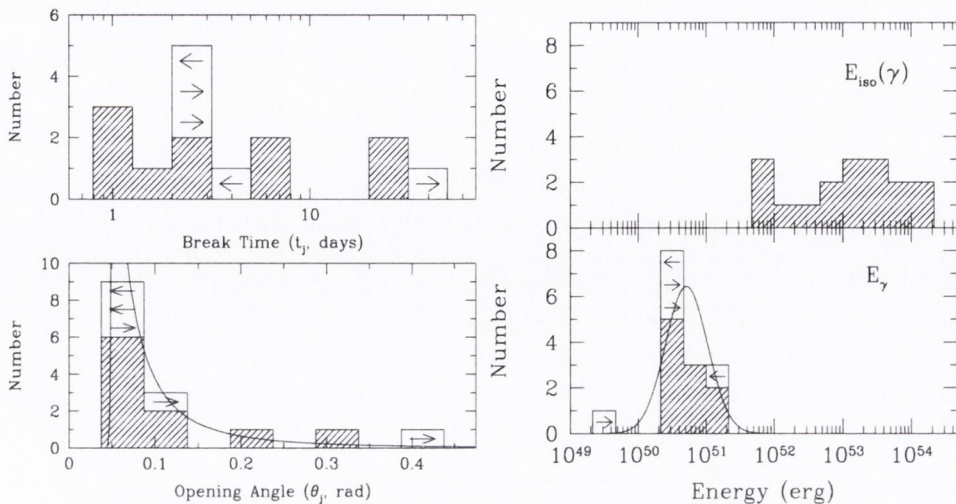


Figure 2-6: (left) Observed distribution of jet break times (top panel) and jet opening angles (bottom panel) (right) Distribution of the apparent isotropic GRB energy of GRBs with known redshift (top panel) vs. the geometry-corrected energy for those GRBs for which the afterglow exhibits a break (bottom panel). Taken from Frail et al. (2001)

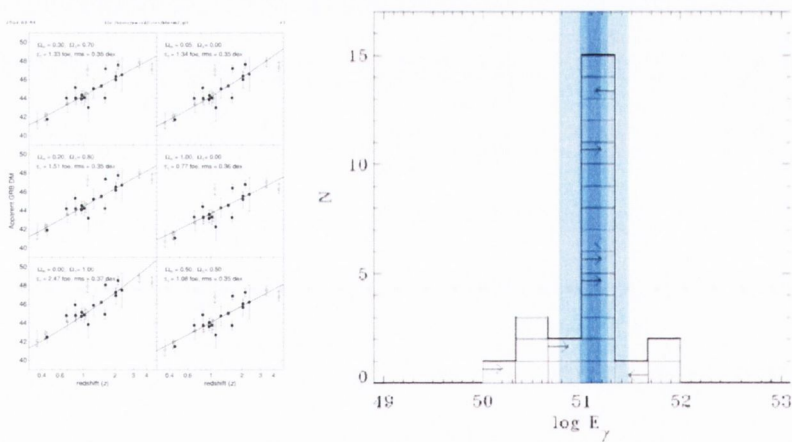


Figure 2-7: (left) GRB Hubble diagram illustrating the difficulty in making cosmographic measurements with GRBs. Shown are Hubble diagrams for six different cosmologies for the 24 GRBs with known redshift and a measurement or constraint on t_{jet} . Clearly, the current sample cannot distinguish between a wide range of cosmologies. (right) Histogram of GRB energies (E) with three equal logarithmic spacings per decade. The histogram shows a narrow distribution of GRB energies about the standard energy $= 1.33 \times 10^{51}$ erg. Taken from Bloom et al. (2003).

accurate enough yet. In other words, the current level of accuracy and data acquisition cannot place meaningful constraints on any fundamental parameters of the universe. To extend GRB physics to this purpose two things must be done. Firstly, Hubble diagrams of GRBs should be based on fundamental quantities such as energy, and secondly a more homogeneous set is needed by a method of subclassification.

The value for E_γ , the total prompt energy release in a certain bandpass, may be found from

$$E_\gamma = S_\gamma \frac{4\pi d_L^2}{1+z} k f_b, \quad (2.6)$$

where S_γ is the fluence recieved in some observed band pass and d_L is the luminosity distance at redshift z . The quantity k is a multiplicative correction of order unity relating the observed bandpass to the standard restframe bandpass. A standard Hubble diagram is distance modulus (DM) vs. redshift, therefore (given $DM = 5\log_{10}(D_l/10pc)$) equation 2.6 becomes,

$$DM = -2.5\log_{10}[S_\gamma \frac{k}{1+z} (1 - \cos\theta_{jet}) 4\pi] + zp, \quad (2.7)$$

where zp is a scaling factor $zp = 30.4940 + 2.5\log_{10}(E_\gamma^{51}/1.5)$. The more strongly clustered E_γ is, the more zp becomes a constant and the more accurate the value DM is. In other words, the variance of E_γ is a direct measurement of the accuracy with which E_γ can be used for cosmographic purposes.

2.4.4 Subclassification - The Wind Case

To understand fully the energetics of GRBs and the variation of E_γ we must first be able to identify apparent sub-classes of GRBs, so that a homogeneous set of GRBs can be identified for cosmographic applications.

Already GRB980519 and GRB980326 (Groot et al. 1998; Vrba et al. 2000) stand out for being significantly lower in energy release than the cosmological set. Both show unusually steep declines in their afterglow spectra, where for a power law such that the brightness decreases with t^α , where $\alpha \sim 2$ instead of ~ 1 at early times. Bloom et al. (2003) propose that bursts with early steeply declining afterglows may be intrinsically under-energetic or a typical energy burst that occurs in a particularly underdense medium.

In interpreting energy measurements Bloom et al. (2003) have explicitly assumed that the afterglow emission before the jet break arises in a medium where density is constant and homogeneous. Since the environments of at least some GRBs are thought to be clumpy (Lazzati et al. 2002; Bersier et al. 2003; Heyl and Perna 2003; Fiore et al. 2005) and wind-blown [i.e., r^{-2} ; Chevalier and Li

1999; Price et al. 2002b], estimations of f_b may be inappropriate for some or all GRBs. We can calculate $\theta_{jet}(wind)$ by inverting the equation for Γ of Chevalier and Li (1999).

$$\theta_j(wind) = 0.169 \left(\frac{1+z}{2} \right)^{-1/4} \left[\frac{E_{iso}(\gamma)}{10^{52} \text{ ergs}} \right]^{-1/4} \times A \quad (2.8)$$

where $A = \dot{M}/4\pi v_w$. This model allows for a more varied circumburst medium. Complex levels of interaction have already been observed using high resolution echelle spectroscopy, showing a structured multicomponent medium (Fiore et al. 2005).

2.4.5 Post-Swift Observations

Since operations with the Swift telescope began in late 2004 the number of bursts with measurable redshifts has increased dramatically. Kocevski et al. (2007) examine a sample of 76 Swift bursts from GRB050126 (Jan. 2005) to GRB070508 (May 2007) in order to verify which of the previously measured relationships still hold with an increased number of GRBs. Most notably the authors use the same methods as previous studies (Frail et. 2001, Bloom et al. 2003, Friedman & Bloom 2005) to examine the effects of beaming on the measured energy release of the GRB. The sample used by the authors is based on all 76 GRBs detected by Swift in comparison to the 48 pre-Swift GRBs for which similar studies were carried out (Friedman & Bloom 2005). Also, their sample determines jet breaks based on the X-ray light as opposed to most pre-Swift jet breaks, which are determined from the optical afterglows.

Their results are summarised in Figure 2-8. The left panel shows a comparison between pre- and post- Swift burst measurements of E_{iso} . The distribution of E_{iso} values for Swift bursts is plotted as the open histogram. Overplotted as a filled histogram is the E_{iso} distribution of the 45 pre-Swift GRBs with known redshift (excluding the GRB-SN events 980425 and 031203 and XRF 020903). The Swift detected distribution of E_{iso} marginally extends to lower energies compared to the pre-Swift sample.

The right hand plot shows the distribution of lower limits on E_γ for all events with no jet breaks (open histogram) in comparison to the E_γ values calculated using the 13 events determined by Panaitescu et al. (2007) to display breaks consistent with jet models (filled histogram). The jet breaks that are consistent with the standard jet model yield a value of $E_\gamma \sim 1.12^{+0.38}_{-2.92} \times 10^{50}$, roughly an order of magnitude below the standard energy derived from the pre-Swift observations (Bloom et al. 2003, Friedman & Bloom 2005).

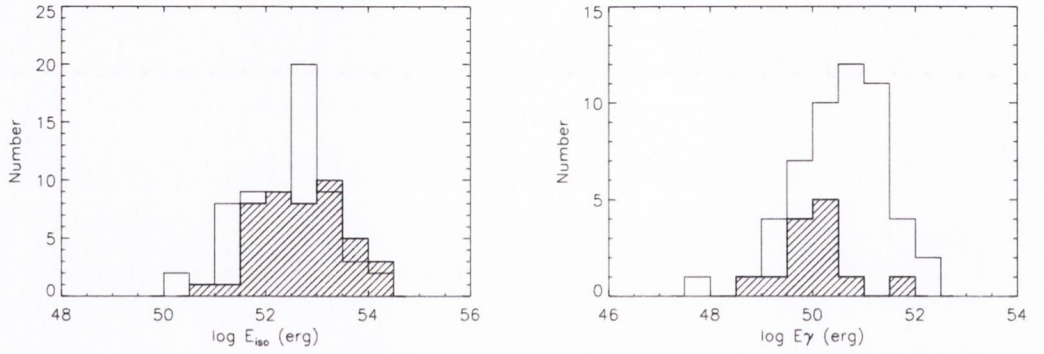


Figure 2-8: (right) Comparison between pre (open histogram) and post (filled histogram) values of E_{iso} . (left) Comparison between lower limit of E_{gamma} as measured for GRBs without jet breaks (filled histogram) and the measured value of E_{gamma} for those burst with an observed jet break in the X-ray light curve. Taken from Kocevski et al. (2007).

2.5 The Amati Relationship and Pseudo Redshifts

Several efforts have been made to establish correlations between certain intrinsic burst properties. It has been suggested throughout the history of GRB research that experimental constraints and instrumental bias could substantially affect results and that observed trends could be merely due to selection effects. As a result, when developing any sort of model based on observations, it is important to be mindful of properties that are intrinsic to the burst and those that may be influenced greatly by selection effects.

2.5.1 The Amati Relationship

In 2002 Amati et al. (from now on A1) published a paper exploring the possible correlation between a number of intrinsic burst properties. A1 uses results from 12 gamma ray bursts with known redshifts. Most bursts in the sample are well fitted by the Band model, whereby the energy spectrum of the burst is fit by two connected power laws. The main parameters are the low energy index α , the high energy index β , the break energy E_0 , and the normalisation parameter A where:

$$N(E) = A \cdot \left(\frac{E}{100 \text{ keV}} \right)^\alpha \cdot \exp(-E/E_0), \quad (2.9)$$

$$N(E) = A \cdot \left[\frac{(\alpha - \beta) \cdot E_0}{100 \text{ keV}} \right]^{\alpha - \beta} \cdot \exp(\beta - \alpha) \cdot \left(\frac{E}{100 \text{ keV}} \right)^\beta \quad (2.10)$$

for $E \leq (\alpha - \beta) \cdot E_0$ and for $E \geq (\alpha - \beta) \cdot E_0$, respectively. A1 then plots the quantities $|\alpha|$, $|\beta|$,

E_p (this is the peak energy emitted in gamma rays) and E_0 against both E_{rad} and $(1 + z)$. E_{rad} is the isotropic equivalent energy in the 1-10,000 keV energy range (equivalent to E_{iso}). A distinct correlation is found for a number of these plots.

Firstly, a general trend of E_{rad} to increase with redshift, z , is found. Also the E_{rad} values of most events in the sample are well above the sensitivity limit. Therefore this trend is intrinsic.

More specifically, a correlation is found between $|\alpha|$, the low energy index, and $(1 + z)$ (see Figure 2-9). The best fit power law is given by:

$$|\alpha| \propto (1 + z)^{-0.78 \pm 0.18} \quad (2.11)$$

Secondly, a distinct relationship between E_p and E_{rad} is found (see Figure 2-9). The best fit power law of this is given by:

$$E_p \propto E_{rad}^{0.52 \pm 0.06} \quad (2.12)$$

The $|\alpha| \propto (1 + z)^{-0.78}$ correlation is weaker but in both cases the most significant correlations are given by $\log |\alpha| \propto \log(1 + z)$ and $\log E_p \propto \log E_{rad}$. In the case of equation 2.12, a similar power law correlation ($E_p \propto \epsilon_{rad}^{0.5}$) is expected in the case of an optically thin synchrotron shock model for an electron distribution with a power law shape.

The $|\alpha| \propto (1 + z)^{-0.78 \pm 0.18}$ correlation is not as straightforward to interpret. However, since $|\alpha|$ ranges from -2/3 to -3/2 for an OTSSM (Optically Thin Synchrotron Shock Model) and synchrotron cooled leptons respectively, this is strong evidence in favour of synchrotron emission as the primary emission model.

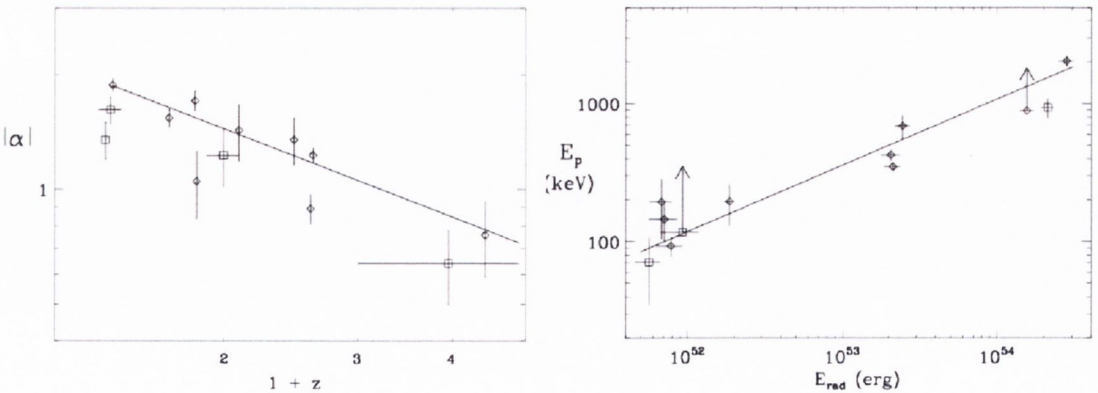


Figure 2-9: (left) $|\alpha|$ vs. $(1+z)$ for all events included in sample. (right) Dependence E_p on E_{rad} using all events in sample. Taken from Amati et al (2002).

2.5.2 The Ghirlanda Relationship

Continuing from the work of Amati et al., Ghirlanda et al. (2004) (GGL04 from here on) took a sample of all bursts with known redshift, νF_ν and peak energy, E_{peak}^{obs} . Also, for most of them the jet opening angle θ_j could be inferred from t_j , the break time. As a result E_γ , the collimation corrected energy can be determined.

GGL04 assume a constant circumburst density, n , and efficiency η_j of 20%. The jet opening angle can therefore be estimated using the formulation given in equation 2.5.

Hence the collimation-corrected energy, E_γ can found, since the isotropic equivalent energy E_{iso} is given by $E_\gamma = (1 - \cos \theta)E_{iso}$. This method was also used by Frail et al. (2001) and Bloom et al. (2003). The result of this showed a remarkable clustering of E_γ around 5×10^{50} erg and 1.3×10^{51} erg, respectively. This suggests that the large range of E_{iso} is due to a collimation and that the GRB energy is potentially quite universal.

From the inferred values of E_γ , GGL04 plotted E_{peak} against E_γ for all GRBs in the sample, more specifically the source frame peak energy, $E_{peak}(1 + z)$ vs. E_γ . GGL04 finds a striking correlation between these two parameters. The best fit powerlaw model (see Figure 2-10, filled symbols with solid line) obtained is:

$$E_{peak} = 267.0 \left(\frac{E_\gamma}{4.3 \times 10^{50}} \right)^{0.706 \pm 0.047} \text{keV} \quad (2.13)$$

Also shown in Figure 2-10 is a plot of E_p vs isotropic equivalent energy E_{iso} . This shows a larger spread with respect to the previous findings of Amati et al. (2002). In this case the best fit power law is given by:

$$E_{peak} = 258.0 \left(\frac{E_{iso}}{1.2 \times 10^{53} \text{erg}} \right)^{0.40 \pm 0.04} \quad (2.14)$$

The fit shows a relatively large scatter of E_{iso} ; however for the same bursts the scatter is much reduced when collimation effects are taken into account.

2.5.3 Post-Swift Results

The results of Amati and Ghirlanda are both intriguing and imply fundamental relationships between the peak energy of the prompt emission and the total energy output of the GRB. Panaitescu (2007) updates these results by including post-Swift GRBs for which the redshifts are known and which show breaks in the X-ray light curves. Figure 2-11 shows two plots for both Ghirlanda and

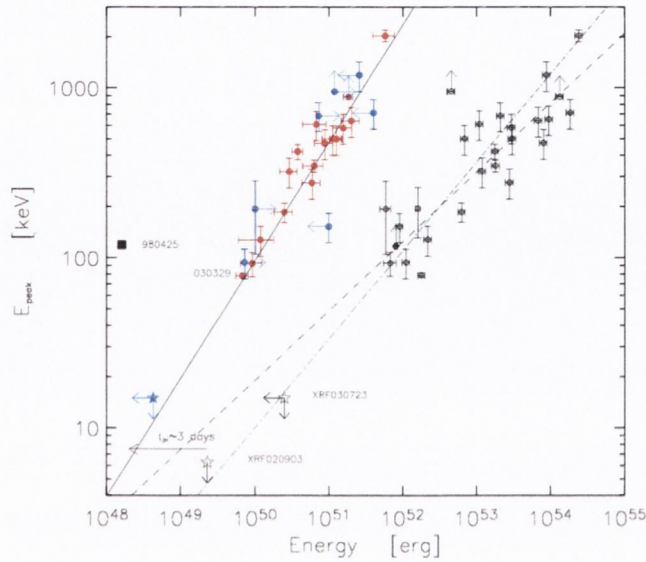


Figure 2-10: (Filled circles) Restframe peak energy E_p versus collimation corrected energy E_γ . (Open circles) E_p versus isotropic equivalent energy E_{iso} . Taken from GGL04.

Amati relations. The author notes that the Amati relationship is more consistent with the combined pre- and post- GRBs than the Ghirlanda relationship. The jet breaks for the post-Swift GRBs are, however, measured from the X-ray light curves and not the optical ones.

One problem with the findings of Panaitescu (2007) and Kocevski et al. (2007, see section 2.4.5) is that the results are based on X-ray light curves. There is mounting evidence (Panaitescu et al. 2006; Perley et al. 2007; Curran et al. 2007; Oates et al. 2007, Molinari et al. 2007) to suggest that the X-ray and optical emission may be selectively affected by energy injection or originate from distinct and separate physical components. Such a two-component model has been proposed by Kumar & Granot (2003) in which the X-ray and optical emissions originate from two distinct jets of differing degrees of collimation. If this were the case the early time jet breaks observed in the X-ray light curves would not be consistent with the late time breaks observed in the optical. This may explain the inconsistency seen in the Ghirlanda relationship from Panaitescu (2007). Likewise the median of E_γ obtained by Kocevski et al. (2007), an order of magnitude lower than pre-Swift values, would not be consistent with the single jet model previously used to determine E_γ .

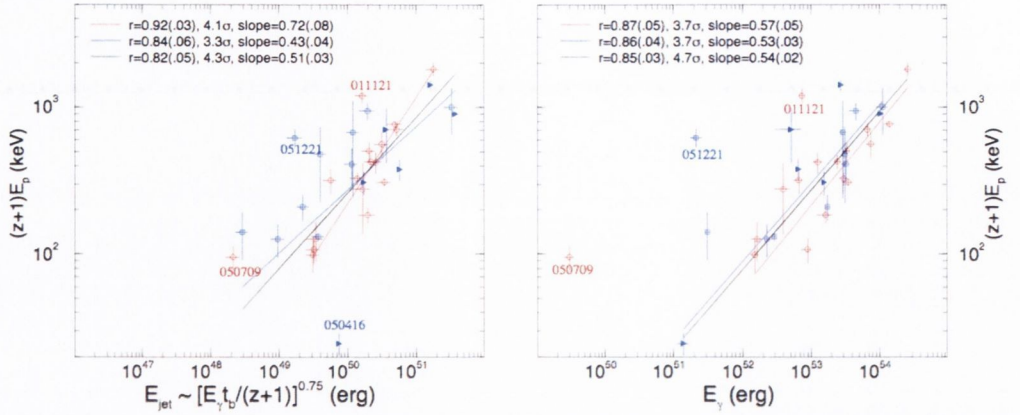


Figure 2-11: Correlation of host-frame peak energy of the νF_ν GRB spectrum and k -corrected 1 keV–10 MeV collimated GRB output (Ghirlanda relation – left panel) and isotropic-equivalent GRB energy release (Amati relation – right panel) for 15 pre-Swift afterglows with optical light-curve jet-breaks (red symbols, fit shown with red line), 9 Swift afterglows with X-ray jet-breaks (blue squares) and 6 without (blue triangles) (fit shown with dashed line), and for the entire set of 30 afterglows (black line). Legends give the linear-correlation coefficient r of plotted quantities in log-log space, significance level for that correlation, and slope of linear best-fit, all accounting for sample variance. Taken from Panaitescu (2007)

2.5.4 Standard Candles: Constraining Ω_M and Dark Energy

Since such a strong correlation between E_γ and E_p was found by GGL04, it is possible, to a certain extent, to use GRBs for cosmographic measurements in order to derive reasonable constraints on fundamental cosmological parameters.

Dai et al (2004) (from here on DLX04), used this $E_\gamma \propto E_p^{1.5}$ relationship to investigate whether or not GRBs could be used as a tool to measure such quantities as the mass density of the Universe, Ω_M . The DLX04 sample consists of 12 bursts with known redshift, observed peak energy E_p and break time t_j .

In equation 2.4 the true value for d_L , the luminosity distance, depends on the cosmology used. For a Friedmann-Robertson-Walker cosmology with mass energy density Ω_M and vacuum energy density Ω_Λ

$$d_L = \frac{c}{H_0} (1+z) |\Omega_k|^{-1/2} \text{sinn} |\Omega_k|^{1/2} \times \int_0^z dz [(1+z)^2 (1 + \Omega_M z) - z(2+z)\Omega_\Lambda]^{-1/2} \quad (2.15)$$

where $\Omega_k = 1 - \Omega_M - \Omega_\Lambda$, and sinn is sinh for $\Omega_k > 0$ and sin for $\Omega_k < 0$.

Thus, the observed distance modulus of a GRB is given by, $\mu_{obs} = 5 \log 10(d_L/10pc)$. From the inferred values for μ_{obs} , and the known values for z , DLX04 produced a Hubble diagram for the given sample, Figure 2-12. Subsequently they find that the mass density $\Omega_M = 0.35^{+0.15}_{-0.15}$.

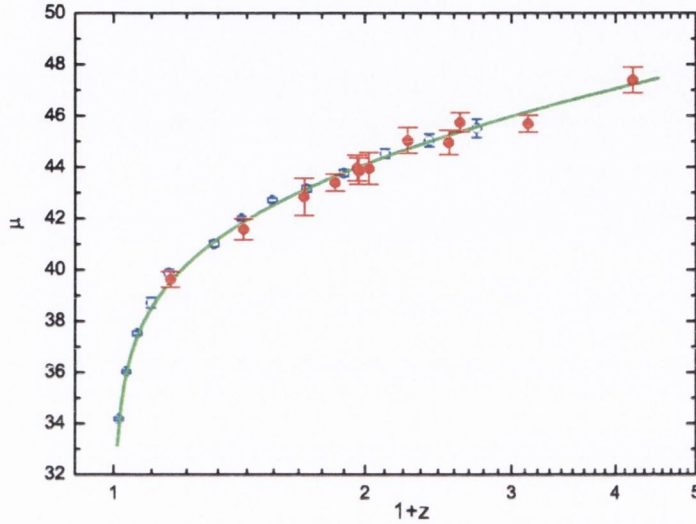


Figure 2-12: Hubble diagram for the GRB sample (filled circles) and the SN Ia from Reiss et al. 2004 (open circles). Taken from Dai et al (2004).

2.5.5 Pseudo Redshifts

A redshift indicator based on the findings of A1 was proposed by Atteia et al. (2003) (from now on A2). The new method obtains an estimate for the redshift of a GRB with an accuracy factor of about 2. The inferred redshifts are called “pseudo redshifts”, and apart from being easily computed they may provide a method for quickly identifying high redshift bursts. To date no method for determining pseudo redshifts has proved that useful as they rely on empirical models and may not be reliable. Other methods for determining redshift without spectra, such as photometric redshift, prove much better indicators.

The basis for A2’s indicator is the recently found correlation between the intrinsic E_p (the peak energy) and E_{rad} (isotropic equivalent energy release in gamma rays; also referred to as E_{iso}) by Amati et al. (2002) ; whereby E_p is roughly proportional to the square root of E_{rad} .

GRB energy spectra are well defined by the Band model, whereby the energy decreases with two connected power laws, with index α for the lower energy power law and index β for the higher energy power law, and E_0 is the break energy. E_p is given by:

$$E_p = E_0 \times (2 + \alpha) \quad (2.16)$$

In constructing their indicator A2 then make the assumption that if the energy emitted in gamma rays will more or less be the product of the number of photons by their typical energy then the isotropic equivalent number of photons, N_γ , is also roughly proportional to the square root of E_{rad} . And subsequently they define N_γ as the number of photons below the break, integrated from $E_p/100$ to $E_p/2$.

With this in mind, it is conjectured that if E_p and N_γ have the same dependence on E_{rad} then the ratio E_p/N_γ should be independent of E_{rad} and could therefore be used to build a distance estimator.

The basic formulation used, involving the ratio N_γ/E_p and the right combination of parameters (according to the author, who tried various combinations), is given by:

$$X = \frac{N_\gamma}{E_p} \sqrt{T_{90}} \quad (2.17)$$

Here E_p is the observed peak energy, N_γ is the observed number of photons between $E_p/100$ and $E_p/2$, and T_{90} is the observed duration.

To derive the pseudo redshift firstly the theoretical evolution of X with redshift must be computed ($\alpha = -1.0, \beta = -2.3$, and $E_0 = 250$ keV). This is then inverted to derive the pseudo redshift. The evolution of X with z can be written as

$$X = A \times f(z) \quad (2.18)$$

where A is a constant of proportionality (in this case $A = 60$). Therefore the pseudo redshift $\hat{z}$ is given by:

$$\hat{z} = \frac{1}{A} \times f^{-1}(X) \quad (2.19)$$

Figure 2-13 shows the value of X as a function of z from which a theoretical relationship can be determined. The coefficient of correlation between z and X is found to be -0.875.

A2 conclude that the dispersion in X is not substantial enough to preclude its use as a redshift indicator. Possible applications of this indicator include statistical properties of GRB populations, constraints of star formation rates at high redshifts and fast identification of high redshift bursts.

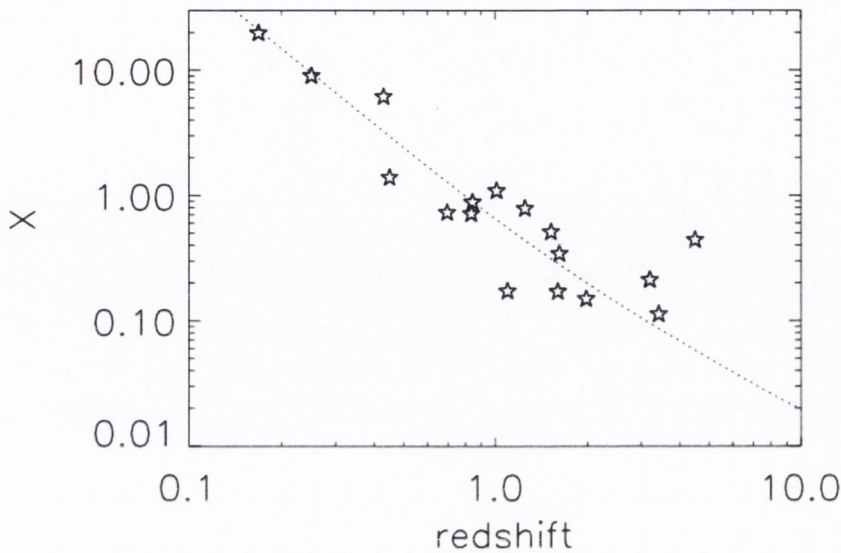


Figure 2-13: Correlation of X with the measured redshifts of 17 GRBs. The dotted line shows the theoretical relation between X and z . Taken from Atteia et al. (2002).

2.5.6 Standard Candles vs. Ghirlanda Relationship

In the previous section we discuss the nature of GRB energetics, from which two interpretations have emerged. Firstly that of the Amati and Ghirlanda relationships, which show the correlation between the peak energy and total energy emitted. The Ghirlanda relationship in particular is a very well defined correlation, leading to the idea that these two properties are indeed correlated. The nature of this correlation is still not understood.

The second is the notion that GRBs are standard candles i.e. each event is releasing the same amount of energy. This was first suggested when the idea of beamed emission was introduced, reducing the spread of E_{iso} to E_γ . This was an indication that the total energy released in γ rays was constant.

The two principles are, however, fundamentally at odds. If GRBs were in fact standard candles then the Ghirlanda relationship could not be true, as this relies solely on the notion of the varying of the peak energy with total energy emitted. Were the total energy output to be constant (or constrained within a small range of values) then by definition the peak energy should also show the same behaviour. The peak energy should, in principle as random a scatter around the central (standard) value as the total energy. This is not the case. For this reason I would consider the idea that GRBs are unlikely to be standard candles.

However, as a matter of exercise, and following from this Chapter's discussion on GRB en-

ergetics, I have used the relationships between observable quantities as a basis for an alternative distance estimator. The details of how this distance estimator was derived and some preliminary results are outlined in Appendix A.

3

The REM Telescope

3.1 Introduction

Due to the transient and unpredictable nature of GRBs and their afterglows it has been a matter of high cost of resources to capture them, the GRB-dedicated Swift has greatly increased the number of bursts detected, but followup observations still require speed and accuracy to detect the afterglow. The intrinsic duration of the observational process, mainly due to the use of devices non-optimized for fast response, did not allow for monitoring of the prompt afterglow, i.e. the emission in the few seconds after the burst itself. In order to overcome this, REM (Rapid Eye Mount, <http://polaris.merate.mi.astro.it/REM>) is a fully robotic fast slewing telescope primarily designed to follow the early phases of the afterglow of GRBs (Zerbi et al. 2001; Chincarini et al. 2003; Covino et al. 2004) detected by space-borne alert systems such as Swift, HETE II, and INTEGRAL.

REM was built and commissioned between 2002-2004, at La Silla Observatory Chile, with an international collaboration led by Brera Observatory, Milan Merate, Italy. It is primarily designed to follow the early phases of the afterglow. Other partners include Catania Observatory (Italy), Rome Observatory (Italy), Service d'Astrophysique (Saclay, France), Dunsink Observatory and

UCD (Ireland), and further the Randall Laboratory of Physics (Ann Arbor, USA) and various other university institutes and observatories in Italy (Bologna, Milan, Perugia, Palermo, Trieste, Ferrara). The limiting magnitudes obtained during the first light tests, June 2003, were well within expectation, reaching the limiting magnitudes in 1 second integration and for a signal-to-noise ratio $S/N=5$ of : $V=17.2$, $R=17.2$, $I=16.0$, $J=14.5$, $H=13.5$, $K=13.0$.

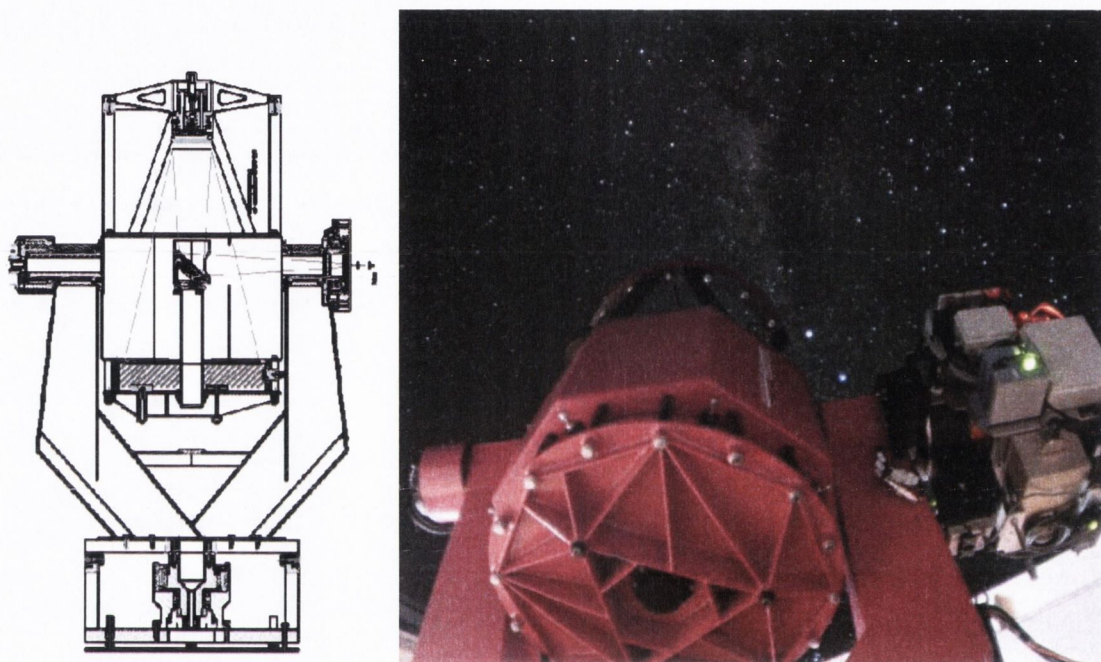


Figure 3-1: (left) A schematic of the REM telescope design. (right) Picture of REM at La Silla with the dome open.

REM hosts a near infra-red imaging camera (REMIR) covering the $0.95\text{--}2.3\ \mu\text{m}$ range with four filters (z' , J , H , K) and an optical imager/spectrograph covering the range $0.45\text{--}0.95\ \mu\text{m}$ (ROSS). They have a field view of 9.9×9.9 arcmin on a 512×512 chip, selected to match the typical error-boxes of GRB alert systems. With such instrumentation REM is an extremely useful facility for a broad range of applications and will serve as a rapid-pointing broadband photometric and spectrographic facility.

REM has a classical Ritchey–Chretien optical scheme mounted in an alt–azimuthal configuration with two Nasmyth focal stations, a 60 cm primary mirror and a total focal ratio of $f/8$, with a maximum speed of $12\ \text{degrees s}^{-1}$. At the two Nasmyth $f/8$ focal stations are mounted the NIR camera and perpendicular to that (the beam is split by a dichroic) a very low dispersion spectrograph using an Amici prism and a set of optical filters. Thanks to this dichroic system, the convergent light

beam is split to feed to cameras that can therefore work simultaneously, allowing for simultaneous optical and NIR observations. A schematic of the design of REM is shown in Figure 3-1. Such an optical configuration allows a compact structure that provides the needed stiffness for fast motion and windy environmental conditions such as those expected in a fully deployable dome at the La Silla observatory.

It is the objective of REM to observe GRBs simultaneously in both the optical and IR on timescales of tens of seconds after the burst trigger. In this way we can study the very early afterglow and prompt emission, observing the initial effect of the GRB on its environment and intrinsic burst properties only observable in the first few minutes.

Further to this, REM improves the wavelength coverage available for GRB observations, most notably at IR wavelengths. Since large quantities of dust, either in the circumburst environment or along the line of sight, can lead to the absence of an optical afterglow due to heavy absorption, an IR transient can be detected even if the optical one is not. Combining the two (IR and optical) datasets, it will be possible to estimate the amount of absorption.

In some circumstances there is a lack of dust. This may be due to destruction or sublimation by the burst continuum. In this case, an IR flash should be observed to start before the optical one, as the IR radiation can penetrate unabsorbed in the cloud while the higher energy photons progressively clean out the dust. The observed IR fluence before the detection of the optical flash would greatly constrain the amount of dust in the cloud. Prior to REM, in the case of GRB990123, ROTSE (another robotic telescope) observed the afterglow just 22s after the burst and found an optical flash (see Figure 3-2). Corresponding IR observations could show a still earlier IR flash.

Due to the extremely high energy budget of GRBs it should be possible to observe them at high redshift. At least some of the bursts without an afterglow could alternatively be high z bursts for which $\text{Ly-}\alpha$ absorption suppresses all the light at optical wavelengths. This Lyman edge falls in the REMIR wavelength range for sources with redshift between 8 and 15, and at lower redshifts the Lyman edge should also be detectable with ROSS.

Using REM and an 8m class telescope (VLT) equipped with a suitable spectrograph, it should be possible to collect a high resolution spectrum of a source at z greater than 10. There are several advantages in having a facility such as REM working in collaboration with other ground based and space based telescopes. After the initial detection it is crucial to begin follow up observations to improve the accuracy of the burst position as quickly as possible. This in turn will allow for larger ground-based telescopes to dedicate time and to obtain such high resolution spectra.

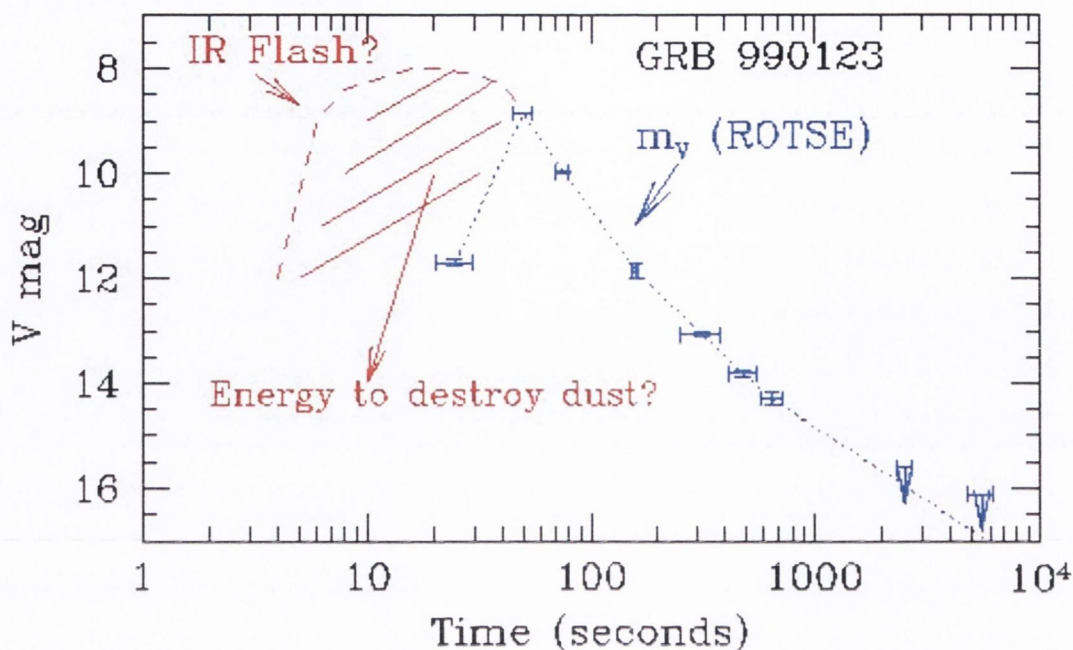


Figure 3-2: ROTSE light curve of GRB 990123. Zerbi et al. (2001).

3.2 Operations as Duty Scientist

The telescope is set up to observe automatically the submitted schedule, except in the case of a GRB alert (given by a space borne alert system), in which case the telescope will automatically observe the transient. The most general working scenario starts with the reception of an alert message from the GCN (<http://gcn.gsfc.nasa.gov/gcn/>), a system that has the capability to distribute to the GRB research community timely information on GRBs. The message announces the detection of a GRB by a space borne observatory. The REM Observing Software (REMOS) checks if the possible target satisfies some minimal visibility constraints (hour angle, altitude, Sun and Moon position, etc.). If these conditions are verified, information from REM Environmental Control Software is retrieved and if observations are possible (humidity, wind, sun altitude, etc. within safety and operational limits) REMOS checks if the system is already busy with observations of a different target. If this is the case, and the source is another GRB, a decisional algorithm is applied. Depending on the specific case a decision is made. In the positive case (new GRB to be observed) or in the case of a lower priority target, REMOS sends a message to the REM Telescope Control System, stopping operations and moving the telescope to the new target. As soon as the telescope is on target (~ 20 - 40 s) REMOS sends a message to begin observations with some predefined templates. The whole set of images is directly sent to a dedicated archive as soon as they are processed.

Although REM is a robotic telescope dedicated to GRB science, this can lead to large gaps in the observing schedule which can be of use for monitoring other sources. Among the applications of REM idle time are AGN and variable star multi-frequency monitoring. REM is used to monitor Galactic Black Hole candidate flare stars as well as Blazars (Fuhrmann et al. 2006). These sources must be included in the nights observing schedule by the REM duty scientist (DS).

My main involvement with the REM program was acting as a DS from mid-2004 until the end of 2006. In May 2004 I visited Brera Astronomical Observatory in Merate, Milan, to attend a REM training meeting given by Stefano Covino. The purpose of the meeting was to familiarise duty scientists with the design and operations. This included a special training in the various commands needed to operate the telescope remotely. The number of DSs has changed over the years with an average of about 8 people at any one time. DSs are normally PhD students or postdoctoral researchers from one of the institutes of the REM collaboration.

The REM telescope is designed to observe remotely and unattended. There exists a number of commands which a user can issue, from any terminal in the world, to send an entry for observation, or to know the status of any of the systems on REM. They are command-line based, so an observer responsible for operations simply connects to the local network via SSH and types the desired command. Operations as duty scientist lasted for about 5 - 10 days every 1 - 2 months, depending on the number of people available.

The DS on-shift responsibilities in general were:

- Planning the night's observation schedule, and inputting the targets through a command line based series of inputs, followed by verifying the night schedule, observation feasibility and instrumental settings for scheduled targets before starting night observations.
- Verifying observations performed during night-time reporting on any possible problem or bug related to both instruments (REMIR and ROSS; hardware and software), to scientific programs (i.e. wrong filters, wrong exp. time., different targets, moonlight, etc.), to meteo and/or any other useful information.
- To send a written report to relevant parties on the previous night's observing. The report includes routine activities as well as troubles encountered.

And in the case of a GRB:

- In the event of GRB the telescope is designed to react promptly and autonomously. However the DS must also be alerted to monitor and verify observations.

- To alert the DS, REMOS sends an SMS message when a trigger has been received.
- The DS must verify that observations are correctly carried out and eventually modify instrumental setup to perform a suitable follow-up program.
- The DS must then retrieve the images as soon as they are ready and perform a “quick look” analysis of them to check for any possible transient.
- In the case of a visible afterglow the DS should send a GCN message to the GRB community reporting on any relevant information e.g. a detection (non-detection) of the afterglow or accurate positioning.
- If necessary the DS must continue observations of the GRB for as long as it is visible.

3.3 REM Data Reduction

There were a number of cases during my work as DS, where either GRBs were not visible from the telescope site or the trigger occurred during the La Silla day. In the cases where such a GRB would become visible during the La Silla night, it was important to begin observations as soon as possible e.g. when the GRB comes into view. One such case was GRB060211B, which occurred during one of my shifts as DS. Next I will describe the observations undertaken and the subsequent reduction and calibration of the data.

3.3.1 GRB060211B

GRB060211B was detected by Swift at 15:55:15 on the 11th Feb. 2006 UT (Mateos et al. 2006). Swift-BAT triggered and located GRB 060211B (trigger=181156). The spacecraft slewed immediately. The BAT on-board calculated location is RA, Dec 75.069d, +14.958d or 05h 00m 17s, +14 7' 27" (J2000), with an uncertainty of 3 arcmin (see Figure 3-3). The X-ray afterglow was then detected (Page et al. 2006) at RA(J2000) = 05h 00m 17.2s, Dec(J2000) = +14 6' 58.9" with an estimated uncertainty of 3.9 arcsec.

The field of GRB 060211B was imaged by the REM telescope located in La Silla (Chile). The field was observed with the REMIR near infrared camera in the J, H, K' filters and the optical imager/spectrograph ROSS in the V, R, I filters, starting approximately 8.5 hrs after the burst on Feb. 12th at 00:30 UT. Once observations had been completed the frames were downloaded from the relevant archives based in Milan and Bologna.

For each filter a number of observations was performed. These frames were then added, leading to a single data point, using the IRAF command *imcombine*. This routine takes a list of input frames, and co-adds them with a number of optional constraints. This was done for each set of observations. The result was a single output image for each filter in the optical and IR.

Once the frames are added together we can use a photometry package to identify all visible sources in the field. Photometry was performed using two packages: SRP for the detection of sources and GAIA to calibrate the REM frames and identify sources using standard stars from online catalogues.

SRP (Swift Reduction Package) is a package created solely for the purpose of quick data reduction of GRB observations. It combines a number of other packages, such as *sExtractor*. Detection of sources was done using the *SRPPhotometry* command. A list of input images is processed, again with a number of optional constraints. The command creates a text output file for each input

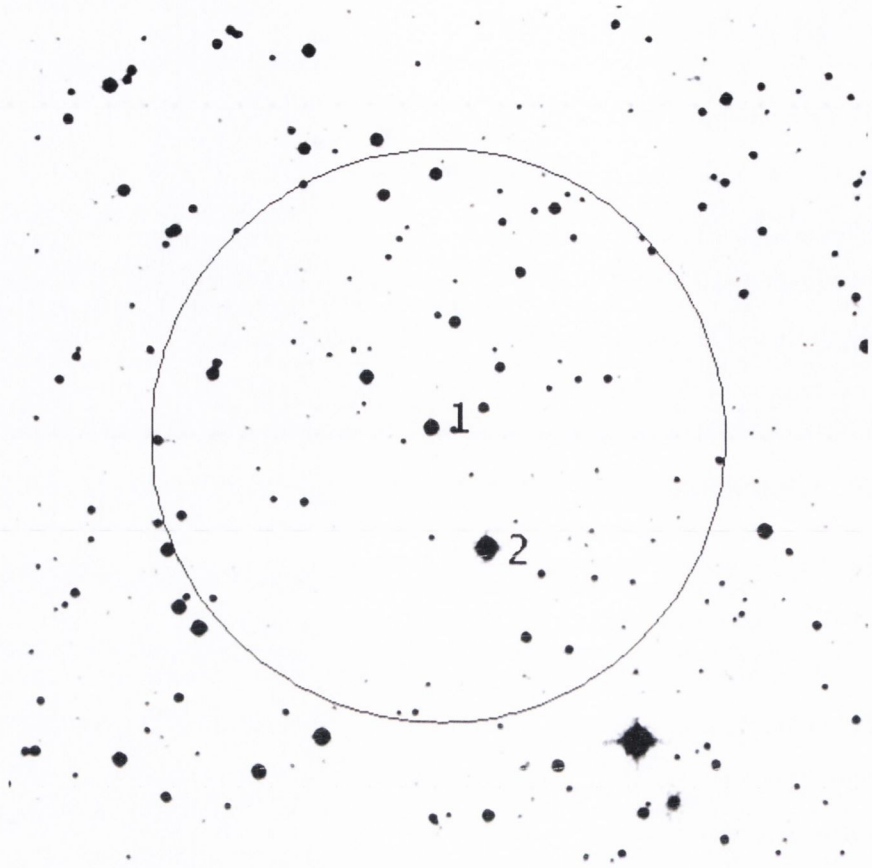


Figure 3-3: *Digital Sky Survey finding chart of GRB060211B with error circle provided by Swift. Page et al. (2006).*

frame with the extension “_photom.dat”, containing a list of sources detected, their positions and uncalibrated magnitudes.

Calibration was done using the package GAIA. The final processed image can be viewed (see Figure 3-5 and 3-6), and the list of sources found using SRP can then be imported. GAIA opens a table with a list of the visible sources along with their derived magnitudes, as found by SRP (see Figure 3-4).

We can calibrate these sources using online catalogs available in GAIA. For a given filter we can download an image of the same part of the sky as seen with REM, with the same sources in view. At this point we need to select one or more standard stars to compute the zeropoint of the magnitude scale, using the relationship:

$$M_{std} = m_{inst} - K * X + a_0 \quad (3.1)$$

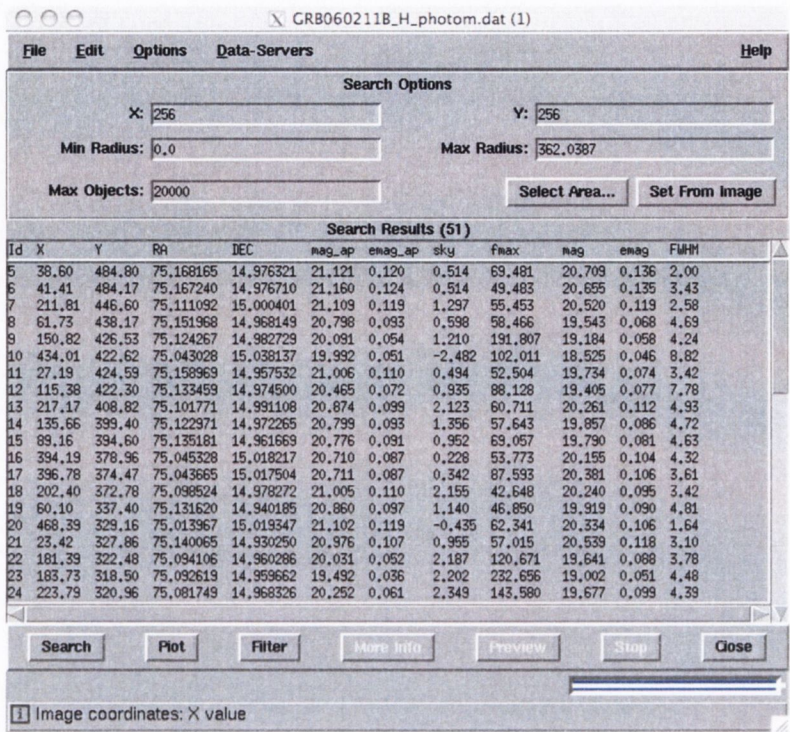


Figure 3-4: Results of source positions as found by SRP.

where M_{std} is the magnitude of the standard star obtained from the relevant catalogue, m_{inst} is the instrumental magnitude of the same star as observed by REM, K is the extinction coefficient (it depends on the atmospheric transmission and therefore varies from site to site), X is the airmass for the observation and a_0 is the zeropoint.

The airmass value is given in the header of the frame, while K can be obtained online from various sources (in this case we use the online reference for FORS1 photometric coefficients). So.

$$a_0 = M_{std} - m_{inst} + K * X \tag{3.2}$$

This process was performed for a number of standard stars clearly visible in the image, to obtain an average value for the zero point. Once the zeropoint is found the magnitude of a new source (i.e. a GRB counterpart) can be derived.

In the case of GRB060211B no sources are detected within the refined XRT error circle (see Figure 3-3) down to limiting magnitudes of $J=16.4$, $H=16.2$, $K=13.9$, $V=17.1$, $R=18.1$, $I=17.3$ (3-sigma upper limits). Once the data had been analysed a GCN report was posted with the relevant information (Ward et al. 2006). Further observations of this burst with other telescopes confirmed that no optical afterglow was associated with this event.

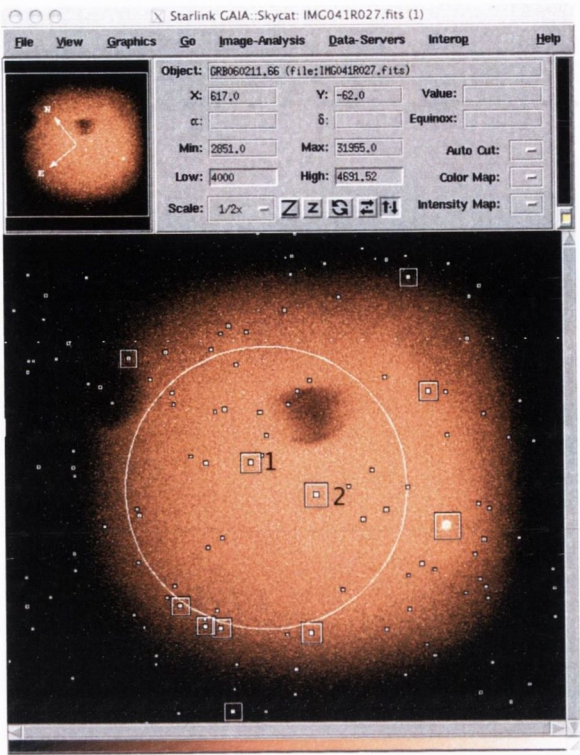


Figure 3-5: ROSS image of the field of GRB060211B, the sources 1 and 2 correspond to the same sources in Figure 3-3.

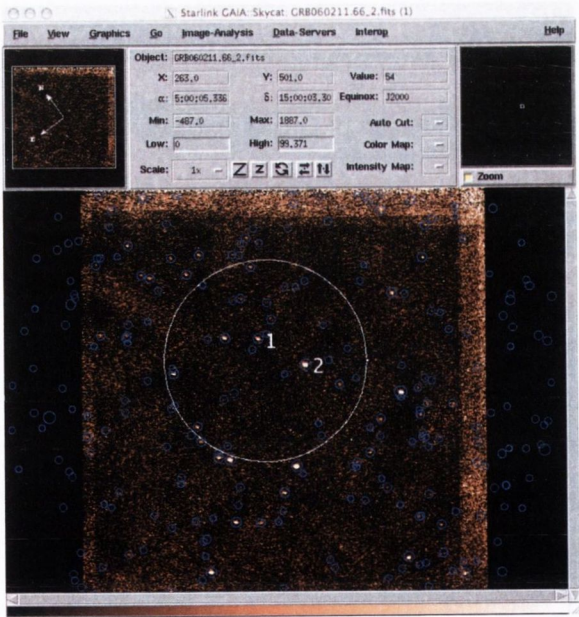


Figure 3-6: REMIR image of the field of GRB060211B, the sources 1 and 2 correspond to the same sources in Figure 3-3.

3.4 Summary of REM Results

Since the beginning of its operation there has been a number of successful results from REM. To date REM has successfully begun autonomous observations of 38 GRBs with 8 detections of afterglows. Although final results vary from burst to burst, it is clear REM has lived up to expectations as a GRB dedicated robotic telescope. In some cases observations commenced, without human intervention, within 10s of seconds after the trigger. A summary of GRBs (including non-detections) observed by REM is given in table 3.1.

REM has detected the afterglows of 9 bursts. The results of each set of observations are summarised briefly as follows.

GRB070508

REM observed the field of the GRB 070508 (Grupe et al. GCN 6383). A set of observations was performed automatically in the optical and near infrared filters (V, R, I and J, H, K, z). Preliminary analysis of the first frames at 4:34:11 UT (~16 min after the burst, ~2 min after the BAT trigger) shows a marginal detection of the UVOT afterglow at $H \sim 15.2$.

GRB070311

We observed the field reported by Mereghetti et al. (GCN 6189). A set of observations was performed automatically in the optical and near infrared filters (V, R, I and J, H, K, z) starting on 2007 March 11 at 01:53:45 UT, 43 s after the Integral trigger and 51 s after the GRB time. Preliminary analysis of the whole dataset shows a possible transient source at coordinate: RA: 05:50:08.21, DEC: 03:22:30.3. The approximate magnitude about 3 minutes after the burst time was $H \sim 14.3$.

GRB061222B

We imaged the field reported by Racusin et al. (GCN 5957). A first set of observations was performed automatically in the optical and near infrared (V,R,I and z' , J, H, K bands). A preliminary analysis allows to detect marginally the afterglow at $H \sim 16.0$ at 4:14:48 UT.

GRB061019

We imaged the field of GRB 061019 reported by Guidorzi et al. (GCN 5728, 5729). A first set of observations was performed automatically in the optical and near infrared (V, R, I and z' , J, H, K)

bands starting on October 19 5:23 UT. A preliminary analysis reveals an uncatalogued source of $K \sim 14.5$ at RA,DEC = (06:06:30.85, +29:34:13.3).

GRB060908

We automatically observed the field of GRB 060908 (Evans et al., GCN 5544) with the ROSS optical camera. Observations started at 09:06:21 UT, about 7 min after the burst, in the R, I and V bands. An uncatalogued fading source was observed in all filters at: RA: 02:07:18.3, DEC +00:20:31. This position is consistent with the one reported in GCN 5544 and GCN 5545. In the R initial image the source is at approximately $R \sim 17$ in 20 sec exposure time.

GRB060607

We imaged the field reported by Ziaee pour et al. (GCN 5233) . A first set of observations was performed automatically in the near infrared (J, H, K, z bands) starting on June 5:13:45 UT. An analysis reveals an uncatalogued source of $H \sim 13.3$ at RA,DEC = (21:58:50.4, -22:29:47).

GRB060418

We imaged the field reported by Falcone et al. (GCN 4966). Observations were performed automatically in the near infrared (J, H, K, z bands) soon after the GRB alert. A single bright source is found in the XRT error circle, not visible in the 2MASS survey. Its H magnitude is ~ 11.25 .

GRB060218

Observations were performed on 2006 Feb 25 from 00:16 to 00:30 UT under mediocre conditions just after the La Silla sunset with the R and J filters. The optical counterpart (Cusumano et al., GCN 4775; Marshall et al., GCN 4779; Mirabal et al., GCN 4784) was detected in both bands with magnitudes: $R = 17.05 \pm 0.17$, $J = 16.90 \pm 0.20$.

REM was primarily designed to observe GRB afterglows. However, since it began observations it has detected just a handful. This is in part due to the lack of knowledge about the early afterglow prior to the launch of the Swift mission. Early afterglow observations indicated that the GRB lightcurve would show a very bright early afterglow. This turned out not to be the case. The majority of GRBs are fainter than expected at these times. The limiting magnitudes of REM simply mean it cannot detect a large number of these bursts.

The most notable success of REM to date are the prompt observations of GRB060418 and GRB060607. For these two bursts observations were obtained within a minute of the trigger. Interpretation of the results allowed for the direct measurement of the initial GRB Lorentz factor Γ_0 (Molinari et al. 2007).

Although my involvement with REM was mainly as a DS, in the case of a GRB occurring during a specific shift, the responsibilities of analysing the data and interpreting the results were for the most part those of the DS. In the case GRB060418 and GRB060607, I was not “on-shift” as DS and therefore my involvement with the data reduction and interpretation was minimal. However, as is the case with many large programs within research, the project relies on a large group of people and published results of any specific observation represent a group effort. In the following section I will summarise the outstanding results obtained by REM for these two bursts.

GRB	Detection	Ref
GRB070802	N	GCN 6704
GRB070509	N	GCN 6395
GRB070508	Y	GCN 6385
GRB070311	Y	GCN 6190
GRB061222B	Y	GCN 5963
GRB061218	N	GCN 5941 / 5937
GRB061217	N	GCN 5928
GRB061202	N	GCN 5897 / 5889
GRB061025	N	GCN 5755
GRB061019	Y	GCN 5730
GRB060908	Y	GCN 5546
GRB060719	N	GCN 5372 / 5356
GRB060719	N	GCN 5343
GRB060714	N	GCN 5328
GRB060607	Y	GCN 5234
GRB060602B	N	GCN 5229
GRB060526	N	GCN 5178
GRB060522	N	GCN 5152
GRB060512	N	GCN 5121
GRB060418	Y	GCN 4967
GRB060413	Y	GCN 4963
GRB060313	N	GCN 4883 / 4868
GRB060218 / SN 2006aj	Y	GCN 4833
GRB060211B	N	GCN 4759
GRB060130	N	GCN 4619
GRB060115	N	GCN 4526
GRB060114	N	GCN 4515
GRB051105B	N	GCN 4223
GRB050607	N	GCN 3538 / 3523
GRB050509	N	GCN 3400 / 3404 / 3427
GRB050408	N	GCN 3205
GRB050306	N	GCN3076
GRB050209	N	GCN 3017
GRB050128	N	GCN 2999 / 3004
GRB041224	N	GCN 2911
GRB041223	N	GCN 2907
GRB041217	N	GCN 2856
GRB040903	N	GCN 2697

Table 3.1: Summary of GRBs observed by REM

3.5 Direct Measurement of GRB Lorentz Factor

When observed, the early stages of gamma-ray burst (GRB) afterglow light curves display a rich variety of phenomena at all wavelengths and contain significant information which may allow the determination of the physical properties of the emitting fireball. The launch of the Swift satellite (Gehrels et al. 2004), combined with the development of fast-slewing ground-based telescopes, has hugely improved the sampling of early GRB afterglow light curves. To date there are several published early optical/near-infrared (NIR) afterglow light curves that cannot be fitted with a simple power-law, testifying that the detections started before the afterglow began its regular decay. To explain the early behaviour of most of them (GRB990123: Akerlof et al. 1999; GRB021004: Kobayashi & Zhang 2003; GRB021211: Fox et al. 2003, Li et al. 2003; GRB041219A: Fan et al. 2005, Vestrand et al. 2005; GRB050730: Pandey et al. 2006; GRB050801: Roming et al. 2006; Rykoff et al. 2006; GRB050820A: Vestrand et al. 2006; GRB050904: Boer et al. 2006; Wei et al. 2006; GRB060206: Wozniak et al. 2006; Monfardini et al. 2006; GRB060210: Stanek et al. 2007) different mechanisms have been proposed, i.e. reverberation of the prompt emission radiation, reverse and refreshed shocks and/or energy injection and, lately, large angle emission (Panaitescu & Kumar 2007).

The main problem with using afterglows to measure burst properties, such as the Lorentz factor Γ , is the short timescales involved. Observations beginning only a few minutes after the burst may miss the vital peak of the afterglow emission, after which the afterglow decays in a self similar way, producing the observed synchrotron spectrum (see section 1.3.2). At this stage the evolution of the light curve is independent of the initial conditions, and any information on the relativistic motion in the GRB jet is lost. While models of the emission processes, involving internal shocks, can put a lower limit on the Lorentz factor (Ruderman 1975; Fenimore et al. 1993; Piran 2000; Lithwick & Sari 2001) this cannot give a precise measurement. Late-time measurements (weeks to months after the GRB) have shown $\Gamma \sim$ a few (Frail et al. 1997; Taylor et al. 2005), but a direct measure of the initial value had still been lacking.

REM, as previously discussed, is a fast-slewing robotic telescope designed primarily to capture the behaviour of the early afterglow. REM has observed two GRBs to date, namely GRB060418 and GRB060607 on short enough timescales to observe the afterglow peak. The results have been published by E. Molinari et al. (2007) on behalf of the REM team. As DS for the REM telescope I was involved in this project as part of the REM team. I was not DS at the time of either of these bursts and therefore had minimal input into the results. These observations show the onset of the

GRB	t_{peak} (s)	t_b (s)	α_r	α_d	κ	$\chi^2/\text{d.o.f.}$
060418	153^{+10}_{-10}	127^{+18}_{-21}	$-2.7^{+1.0}_{-1.7}$	$1.28^{+0.05}_{-0.05}$	$1.0^{+0.4}_{-0.4}$	33.3/16
060607A	180^{+5}_{-6}	153^{+12}_{-12}	$-3.6^{+0.8}_{-1.1}$	$1.27^{+0.16}_{-0.11}$	$1.3^{+0.9}_{-1.1}$	28.5/19

Table 3.2: Best fit values of the light curves of the first hour of observations for GRB 060418 and the first 1000 s for GRB 060607A (1σ errors), using the smoothly broken power-law reported in Sect. 3.5.2.1 with $t_{\text{peak}} = t_b(-\alpha_r/\alpha_d)^{1/[\kappa(\alpha_d-\alpha_r)]}$. The relatively large χ^2 of the fit results from small-scale irregularities present throughout the light curve (see Figures 3-7 and 3-8).

afterglow and its decay at NIR (Near - Infra Red) wavelengths.

3.5.1 Observations

GRB 060418 and GRB 060607A were detected by the Swift satellite at 03:06:08 UT (Falcone et al. 2006a) and 05:12:13 UT (Ziaeepour et al. 2006), respectively. The Swift XRT started observing the fields 78 and 65 s after the trigger, respectively. For both bursts a bright, previously uncatalogued fading source was singled out. The XRT light curves show prominent flaring activity, superimposed on the regular afterglow decay. For GRB 060418 a prominent peak, also visible in the BAT data, was observed at about 128 s after the trigger (Falcone et al. 2006b) while the XRT light curve of GRB 060607A was characterised by at least three flares (Page et al. 2006). The redshift is $z = 1.489$ for GRB 060418 (Dupree et al. 2006; Vreeswijk & Jaunsen 2006) and $z = 3.082$ for GRB 060607A (Ledoux et al. 2006).

The REM telescope reacted promptly to both GCN alerts and began observing the field of GRB 060418 64 s after the burst (39 s after the reception of the alert) and the field of GRB 060607A 59 s after the burst (41 s after the reception of the alert). For both targets a bright NIR source was identified (Covino et al. 2006a,b). ROSS could not observe these two GRBs due to maintenance work. REM followed the two events down to the sensitivity limits, adopting two different observing strategies. In the former case multi-colour $z'JHK'$ -band observations were carried out while in the latter case only the H filter was used in order to get a denser sampling of the light curve in just one band. All the photometric data are reported in Molinari et al. (2007).

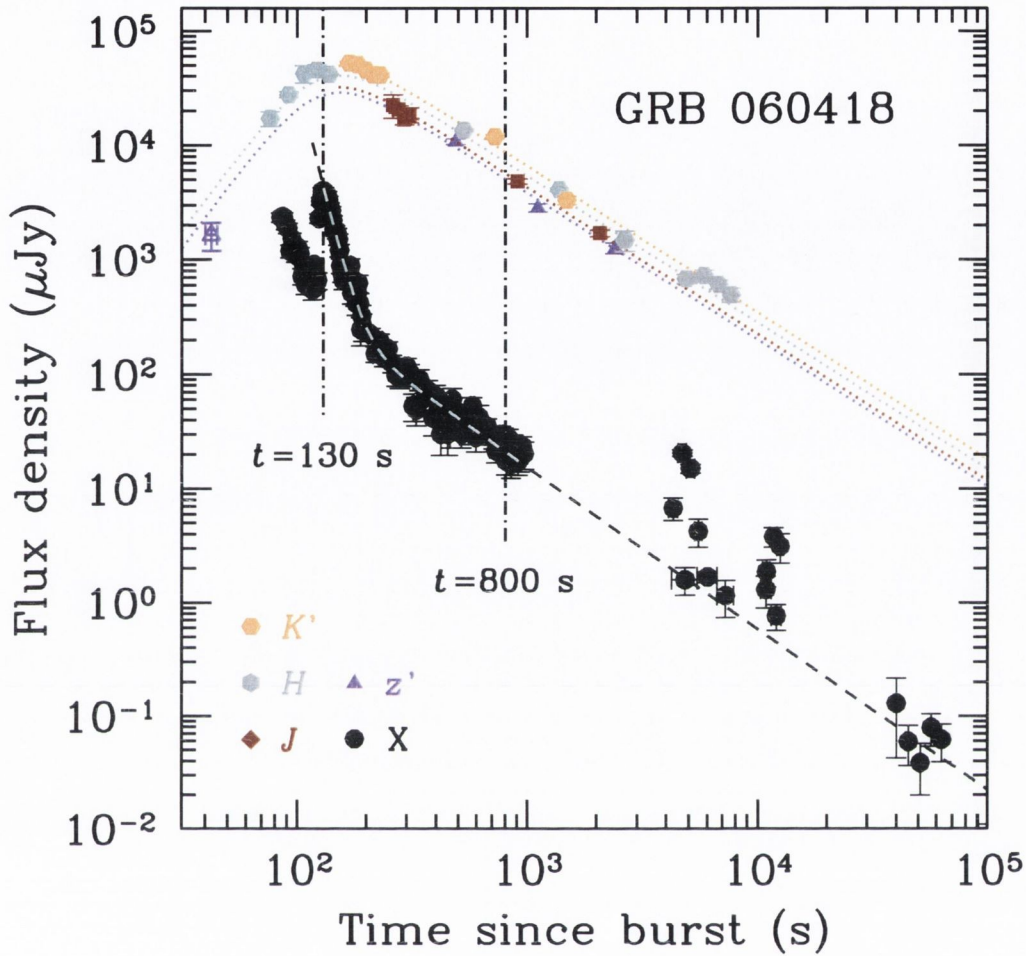


Figure 3-7: NIR and X-ray light curves of GRB 060418. The dotted lines show the models of the NIR data using the smoothly broken power law (see Sect. 3.5.2.1), while the dashed line shows the best-fit to the X-ray data. The vertical lines mark the epochs at which we computed the SED (Figure 3-9).

3.5.2 Results and Discussion

3.5.2.1 Light curve modelling

Figures 3-7 (GRB 060418) and 3-8 (GRB 060607A) show the NIR and X-ray light curves of the two afterglows. The X-ray data have been taken with the *Swift* XRT, and the NIR light curves are REM observations. The NIR light curves of the two events show a remarkable similarity. Both present an initial sharp rise, peaking at 100–200 s after the burst. The NIR flux of GRB 060418 decays afterwards as a regular power law. The NIR light curve of GRB 060607A shows a similar,

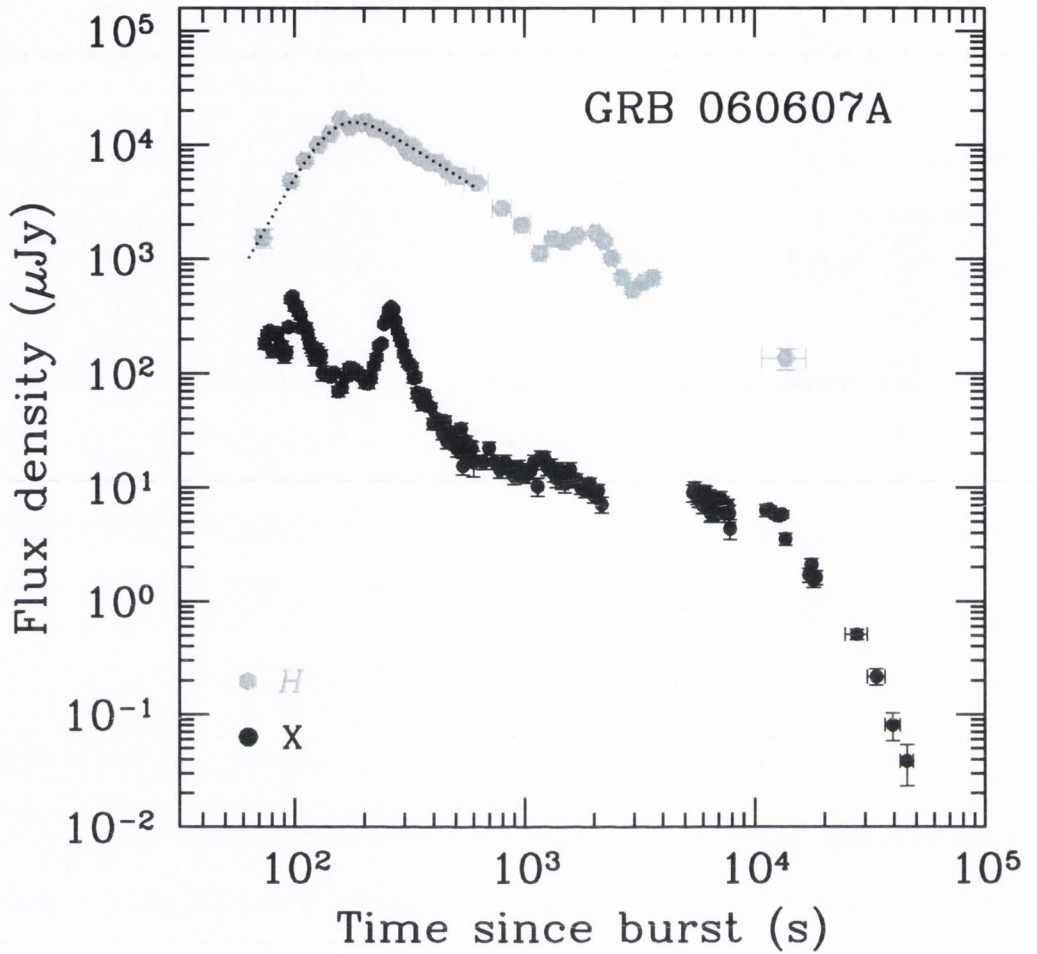


Figure 3-8: *H*-band and X-ray light curves of GRB060607A. The dotted line shows the model to the NIR data using the smoothly broken power law (see Section 3.5.2.1).

smooth behaviour up to ~ 1000 s after the trigger, followed by a rebrightening lasting ~ 2000 s.

The NIR light curves were fitted using a smoothly broken power law. The time at which the curve reaches its peak, t_{peak} , was measured for both bursts, giving values of 153 ± 10 s and 180 ± 9 s for GRB 060418 and GRB 060607A respectively.

As for many other GRBs observed by *Swift*, the early X-ray light curves of both events show several, intense flares superimposed on the power-law decay (Chincarini et al. 2007). In particular, for GRB060418 a bright flare was active between ~ 115 and 185 s. Excluding flaring times, the decay is then described by a power law with decay slope $\alpha_X = 1.42 \pm 0.03$. The X-ray light curve of GRB 060607A is more complex and presents two large flares within the first 400 s. After that the flux density decreases following a shallow power law (with small-scale variability), until steepening

sharply at $t \sim 10^4$ s.

From a comparison of the X-ray and NIR light curves of both bursts, it is apparent that the flaring activity, if any, is much weaker at NIR frequencies. It is thus likely that the afterglow peak, visible in the NIR, is hidden in the X-ray region. In the case of GRB 060418, thanks to our multicolour data, this can be confirmed by considering the NIR/X-ray spectral energy distribution (SED; Figure 3-9). At $t = 800$ s, when both the NIR and X-ray light curves are decaying regularly, the SED is described by a synchrotron spectrum, with the cooling frequency lying at $\nu_{\text{cool}} \sim 3 \times 10^{15}$ Hz. The spectral slopes at NIR and X-ray wavelengths are $\beta_{\text{NIR}} = 0.65 \pm 0.06$ and $\beta_{\text{X}} = 1.03 \pm 0.04$, respectively. A small amount of extinction in the host ($A_V = 0.10$ mag assuming the SMC extinction curve) was considered to make β_{NIR} consistent with the synchrotron expectation $\beta_{\text{NIR}} = \beta_{\text{X}} - 0.5$. The situation is clearly different at early times, when X-ray flaring is active: the X-ray component is softer ($\beta_{\text{X}} = 1.27 \pm 0.03$) and much brighter than the extrapolation of the NIR emission (even including the dust correction). This implies a different origin for the X-ray emission. For GRB 060607A, the light curve is complicated by several flares. As there are no multicolour data, a detailed analysis is not possible.

3.5.2.2 Determination of the Lorentz factor Γ_0

The spectral and temporal analysis of these two bursts agrees with the interpretation of the NIR afterglow light curves as corresponding to the afterglow onset, as predicted by the fireball forward shock model (Sari & Piran 1999; Meszaros 2006). According to the fits, the light curves of the two afterglows peak at a time $t_{\text{peak}} > T_{90}$ as expected in the impulsive regime outflow ('thin shell' case). In this scenario the quantity $t_{\text{peak}}/(1+z)$ corresponds to the deceleration timescale $t_{\text{dec}} \sim R_{\text{dec}}/(2c\Gamma_{\text{dec}}^2)$, where R_{dec} is the deceleration radius, c is the speed of light and Γ_{dec} is the fireball Lorentz factor at t_{dec} . It is therefore possible to estimate Γ_{dec} (Sari & Piran 1999), which is expected to be half of the initial value Γ_0 (Panaitescu & Kumar 2000; Meszaros 2006). According to Sari & Piran (1999) for a homogeneous surrounding medium with particle density n , we have

$$\Gamma(t_{\text{peak}}) = \left[\frac{3E_{\gamma}(1+z)^3}{32\pi n m_p c^5 \eta t_{\text{peak}}^3} \right]^{1/8} \approx 160 \left[\frac{E_{\gamma,53}(1+z)^3}{\eta_{0.2} n t_{\text{peak},2}^3} \right]^{1/8}, \quad (3.3)$$

where $E_{\gamma} = 10^{53} E_{\gamma,53}$ erg is the isotropic-equivalent energy released by the GRB in gamma rays, $t_{\text{peak},2} = t_{\text{peak}}/(100 \text{ s})$, $\eta = 0.2 \eta_{0.2}$ is the radiative efficiency and m_p is the proton mass. We use $E_{\gamma} = 9 \times 10^{52}$ erg for GRB 060418 (Golenetskii et al. 2006) and $E_{\gamma} \sim 1.1 \times 10^{53}$ erg for GRB 060607A (Tueller et al. 2006). Substituting the measured quantities and normalising to the

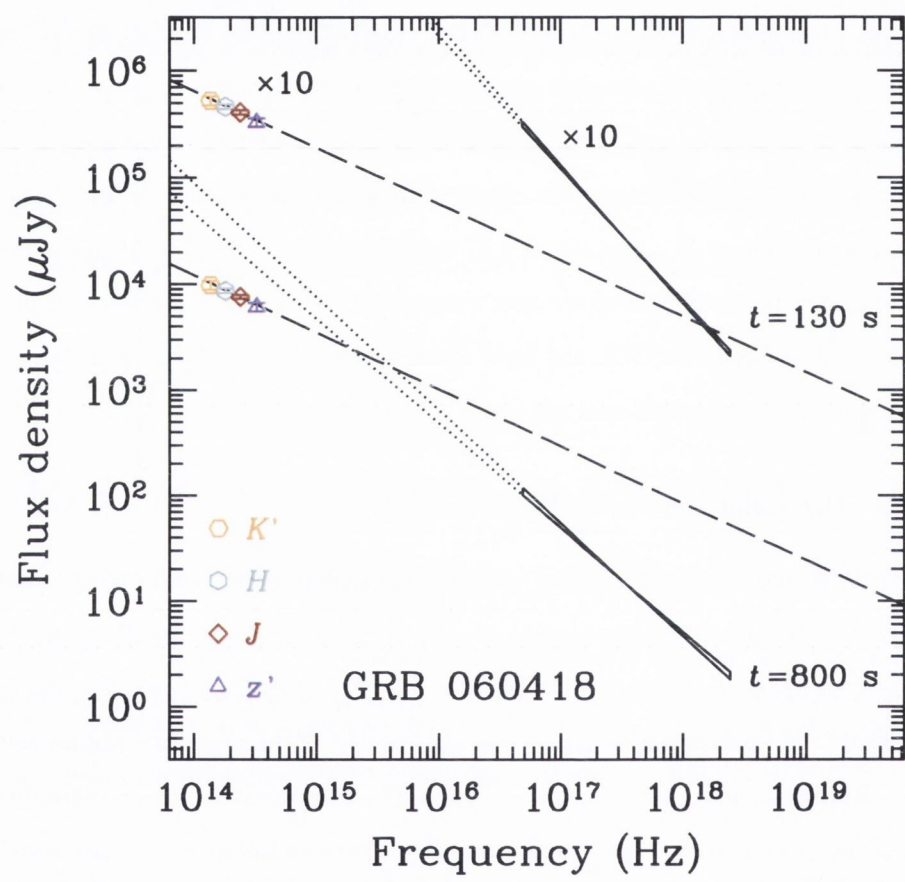


Figure 3-9: SED of the GRB 060418 afterglow at 130 and 800 s after the trigger. NIR data have been corrected for Galactic and host extinction ($A_V = 0.74$ and 0.10 mag, respectively).

typical values $n = 1 \text{ cm}^{-3}$ and $\eta = 0.2$ (Bloom et al. 2003), we infer for both bursts a value of $\Gamma_0 \approx 400 (\eta_{0.2} n)^{-1/8}$. This value is very weakly dependent on the unknown parameters n and η , and therefore provides a robust determination of Γ_0 .

The determination of t_{peak} is in principle affected by the choice of the time origin t_0 , which we set to the BAT trigger time (Lazzati & Begelman 2006; Quimby et al. 2006). These authors have, however, shown that this effect is small, and mostly affects the rise and decay slopes rather than the peak time (especially when t_{peak} is larger than the burst duration, as for GRB 060418 and GRB 060607A). The measurement of Γ_0 is thus not very sensitive to the exact choice of t_0 .

3.5.3 Conclusions

The REM discovery of the afterglow onset has demonstrated once again the richness and variety of physical processes occurring in the early afterglow stages. The very fast response observations presented here provide crucial information on the GRB fireball parameters, most importantly its initial Lorentz factor. This is the first time that $\Gamma(t_{\text{peak}})$ has been directly measured from the observations of a GRB. The measured Γ_0 value is well within the range ($50 < \Gamma_0 < 1000$) envisaged by the standard fireball model (Piran 2000; Guetta et al. 2001; Soderberg & Ramirez-Ruiz 2002; Meszaros 2006). It is also in agreement with existing measured lower limits (Lithwick & Sari 2001; Zhang et al. 2006). Although the values for Γ_0 are comparable for GRB 060418 and GRB 060607A, as noted in the introduction prompt optical detections have shown very different behaviours, so this value should not be taken as common to every GRB.

Using $\Gamma_0 = 400$ it is possible to derive other fundamental quantities characterising the fireballs of the two bursts. In particular, the deceleration radius is $R_{\text{dec}} \approx 2ct_{\text{peak}}[\Gamma(t_{\text{peak}})]^2/(1+z) \approx 10^{17} \text{ cm}$. This is much larger than the scale of $\sim 10^{15} \text{ cm}$ where the internal shocks are believed to power the prompt emission (Meszaros & Rees; Rees & Meszaros 1994), thus providing further evidence for a different origin of the prompt and afterglow stages of the GRB.

4

High Resolution Spectroscopy of GRB021004

4.1 Introduction

In the first of the preceding three Chapters dedicated to work carried out on high resolution spectroscopy of GRB host environments, we try to disentangle the various absorption components associated with the circumburst environment. I began work with a collaboration, the PI of which is Fabrizio Fiore, dedicated to obtaining high resolution VLT spectroscopy in November 2003, and visited Rome Observatory. The purpose of the visit was to learn the techniques needed to reduce and analyse UVES (Ultra-violet Visible Echelle Spectrograph) data. I then began work on GRB021004. I primarily worked on the reduction and analysis of the spectra, leading to the evaluation of column densities of various absorption components, the results of which are used to estimate ionisation conditions in the GRB host environment. The results in this Chapter have been published by Fiore et al. (2005).

4.2 A Flash in the Dark

For a few hours after their onset, Gamma Ray Bursts (GRBs) are the brightest beacons in the far Universe, offering a superb opportunity to investigate both GRB physics and high redshift galaxies. Tens of minutes after a GRB, its optical afterglow can be as bright as magnitude 13–15; a few hours later a magnitude of 16–19 is often achieved. Bright examples are the cases of GRB 990123 ($z=1.600$), for which the reverse shock reached $R=9$ –10 mag 1 minute after the GRB and the optical afterglow reached $R=14$ mag 12 minutes after the GRB (e.g. Akerlof et al. 1999, Galama et al. 1999), and GRB 030329 ($z=0.1685$), for which the optical afterglow reached $R=12.7$ mag at 1.5 hours from the GRB and decreased down to $R=19$ mag after ~ 10 days (e.g. Price et al. 2003; Stanek et al. 2003). High resolution (a few tens of km/s in the optical band), high quality (signal-to-noise > 10 per resolution element) spectra can therefore be gathered, provided that the afterglow is observed rapidly by 8m class telescopes. Since GRBs are associated with the collapse of massive stars (see Woosley 1993, Paczynski 1998, MacFadyen & Woosley 1999, Vietri & Stella 1998 for theoretical reasons and Galama et al. 1998, Stanek et al. 2003, Hjorth et al. 2003 and Della Valle et al. 2003 for observational reasons), this is expected to open a new window in the study of the environment in which intermediate to high redshift star-formation occurs and, in particular, on the physical, chemical and dynamical state of the inter-stellar matter (ISM) of the GRB host galaxies.

The study of $z > 1$ galaxies has so far mostly relied upon Lyman-break galaxies (LBGs) at $z=3$ –4 (see e.g. Steidel et al. 1999) and galaxies which happen to be along the line of sight to bright background QSOs. Some of these systems are associated with damped $\text{Ly}\alpha$ systems (DLA, see e.g. Pettini et al. 1997). However, LBGs are characterized by pronounced star-formation and their inferred chemical abundances may be related to these regions rather than being representative of typical high z galaxies. GRB afterglows provide an independent tool to study the ISM of high z -galaxies. Savaglio, Fall & Fiore (2003) studied the metal abundances in three GRB host galaxies using low-medium resolution spectroscopy and a curve-of-growth analysis. They found metal-column-densities higher than in QSO-DLAs and a strong inverse correlation between $[\text{Si}/\text{Zn}]$, $[\text{Cr}/\text{Zn}]$ and $[\text{Fe}/\text{Zn}]$ and the Zn column density, indicating a dense environment and large dust depletion. On the other hand, Vreeswijk et al. (2004) found indications for a relatively low metallicity and low dust content in the ISM of the $z=3.372$ host galaxy of GRB 030323, using FORS2 low and intermediate resolution spectroscopy. Using again a curve of growth analysis, and taking advantage of ultra-deep *Gemini* multi-object spectrograph observations, Savaglio et al. (2004) studied the ISM of a sample of faint K-band selected galaxies at $1.4 < z < 2.0$, finding MgII and FeII abundances

much higher than in QSO-DLAs and similar to those in GRB host galaxies.

More can be done with high-resolution ($R > 20000$) observations because: (i) lines can be separated; (ii) metal column densities can be measured through a fit to the line profile; (iii) fainter lines can be measured; (iv) information on the gas dynamics in the GRB host galaxies can be derived. Furthermore, as suggested by the comparison of the Vreeswijk et al. (2004) and the Savaglio et al. (2004) studies, GRB afterglows allow us to probe galaxy ISM at much higher redshifts than even ultra-deep, standard galaxy spectroscopy, such as the Gemini Deep Deep Survey.

For all these reasons we started a pilot program to observe bright GRB afterglows of promptly localized GRBs with UVES@VLT. The program has been conceived and designed to make full use of the GRB afterglows discovered by the GRB-dedicated *Swift* mission.

The HETE-2 FREGATE, WXM and SXC instruments detected GRB021004 on 2002 Oct. 4 12:06:13.57 UT (Shirasaki et al. 2002). The WXM flight localization software produced a reliable and relatively accurate position 49 seconds after the burst for GRB021004 (error box of 30' radius). A bright optical counterpart was identified 10 minutes after the triggers by Fox et al. (2002, 2003). Ground analysis of the HETE2 data performed a few hours after each GRB improved the localization of the event, providing error boxes of 2' radius. UVES observations started 13.52 hours after the GRB021004 trigger (Savaglio et al. 2002).

Optical low to intermediate resolution spectroscopy of the afterglow of GRB021004 was obtained by Moller et al. (2003), Mirabal et al. (2003), Matheson et al. (2003) and Schaefer et al. (2003). One of the main conclusions of these works is that density fluctuations on top of a regular wind density profile are able to explain the presence of both strong, blue-shifted, high-ionisation absorption line systems and irregularities in the optical light curve. Schaefer et al. (2003) propose a scenario where a clumpy wind originates from a massive star progenitor (a Wolf-Rayet star), while Mirabal et al. (2003) suggest that the ionised absorption takes place in a fragmented shell nebula around the GRB progenitor. A subsequent study by Chen et al. (2006), however, discards this scenario, suggesting such a wind bubble could not survive the intense UV radiation from the GRB explosion. Their conclusion is that the observed blue shifted absorbers are merely line-of-sight intervening systems. In this study of the UVES high resolution spectra of GRB021004 we attempt to disentangle the numerous components and apply our own conclusions about the possibility of wind scenario.

Date UT	Dichroic	B. Arm C.W.	R. Arm C.W.	slit ^a	seeing ^a	exposure ^b	time since GRB ^c
05/10/02 01:37:37	2	4370Å	8600Å	1	≤ 1	30	13.52
05/10/02 02:10:53	1	3460Å	5800Å	1	≤ 1	30	14.08
05/10/02 04:09:54	1	3460Å	5800Å	1	≤ 1	60	16.06

Table 4.1: *Journal of observations.* ^aarcsec; ^bmin; ^chr

4.3 Observations and data reduction

In the framework of ESO program 70.A–0599 we observed the afterglow of GRB021004 with the high resolution UV–visual echelle spectrograph (UVES, Dekker et al. 2000), mounted at the VLT–UT2 telescope. Table 4.3 gives the log of the observations used. A further 1 hour dichroic 1 observation is available in the ESO archive, but we were not able to extract a reliable spectrum from this observation, which has therefore been discarded. In order to maximize the signal to noise ratio the CCD was rebinned to 2×2 pixels. The data reduction has been performed using the UVES pipeline (<http://www.eso.org/observing/dfo/quality/UVES/pipeline/>). The final useful spectra extend from about 4250Å to about 9400Å and were rebinned to 0.1Å to increase the signal to noise. The resulting resolution element, set to two pixels, ranges then from 14 km/s at 4200Å to 6.6 km/s at 9000Å. The noise spectrum, used to determine the errors on the best fit line parameters, has been calculated from the real background subtracted and rebinned spectrum using line-free regions. This therefore takes into account both statistical errors and systematic errors in the pipeline processing and background subtraction.

Figures 4.1 and 4.2 plot the full UVES spectrum of GRB021004, for which both UVES dichroics, and both red and blue arms, were used, allowing us to obtain a particularly wide spectral coverage, extending from $\sim 4250\text{Å}$ to $\sim 9400\text{Å}$.

4.4 Column Densities

The line fitting was performed using the MIDAS package FITLYMAN (Fontana & Ballester 1995). This uses a Voigt profile and yields independently the column density N and the Doppler parameter b for each absorption component. The Doppler parameter corresponds to the broadening of the line width due to the thermal motion of the molecules. For each absorption system several lines, spread over the entire spectral range covered by the UVES observations, were fitted simultaneously, using the same number of components for each line, and the same redshift and b value for each component.

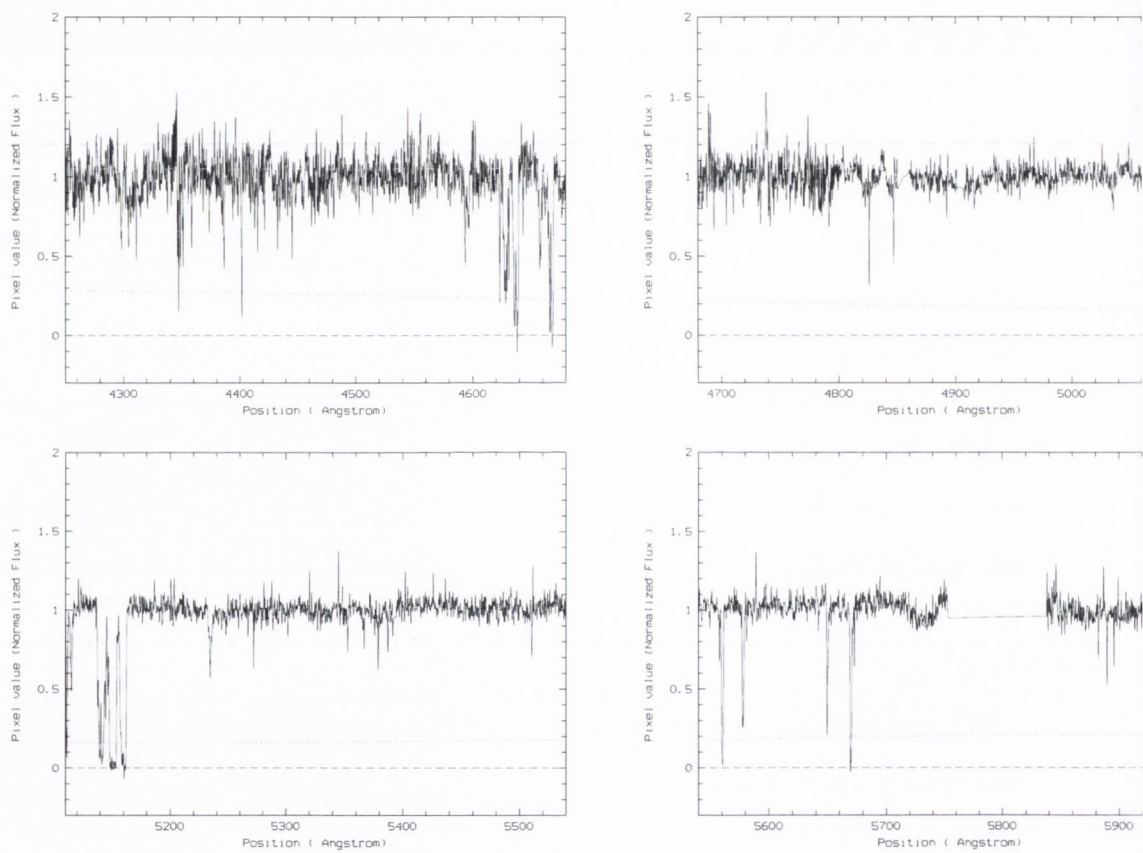


Figure 4-1: UVES spectrum of the GRB021004 afterglow smoothed with a Gaussian function with $\sigma = 1.5$ pixel . The dotted line is the error spectrum.

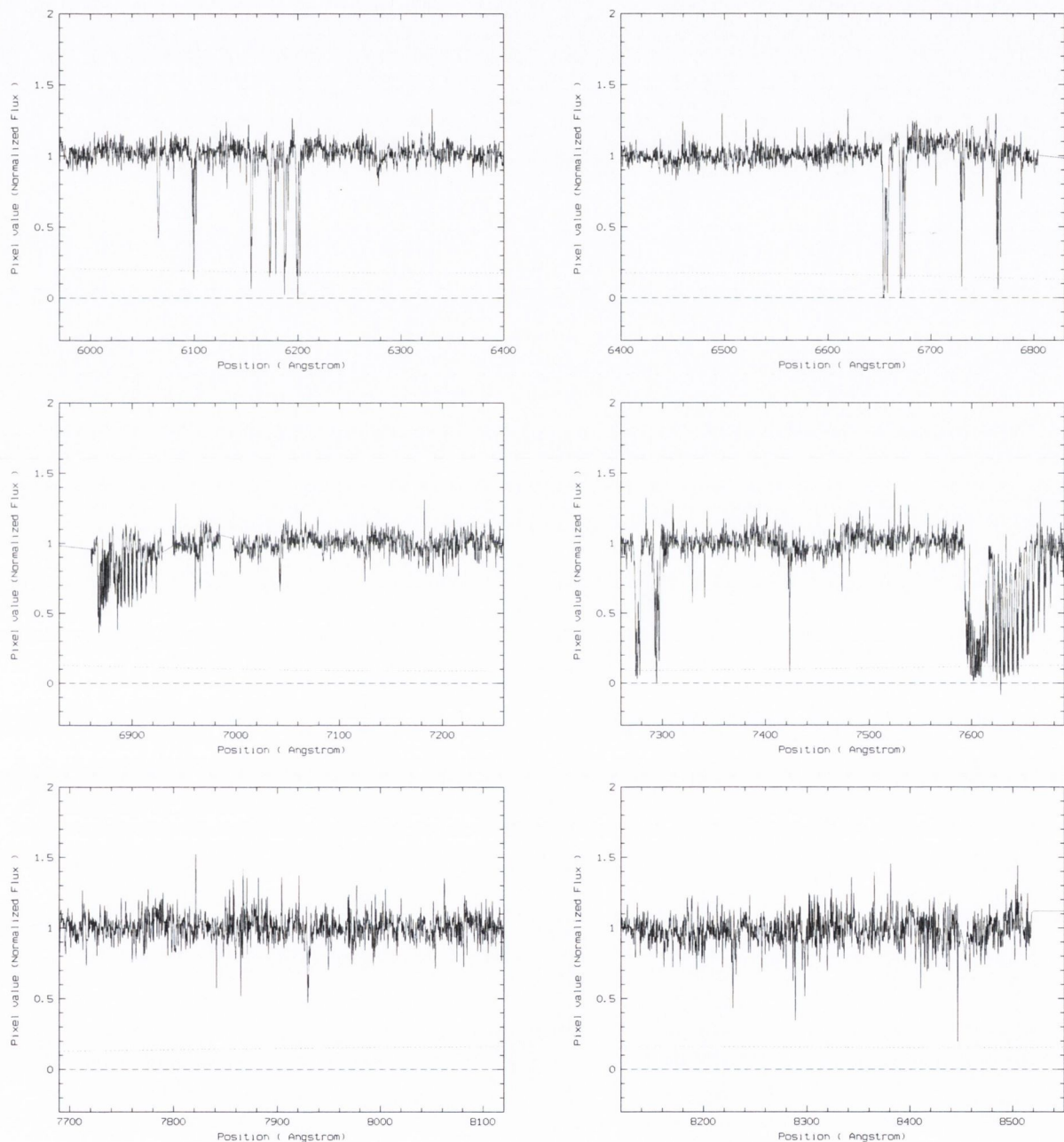


Figure 4-2: UVES spectrum of the GRB021004 continued.

We consider the absorption systems at the following redshifts and velocities (in km/s) with respect to the Ly α emission of the host galaxy (Mirabal et al. 2003): $z=2.328$, $v=0$ (system A in Figure 4-3); $z=2.328$, $v=-139$ km/s (system B); $z=2.328$, $v=-224$ km/s (system C); $z=2.321$, $z=2.298$; $z=2.296$. For these systems we detected CIV, CII, SiIV, AlII, AlIII, MgII and FeII lines (see Table 4.2). We report in the Table 4.2 also the tentative identification of a SiII λ 1304 line at $z=2.2953$. This is close to but not coincident with the redshift of systems $z=2.296$. We therefore consider this identification uncertain, and we do not consider this line in the following analysis.

Unfortunately, the Ly α absorption associated with the $z=2.328$ systems falls exactly in the gap between the dichroic 1 and 2 blue arm spectra, and therefore is not covered in this study. ZnII and CrII absorption lines for the main $z=2.328$ and $z=2.321$ systems fall in the region affected by atmospheric telluric features and are therefore not accessible.

Figure 4-3 shows the CIV and SiIV doublets of the above 6 systems. Note that the CIV λ 1548 lines of the $z=2.328$ A,B,C systems are strongly blended with the CIV λ 1550 line of the $z=2.321$ system, while the SiIV λ 1402 line of the $z=2.298$ system is blended with the SiIV λ 1393 line of the $z=2.321$ system. Each of the six systems actually comprises several components, within a velocity range of several tens of km/s. For this reason the identification of the different systems is somewhat subjective, the true message being that the geometry and kinematics of the ISM clouds probed by the GRB line of sight are complex. Nevertheless, sticking to the above system identifications will be useful.

There are 13 lines in Table 4.2 associated with the $z=2.328$ systems, 5 lines associated with the $z=2.321$ system, and up to 17 lines associated to the $z=2.296$ - 2.298 systems. Some of these lines can be split further in several components. To test the robustness of the fit, in terms of accuracy and stability of the results, we performed many fits, using several combination of lines/systems. We found that the fits presented below are a good compromise between increasing the statistical precision of the fit, obtained increasing the number of lines fitted simultaneously, and the stability/repeatability of the results.

For the $z=2.328$ A,B,C and $z=2.321$ systems we fitted simultaneously the CIV λ 1550, 1548, CII λ 1334, CII* λ 1335, SiIV λ 1402, 1393 AlII λ 1670 and the AlIII λ 1854 line. We excluded from the fit the $z=2.328$ AlIII λ 1862 line because its blue wing is strongly blended with another line, and the $z=2.321$ AlIII λ 1862 line because it is strongly blended with the FeII λ 2600 line of one of the components of the $z=1.38$ intervening system. For the same systems we also fitted the FeII λ 2382, FeII λ 2374 FeII λ 2344 FeII λ 1608, MgII λ 2803 and MgII λ 2796 lines simultaneously. Figure 4-4

System	v. shift ^a	SiIV	CIV	CII	CII*	AlII	FeII	MgII
2.328_A	0	15.30±0.56	>15.2	13.40±0.45	13.90±0.58	13.55±0.35 ^c	13.34±0.15	13.82±0.24
2.328_B	-139	14.27±0.16	>14.4	<13.2	<13.2	12.23±0.35	12.53±0.24	12.93±0.60
2.328_C	-224	13.24±0.17	14.40±0.11	<13.2	<13.2	<12.0	<12.3	<12.8
2.321	-632	14.11±0.08	15.04±0.05	<13.2	<13.2	<12.0	<12.3	<12.8
2.298	-2729	13.43±0.33	14.16±0.20	14.28±0.20 ^b	<13.2	<12.0	12.68±0.20	13.22±0.10
2.296	-2913	13.79±0.16	14.72±0.25	13.43±0.40	^b	<12.0	<12.3	12.68±0.21

Table 4.2: *GRB021004. Logarithmic ion column densities in cm^{-2} . Errors, upper and lower limits are 90% confidence intervals; ^akm/s; ^b the z=2.296 CII* line is completely blended with the z=2.298 CII line; ^c for system z=2.328_A we measured also a column density of AlIII of 13.66 ± 0.30 .*

shows the line spectra in velocity space, along with the best fit model, while Table 4.2 presents the best fit abundances along with the velocity shift of each system with respect to the redshift of the host galaxy, assumed to be 2.328 for GRB021004 (Mirabal et al. 2003). We used 2 components for the z=2.328_A system, and 1 component for the other 3 systems. The best fit Doppler parameter b ranges from a minimum of 12 ± 6 km/s (one of the components of the z=2.328_A system) up to a maximum of 107 ± 10 km/s (system z=2.321). Of course, different b values are obtained using a higher (or lower) number of components. Unfortunately, the signal to noise ratio of our spectrum is not good enough to identify unambiguously the different components. On the other hand, we verified that the total best fit column density of each system is stable, within the statistical errors, changing the number of components in each system.

Similar series of fits were performed for the z=2.296 and z=2.298 systems, for which we used 1 and 2 components, respectively (see Figure 4-5). Table 4.2 gives again the best fit abundances for these 2 systems. The best fit Doppler parameter b ranges from 9 ± 7 km/s to 40 ± 13 km/s.

The detection of both high and low ionisation lines, feasible thanks to the extremely wide spectral coverage achieved by UVES, allows us to obtain constraints on the ionisation status of the gas responsible for the UV absorption, by comparing ion column density ratios with the predictions of photoionisation codes. Unfortunately, we were not able to measure column densities of different ions of the same element, except for CII/CIV and AlII/AlIII for system z=2.328_A, and CII/CIV for system z=2.298. In the other cases we are forced to use ratios of column densities of different ions of different elements in this analysis. These estimates of the gas ionisation parameter are therefore somewhat degenerate with respect to relative element abundances. We used the Grevesse & Anders (1989) meteoritic abundances with extensions by Grevesse et al. (1993).

Figure 4-6 shows the logarithmic ratio between the CIV, CII, FeII, AlII and MgII column den-

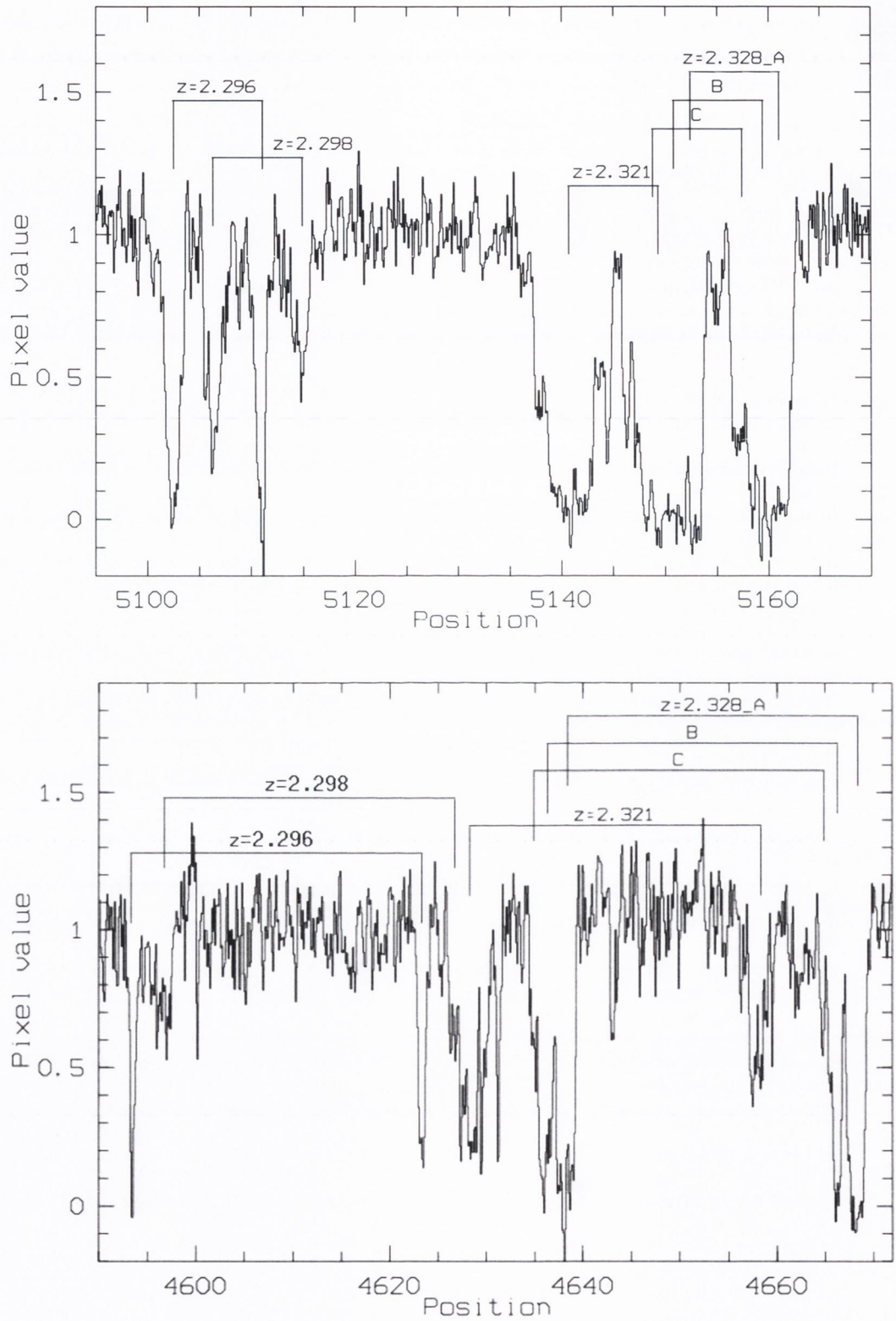


Figure 4-3: CIV (upper panel) and SiIV (lower panel) absorption systems in the UVES spectra of GRB021004 for $z=2.328$ (see Table 4.4)

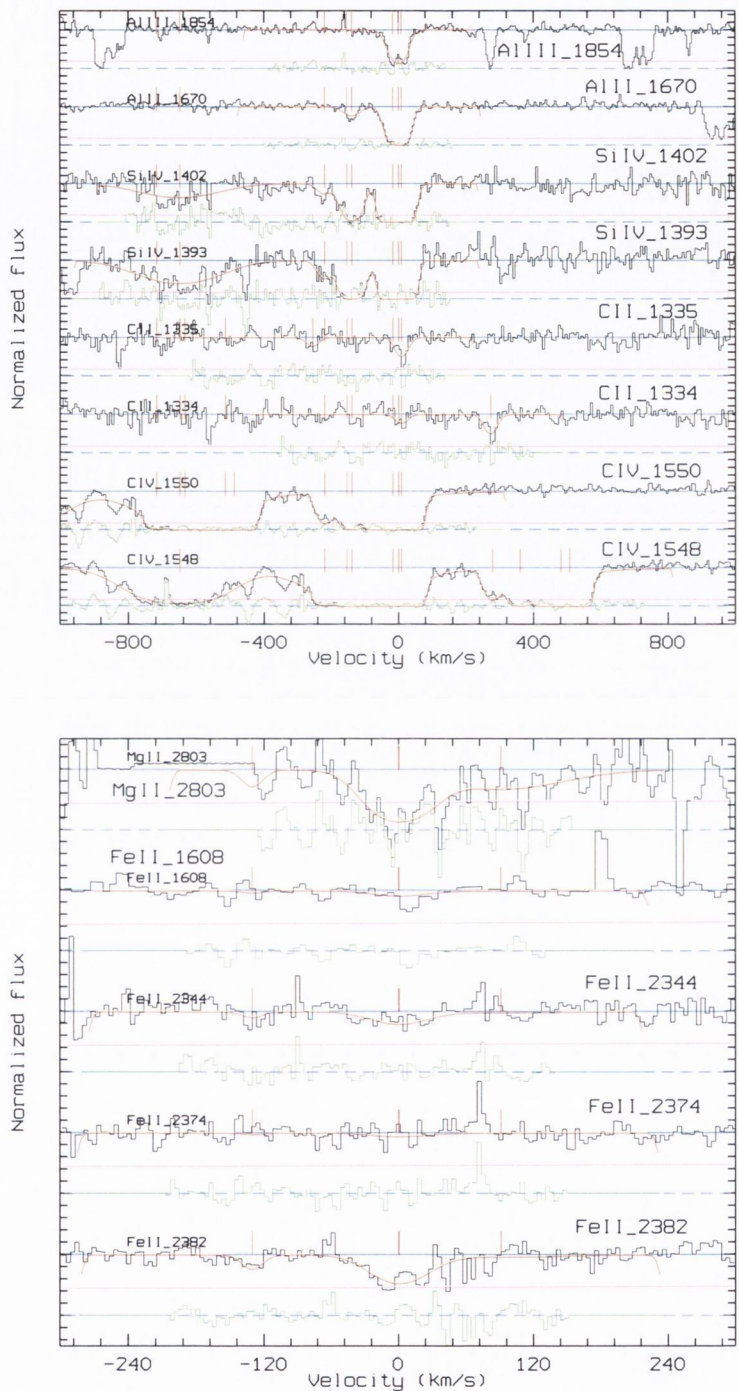


Figure 4-4: GRB021004. Upper panel: UVES spectrum near the C IV λ 1550, 1548, C II λ 1334, C II λ 1335, Si IV λ 1404, 1393, Al III λ 1670 and Al III λ 1854 lines for the $z=2.328$ and $z=2.321$ systems in velocity space, along with the best fit model (solid line) and residuals (grey). Lower panel: same for the Fe II λ 2382, Fe II λ 2374, Fe II λ 2344, Fe II λ 1608 and Mg II λ 2803 lines. The zero in the velocity scale refers to the redshift of the host galaxy.

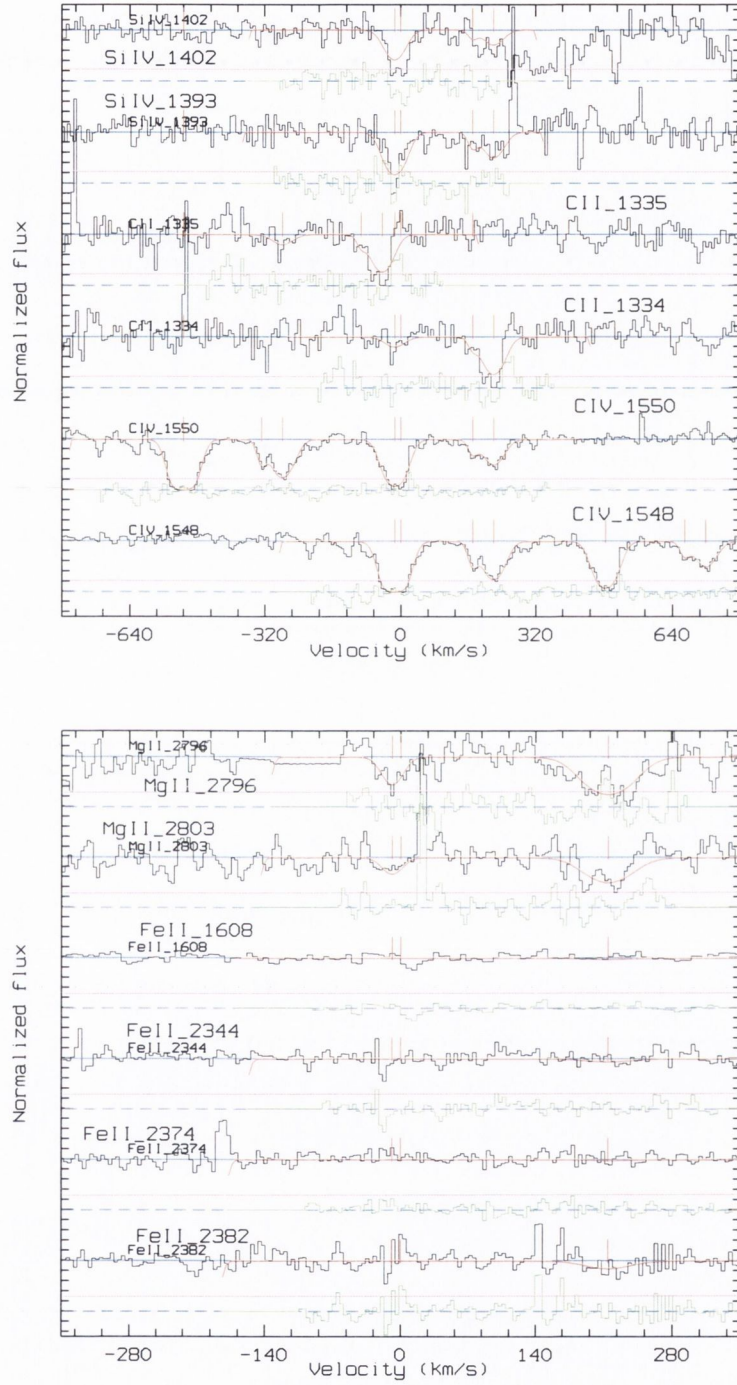


Figure 4-5: GRB021004. Upper panel: UVES spectrum near the CIV $\lambda\lambda$ 1550, 1548, CII λ 1334, CII λ 1335, SiIV $\lambda\lambda$ 1404, 1393 lines for the $z=2.298$ and $z=2.296$ systems in velocity space, along with the best fit model (solid line) and residuals (grey). Lower panel: same for the FeII λ 2382, FeII λ 2374, FeII λ 2344, FeII λ 1608, MgII λ 2803 and MgII λ 2796 lines. The zero in the velocity scale refers to $z=2.296$.

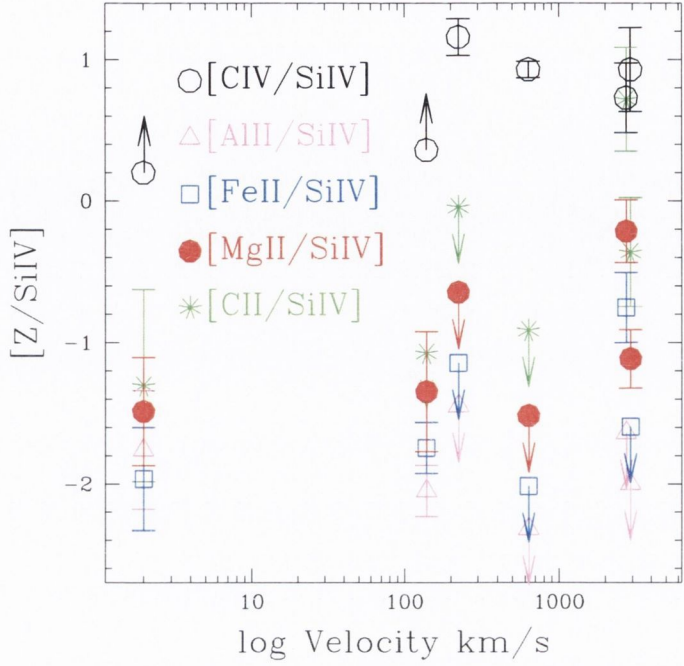


Figure 4-6: The logarithmic ratio between the CIV, CII, FeII, AlII and MgII column densities to that of SiIV for the six absorption systems as a function of the negative velocity shift with respect to the redshift of the host galaxy.

sities and that of SiIV for the six absorption systems as a function of the velocity shift with respect to the redshift of the host galaxy. No large variation of the ion ratios are seen for the six systems. We compared these line ratios to the predictions obtained by simulating a gas cloud illuminated by an ionising continuum. We used Cloudy (vs 90.04, Ferland et al. 2002) to build grids of photoionisation models as a function of U , the ionisation parameter. U is defined as the ratio between the ionising photon density and the electron density of the gas. It is computed assuming a constant density profile throughout the cloud, and a plane parallel geometry. We studied gas densities between 1 cm^{-3} and 10^8 cm^{-3} . The ionising continuum was assumed to be a power law, $F(E) \propto E^{-\Gamma}$ photons $\text{cm}^{-2} \text{ s}^{-1}$, with cutoffs at low and high energies. The high energy cutoff is fixed at 10^{21} Hz , while we run the simulations for different low energy cutoffs, from 10^0 Hz to 10^{14} Hz . We produced several sets of simulations with Γ in the range 1–2. The ionising continuum is constant in time. GRBs are highly variable sources and the ionisation structure of the gas can be better studied using a time-dependent photoionisation code, such as those of Nicastro et al. (1999) and Perna & Lazzati (2002). Nevertheless, our simpler approach is instructive in identifying general trends.

The predicted photoionisation equilibrium ion ratios of [MgII/SiIV], [FeII/SiIV], [AlII/SiIV]

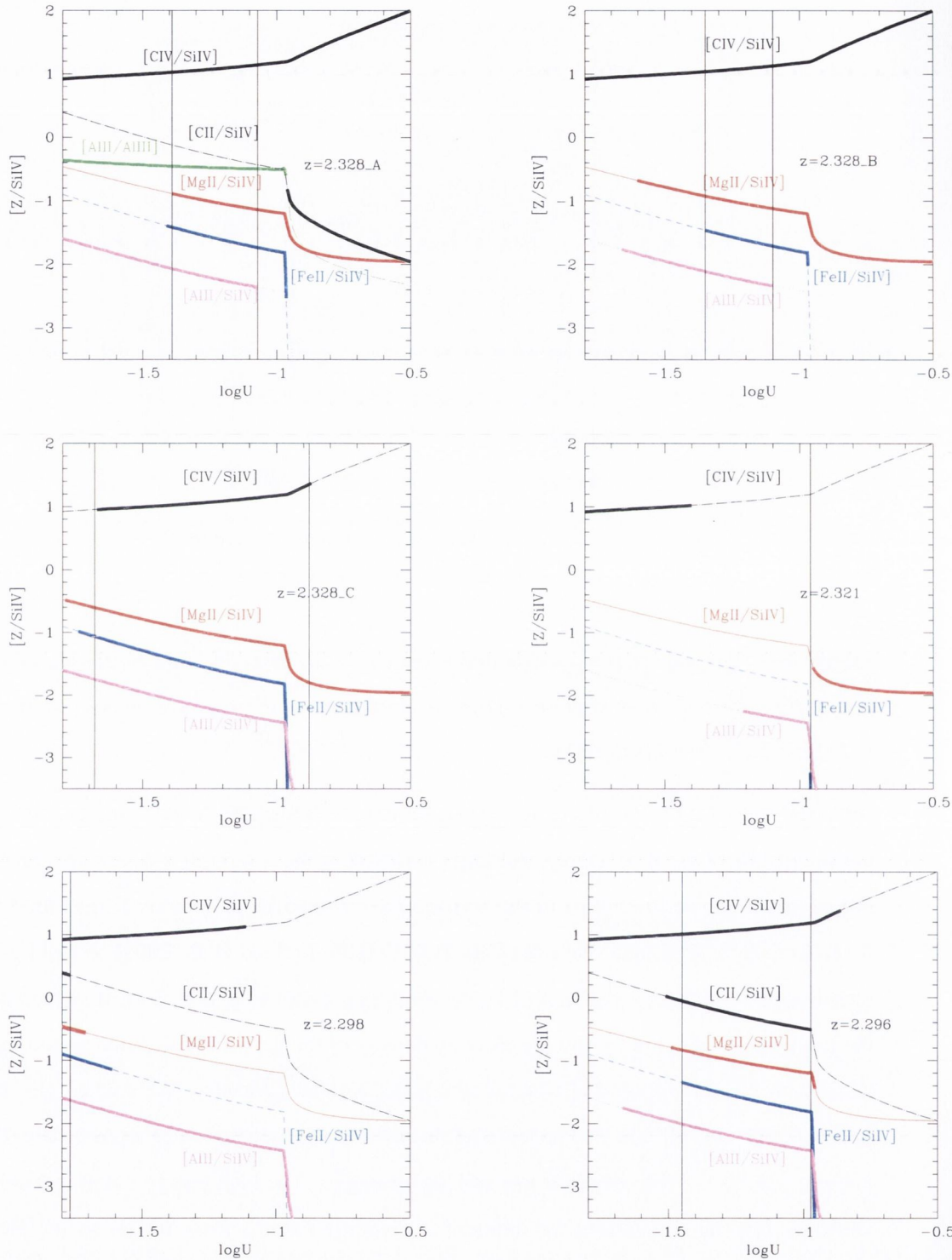


Figure 4-7: Ion ratios from *CLOUDY* models for the six absorption systems, assuming a gas density of 1 cm^{-3} : $[\text{MgII}/\text{SiIV}]$ = solid red curves, $[\text{FeII}/\text{SiIV}]$ = dashed blue curves, $[\text{AlII}/\text{SiIV}]$ = dotted magenta curves and $[\text{CIV}/\text{SiIV}]$ and $[\text{CII}/\text{SiIV}]$ = dot-dashed black curves. The line indicating the model values is thick when it is consistent within 90% with the measured ion ratios. The vertical solid lines mark the range of allowed U values in each panel.

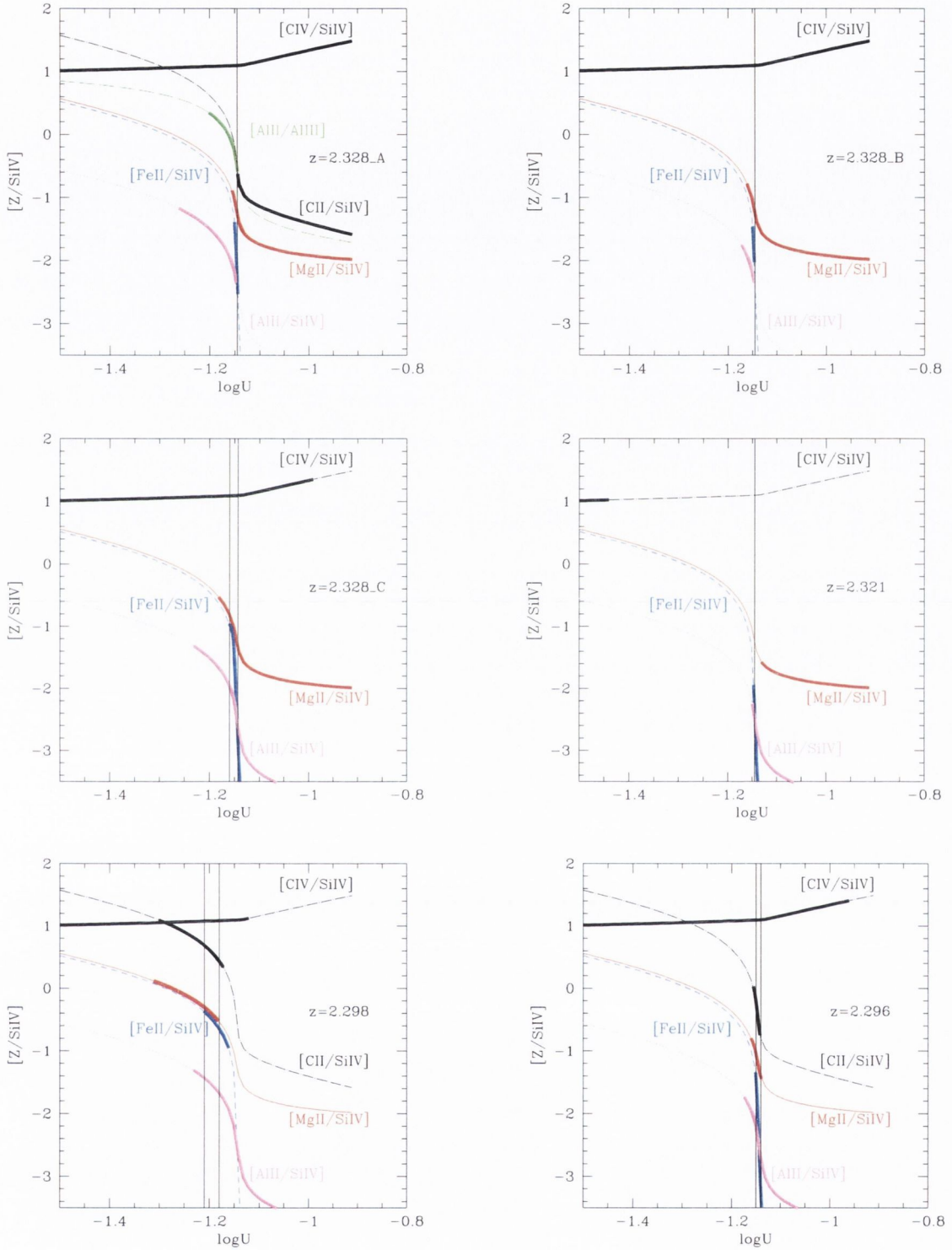


Figure 4-8: Ion ratios from CLOUDY photoionisation models for the six absorption systems assuming a gas density of 10^8 cm^{-3} . Curves as in Figure 4-7. The line indicating the model values is thick when it is consistent within 90% with the measured ion ratios, as in Figure 4-7. The vertical solid lines mark the allowed U values in each panel.

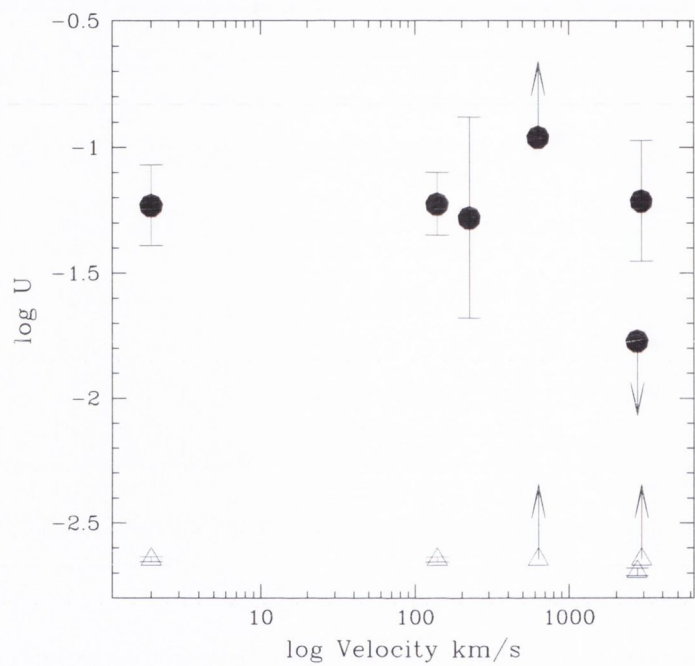


Figure 4-9: The logarithm of the best fit ionisation parameters from Figure 4-7 ($n=1 \text{ cm}^{-3}$ filled circles) and from Figure 4-8 ($n=10^8 \text{ cm}^{-3}$, open triangles, shifted by $\log U=-1.5$), as a function of the velocity shift with respect to the redshift of the host galaxy. Error-bars and upper limits represent the purely statistical 90% confidence intervals.

and [CIV/SiIV] are shown in Figure 4-7 for $\Gamma = 2$ and $n=1 \text{ cm}^{-3}$ and Figure 4-8 for $\Gamma = 2$ and $n=10^8 \text{ cm}^{-3}$. For each of the six redshift systems, thick segments superimposed on these curves indicate our 90% confidence determinations for these ratios. In Figure 4-7 (for $n=1 \text{ cm}^{-3}$) the [MgII/SiIV], [FeII/SiIV] and [AlII/SiIV] ion ratios for the systems $z=2.328 \text{ A}$, $z=2.328 \text{ B}$, $z=2.328 \text{ C}$, and $z=2.296$ are all consistent with the same ionisation status. For the system $z=2.328 \text{ A}$ we measured the column density of AlII and AlIII. Also their ratio is consistent with the ionisation parameter inferred from the above ion ratios, see Figures 4-7 and 4-8. For the same system we measured the column density of CII. The [CII/SiIV] ion ratio indicates a ionisation parameter somewhat higher than that indicated by the other ion ratios for $n=1 \text{ cm}^{-3}$ (see Figure 4-7), while for $n=10^8 \text{ cm}^{-3}$ the ionisation parameter is fully consistent with that indicated by the other ion ratios (Figure 4-8). The system at $z=2.298$ shows a ionisation parameter lower than that of system $z=2.328 \text{ A}$, while the system at $z=2.321$ shows a higher ionisation parameter. However, all ionisation parameters systems are consistent with a remarkably narrow range: $10^{-1.7} < U < 10^{-1}$, for $n=1 \text{ cm}^{-3}$ and $10^{-1.2} < U < 10^{-1}$, for $n=10^8 \text{ cm}^{-3}$ see Figure 4-9, which plots the ionisation parameters as a function of the velocity for the six systems. We note that in these ranges of U the [FeII/MgII] ratio varies by less than 30%, and the value found for the three systems in which we detect FeII and MgII lines ([MgII/FeII] ≈ 0.4) is consistent with what is expected from meteoritic abundances (and as was adopted for the CLOUDY calculations). This value is also in the range found for the Galactic ISM $0.1 < [\text{Mg}/\text{Fe}] < 0.8$. It is somewhat higher than that found by Savaglio et al. (2004) in a sample of faint K-band selected galaxies at $1.4 < z < 2.0$ of $-0.84 < [\text{Mg}/\text{Fe}] < 0.13$. Assuming meteoritic abundances the hydrogen column density of the densest system ($z=2.328 \text{ A}$) is $\geq 5 \times 10^{19} \text{ cm}^{-2}$, where the equality yields if all Si is in the form of SiIV. This column is so low that would have easily escaped detection in the Chandra X-ray spectrum (Butler et al. 2003) and it is consistent with the upper limit given by Moller et al. (2003).

Qualitatively similar results are drawn from the analysis of the $n=10^8 \text{ cm}^{-3}$ curves, although the range of acceptable ionisation parameters for the 6 systems is narrower, see Figure 4-8. Qualitatively similar results were also obtained for the $\Gamma = 1$ models.

4.4.0.1 The $z=2.328 \text{ A}$ system

For this system we detect the CII $\lambda 1335$ fine structure line. Unfortunately, the CII $\lambda 1334$ ground state line is barely visible (with a signal to noise of just 2). The presence of a strong CII line suggests either a high gas density or a strong radiation field (Srianand & Petitjean 2000, 2001,

Silva & Viegas 2002). Their ratio can be used to constrain the gas density or the radiation field (if both lines are detected one may solve for both variables, as shown by Srianand & Petitjean 2000), so their detection in GRB spectra looks very promising to constrain the physical properties of the absorbing gas.

For this system the CIV line is strongly saturated and so it cannot be used together with the CII to constrain the gas ionisation status. As discussed in the previous section, within rather large uncertainties, the [CII/SiII] would suggest for $n=1 \text{ cm}^{-3}$ a ionisation parameter somewhat higher than that indicated by all other line ratios, assuming meteoritic abundances. This may be explained by a slight under-abundance of C with respect to Si in this system. A similar conclusion applies to system $z=2.321$, see below.

The CIV $\lambda 1548$ lines of the $z=2.328$ A,B and C systems are blended with the CIV $\lambda 1550$ of the $z=2.321$ system, suggesting the presence of line locking, as first reported by Savaglio et al. (2002). Line locking is usually interpreted as the signature of line radiation pressure acceleration (see e.g. Foltz et al. 1987, Srianand & Petitjean 2000).

4.4.0.2 The $z=2.321$ system

For this system (as for $z=2.328_C$) we were able to detect CIV and SiIV absorption lines only. The upper limits on the MgII and FeII transition allow us to put a significant lower limit on the ionisation parameter of $U \geq 10^{-1}$ for this system for a gas density of 1 cm^{-3} and $U \geq 10^{-1.2}$ for a gas density of 10^8 cm^{-3} . For $n=1$, this is higher than the values for the other systems at a confidence level better than 90%. The [CIV/SiIV] ratio is formally inconsistent with this higher ionisation parameter, but the disagreement is marginal, taking into account that the CIV/SiIV curves in Figures 4-7 and 4-8 are very flat, and therefore small differences in the observed CIV/SiIV ratio would translate in large differences in the ionisation parameter. Also in this case the disagreement may be explained by a slight under-abundance of C with respect to Si.

4.4.0.3 The $z=2.296$ and $z=2.298$ systems

Given the relatively high velocity shift of about 3000 km/s between the $z=2.296$ and $z=2.298$ systems and the host galaxy redshift, there is the possibility, at least in principle, that these systems are not associated with the GRB host galaxy but rather are intervening systems. We evaluated the probability of finding intervening CIV systems within 3000 km/s from the GRB host galaxy, from the density distribution of CIV systems given in D'Odorico et al. (1998) and Petitjean & Bergeron

(1994). The probability of finding by chance two systems with column densities equal or larger than those given in Table 4.2 for these two lowest redshift systems is 1.2×10^{-5} , while the probability for only one of these systems is 0.1% for the $z=2.296$ system and 0.5% for the $z=2.298$ system. In Chapter 6, for the spectra of GRB060607 we detect a number of systems relatively close together, the smallest Δv for which is ~ 1500 km / s.

The $z=2.298$ system has a ionisation parameter $< 10^{-1.7}$ at the 90% confidence level for a gas density of 1 cm^{-3} (around $10^{-1.2}$ for a gas density of 10^8 cm^{-3}). This is the lowest of the ionisation parameters found in the 6 systems. Furthermore, for this system we detect a rather strong CII $\lambda 1334$ ground state line but not the CII* $\lambda 1335$ line, see Figure 4-5, again indicating a lower radiation field (or a lower gas density).

The observed wavelength of the $z=2.298$ system CII $\lambda 1334$ line coincides with the wavelength of the $z=2.296$ CII* $\lambda 1335$ line (see Table 4.2).

4.4.0.4 Intervening systems

Two main intervening systems are present along the line of sight to GRB021004, one around $z=1.60$ and the other around $z=1.38$ (see eg. Mirabal et al. 2003, Moller et al 2003). The UVES high resolution spectrum of GRB021004 allows an accurate study of these systems, which are split in several components (see Table 4.3).

The system at $z=1.38$ consists at least 3 components at $z=1.3807$ (1.38_A), $z=1.3802$ (1.38_B), $z=1.3795$ (1.38_C). The latter system is also split in several parts in the range 1.3793-1.3798. The total velocity range spanned by the system is ~ 180 km/s. We detected the following lines belonging to this system: SiII $\lambda 1808$, AlIII $\lambda 1854$, FeII $\lambda 2344$, FeII $\lambda 2374$, FeII $\lambda 2586$, MgII $\lambda \lambda 2796, 2803$, and MgI $\lambda 2852$.

The system at $z=1.60$ is made by at least 4 components at $z=1.6028$ ($z=1.60_A$), $z=1.6024$ ($z=1.60_B$), $z=1.6019$ ($z=1.60_C$) and $z=1.6014$ ($z=1.60_D$). The total velocity range spanned by the system is of ~ 160 km/s. For this system we detected the following lines: AlIII $\lambda 1670$, FeII $\lambda 2344$, FeII $\lambda 2374$, FeII $\lambda 2382$, FeII $\lambda 2586$, MnII $\lambda 2594$, FeII $\lambda 2600$, MnII $\lambda 2606$, MgII $\lambda \lambda 2796, 2803$, and MgI $\lambda 2852$.

We estimated the column densities of the ions of the intervening systems using the same fitting procedure used for the six systems associated with the GRB host galaxy. They are given in Table 4.3.

System	v. shift ^a	FeII	MgII	SiII	AlIII
z=1.38_A	0	15.68±0.16	13.23±0.07	15.12±0.20	13.02±0.20
z=1.38_B	-63	–	12.92±0.32	–	–
z=1.38_C	-150	14.75±0.40	15.20±0.70	–	–
System	v. shift ^a	FeII	MgI	MgII	AlII
z=1.60_A	0	13.69±0.16	11.33±0.26	13.54±0.21	12.66±0.27
z=1.60_B	-46	12.63±0.16	11.64±0.18	12.95±0.10	–
z=1.60_C	-104	14.35±0.18	12.80±0.27	15.45±0.80	13.24±0.50
z=1.60_D	-160	13.57±0.10	11.82±0.14	13.47±0.06	12.58±0.25

Table 4.3: Log. ion column densities in cm^{-2} of the GRB021004. Errors, upper and lower limits are 90% confidence intervals; ^a km/s.

4.5 The origin of the blue-shifted absorbers

4.5.1 Case 1: A clumpy wind environment

GRB021004 shows absorption systems which span ~ 3000 km/s in velocity towards the observer (no receding system is detected). The systems are most likely local to the GRB since the probability of finding two or more different absorption systems along the line of sight by random fluctuations is negligible.

It has been suggested that radiative acceleration by the prompt GRB emission may be responsible for the high detected speeds (Schaefer et al. 2003). However, this seems unlikely since low ionisation ions such as FeII and MgII are present in the high velocity absorber. The radiative acceleration is dominated by the GRB and early afterglow radiation. It is therefore unlikely that recombination can be so rapid as to have any influence on the acceleration of the absorbing material. In the photoionisation phase each nucleon receives an amount of energy comparable to the ionisation potential of the *K*-shell electron. For a solar metallicity plasma the acceleration is regulated by H atoms and, at the end of the photoionisation, the absorbing material has an outward velocity of:

$$v_{\text{ion}} \sim \sqrt{\frac{h\nu_{\text{ion}}}{m_p}} \sim 50 \text{ km/s} \quad (4.1)$$

Once the gas is fully ionised, acceleration proceeds due to radiation pressure on free electrons through Inverse Compton (IC) interactions. For a burst of isotropic equivalent energy E_{iso} the IC acceleration is obtained by momentum conservation:

$$v_{\text{IC}} = \frac{E_{\text{iso}} \sigma_T}{4\pi R^2 m_p c} \sim 0.6 R_{18}^{-2} \text{ km/s} \quad (4.2)$$

we conclude that at the minimum distance of the absorbing medium $R \sim 10^8$ cm (Lazzati et al. 2002; Heyl & Perna 2003; in order to be ahead of the fireball at the time at which absorption is detected) radiative acceleration is unable to propel the absorber to an outflowing speed comparable to the value(s) observed.

Possible explanations for the large outflowing speed are either a supernova exploded several years prior to the GRB (Vietri & Stella 1998) or a high velocity wind from the progenitor Wolf-Rayet (WR) star (MacFadyen & Woosley 1999; Schaefer et al. 2003; Mirabal et al. 2003). The large velocity spread with similar ionisation parameter is however difficult to account for in a SNR scenario, where values around a typical expansion velocity would be expected. On the other hand, WR winds are known to be clumpy and velocities up to ~ 4000 km/s were detected from P-Cygni profiles (Niedzlieski & Skórzyński 2002).

In this work we derived physical parameters of the absorbers under the assumption of equilibrium conditions which, ~ 0.5 days after the GRB explosion, are attained only if the electron density in the absorber is $n \sim 10^{7-8}$ cm $^{-3}$. Assuming equilibrium conditions, the total column density of the absorber can be computed from the ion column density corrected for the ionisation fraction. Consider the SiIV line in the A system. The density is given by:

$$n = \frac{N_{\text{Si}}}{A_{\text{Si}} R \eta} \sim \frac{10^{15.3}}{4 \times 10^{-5} 10^{18} R_{18} 10^{-6} \eta_{-6}} \approx 5 \times 10^7 R_{18}^{-1} \eta_{-6}^{-1} \text{ cm}^{-3} \quad (4.3)$$

where R is the fireball radius at the time the lines were observed, A_{Si} is the Si abundance and η is the ratio of the width of the absorbing shell over its radius. The ionisation parameters derived above and implications discussed here are therefore relevant only in the case of an extremely clumpy wind or SNR.

The photoionisation results of CLOUDY yield an ionisation parameter constrained in a relatively small range $10^{-1.7} < U < 10^{-1}$. In a single explosion GRB model, the ionisation parameter scales with the square of the outflow velocity, since the absorber's distance scales with velocity as well. Even though the ionisation parameter depends on the electron density, it seems unlikely that density variations are such as to compensate for the large velocity difference. In a wind environment, on the other hand, the ionisation parameter is constant since the photon density and particle density scale with the same power of the distance. The relatively small variations in the inferred U , which do not show any clear trend with velocity, can therefore be interpreted as density fluctuations on top of a regular R^{-2} wind density profile (as already discussed by e.g. Schaefer et al. 2003 and Mirabal et al. 2003).

4.5.2 Case 2: A possible intervening absorber?

In a recent study by Chen et al. (2007) have shown an alternative to the clumpy wind environment described in the previous section. The likelihood of the absorbers we observe at ~ 3000 km / s originate in a clumpy wind, driven by a Wolf-Rayet type progenitor, becomes less when considering the effect the GRBs intense ionising field has on its circumburst environment. Firstly, it is certainly possible to find an intervening absorber at these distances from the GRB host system. In Chapter 7 I analyse the spectra of GRB060607 where such a blueward intervening absorber is seen.

Recent studies have also shown that the intense UV field from the GRB will substantially increase the ionisation status of the surrounding medium (Prochaska et al. 2006; Shin et al. 2006; Vreeswijk et al. 2006). Within 30 pc of the GRB site no ions are thought to survive, and beyond this the GRB will substantially ionise its environment out to ~ 1 kpc. Wolf-Rayet winds have been observed to have a typical size of < 10 pc (Gruendl et al. 2000). Also, in the spectra of GRB021004 we observe two blue-shifted absorbers ~ 3000 km / s. While one absorber is expected from an expanded bubble from a Wolf-Rayet (Van Marle et al. 2005), the presence of two components is more difficult to explain. With this in mind and due to the lack of fine structure transitions for these components, it is therefore more likely that these components are not part a wind but intervening systems along the line-of-sight.

4.6 Conclusions

One of the straightforward results of our UVES high resolution observations of GRB021004 is that the ISM of the host galaxies is complex, and many components contribute to each main absorption system. These components span a total velocity range of up to about 3000 km/s. We detect both high ionisation lines such as CIV and SiIV, and low ionisation lines such as MgII and FeII. Several narrow components are resolved down to a width of a few tens of km/s. This allowed us to constrain the ionisation parameter of the gas of the different absorption systems. Combined with photoionisation results obtained with CLOUDY the ionisation parameters appear to lie in a relatively small range, with no clear trend with the system velocity. This can be interpreted as density fluctuations on top of a regular R^{-2} wind density profile. The findings of Chen et al. (2007), however, show this is unlikely. The [MgII/FeII] ratio of ≈ 0.4 found for systems $z=2.328$ A, $z=2.328$ B, and $z=2.298$ is consistent with what is expected from meteoritic abundances. Assuming these abundances, the measured SiIV column density for system $z=2.328$ A implies a lower limit of $\geq 5 \times 10^{19}$ cm $^{-2}$ to

the system total hydrogen column density.

Indeed, our study shows that rapid reaction to the GRB triggers, high resolution and wide spectral coverage are the key ingredients to study GRB host galaxies. It should be noted that these observations were precursors to the RRM now available on VLT, utilizing the high speed positioning available from the Swift satellite. The observations of this burst began ~ 13.5 hours after the burst; however, later observations (notably GRB060418 and GRB060607) achieved observations beginning ~ 10 mins after the trigger.

5

High Resolution Spectroscopy of GRB050922C

5.1 Introduction

Soon after the discovery of the cosmological origin of Gamma-Ray Bursts (GRBs) it was realized that they provide powerful tools to investigate the high redshift Universe. Minutes to hours after a GRB, its optical afterglow can sometimes be as bright as magnitude 13–18, such that it can be used as a bright beacon to gather high resolution (a few tens of km s^{-1} in the optical band), high quality (signal to noise > 10 per resolution element) spectra. Absorption lines produced by the matter along the line of sight are superimposed on these spectra and allow a detailed investigation of the medium surrounding the GRB and of the host galaxy interstellar matter (ISM).

As of today, about a dozen GRBs have been observed with high resolution spectrographs (and fewer than one hundred with standard low resolution spectrographs, see Savaglio et al. (2006) and references therein). These high resolution spectroscopic observations showed that the absorption systems along GRB sightlines are complex, with many components. They are resolved down to a width of a few tens km s^{-1} and contribute to each main absorption system, spanning a total velocity range of up to thousands km s^{-1} . Both low and high-ionisation lines are normally observed, as

well as fine structure lines of CII, SiII, OI, FeII etc. This is at odds with what is observed from high-resolution spectroscopy of QSO DLAs (Srianand et al. 2005). First, the equivalent widths and the inferred optical depths along GRB sightlines are much greater than both QSO DLAs and those associated with galaxies along QSO sightlines. Second, despite more than 30 years of investigations, only sparse detections of fine-structure lines are available along QSOs sightlines due to a lower density environment around them (Srianand & Petitjean 2000; 2001; Hall et al. 2002).

The main reasons for these marked observational differences are probably linked to the characteristics of the phenomena and to their host galaxies. QSOs are long-lasting sources that ionise, partially or totally, the gas over their entire host galaxy. Instead, GRBs are transient phenomena, affecting only smaller regions, close to the site of the GRB explosion. Moreover, the star-forming regions surrounding GRBs are probably much richer in enriched gas than the giant elliptical galaxies, which are the typical host of luminous QSOs (Savaglio et al. 2006). On the other hand, faint metal line systems along QSO sightlines probe mainly galaxy haloes, rather than their bulges or discs. Therefore, GRBs constitute a complementary tool to investigate the ISM of typical high redshift galaxies.

After the first pioneering programs that used BeppoSAX and HETE2 triggers to obtain high resolution spectroscopy of the optical afterglows 12-24 hours after the bursts (Fiore et al. 2005), we are now in a “golden age” for this kind of studies. This is because of the GRB-dedicated Swift satellite which provides accurate GRB positions on time scales as short as tens of seconds, and the Rapid Response Mode (RRM) of the ESO/VLT. Using this new revolutionary observing mode it is possible to obtain GRB afterglow spectra from an 8m class telescope with delays from ~ 10 min down to a few hours after the GRB event.

The absorption systems along GRB sightlines can be divided into three broad categories: (1) systems associated with the GRB surrounding medium. (2) Systems associated with random clouds of the ISM of the host galaxy along the line of sight. These systems show low ionisation lines and ground state lines, implying distances from the GRB explosion site larger than ~ 100 pc. (3) Systems originating in the intergalactic matter along the line of sight. The physical, dynamical and chemical state of the medium in the star-forming region hosting the GRB progenitor can be modified by the GRB (long type), through shock waves and ionising photons. Strong fine structure lines are always observed in these systems. Physical and geometrical parameters for the absorbers can be derived comparing the observed line ratios to those predicted by ionisation codes (Perna & Lazzati 2002; Lazzati et al. 2006; Vreeswijk et al. 2007).

The distinction between the first and second category is not always clear-cut. Vreeswijk et al. (2007) discovered large variations of FeII fine-structure lines in the spectra of GRB060418 on rest frame time scales of a fraction of an hour, and interpreted them as due to GRB UV pumping. Their detailed modeling of the observed variability suggests a distance of the FeII absorbing cloud from the GRB explosion site of ~ 1.7 kpc, comparable to the size of a typical galaxy at $z \sim 1.4$. This would imply that, at least in this case, the entire galaxy (or a significant fraction of it) is affected by the GRB explosion.

Our goal is to better disentangle different absorption systems by using Ultra-violet and Visual Echelle Spectrograph (UVES, Dekker et al. 2000) observations of GRB050922C. The burst was detected by Swift on 2005 September 22 19:55:50 UT (Norris et al. 2005) and, after 4s, by Konus Wind (Golenetskii et al. 2005). ROTSE discovered a transient source at $RA(J2000)=2^h09^m33^s.1$ and $DEC(J2000)=-08^d45'29''.8$ 172.4s after the burst, which was promptly identified as the optical afterglow of GR050922C (Rykoff et al. 2005) with an R magnitude of 14.7. The redshift of the GRB, $z=2.1992$, was determined by (Jakobsson et al. 2005) using ALFOSC at the Nordic Optical Telescope at the Observatorio del Roque de los Muchachos in La Palma. This redshift was confirmed shortly after through TNG/Dolores spectroscopy (Piranomonte et al. 2005). The afterglow was then observed by UVES/VLT at high spectroscopic resolution ($R \sim 40000$) about 3.5 hours after the burst, when its R band magnitude was $R=19.0$. The spectrum of GR050922C is especially rich of features and contains clear examples of the three system categories discussed above. There are strong intervening systems at $z=1.5664$, 1.9891 , 2.0087 , 2.0778 , 2.1421 (confirmed also by Sudilovsky et al. 2007).

The system associated with the host galaxy presents several components, some showing strong high-ionisation lines and strong fine-structure lines, and some showing only low-ionisation transitions, thus suggesting that we detect in this GRB both the circumburst medium and random clouds of the host galaxy ISM along the line of sight.

This work was, again, carried out in collaboration with Rome Observatory. The data reduction was performed by Valerio D'Elia, Fabrizio Fiore, Silvia Piranomonte and myself. The analysis of the spectra, identification of the various components and the subsequent line fitting were carried out predominantly by myself and Silvia Piranomonte. The analysis of the spectra was carried out by myself, Silvia Piranomonte, Susanna Vergani, Fabrizio Fiore and Valerio D'Elia.

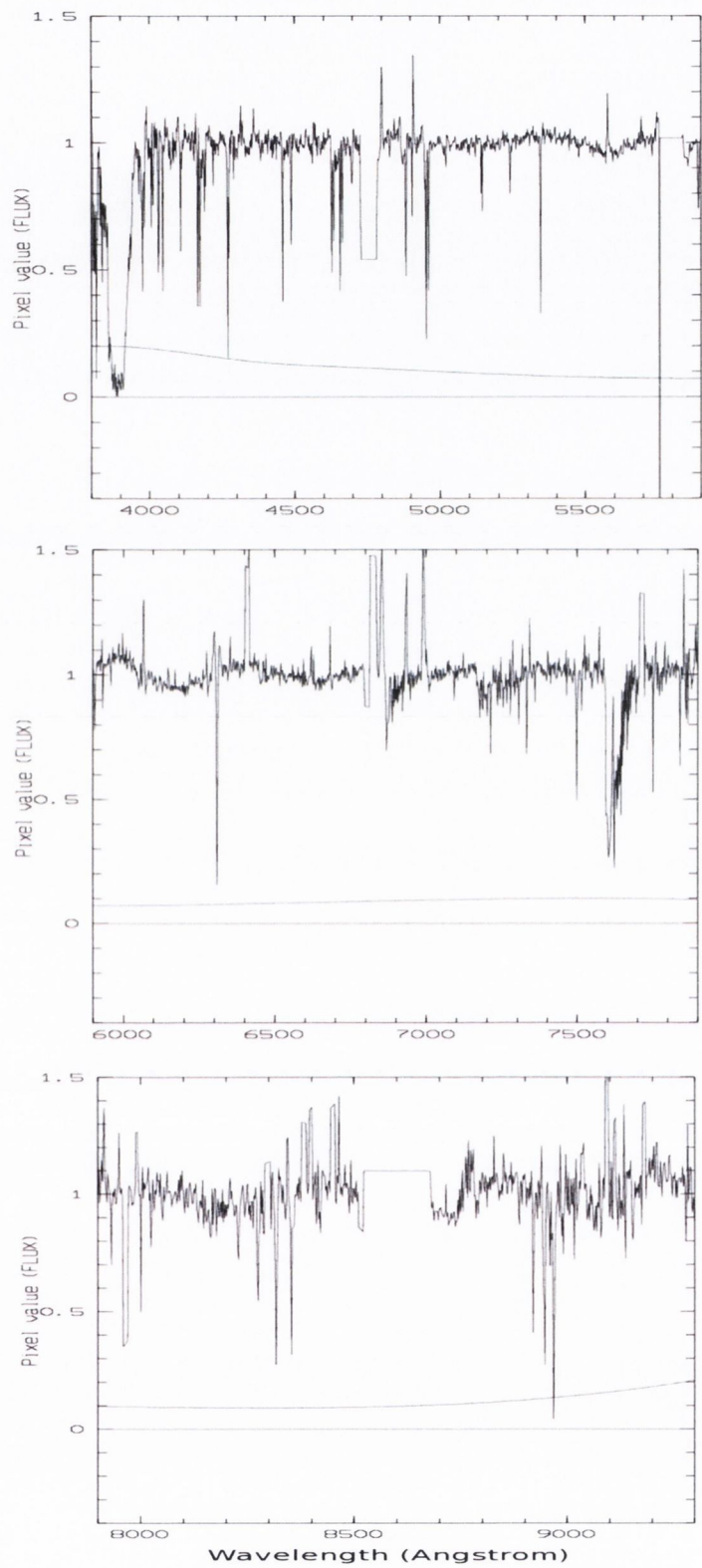


Figure 5-1: The full high resolution spectrum of GRB050922C. Horizontal lines represent the noise spectrum.

5.2 Observations and Data Analysis

5.2.1 VLT Observations

In the framework of ESO program 075.A-0603 we observed the afterglow of GRB050922C with UVES mounted at the VLT-UT2 telescope. Table 5.1 gives the log of the observations. Both UVES dichroics, as well as the red and the blue arms, were used. This allowed us to achieve a particularly wide spectral coverage, extending from $\sim 3200\text{\AA}$ to $\sim 10000\text{\AA}$. In order to maximize the signal to noise ratio the CCD was rebinned in 2×2 pixels. The data reduction was carried out by using the UVES pipeline (Ballester et al. 2000). The final useful spectra extend from about $3750\text{\AA}$ to about $9780\text{\AA}$ and were rebinned to $0.1\text{\AA}$. The resolution element, set to two pixels, ranges then from 14 km s^{-1} at $4200\text{\AA}$ to 6.6 km s^{-1} at $9000\text{\AA}$. The noise spectrum, used to determine the errors on the best fit line parameters, was calculated from the background subtracted and rebinned spectrum using line free regions. This takes into account both statistical errors and systematic errors in the pipeline processing and background subtraction.

5.2.2 Column densities

The line fitting was performed using the MIDAS package FITLYMAN (Fontana & Ballester 1995). This uses a Voigt profile and yields independently the column density N and the Doppler parameter b for each absorption component. For each absorption system several lines, spread over the entire spectral range covered by the UVES observations were fitted simultaneously, with the same number of components for each line, and the same redshift and b value for each component. In the resulting plots the red line represents the model fit, while the green line represents the noise.

Date UT	Dichroic	B. Arm C.W.	R. Arm C.W.	slit ^a	seeing ^a	exposure ^b	time since GRB ^c
09/22/05 00:07:17	1	3460Å	5800Å	1	$\lesssim 1$	50	4.15
09/22/05 01:02:09	2	4370Å	8600Å	1	$\lesssim 1$	50	5.07

Table 5.1: Journal of observations. ^aarcsec; ^bmin; ^chr

5.3 Summary of the absorption systems

The high resolution spectrum of GRB050922C (See Figure 5-1) exhibits a large number of absorption features, belonging to different absorption systems. The main system is due to the gas inferred to be in the host galaxy, at redshift $z=2.1992$. We identified five more intervening absorbers at

$z < 2.1992$ ($z=1.5664, 1.5691, 1.9891, 2.0087, 2.0778$ and 2.1416). Sudilovsky et al. (2007) found one more intervening systems $z=1.6911$, but we could not confirm that this is real because the CIV doublet is coincident with the SiII $\lambda 1304\text{\AA}$ and OI $\lambda 1302\text{\AA}$, OI* $\lambda 1304\text{\AA}$ of the main system at $z=2.1992$.

In the following each system is briefly illustrated in the next subsections.

5.3.1 The host galaxy at $z=2.1992$

This is the system with the highest number of features in the UVES spectrum. Figure 5-1 shows the Ly- α absorption at $\sim 3870\text{\AA}$. The redshift inferred from this feature is confirmed by a high number of metal-line transitions, the narrowest of which allows a more precise determination: $z=2.1992\pm 0.0005$. This system exhibits a large number of absorption lines, from the neutral hydrogen Ly- α and neutral metal-absorption lines (OI, NI and FeI) and low-ionisation lines CII, SiII, MgII, AlII, FeII and AlIII to high-ionisation absorption features CIV, SiIV, NV, PV, OVI. In addition, strong fine structure lines CII*, SiII*, OI*, OI**, FeII*, OIII** have been identified. The total velocity range spanned by this system is ~ 210 km/s. This system is discussed in detail in the next sections.

5.3.2 The intervening absorber at $z = 2.1416$

The intervening system at $z=2.1416$ shows one main component spanning a velocity range of ~ 20 km s^{-1} (see Figure5-2). This system presents the CII low-ionisation line and the CIV transition, as well as HI. The column densities we derived are shown in Table 5.2.

Ion	2.1416a
HI	18.1 ± 0.1
CII	13.91 ± 0.07
CIV	13.29 ± 0.07

Table 5.2: Column densities for the $z=2.1416$ intervening system

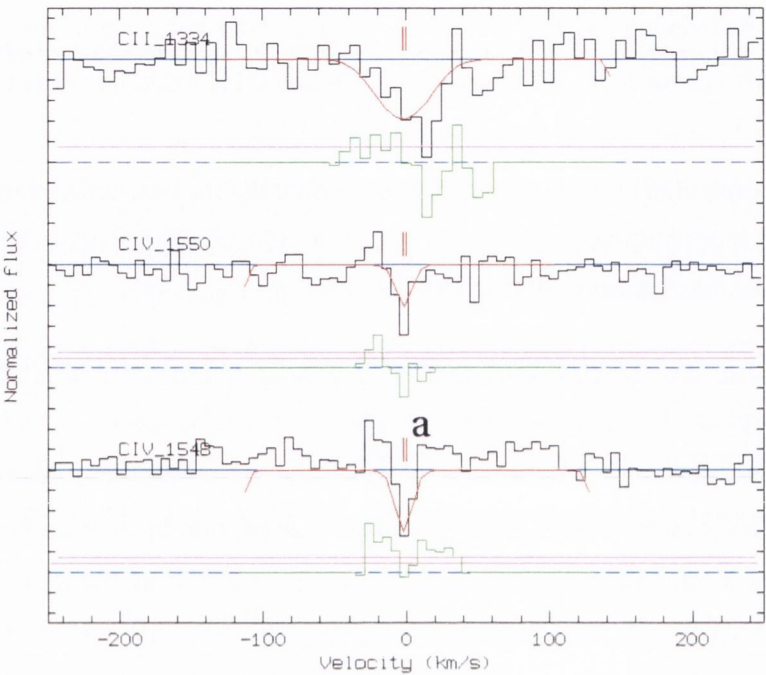


Figure 5-2: The intervening absorber at $z = 2.077$

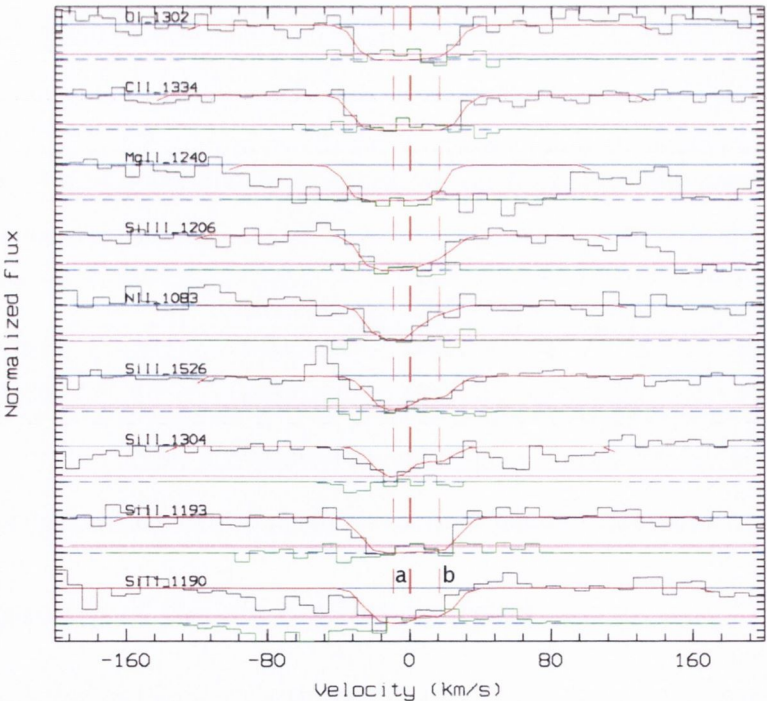


Figure 5-3: The intervening absorber at $z = 2.077$

5.3.3 The intervening absorber at $z = 2.0770$

The intervening system at $z=2.077$ shows two main components spanning a velocity range of $\sim 50 \text{ km s}^{-1}$ (see Figure5-4). This system presents neutral metal-absorption lines (OI, NI), many low-ionisation lines (FeII, SiII, NII, MgII, CII, TiII) and some high-ionisation transitions (SiIII, AlIII, SiIV). The column densities we derived are shown in Table 5.3. Sudilovsky et al. (2007) found also a CIV transition in this system. We were not able to find this doublet because that part of the spectrum was between two parts that were joined together. We were not able to measure the Lyman α for this system because it lies in a region where two parts of the spectrum are joined together, leaving a gap where no lines can be detected.

Ion	2.077a	2.077b
FeII	14.45 ± 0.08	13.06 ± 0.04
SiII	14.18 ± 0.08	13.54 ± 0.07
NII	14.56 ± 0.06	13.26 ± 0.06
MgII	-	19.02 ± 0.51
CII	15.67 ± 0.34	14.32 ± 0.30
SiIII	13.85 ± 0.56	12.52 ± 0.25
OI	15.60 ± 0.30	14.41 ± 0.18
NI	14.19 ± 0.10	13.37 ± 0.22
TiII	13.87 ± 0.12	13.53 ± 0.13
AlIII	-	12.16 ± 0.11
SiIV	13.05 ± 0.09	12.54 ± 0.18

Table 5.3: Column densities for the $z=2.077$ intervening system

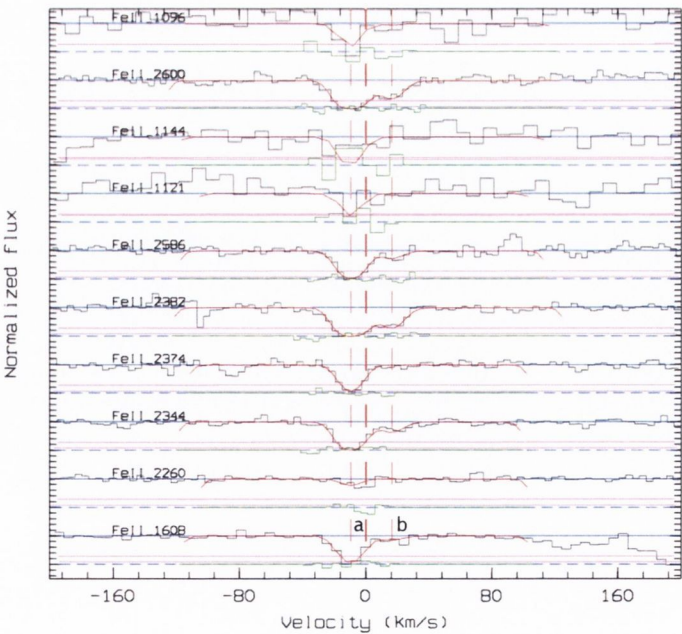


Figure 5-4: The intervening absorber at $z = 2.077$

5.3.4 The intervening absorber at $z = 2.0081$

The intervening system at $z=2.0081$ shows four main components spanning a velocity range of $\sim 140 \text{ km s}^{-1}$. (see Figure5-5). This system presents one low-ionisation line (MgII) and some high-ionisation transitions (SiIV, CIV). The column densities we derived are shown in Table 5.4. For this system we could disentangle the HI column density for each of the four components.

Ion	2.0081a	2.0081b	2.0081c	2.0081d
HI		18.2 ± 0.2		
SiIV	12.12 ± 0.38	12.16 ± 0.39	13.59 ± 0.16	12.39 ± 0.22
CIV	13.18 ± 0.08	13.56 ± 0.05	15.33 ± 0.49	13.70 ± 0.04
MgII	-	12.00 ± 0.16	12.64 ± 0.04	-

Table 5.4: Column densities for the $z=2.0081$ intervening system

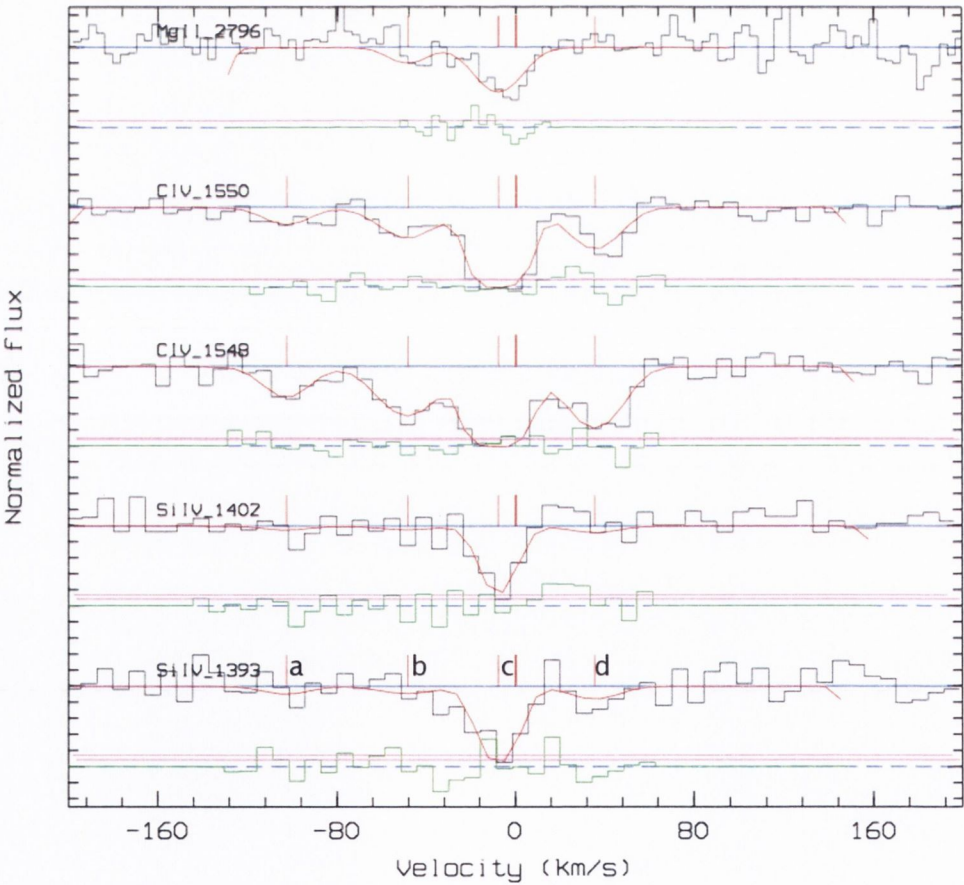


Figure 5-5: The intervening absorber at $z = 2.0081$

5.3.5 The intervening absorber at $z = 1.9885$

The intervening system at $z=1.9985$ shows three main components: $z=1.9885a$, $1.9885b$ and $1.9885c$, spanning a velocity range of $\sim 120 \text{ km s}^{-1}$. (see Figure5-6). It presents both neutral metal-absorption lines (CI) and high-ionisation lines (SiIII, CIV). The column densities we derived are shown in Table 5.5. Again a total HI column density was measured.

Ion	1.9885a	1.9885b	1.9885c
HI		18.2 ± 0.4	
CIV	13.78 ± 0.05	14.19 ± 0.09	13.79 ± 0.04
SiIII	12.46 ± 0.23	12.76 ± 0.15	12.96 ± 0.10
CI	-	16.33 ± 0.36	-

Table 5.5: Column densities for the $z=1.9985$ intervening system

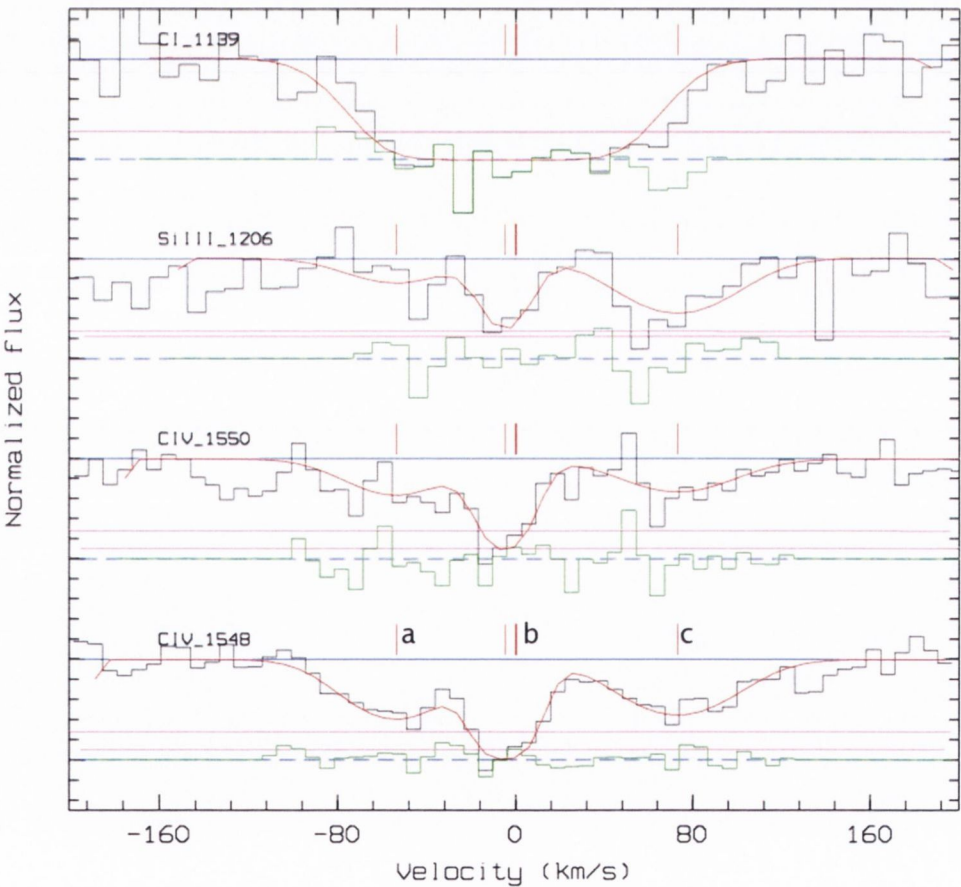


Figure 5-6: The intervening absorber at $z = 1.9985$

5.3.6 The intervening absorber at $z = 1.5691$ and at $z = 1.5664$

We consider here the intervening system at $z = 1.5691$ and $z=1.5664$ together as the velocity shift between them is very little. They show a high ionisation line (CIV) and a low ionisation line (CII), (see Table 5.6). The Lyman α line for this system was, again, in a region between two parts of the spectrum and was, therefore, not possible to fit.

Ion	1.5664a	
CII	13.56 ± 0.22	-
CIV	13.70 ± 0.07	-
Ion	1.5691a	1.5691b
CII	13.44 ± 0.29	-
CIV	14.16 ± 0.08	14.12 ± 0.09

Table 5.6: Column densities for the $z=1.5691$ and 1.5664 intervening system

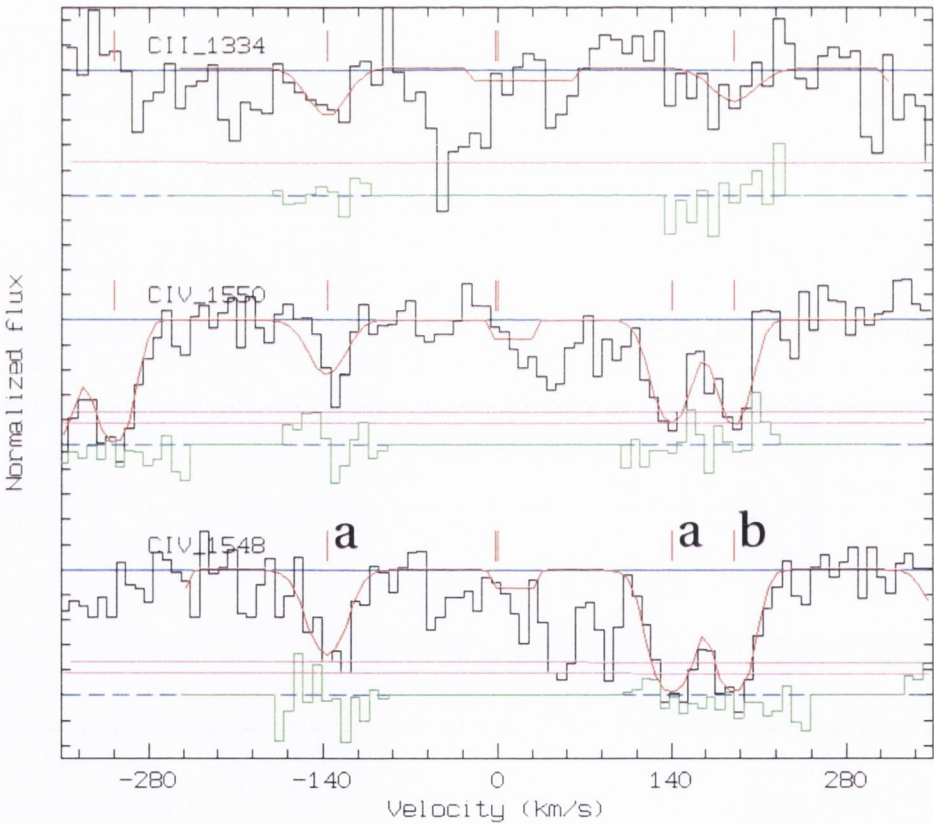


Figure 5-7: The intervening absorber at $z = 1.5664$ and $z = 1.5691$

5.4 The $z=2.1992$ absorption system: physical properties of the GRB environment and host galaxy ISM

This system is most likely associated with the GRB host galaxy. Likewise most GRB host galaxy absorption systems (Fiore et al. 2005; D’Elia et al. 2007; Vreeswijk et al. 2007; Prochaska et al. 2006) it presents many components, spanning a rather large velocity range ($\sim 210 \text{ km s}^{-1}$). Interestingly, different components exhibit different transitions: some exhibit low-ionisation lines, high-ionisation lines and fine-structure lines, some exhibit low-ionisation lines only. An example is given in Figure 5-8. Six components, labeled from (a) to (g), are identified for the SiIV and CIV doublets, spanning a velocity range from -75 to $+140 \text{ km s}^{-1}$. Each component has a width from 10 to 25 km s^{-1} . Component (d) has nearly zero velocity shift and it may be associated with the GRB surrounding medium, because of the strong SiII* $\lambda 1309$ and high-ionisation transitions. Also this component is not detected in MgI. Fainter, but still significant SiII* lines are associated with components (e) and (f) too. On the other hand, the SiII $\lambda 1304$ component labeled (b) at $\sim -58.60 \text{ km s}^{-1}$ is not present in either SiIV and SiII* transitions, suggesting that this component is due to some host galaxy cloud along the line of sight not modified by the GRB radiation field. Indeed, this component is seen in MgI absorption (Figure 5-11, implying a distance from the GRB site $\geq 100 \text{ pc}$ (Prochaska et al. 2006)).

The complex line profile, and the fact that different components may exhibit physically different line transitions, made it impossible to fit the system with a single Voigt profile. Therefore we identified the different components before deriving the column densities through a fitting procedure. The main goal of this work is indeed to disentangle the relative contribution of the different components. We use the less saturated transitions to guide this identification. We identified 7 components for the $z=2.1992$ system ((a) through (g); see Figure 5-8). The redshifts of components (a) to (g), and therefore their velocity shift with respect to $z=2.1992$, which has been taken as a reference, were determined using the CIV and SiIV lines. The redshift of the (b) component was determined by using the SiII transitions. The redshifts and doppler parameters were then fixed when fitting all other lines belonging to each component with Voigt profiles. The ion column densities of each component of the main absorption system at $z=2.1992$ are given in Table 5.4.

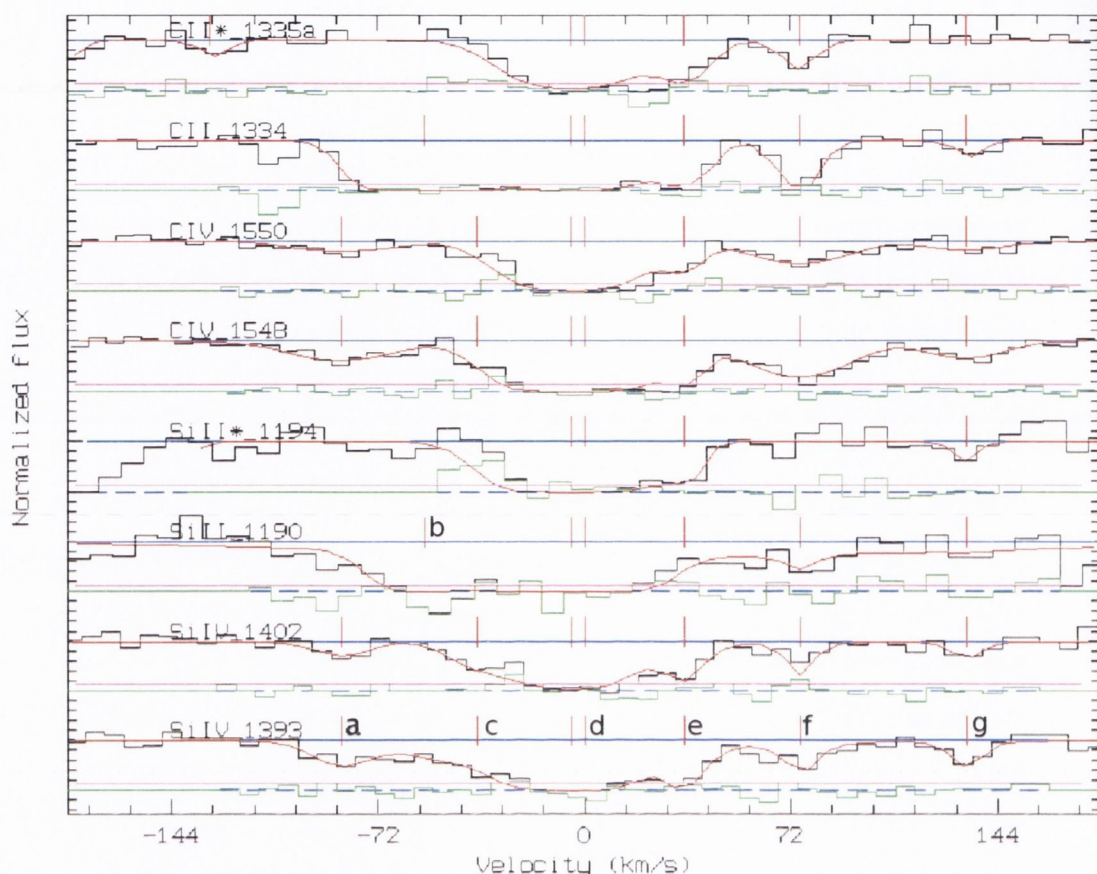


Figure 5-8: The UVES spectrum around the lines Si IV $\lambda 1393, 1402$, Si II $\lambda 1190$, Si II* $\lambda 1194$ lines, CIV $\lambda 1548, 1550$, CII $\lambda 1334$, CII* $\lambda 1335$ lines. The zero of the velocity scale refers to the redshift of the host galaxy, $z=2.1992$.

5.4.1 Low-ionisation lines

Strong low-ionisation lines were detected for all components. In four cases (Mg II, C II, Al II and Al III) reliable estimates of the ion column density for (d), (e), (f), (g) and (b) components were possible. In all cases, strong blending of the (a) and (c) components with the (b) one renders such an estimate difficult for these components. We observe the Si II ($\lambda 1190\text{\AA}$, $\lambda 1193\text{\AA}$, $\lambda 1260\text{\AA}$, $\lambda 1304\text{\AA}$, $\lambda 1526\text{\AA}$), C II ($\lambda 1334\text{\AA}$), Mg II doublet ($\lambda 2796\text{\AA}$, $\lambda 2803\text{\AA}$), Al II $\lambda 1670\text{\AA}$ and the Al III doublet ($\lambda 1854\text{\AA}$, $\lambda 1862\text{\AA}$). From Table 5.4 we can see that the host galaxy component (b) is present in all low ionisation lines (see also Figure 5-9).

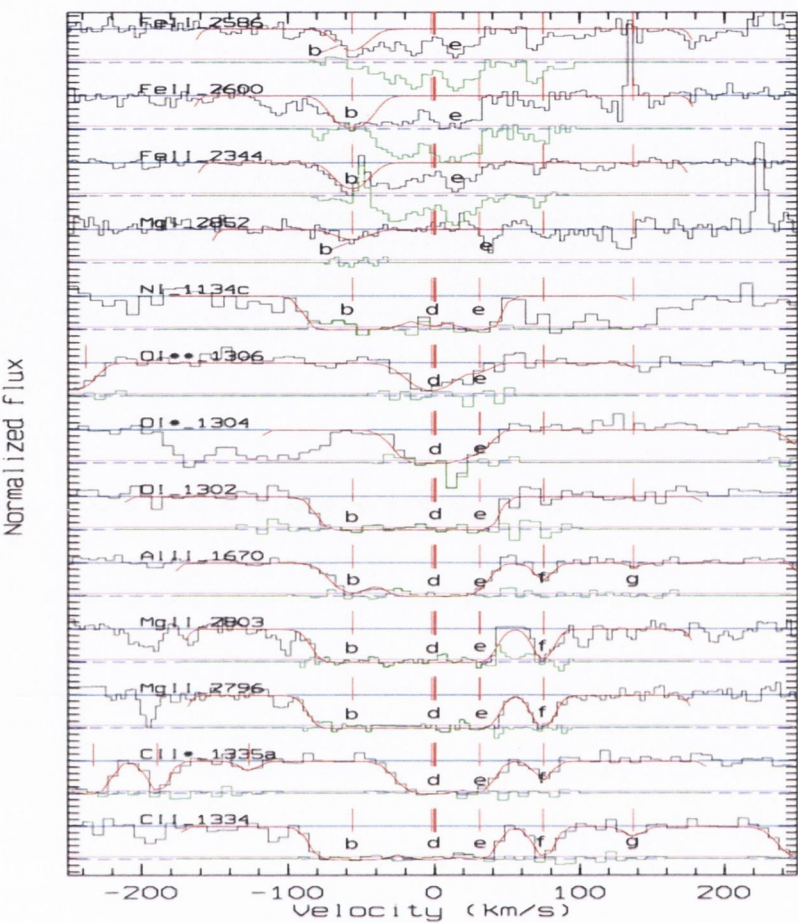


Figure 5-9: The “host galaxy” component (b) is present in all low-ionisation lines. Components (a) and (b), observed for the higher ionisation states, cannot be separated from the (b) component for these lines

5.4.2 High-ionisation lines

Figure 5-10 shows all high-ionisation lines (PV, NV doublet, OVI doublet) identified together with SiIV and CIV. Significant column densities of CIV and SiIV are detected for all six components (a) to (f). NV and OVI are detected for components (c) and (d) only. PV is only found for the (c) component and yields a limit for component (d). Confusion with the Lyman- α forest makes it difficult to search for faint OVI and NV lines for the other components or to compute robust upper limits.

No high-ionisation lines were detected for component (b).

Ion	2.1992a	2.1992b	2.1992c	2.1992d	2.1992e	2.1992f	2.1992g
km s ⁻¹	-83.26	-58.60	-37.88	-0.39	+33.15	+77.54	+136.73
NI	-	SAT(**)	-	SAT	SAT	-	-
MgI	(*)	11.80±0.12	(*)	< 11.75	11.99±0.11	11.60±0.17	11.90±0.10
OI	-	15.40±0.33	-	SAT	SAT	-	-
OI*	-	-	-	15.14±0.11	13.95±0.21	<13.68	-
OI**	-	-	-	14.53±0.08	13.39±0.32	<13.69	-
MgII	(*)	14.60±0.32	(*)	14.79±0.57	13.57±0.29	13.38±0.25	-
CII	(*)	15.48±0.36	(*)	14.61±0.21	14.56±0.48	14.19±0.34	13.08±0.20
CII*	-	< 13.25	-	14.59±0.12	14.16±0.26	13.52±0.15	-
SiII	(*)	14.26±0.07	(*)	14.77 ± 0.11	13.87 ± 0.19	14.69 ± 0.22	11.81 ± 0.46
SiII*	-	< 12.95	-	14.28 ± 0.04	13.11 ± 0.14	13.06 ± 0.14	
AlII	(*)	12.90±0.05	(*)	13.97±0.25	12.13±0.23	12.15±0.07	10.59±1.49
AlIII	(*)	11.84±0.13	(*)	12.09±0.04	11.30±2.70	-	-
CIV	13.40±0.05	< 13.26	13.15±0.09	14.98±0.24	13.63±0.07	13.78±0.03	13.16±0.07
SiIV	13.07±0.07	< 13.17	13.15±0.12	14.33±0.15	13.33±0.10	13.06±0.06	12.76±0.09
NV	-	-	-	14.06±0.08	15.34±0.67	-	-
PV	-	-	-	14.06±0.07	<12	-	-
OVI	-	-	-	15.24±1.96	14.64±0.16	-	-
Fe	2.1992a	2.1992b	2.1992c	2.1992d(1) – 2.1992d(2)	2.1992e	2.1992f	2.1992g
km s ⁻¹	-83.26	-58.60	-37.88	-13.3 / +15.74	+33.15	+77.54	+136.73
FeII	-	13.67±0.04	13.75±0.03	13.29±0.11 / 13.73±0.04	-	14.28±0.36	-
FeII*	-	-	-	- / 13.36±0.07	-	-	-

Table 5.7: Derived column densities for the $z = 2.1992$ system. (*) this component is blended by the host galaxy component (b), so we cannot determine the relative column density. (**) Saturated component

5.4.2.1 The atoms MgI and OI

We detect significant amounts of both neutral Mg and O. The first ionisation energy of Mg lies below the 1Ryd threshold, at 7.6 eV. This transition is not screened by H absorption and therefore Mg would be ionised easily by the strong radiation coming from the GRB. As a consequence, the presence of significant MgI implies large distances (> 100 pc, Prochaska et al. 2006) of the gas clouds from the GRB site. MgI is detected for components (b), (e), (f), (g) (see Fig 5-11). These components are therefore likely to be associated with gas clouds which are little affected by the GRB radiation field. MgI is not detected for components (c) and (d), the latter being the component with the strongest high-ionisation and fine-structure lines, see Table 5.4. Another good indication that components (c) and (d) are closer to the site of the GRB than the other components.

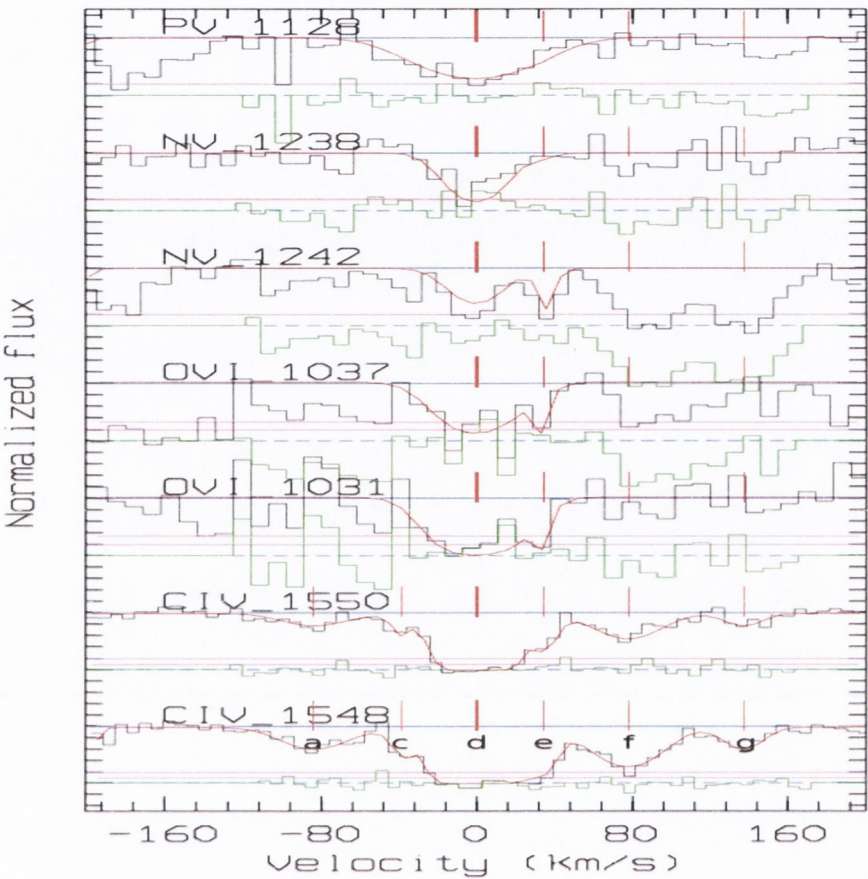


Figure 5-10: High-ionisation absorption lines for the redshift system of the GRB host galaxy.

5.4.2.2 Fine-structure lines

We detected several fine-structure lines associated with components (d), (e) and (f). We identified the following lines arising from fine structure levels: SiII* $\lambda 1194\text{\AA}$ SiII* $\lambda 1197\text{\AA}$ SiII* $\lambda 1264\text{\AA}$ SiII* $\lambda 1309\text{\AA}$ SiII* $\lambda 1533\text{\AA}$ CII* $\lambda 1335\text{\AA}$ OI* $\lambda 1304\text{\AA}$ OI** $\lambda 1306\text{\AA}$. The redshifts of all these lines were fixed to those of the corresponding components in the CIV and SiIV systems.

We also detect three FeII fine-structure lines. FeII* $\lambda 1618\text{\AA}$ FeII* $\lambda 1621\text{\AA}$ FeII* $\lambda 2365\text{\AA}$. The redshift of these lines is shifted from that found for component (d) using the CIV and SiV systems by about 20 km s^{-1} , see Figure 5-12. This suggests that additional structure is actually present in this absorption system. In the following we consider the FeII fine-structure lines as associated with component (d) without making further splitting in velocity. No FeII fine-structure transition is found for the other six components and, in particular, no fine-structure line was found at a redshift consistent with that of component (b).

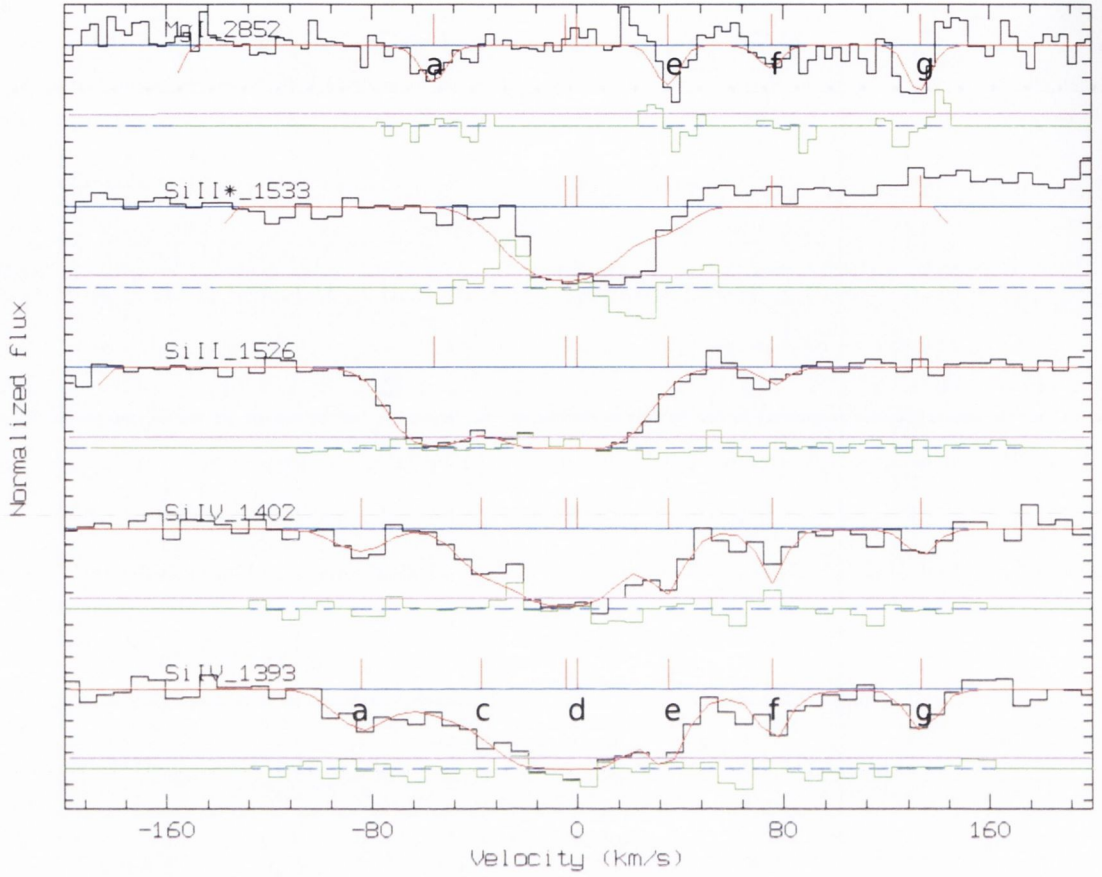


Figure 5-11: The top panel shows the MgI absorption features. A number of components that appear for other ions do not appear for MgI.

5.5 Properties of the medium surrounding the GRB

5.5.1 Fine-structure line excitation I: constraining the density of the gas

As shown in section 5.4.2.2, for this burst we found several fine-structure transitions. These levels can be populated through (1) excitation indirectly by ultra-violet (UV) photons, followed by fluorescence, (2) collisions between the ion and other particles like free electrons, and/or (3) direct photo-excitation by infra-red (IR) photons. The first mechanism has been shown to be the preferred mechanism in only one case: GRB060418 (Vreeswijk et al. 2007). The latter mechanism is the less dominant one and we will not consider it. Whatever the case, the physical conditions of the interstellar medium can be probed through the detection of transitions from these energetically lower excited levels.

For GRB050922C fine-structure transitions are present in component (c) (d) and (e) (see Table

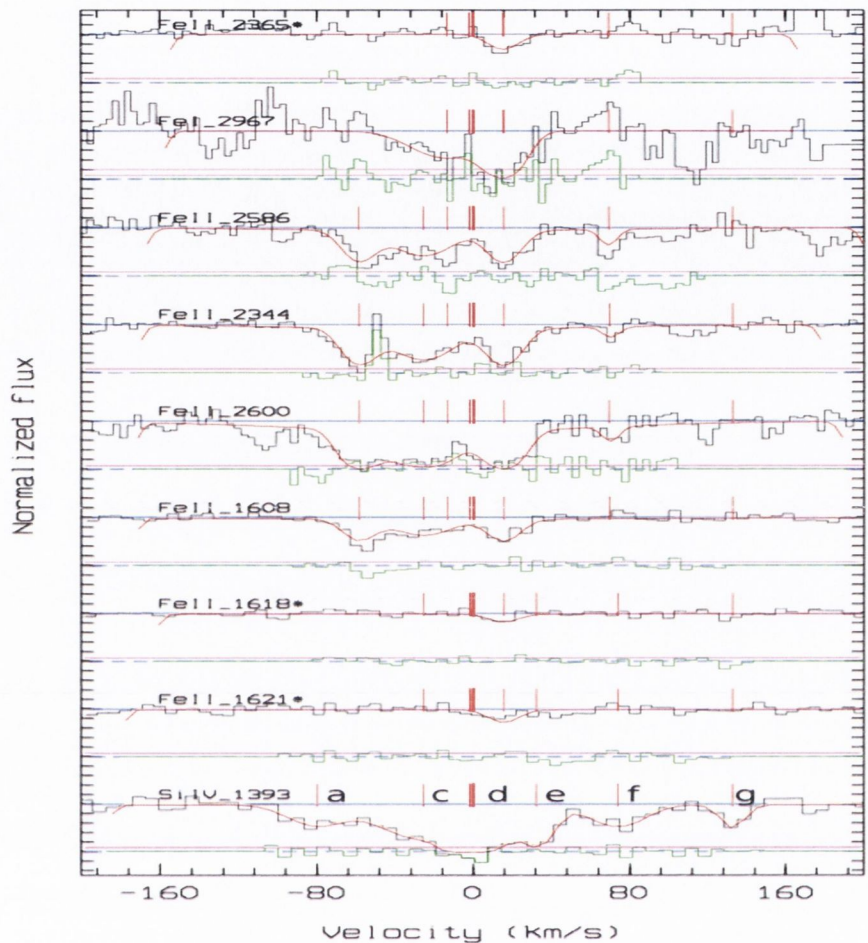


Figure 5-12: We detect a number of FeII and FeII* transitions.

5.4).

If we assume that collisions with electrons are the dominant excitation mechanism, we can put constraints on the electron density of the components where we found such transitions. A method to estimate the electron density is presented by Prochaska et al. (2006). We can compare our results on the SiII*/SiII II* and FeII*/FeII ratios with Figure 9 of Prochaska et al. (2006), showing collisional excitation of the first excited state relative at the ground state for Si⁺, Fe⁺ and O⁰. We can use only SiII and FeII because oxygen is saturated. From this comparison we find for SiII an electron density, n_e , in the range $1.3 - 3 \times 10^2 \text{ cm}^{-3}$ for component (c), n_e in the range $1.2 - 2 \times 10^2 \text{ cm}^{-3}$ for component (d) and $n_e < 2 \times 10^1 \text{ cm}^{-3}$ for component (e).

We have evaluated the electron density of component (c) also using the FeII transitions. This produces a result $n_e \sim 0.1 - 5 \times 10^5 \text{ cm}^{-3}$ inconsistent with the previous estimate. A possible reason

for this inconsistency may be our simple description of a complex system (the excited transition lines are shifted by 20 km s^{-1} from the ground level lines).

5.5.2 Fine-structure line excitation II: constraining the radiation field

A competitive mechanism responsible for the presence of fine-structure levels is indirect UV pumping. If this is the dominant excitation mechanism, we can constrain the GRB radiation field and the distance of the gas from the GRB. Prochaska et al. (2006), using the PopRatio code developed by Silva & Viegas (2001, 2002), analyzed the relation between the far UV radiation field intensity and the relative fraction of excited fine-structure states with respect to their ground levels (for OI, SiII and FeII, see their Figures 7 and 8). In the following we make use of these Figures to estimate the radiation-field intensity from our column density data.

Using Figure 7 of Prochaska et al. (2006), we find that our measured ratio ($SiII^*/SiII = -0.49 \pm 0.12$) for component (c) is compatible with a radiation field intensity of $G/G_0 = (2_{-1}^{+3} \times 10^5$ (90% confidence interval; $G_0 = 1.6 \times 10^{-3} \text{ erg cm}^{-2} \text{ s}^{-1}$ is the Habing constant).

On the other hand, the ratio ($FeII^*/FeII = -0.50 \pm 0.11$) for component (c) is compatible with a radiation field intensity $G/G_0 = (6_{-5}^{+4} \times 10^6$ (90% confidence interval).

This evaluation with the FeII fine-structure lines is therefore consistent with the presence of a component very near the GRB site that is subjected to a very high radiation field.

For component (d) we found that the SiII ratio ($SiII^*/SiII = -0.76 \pm 0.24$) is compatible with a radiation field intensity of $G/G_0 = (8 \pm 1) \times 10^4$.

For component (e) we found that the SiII ratio ($SiII^*/SiII = -1.42 \pm 0.35$) is compatible with a radiation field intensity of $G/G_0 = (1_{-1}^{+1} \times 10^4$.

We cannot confirm in this burst that the UV pumping is the dominant mechanism, but we can say that component (c) experiences the highest radiation field, suggesting that this is the component closer to the GRB site.

5.5.3 Metallicity

Figure 5-13 shows the Ly- α absorption features. It is impossible to discriminate between the six components identified from the analysis of CIV and SiIV. Hydrogen absorption results in very broad lines with damped wings, reaching well beyond the velocity range of the heavier ions. Since a component by component analysis is not possible, we can only estimate the metallicity of the circumburst material in terms of the ratio $[X/H]$ between the total absorption column of the X

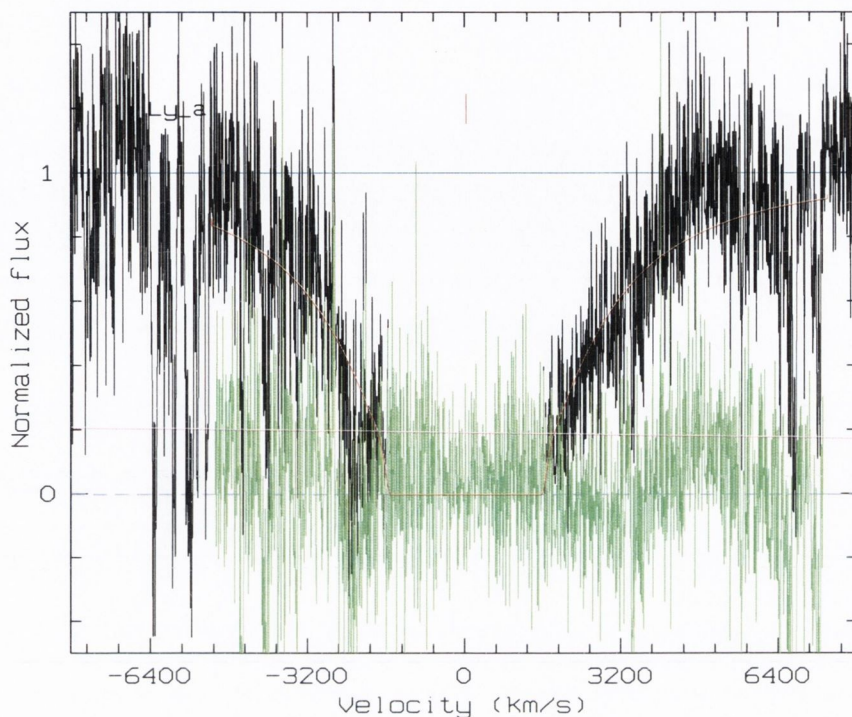


Figure 5-13: The $\text{Ly-}\alpha$ absorption feature for the system of the GRB host galaxy.

element with respect to that of hydrogen. Since we only probe neutral hydrogen and not hydrogen which has been ionised by the burst, our values for the metallicity should only be considered as an estimate.

For this burst we measured a column density $\log N(\text{H}_I) = 21.27 \pm 0.1$ or $(1.86 \pm 0.05) \times 10^{21} \text{ cm}^{-2}$, similar with what was found by Jakobsson et al. (2006).

In order to determine the column density through X-ray measurements, we have analyzed also the X-ray telescope (XRT) Swift data for GRB050922C in a time interval ranging from 5ks to 12ks from the BAT trigger. The analysis was done by fitting the X-ray spectrum with a power law plus two warm absorbers, one at the redshift of the observer, and the other at the redshift of the GRB. For this analysis we assume solar abundances.

With X-ray data, we found a value for the neutral hydrogen column density of $(0.7 \pm 0.3) \times 10^{21} \text{ cm}^{-2}$ not consistent with the one found from our UVES data. Watson et al. (2007) already discussed this result comparing H I column densities from $\text{Ly}\alpha$ absorption to the metal column densities from the X-ray absorption in GRB afterglows of seventeen bursts, suggesting that the two methods may be probing different regions of HI. Hydrogen ionised by the GRB would not contribute

to Lyman α absorption but would contribute to the that measured from the X-ray spectrum.

Ion	$\log N \text{ (cm}^{-2}\text{)}$	$\log N^{(a)} \text{ (cm}^{-2}\text{)}$	$\log(X/H)$	z
HI	21.27 ± 0.12	-	-	-
CII	15.17 ± 0.48	-	-	-
CIV	15.05 ± 0.24	-	-	-
C	-	15.41 ± 0.48	-5.85 ± 0.48	-2.24 ± 0.48
SiII	15.13 ± 0.46	-	-	-
SiIV	14.50 ± 0.15	-	-	-
Si	-	15.22 ± 0.46	-6.04 ± 0.46	-1.58 ± 0.46
OVI	15.33 ± 1.96	-	-	-
O	-	15.33 ± 1.96	-5.93 ± 1.96	-2.62 ± 1.96
NV	14.85 ± 0.45	-	-	-
N	-	14.85 ± 0.45	-6.42 ± 0.45	-2.35 ± 0.45
AlII	14.02 ± 0.25	-	-	-
AlIII	12.79 ± 0.04	-	-	-
Al	-	14.22 ± 0.25	-7.05 ± 0.25	-1.52 ± 0.25
PV	14.06 ± 0.07	-	-	-
P	-	14.06 ± 0.07	-7.21 ± 0.07	-0.72 ± 0.07
MgI	12.33 ± 0.17	-	-	-
MgII	14.65 ± 0.57	-	-	-
Mg	-	14.65 ± 0.57	-6.62 ± 0.57	-2.16 ± 0.57
FeII	14.53 ± 0.33	-	-	-
Fe	-	14.53 ± 0.33	-6.74 ± 0.33	-2.11 ± 0.33

Table 5.8: *Metallicity of the circumburst material.* ^(a) *Total column density of the element*

Table 5.8 gives our metallicity estimates. The second column gives the sum of the column densities of the six components (all components we found apart from the (b) one) for each ion (including ground states and the excited fine-structure levels, if these are present). The third column gives the total column density for each element which is obtained by adding together the column densities of the different ions of each element. The fourth and fifth columns give the metallicity of the element and the metallicity with respect to the solar one respectively.

The above estimates are not corrected for depletion in dust grains. In the ISM of the Milky Way, the fraction of iron in the gas phase ranges from about 20% of the total in the warm and diffuse gas of the halo, to less than 1% in the cool disk ISM (Savage & Sembach 1996). Because of the intense GRB radiation field which can destroy dust grains up to large distances, the situation can be very different in a GRB surrounding medium (Waxman & Draine 2000; Fruchter, Krolik &

Rhoads 2001; Draine & Hao 2002; Perna & Lazzati 2002; Perna et al. 2003), and also this does not necessarily include all transitions for each element.

5.5.4 C/Fe ratio

Following D'Elia et al. (2007) we calculated the average $[C/Fe]$ ratio, an estimator of the enrichment of the α elements relative to iron. We measure a mean $[C/Fe]=0.38\pm0.75$, consistent with the value predicted by the models of Pipino & Matteucci (2004, 2006) for a galaxy younger than 1 Gyr subject to a burst of star-formation. In such a case also a low $[Fe/H]$ value is predicted, close to that in Table 5.8, and similar to what found by D'Elia et al. (2007) for GRB050730. Again, we note that mean abundance estimates may be affected by large systematic uncertainties.

5.6 Discussion and Conclusions

We plot in Figure 5-14 low to high-ionisation ion ratios for the seven components of the $z=2.1992$ system. The different behaviour of component (b) with respect to all the others and in particular to component (d) is evident from this plot. The most natural explanation for this behaviour is to assume that the various components do not belong to the same physical region in the host galaxy. The strength of the high ionisation lines and of the fine-structure lines, the absence of MgI absorption, the analysis of the ratio of the excited levels to ground levels and the metallicity analysis suggest that component (d) may be related with the GRB site neighbourhood, at a distance from the GRB site $< 50 - 100\text{pc}$.

Conversely, the presence of strong MgI absorption, absence of high-ionisation lines and excited transitions and low metallicity in some cases, suggest that the (b) component is located further away from the GRB site, in a region of the host galaxy not affected by the GRB radiation field ($> 1\text{kpc}$).

The presence of neutral elements in the spectra of GRB afterglows is important, because it can place strong constraints on the distance of the gas from the GRB. In the afterglow spectra of GRB050922C we detect neutral MgI for four components: (b) (e) (f) and (g), see Figure 5-11. This implies that the gas clouds related to these components are at distances greater than 100 pc from the GRB site.

Two of these four components, (e) and (f), do show fine-structure transitions. If the dominant excitation mechanism is UV pumping from the GRB radiation field, this suggests a distance $\leq 1\text{kpc}$ from the GRB site (Prochaska et al. 2007). Therefore components (d) and (e) should be located at distances between 100 and 1000 pc from the GRB site. This may explain why component (d)

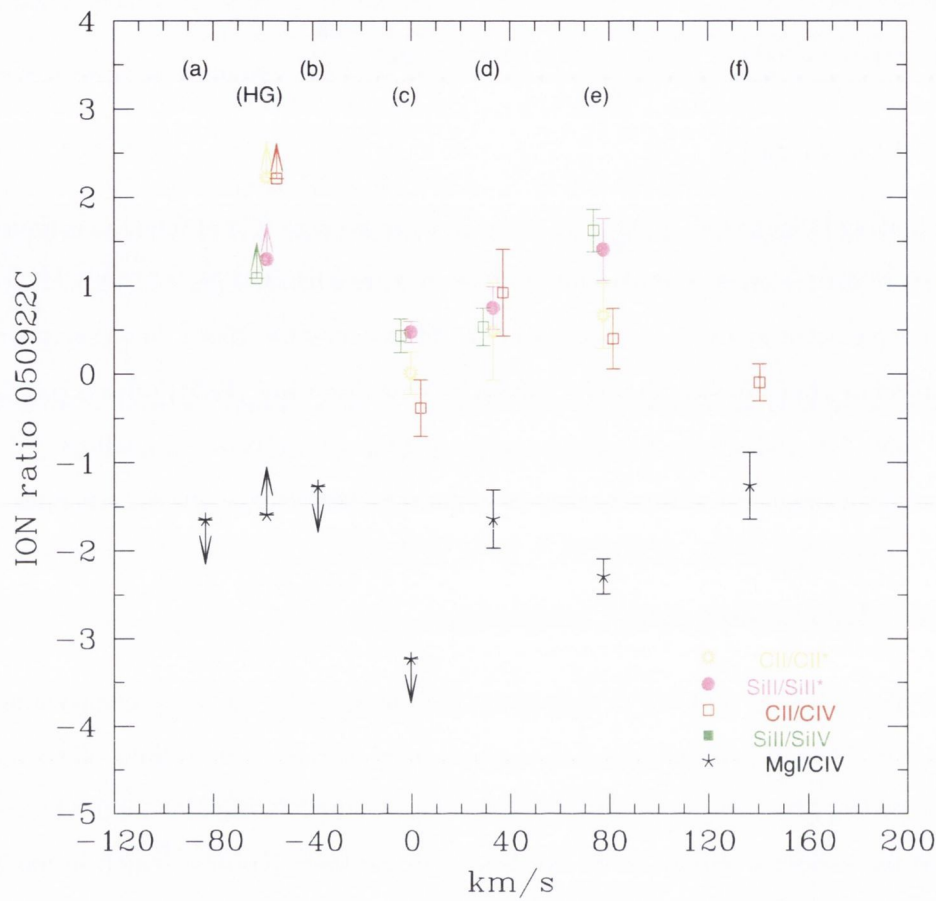


Figure 5-14: Logarithmic column density ratios of low to high-ionisation ions for the seven components of the $z=2.1992$ system.

exhibits also high-ionisation absorption (CIV, SiIV, NV, PV, OVI).

6

High Resolution Spectroscopy of GRB060607

6.1 Introduction

The previous two chapters have dealt with high resolution spectroscopy of GRB afterglows and how such studies can demonstrate the complex and diverse environments associated with GRB host galaxies. Here we continue the study of GRB environments with high resolution observations of GRB060607.

GRB021004 was one of the first examples of how important high-resolution follow-up observations of GRBs are, and showed for the first time the complex nature of the circumburst environment. Individual components could be identified, suggesting a clumpy environment, with some components moving at relative velocities of ~ 3000 km / s. Although helping to reveal the true diversity of the GRB circumburst environment, the observations began ~ 13.52 hours after the burst. From the results of these observations it was clear that if it were possible to obtain such high quality spectra within minutes of the burst a far greater amount could be learned about the kinematics, the structure of the medium directly around the GRB, and the excitation mechanisms involved. Since the observations of GRB021004, a dedicated rapid response mode (RRM) is now active on VLT,

allowing for observations to commence for a suitable burst within minutes of the trigger.

GRB050922C furthered this study by highlighting an even more complex view of the circum-burst environment. We detect seven components associated with the system of the host galaxy. We also identified fine structure absorption features for a number of components associated with the burst, suggesting a highly dense medium. Using ion ratios we were able to study which possible excitation mechanisms were involved. We analyze further the issue of disentangling different absorption systems using Ultra-violet and Visual Echelle Spectrograph (Dekker et al. 2000) with GRB060607.

Whereas the previous two bursts were observations undertaken as part of a larger collaboration, the observations of GRB060607 became public immediately, giving me a chance to begin an independent study of the data. GRB060607 differs strongly from the previous two bursts for a number of reasons. Both of the previous bursts showed rich host galaxy absorption features, while the absorption system of the GRB060607 host galaxy shows little detail and few absorption lines. Further to this we detect numerous intervening systems along the line of sight that show much greater detail and complexity, as well as higher hydrogen column densities, $N(\text{H I})$, than that of the host galaxy. In this chapter we further our study of GRB environments with a detailed study of the GRB060607 host environment and its intervening absorbers.

The burst was detected by Swift at 05:12:32 UT 7th of June 2006 (Norris et al. 2006) XRT, the Swift X-ray telescope, began observations 65 seconds after the trigger and revealed a new uncatalogued X-ray source (Ziaeepour et al. 2006). Then, 75 seconds after the trigger UVOT, the Swift UV-visible telescope began observations and confirmed the presence of the afterglow. REM also observed this burst, with observations beginning 59 seconds after the burst. While the REM observations were the first to begin, they were not the first to be reported. Details of the REM observations are presented in Chapter 3.

The afterglow was then observed by UVES/VLT at high spectroscopic resolution ($R \sim 40000$) at 05:19:52 UT, 7.5 minutes after the burst as part of the ESO programme 077.D-0661(A). A redshift value of the GRB, $z=3.082$, was determined by Ledoux et al. (2006) using these UVES observations. This value is reported again by Sudilovsky et al. (2007). However, the highest redshift system we find is 3.074, using Lyman α absorption along with CIV and SiIV absorption lines. The Lyman α line is quite narrow in comparison with other GRB hosts at $\Delta v \sim 220$ km/s, which along with the metal absorption lines at the same redshift confirms the accuracy of our result. The only other absorption feature that could account for a redshift of 3.082 is at 4960Å (see Figure 6-1), which if

taken as Lyman α would give a redshift of ~ 3.082 . However there are no coinciding metal lines at this redshift, and through further analysis we find that the feature at $4960\text{\AA}$ is actually SiII $1260\text{\AA}$ at redshift 2.933. We therefore report the redshift of this burst to be $z=3.074$.

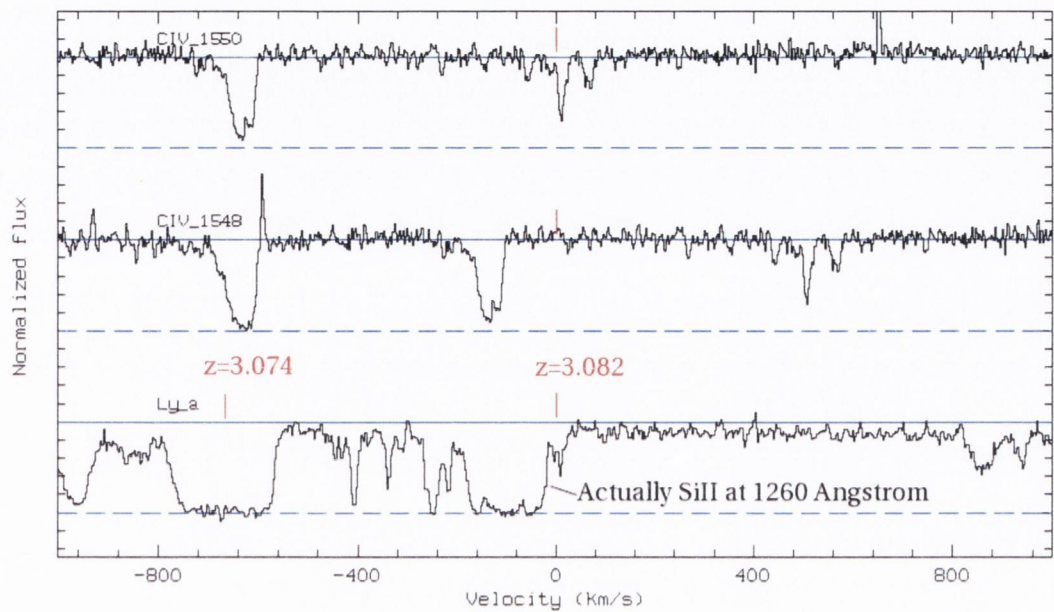


Figure 6-1: The identification of the redshift was achieved using the Ly α absorption line, with the corresponding CIV doublet at $1548\text{\AA}$ and $1550\text{\AA}$.

Although this system is likely to be due to the host galaxy of the GRB, it does not show much complexity in its structure. There are, however, strong intervening systems at $z=3.047, 2.933, 2.89, 2.278$ and 2.217 . Sudilovsky et al. (2007) have done a similar study of this GRB, in order to study the intervening systems of GRB line of sights. In addition to the higher redshift systems at $2.89 < z < 3.074$, they also report lower redshift systems at $z=2.2783, 2.2180, 2.2165$. We have analysed these also but deal with the two systems at $z=2.2180$ and 2.2165 as one.

GRB060607 has shown the true potential of VLT in RRM, with observations commencing just 7.5 minutes after the Swift trigger - a first for GRBs. Such prompt observations make it possible for a series of observations to be taken soon after the burst, which indeed materialised. This allows for the possible detection of variability in the absorption line equivalent widths, through which the excitation mechanism can be found. In the case of GRB060418 (Vreeswijk et al. 2007), UVES observations began ~ 10 minutes after the burst. Through subsequent variations in the column densities of fine structure lines they found direct evidence for the presence of UV pumping.

6.2 Observations and data reduction

Observations were made with UVES mounted at the VLT-UT2 telescope, and were made public immediately. Both UVES dichroics, as well as the red and the blue arm, were used. This allows us to achieve a particularly wide spectral coverage, extending from $\sim 3200\text{\AA}$ to $\sim 9500\text{\AA}$. The data reduction has been performed using the UVES pipeline (Ballester et al. 2000). The final useful spectra extend from about $3750\text{\AA}$ to about $9780\text{\AA}$. A plot of the entire spectrum is shown in Figure 6-2. The resolution element, set to two pixels, ranges then from 14 km/s at $4200\text{\AA}$ to 6.6 km/s at $9000\text{\AA}$. The noise spectrum, used to determine the errors on the best-fit line parameters, has been calculated from the background subtracted and rebinned spectrum, using line-free regions. This therefore takes into account both statistical errors and systematic errors in the pipeline processing and background subtraction.

Time UT	Exposure ^a	Dichroic	Arm	time since GRB ^a
05:20:02.911	179.999	1	RED	450
"	180.001	1	BLUE	"
05:24:15.238	300.001	1	BLUE	794
"	299.999	1	RED	"
05:30:25.749	600.001	1	BLUE	1078
"	599.999	1	RED	"
05:41:38.085	1200.001	1	BLUE	1746
"	1199.999	1	RED	"
06:02:59.624	2400.001	1	BLUE	2847
"	2399.999	1	RED	"
06:46:54.267	4800.001	2	BLUE	5482
"	4799.999	2	RED	"
08:12:23.308	2500.001	2	BLUE	10343
"	2499.999	2	RED	"

Table 6.1: Journal of observations. (^a = seconds)

Several observations were performed beginning ~ 7.5 min after the burst. The set of observations is summarised in table 6.1. A number of shorter exposures was performed earlier on in the observation, with the exposure time gradually increasing. As not all exposures were performed with both dichroics for the full duration of the observations, the ones used for the analysis of the absorption lines and possible variability were the 2400s exposure taken with dichroic 1 at 06:02:59.624 UT, which was taken 2847s after the burst (see table 6.1). Dichroic 1 covers the region between $3750\text{\AA}$ - $6600\text{\AA}$. This was the observation with the greatest exposure time which covered the region of the spectrum where the relevant absorption features are found.

The line fitting was performed using the MIDAS package FITLYMAN (Fontana & Ballester 1995). This uses a Voigt profile, and yields independently the column density N and the Doppler

parameter b for each absorption component. For each absorption system several lines, spread over the entire spectral range covered by the UVES observations, were fitted simultaneously, with the same number of components for each line, and the same redshift and b value for each component.

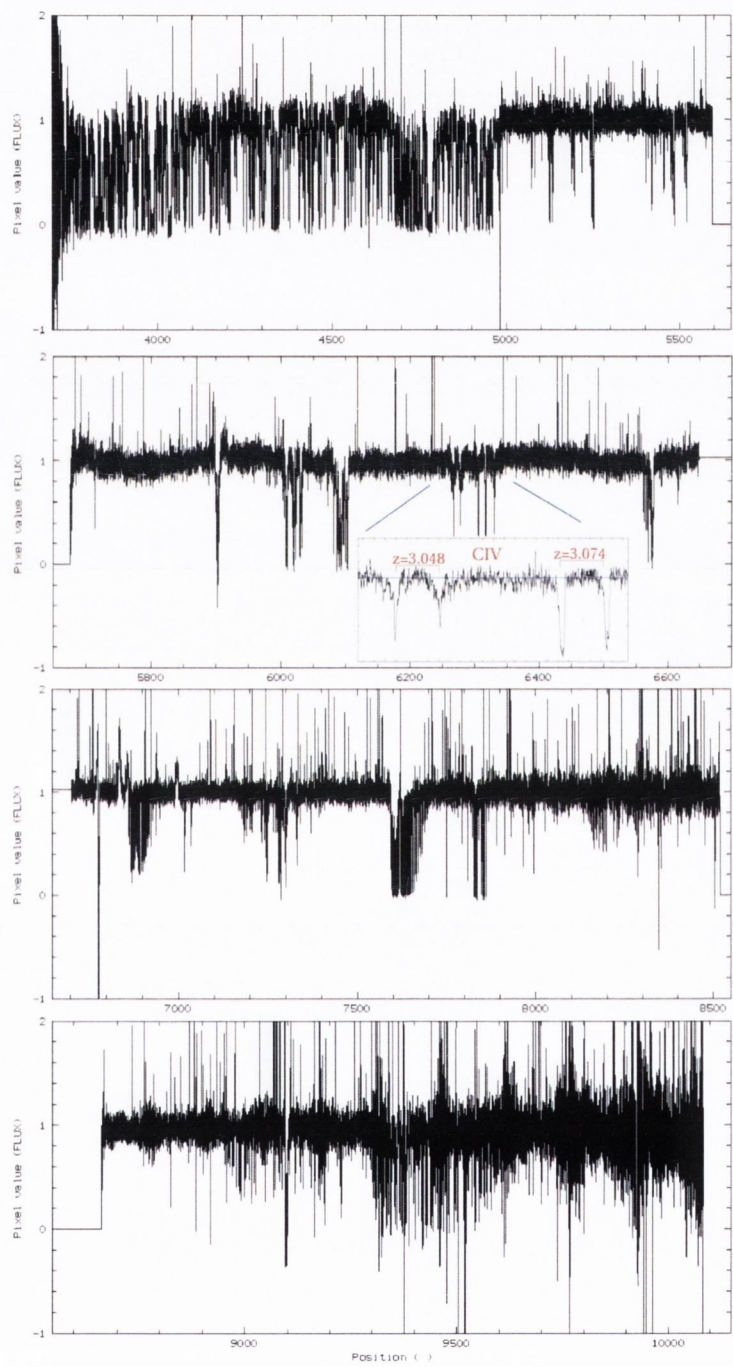


Figure 6-2: Entire UVES spectrum of GRB060607. The CIV systems at $z=3.048$ and $z=3.074$ can be seen at $\sim 6300\text{\AA}$

6.3 The Redshift System of the GRB host galaxy

The highest redshift system we find is at $z=3.074$, and is likely to be due to the host galaxy of the GRB. The initial detection was done by identifying Ly α and Ly β absorption lines and was confirmed with the detection of CIV and SiIV (see Figure 6-4).

Unlike most high resolution spectra obtained for GRBs, the system of GRB060607 is not rich in features. We do not detect any low ionisation lines. The only high ionisation transitions we detect are CIV and SiIV (see Figure 6-4). The second component of the SiIV doublet at $1393\text{\AA}$ is in a region of the spectrum where there is a break between filters, and it was therefore impossible to fit accurately.

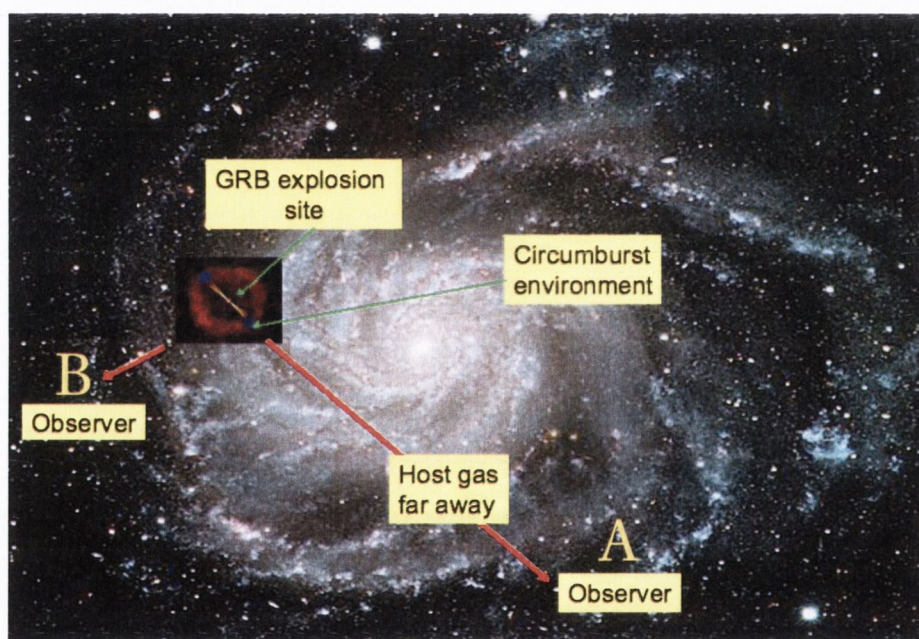


Figure 6-3: The line of sight of GRB can cross through large portions of a galaxy giving a rich multi-component absorption spectrum (Observer A), whereas, if the GRB were observed through less of the galactic material the observed spectrum would not be as complex (Observer B).

The column densities derived for CIV and SiIV suggest that low ionisation lines such as CII and SiII are not detectable. We can give upper limits of $\log N < 12.12 \text{ cm}^{-2}$ and $< 13.41 \text{ cm}^{-2}$ for their logarithmic column densities. This was achieved by fitting the region of the spectrum where these transitions should occur. This poses a number of questions as to what region is being probed, as we do not detect any low ionisation lines or other high ionisation lines that would normally (see Chapters 4 and 5) be associated with the circumburst medium or host galaxy. One possible explanation is that the line of sight does not intersect metal-rich regions of the host galaxy (see

Figure 6-3, observer A). Perhaps this indicates that the GRB is at the outer regions of the galaxy closest to the observer.

The lack of complexity in the absorption features indicates also that we are not probing directly the circumburst medium. In the previous chapter we found a lack of MgI for a number of absorption components, which were detected for other ions. This was strong evidence to suggest that the components for which there was no MgI were being directly affected by the GRB explosion, and that the MgI was being completely ionised out to a distance of > 100 pc (Prochaska et al. 2006). In a scenario such as observer B in Figure 6-3 the GRB line of sight would not intersect the metal-rich host galaxy, leaving a less complex set of absorption systems.

We identify four separate components using the CIV doublet (1548Å, 1550Å), spanning ~ 60 km / s (see fig 6-4). This system is quite weak in comparison with those of other GRB host environments. The total logarithmic column densities measured for C and Si are $14.36 \pm 0.17 \text{ cm}^{-2}$ and $13.52 \pm 0.46 \text{ cm}^{-2}$, respectively. This is to be compared with $15.76 \pm 0.79 \text{ cm}^{-2}$ and $16.45 \pm 1.10 \text{ cm}^{-2}$, respectively, for GRB050922C. For identifying the separate components we have assigned 0 km / s to the redshift 3.074, with the velocity shift of each component given relative to that redshift. We have done this because there is no way of telling the precise redshift of the GRB, or finding a central component. We can only assign a redshift to the GRB based on the observed components, some of which may not be directly affected by the GRB. This redshift was chosen as a central point between the four components. The results of the fit are given in table 6.2 (values are given as $\log(N) \text{ cm}^{-2}$).

Ion	-44km s ⁻¹	-24 km s ⁻¹	-4 km s ⁻¹	17 km s ⁻¹
HI	-	-	15.49 ± 0.36	-
SiIV	-	12.62 ± 0.35	13.40 ± 0.08	12.58 ± 0.29
CIV	13.14 ± 0.07	13.32 ± 0.11	14.14 ± 0.05	13.77 ± 0.09

Table 6.2: Column densities derived for the absorption system of the GRB host galaxy. Values for N are given as $\log_{10} N \text{ cm}^{-2}$.

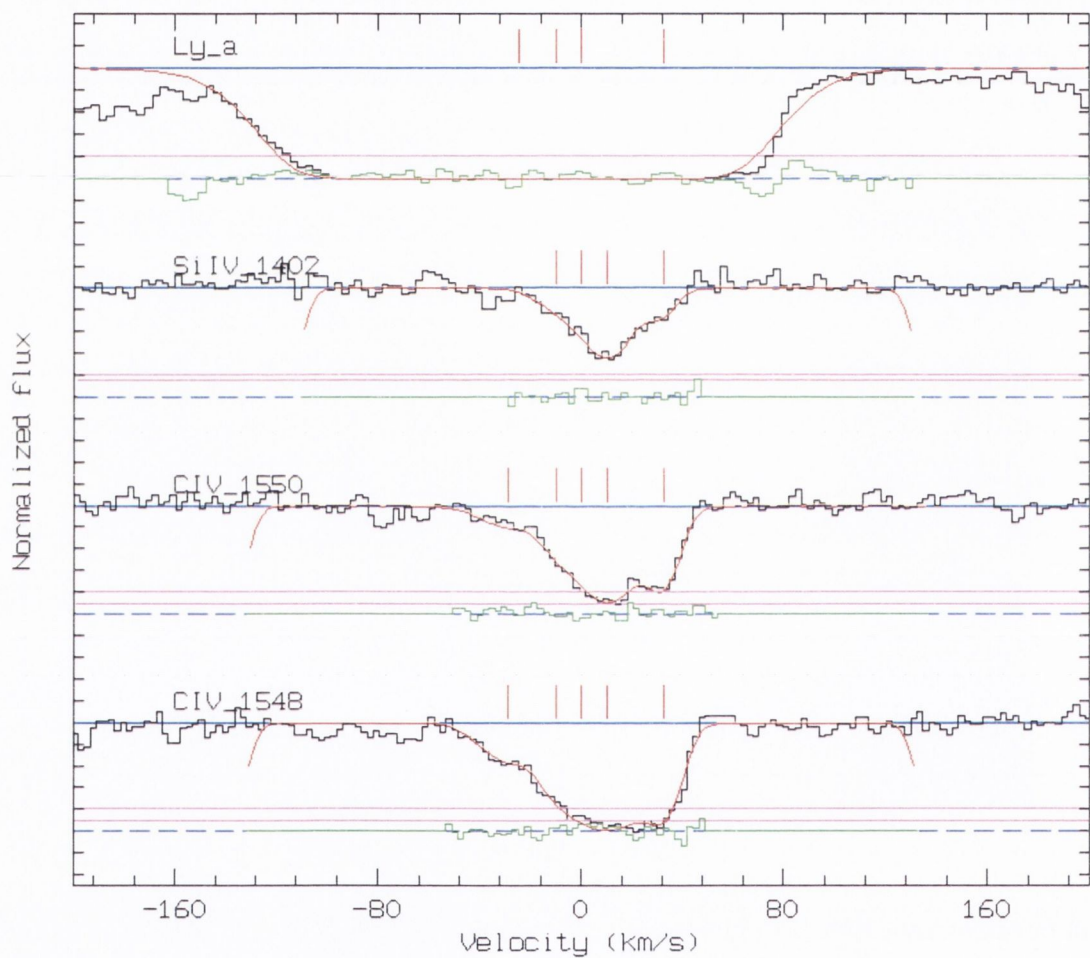


Figure 6-4: The spectrum of GRB060607 at $z=3.074$. We detect high ionisation lines CIV and SiIV

6.3.1 Variability

Beginning ~ 7.5 minutes after the burst a series of observations was performed (see table 6.2). Using the five sets of data taken at 450, 794, 1078, 1746 and 2847 seconds after the burst we can test for the presence of variability in the column density of the absorption lines. These five exposures were taken with dichroic 1 which covers the wavelength range where the CIV and SiIV are present. The last four exposures used dichroic 2 which has a wavelength coverage $> 6600\text{\AA}$, so can therefore not be directly compared with the earlier exposures. The strongest absorption feature is the CIV doublet at $1548\text{\AA}$ and $1550\text{\AA}$, for which we detect four components as reported in the previous section. Figure 6-5 shows the superposition of three of the spectra at times $t=450$, 1746 and 2847s after the burst, for both CIV (at $1550\text{\AA}$) and SiIV (at $1402\text{\AA}$). These were 180, 1200 and 2400 second exposures, respectively.

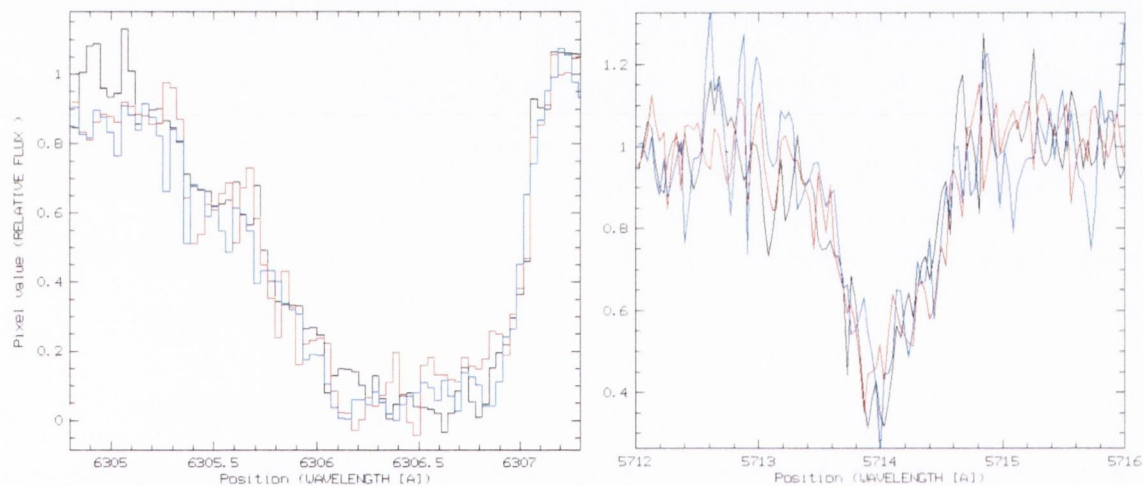


Figure 6-5: Superposition of three $t=450$ s (red), 1746s (blue) and 2847s (black) spectra at the position of CIV $1550\text{\AA}$ (left) and SiIV $1402\text{\AA}$ (right) absorption features.

The total column density for CIV and SiIV was measured at each time interval and the results are plotted as $\log N$ vs. time after burst in Figure 6-6. For the CIV we used the doublet at $1550\text{\AA}$, $1548\text{\AA}$ and for SiIV the single observable line at $1402\text{\AA}$. Although we do detect variation in the column density, notably a rise in the column density, the results are inconclusive due to the large errors. There are no errors shown for Figure 6-6, because for the earlier exposures they were too large to fit within the plot (the errors were of the order of $10^{0.5}$ and 10^1 for CIV and SiIV respectively). This is no doubt due to the lower signal to noise of the earlier exposures. A further analysis including modeling of the evolution of the CIV and SiIV column density with time would give a better indication of what should be expected.

Nonetheless as a preliminary analysis we do notice a trend in the variation of the column density between the two ions. There is a noticeable increase at earlier times followed by a decrease at ~ 200 s, and then again by an increase at ~ 600 s. Previous work using ionisation modeling codes, by Vreeswijk et al. (2007), shows that in the case of UV pumping, as a possible excitation mechanism, the column density can undergo a steep increase followed by a steady decline as various energy levels are populated by the ionisation continuum and then decay (see Figure 6-7). Their results, however, are based on Fe and Ni transitions and cannot be applied to our fits. Our result does indicate, however, an early time increase in the column density of CIV, possibly as a result of ionisation due to UV pumping.

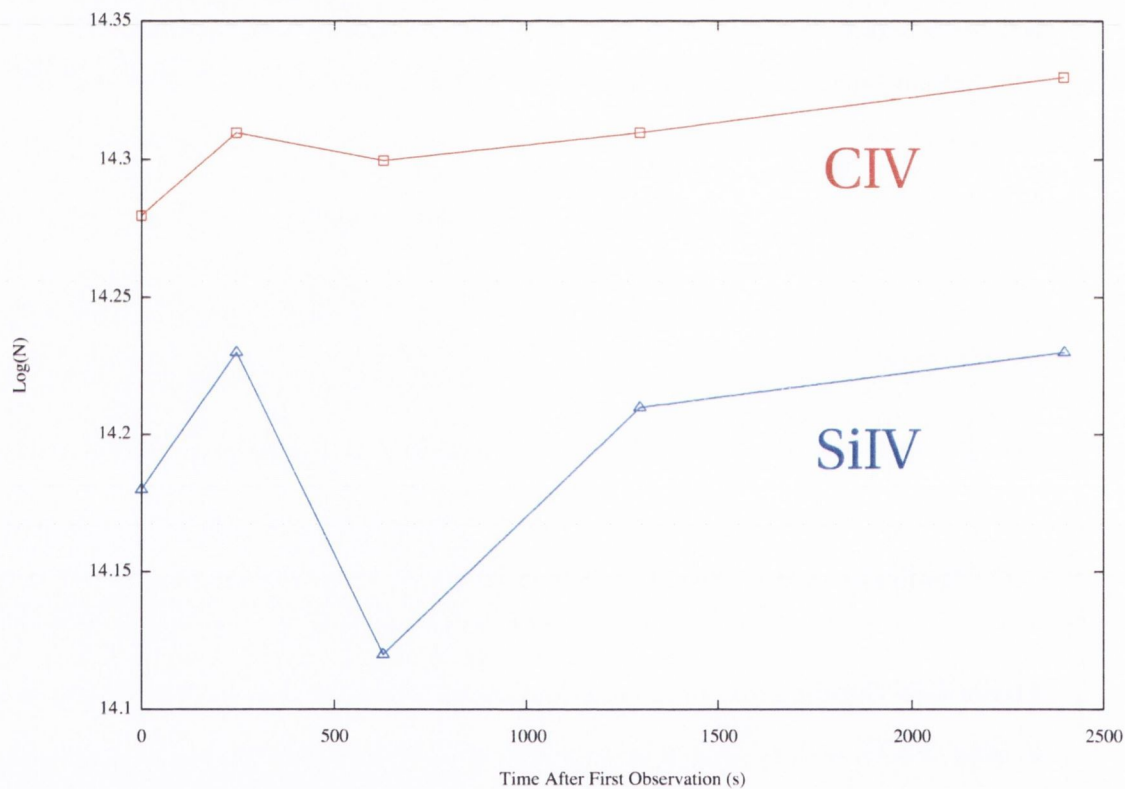


Figure 6-6: The variation in column densities of SiIV and CIV do show a trend, most noticeably an early time increase. The values for the column densities of SiIV have been increased by a factor of $10^{0.7}$ to make them more visible in the comparison between the two ions.

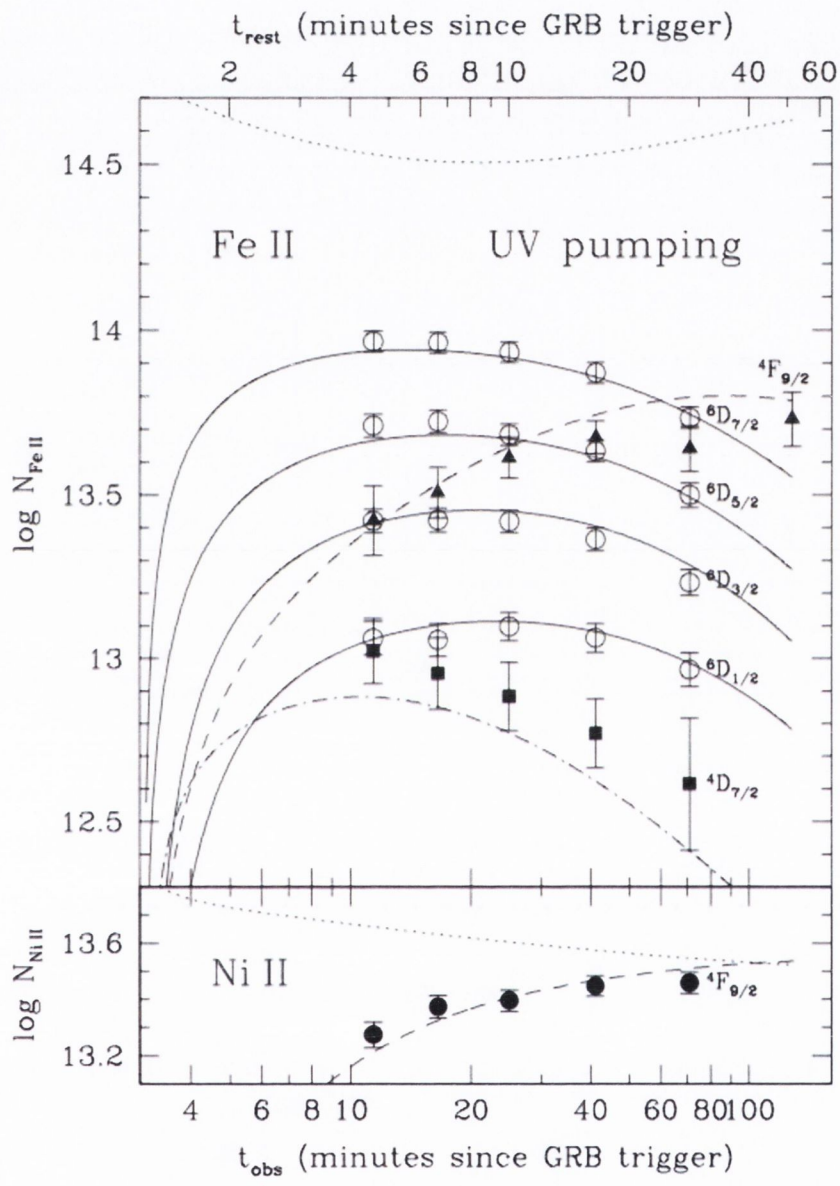


Figure 6-7: The comparison between the expected variation of the column density of different transitions of FeII and NiI (lines), along with the observed values form GRB060418 (data points). Taken from Vreeswijk et al. 2007.

6.4 Intervening Systems

6.4.1 Intervening System at $z=3.048$

The second highest redshift system we detect is at $z = 3.048$. Again this system is comparatively weak. We detect both high and low ionisation lines, CIV, SiII and CII. We find four components spanning $\sim 180 \text{ km / s}$ (see Figure 6-8). We also find a large Lyman α absorption feature, far larger than that of the GRB host. The redshift for this system was chosen as the redshift of the strongest component for CII and SiII. This choice is somewhat subjective, as the Lyman α line is far broader than the other components, and is, in all likelihood, a combination of a number of components.

Ion	-130 km s ⁻¹	-32km s ⁻¹	+16km s ⁻¹	0km s ⁻¹
HI	-	-	19.36 $\pm$ 0.03	-
SiII	-	-	-	12.54 $\pm$ 0.11
CII	-	-	-	13.82 $\pm$ 0.06
CIV	13.05 $\pm$ 0.07	13.43 $\pm$ 0.10	13.59 $\pm$ 0.06	13.26 $\pm$ 0.07

Table 6.3: Column densities ($\log(N) \text{ cm}^{-2}$) derived for the absorption system at $z=3.048$.

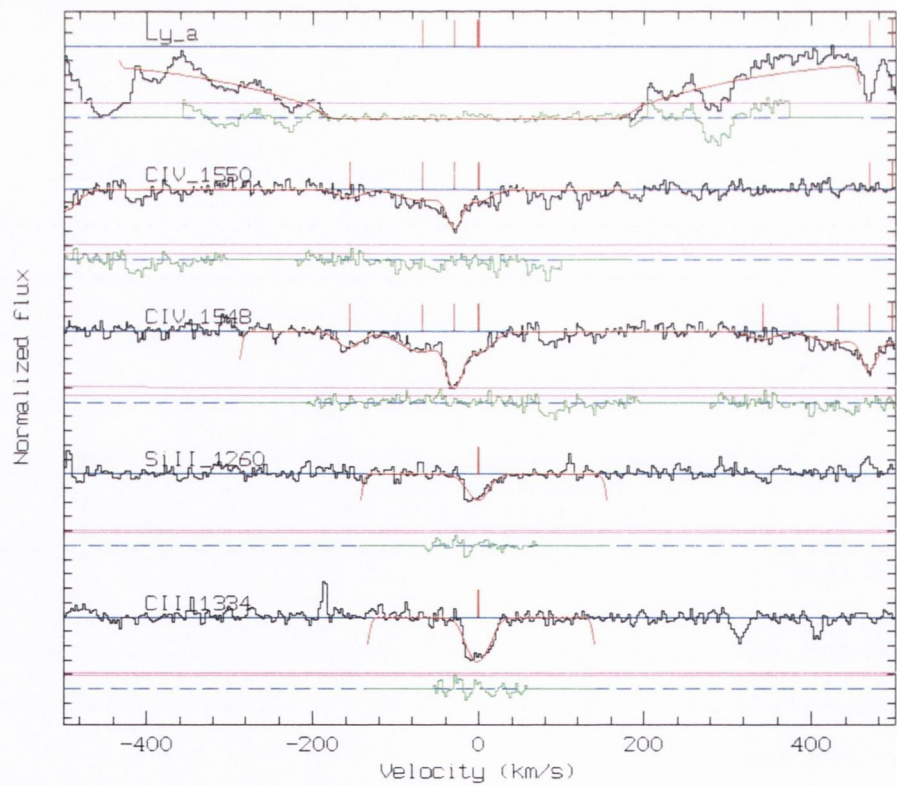


Figure 6-8: The spectrum of GRB060607 at $z=3.048$. We detect both high and low ionisation lines (CIV, CII and SiII)

6.4.2 Intervening System at $z=2.933$

The intervening system we detect at $z=2.933$ is by far the most complex intervening system along the line of sight, and is in fact the most complex intervening absorption system observed in any of the high resolution spectra of GRBs observed to date. We detect eleven separate components spanning ~ 700 km/s (see Figures 6-9, 6-10 and 6-11). There is a large corresponding Lyman α absorption system with $\log N = 19.89 \pm 0.03$ (see Figure 6-12). We detect both high and low ionisation lines, the results of which are summarised in table 6.4. Along with CIV and SiIV, we also detect such low ionisation species as OI, CII, SiII, AlII, FeII and NiI, as well as high ionisation lines such as AlIII.

Ion	-340 km s ⁻¹	-70km s ⁻¹	1 km s ⁻¹	87 km s ⁻¹	121 km s ⁻¹
HI	19.89 ± 0.03	-	-	-	-
OI	-	-	-	13.61 ± 0.15	-
CII	13.36 ± 0.00	13.91 ± 0.00	14.97 ± 0.00	14.40 ± 0.00	14.15 ± 0.00
SiII	-	12.86 ± 0.08	13.89 ± 0.00	13.90 ± 0.54	12.62 ± 0.15
AlII	-	12.75 ± 0.04	13.36 ± 0.30	12.39 ± 0.05	12.10 ± 0.09
FeII	-	-	13.08 ± 0.26	-	-
AlIII	-	12.34 ± 0.21	-	-	-
CIV	13.74 ± 0.04	14.08 ± 0.03	-	14.44 ± 0.03	14.08 ± 0.14
SiIV	12.86 ± 0.08	13.40 ± 0.00	-	12.98 ± 0.08	12.73 ± 0.14

Ion	144 km s ⁻¹	176 km s ⁻¹	212 km s ⁻¹	242 km s ⁻¹	297 km s ⁻¹	340 km s ⁻¹
HI	-	-	-	-	-	-
OI	-	13.86 ± 0.10	13.62 ± 0.31	14.50 ± 0.07	14.52 ± 0.07	-
NiI	13.79 ± 0.25	13.28 ± 0.23	16.15 ± 0.73	13.63 ± 0.14	12.94 ± 0.19	-
CII	13.99 ± 0.00	14.24 ± 0.00	12.81 ± 0.00	14.79 ± 0.00	15.09 ± 0.41	13.55 ± 0.00
SiII	13.33 ± 0.11	13.42 ± 0.19	13.47 ± 0.40	15.63 ± 0.85	14.78 ± 0.61	12.54 ± 0.13
AlII	12.05 ± 0.12	12.86 ± 0.07	12.36 ± 0.30	13.36 ± 0.04	12.87 ± 0.05	13.46 ± 0.19
FeII	13.19 ± 0.10	13.42 ± 0.17	13.85 ± 0.06	13.49 ± 0.06	-	-
AlIII	-	12.67 ± 0.20	13.14 ± 0.13	13.15 ± 0.11	12.97 ± 0.20	-
CIV	13.57 ± 0.80	13.94 ± 0.17	14.63 ± 0.05	14.88 ± 0.47	12.60 ± 0.75	-
SiIV	13.30 ± 0.00	13.34 ± 0.00	12.88 ± 0.27	14.22 ± 0.05	13.13 ± 0.15	12.50 ± 0.15

Table 6.4: Column densities derived for the absorption system at $z=2.933$ (values are given as $\log(N) \text{ cm}^{-2}$).

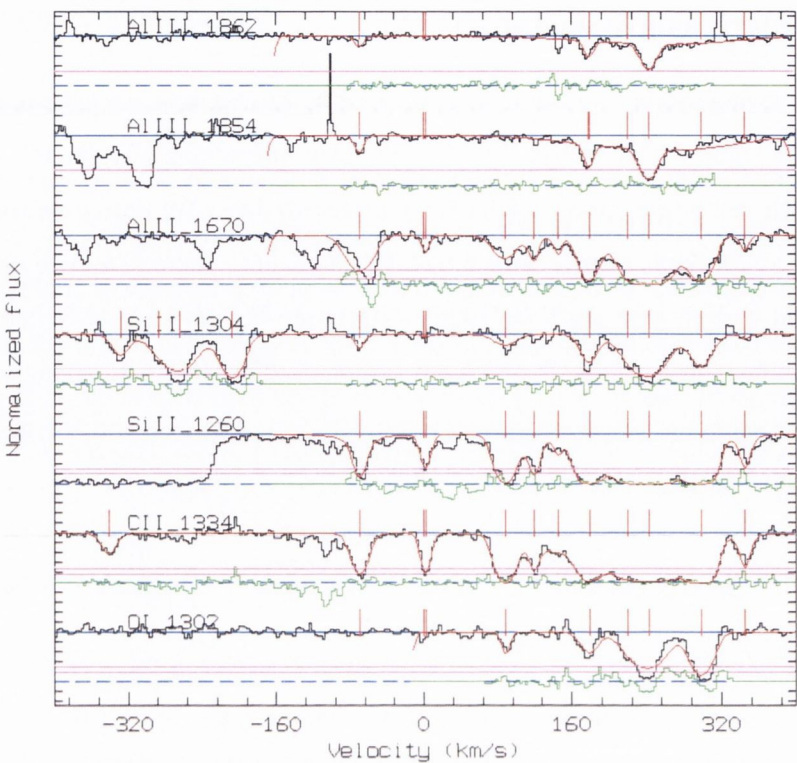


Figure 6-9: Low ionisation absorption lines (OI, CII, SiII, AlII and AlIII) at $z=2.933$.

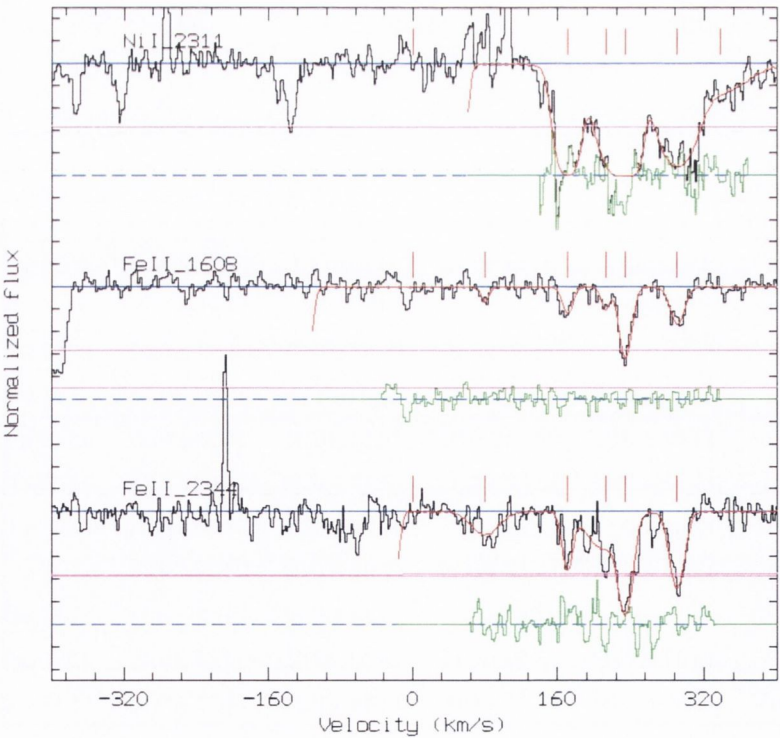


Figure 6-10: FeII and NiI absorption at $z=2.933$.

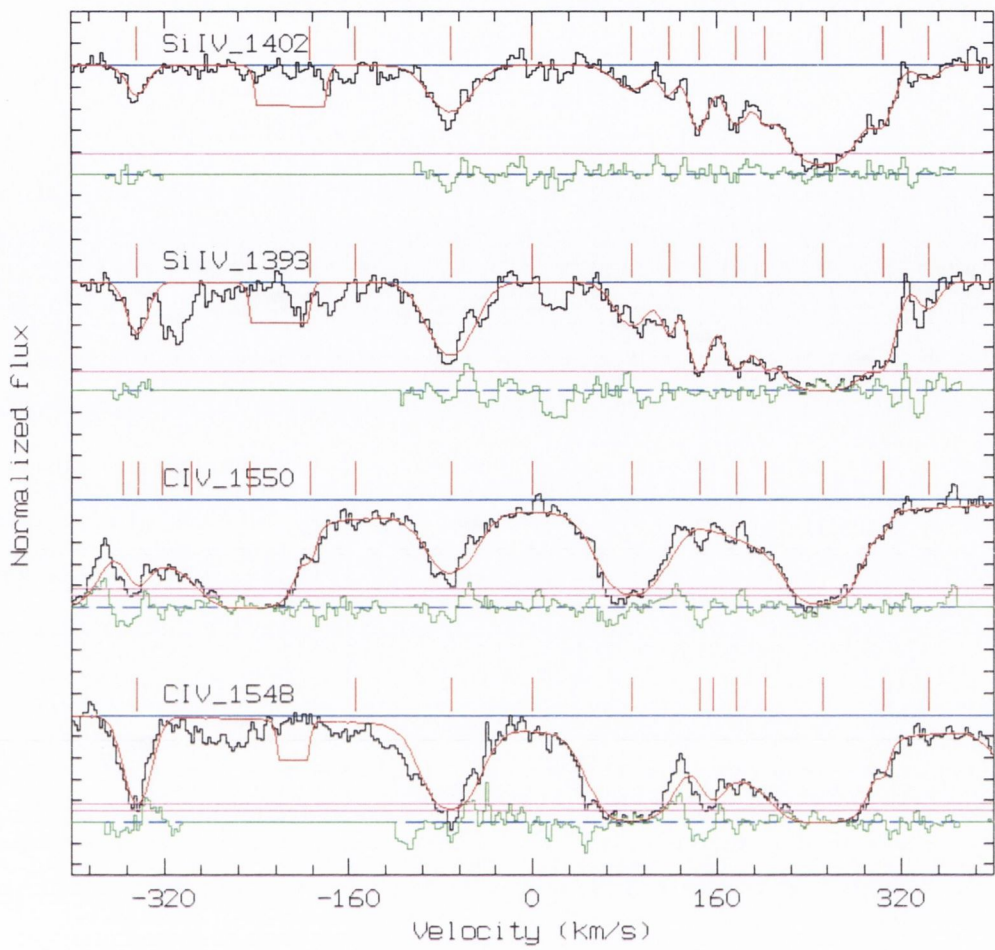


Figure 6-11: High ionisation absorption lines of C IV and Si IV at $z=2.933$.

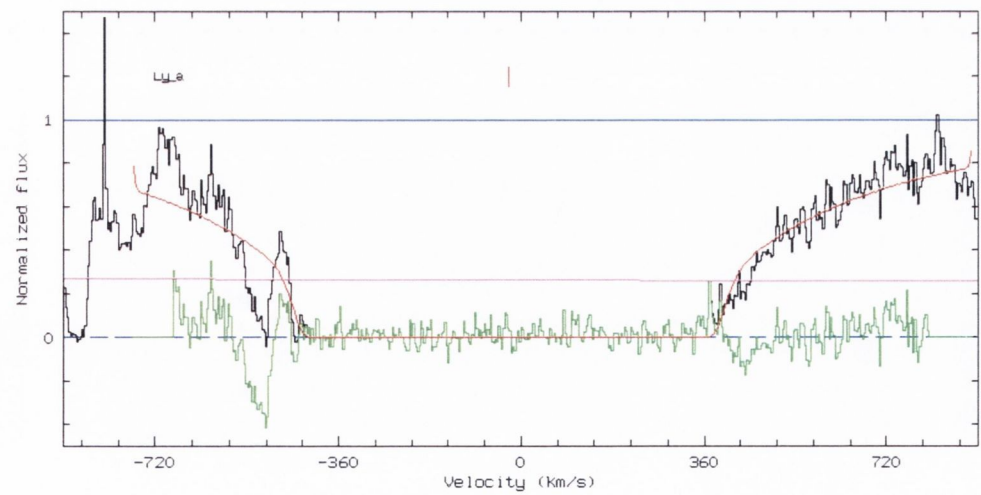


Figure 6-12: Lyman α absorption at $z=2.933$.

6.4.3 Intervening System at z=2.89

We detect another intervening system along the line of sight, at z=2.89. This system can be taken as three separate systems at z~2.8807, 2.8888 and 2.8957. Each of the three systems has corresponding Lyman α absorption (see Figure 6-13). The central system, at z=2.8888, is the most complex with five separate components and the largest of the Lyman α column densities, $\log N = 18.75 \pm 0.13$. We detect both high and low ionisation lines, CII, CIV and SiIV, for this system. The derived column densities are summarised in table 6.5.

Due to some blending with the various components of the CIV doublet, some components appear to be part of a different redshift system. For example, in the bottom panel of Figure 6-13 are given the CIV 1548Å absorption features. To the left of the central system (at ~ -50 km / s) there appears to be a lone CIV 1548Å feature that does not coincide with its doublet pair (CIV 1550Å). However, on closer inspection we find that is in fact a CIV 1550Å transition at ~ -600 km / s. The clearest illustration of the three separate systems is the SiIV doublet at 1393Å and 1402Å, in conjunction with the Lyman α features. Using these we can disentangle which components belong to which systems.

The two other systems at z=2.8807 and 2.8957 show just a single component for both SiIV and CIV, with both Lyman α column densities around 10^{15} . If the three systems are taken as coming from a single object, the total velocity difference is ~ 1160 km / s. However the three systems show distinct Lyman α absorption components, the two smaller of which have column densities of the order of 10^{15} , comparable to that of the GRB host.

	z=2.8807	z=2.8888					z=2.8957
Ion	-603 km s ⁻¹	-28 km s ⁻¹	-3 km s ⁻¹	25 km s ⁻¹	105 km s ⁻¹	153 km s ⁻¹	560 km s ⁻¹
HI	15.22 ±0.54		18.75 ± 0.13				14.90± 0.20
CII		13.73±0.30	12.90 ±0.24			12.84 ±0.31	13.43 ±0.11
CIV	13.87±0.03	14.16 ± 0.18	14.26± 0.09	13.91 ±0.10	13.91 ±0.06	13.45 ±0.04	13.42 ± 0.39
SiIV	12.60±0.12	13.83± 0.37	12.96± 0.08	12.79± 0.21	13.06± 0.12	12.34 ± 0.19	12.70 ±0.10

Table 6.5: Column densities derived for the absorption system at z=2.89 (values are given as log(N) cm⁻²).

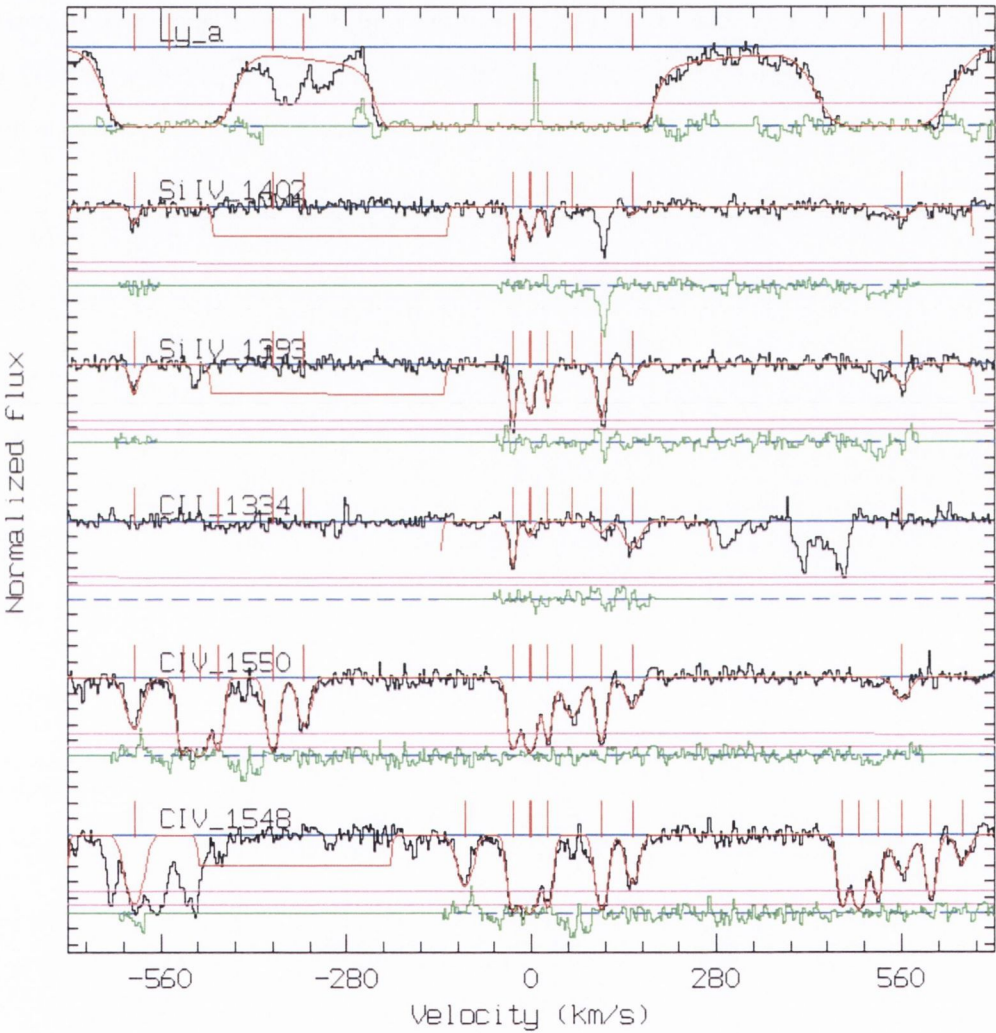


Figure 6-13: Three absorption systems are found around the large central system at $z=2.89$

6.4.4 Intervening System at $z=2.278$ and 2.217

Two nearer systems are found at $z=2.278$ and 2.217 . The system at 2.278 is the only system for which we detect MgII. However, there may be MgII present for the higher redshift systems but the doublet at $2796\text{\AA}$ and $2803\text{\AA}$ is beyond the edge of the spectrum for these systems and is therefore undetectable. We also detect a number of other low and high ionisation lines, such as CII, SiII, CIV and SiIV; the results of the fits are summarised in table 6.6. This $z=2.278$ system shows a single component for the metals with a large corresponding Lyman α absorption line (see Figure 6-14).

The system at $z=2.217$ is another curious example. We detect four systems spanning ~ 250 km/s (see Figure 6-15). What makes this system unique among all the others is that the Lyman α line extends across the same velocity range as the metals. We can disentangle at least one of the Lyman α components that corresponds with the CIV absorption line at the same redshift. For the component at $\sim +120$ km/s the Lyman α component can be clearly resolved (see Figure 6-15).

Ion	0 km s^{-1}
HI	19.85 ± 0.27
CII	14.24 ± 0.33
SiII	13.55 ± 3
MgII	13.28 ± 0.12
CIV	13.73 ± 0.05
SiIV	13.42 ± 0.10

Table 6.6: Column densities derived for the absorption system at $z=2.278$ (values are given as $\log(N) \text{ cm}^{-2}$).

Ion	-98 km s^{-1}	-23 km s^{-1}	52 km s^{-1}	123 km s^{-1}
HI	-	15.01 ± 0.85	-	13.40 ± 1.81
CIV	13.63 ± 0.06	13.25 ± 0.10	13.15 ± 0.17	13.58 ± 0.10

Table 6.7: Column densities derived for the absorption system at $z=2.217$

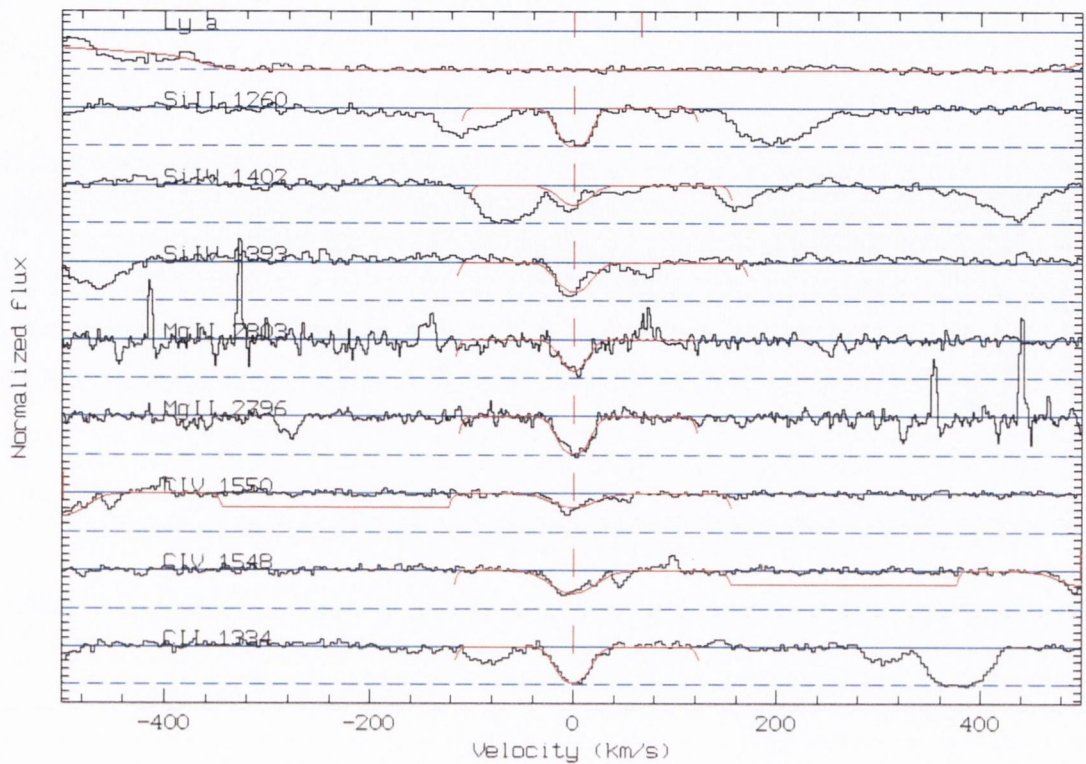


Figure 6-14: Absorption systems at redshift 2.278

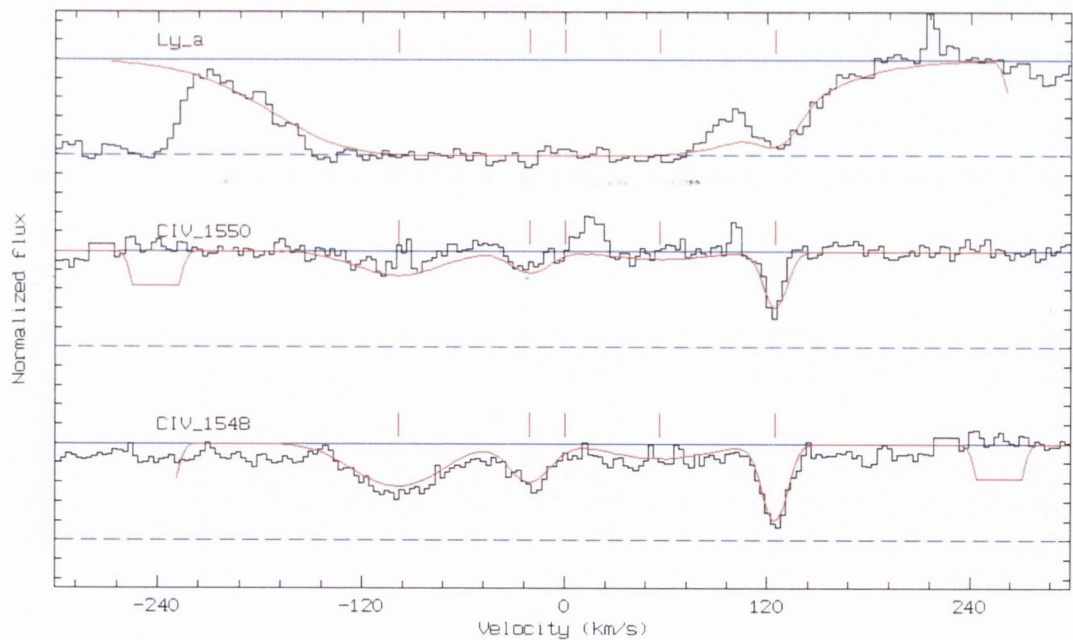


Figure 6-15: Absorption systems at redshift 2.217. A number of lone components appear (for SiIV 1402Å, at ~ 70 km / s and 160 km / s, but these have no coinciding component for SiIV 1393Å so should not be counted as part of this redshift system.)

6.4.5 Metallicity of the Host System

Figure 6-4 shows the Lyman α absorption feature of the host galaxy system. It is impossible to discriminate between the four components identified from the analysis of CIV and SiIV. This Lyman α system has quite a small column density in comparison with others observed for GRB host galaxies (see Chapter 4 and 5).

Since a component-by-component analysis is not possible, we can only estimate the metallicity of the circumburst material in terms of the ratio $[X/H]$ between the total absorption column of the X element with respect to that of hydrogen. Since the latter may include hydrogen in the outer regions of the galaxy not associated with the region around the GRB, we will probably underestimate the metallicity of the inner absorption clouds. Therefore such estimates should be considered only as a lower limit to the true metallicity of the gas.

Using the inferred value for the column density of Lyman α ($N(H_I)$), and combined column densities for the other ions (see table 6.2), the metallicity of the circumburst medium can be obtained. The metallicity is measured using the formula (Srianand et al., 2000):

$$[X/H] = \log N(X) - \log N(H_I) \tag{6.1}$$

and

$$z = [X/H] - [X/H]_{\odot} \tag{6.2}$$

for the metallicity relative to that measured in the sun.

Ion	$\log N \text{ (cm}^{-2}\text{)}$	$[X/H]$	z
HI	15.49 ± 0.36	-	-
C	14.36 ± 0.17	-1.13 ± 0.40	2.48 ± 0.48
Si	13.52 ± 0.46	-1.97 ± 0.58	2.49 ± 0.58

Table 6.8: Metallicity derived from the absorption system of the host galaxy (values are given as $\log(N) \text{ cm}^{-2}$).

Table 6.8 gives our metallicity estimates. The above estimates are not corrected for depletion in dust grains. In the ISM of the Milky Way, the fraction of the iron in gas phase ranges from about 20% of the total in the warm and diffuse gas of the halo, to less than 1% in the cool disc ISM (Savage & Sembach 1996). Because of the intense GRB radiation field which can destroy dust

grains, the situation can be very different in a GRB surrounding medium (Waxman & Draine 2000, Draine & Hao 2002, Perna & Lazzati 2002, Perna, Lazzati & Fiore, 2003).

We can see from our results that the inferred value for the metallicity is consistent for both measurements, using Si and C. The value obtained, ~ 2.49 suggests a metallicity value that is much higher than previously measured for GRB hosts (see Chapter 5). This is due in part to the low hydrogen column density observed. Using values for $N(\text{HI})$ on a par with what has been previously observed (e.g. $N(\text{HI}) = 10^{21.27}$ for GRB050922C) would give a metallicity in the region of ~ 2.5 , which is somewhat closer to what would be expected.

6.5 Comparison with X-ray Observations

Apart from measuring the column density directly using Lyman α to infer the amount of Hydrogen present in the host galaxy, it is also possible to measure the Hydrogen column density through X-ray measurement. The two techniques differ in their approach. The Hydrogen absorbing the UV flux observed in the UVES spectra is HI i.e. ionised Hydrogen. The Hydrogen column density measured through X-ray observations is inferred through a fit of the X-ray spectrum. The X-ray spectrum will show absorption due to neutral Oxygen, from which the Hydrogen abundance can be extrapolated, using solar abundances.

A study of the X-ray spectrum of GRB060607A (Watson et al. 2007) has found a much higher value for the Hydrogen column density of $N_H \sim 10^{21.74}$. This is many orders of magnitude higher than the value we have obtained with absorption spectra. Watson et al. (2007) study a number of bursts for which both X-ray N_H and spectroscopic $N(\text{HI})$ are measured. Interestingly there is little correlation between the two. One suggestion is that the two methods are probing different material in the host galaxy. The lack of large $N(\text{HI})$ column densities may suggest that most of the Hydrogen has been ionised by the burst, thus not contributing to the absorption, and is therefore not truly indicative of the total Hydrogen present in the host galaxy. The metals used to infer N_H from the X-ray spectrum are not as affected by the GRB and thus give a larger value for the amount of Hydrogen.

It should be noted that the X-ray measurement of N_H is not a direct one. The value is an extrapolation based on solar abundances. Also, this measurement is strongly based on the Oxygen absorption edge at 0.52 keV. At higher redshift this becomes harder to measure. It should also be noted that in the case of GRB060607A there were a number of intervening systems along the line of sight, each of which had a Hydrogen column density far higher than that of the host galaxy. A

number of which were at redshifts comparable to that of the host galaxy. I feel a more detailed study should be carried as to whether the existence of such large intervening absorbers could affect the inferred X-ray Hydrogen column density.

6.6 Discussion

The results of our analysis of the spectra of GRB060607 have shown many features different from what has been previously seen in other GRB spectra. Not only does the highest redshift system show very few metal absorption lines, but there is a correspondingly small column density of Hydrogen. Further to this the other redshift systems along the line sight show a far greater complexity. Through the disentangling of various components we find that the system at $z=2.933$ has 11 components, taken as one system. This system also shows the greatest number of metals with the column density of C and Si larger than for any of the other systems. So what is the nature of the GRB host galaxy? And is it just a case that the GRB line of sight has crossed a number of complex galactic environments? As previously discussed (section 6.3), one possibility is that the site of the GRB explosion is at the edge of a galaxy which is closest to us. Therefore the light from the GRB is not passing through as much material as it would if the GRB were occurring in a region of the galaxy further away from us.

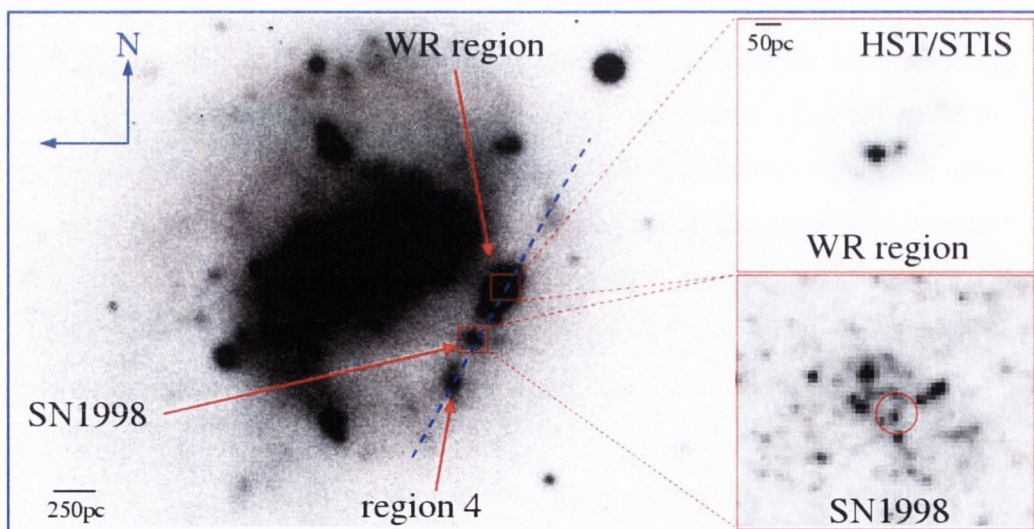


Figure 6-16: High resolution image of the host galaxy of GRB980425 / SN 1998bw. The site of the GRB is ~ 250 pc from a dense starforming region. Taken from Hammer et al. (2006).

Another possibility is that the GRB has exploded in a region outside the starforming region in which the progenitor was originally formed. Massive stars are subjected to strong interactions within the core of massive stellar clusters. Some of them can be kicked out after such events, like a ball in a billiards game. Then, having acquired sufficient momentum, the runaway star may travel for a few millions years, losing its envelope before a GRB occurs many parsecs from its original position. This scenario was investigated by Hammer et al. (2006), whereby high spatial resolution imaging has shown that some GRBs (in their case GRB980425, GRB020903 and GRB030329) have occurred 100s of parsecs away from dense stellar regions, where the presence of Wolf-Rayet star formation has been detected (see Figure 6-16).

These GRBs may then come from OB runaway stars. OB runaways are massive stars that have been ejected from their birthplaces with velocities up to 200 km/s. Two mechanisms have been proposed to explain them; a supernova occurring in a binary allowing the companion to escape with a velocity of the same order as the orbital velocity (Blaauw 1964); close dynamical interactions in dense star clusters may also eject massive stars with high velocities (Poveda 1967). Both scenarios may result in the ejected star having a high angular velocity, possibly through mass transfer prior to the ejection (in the case of the supernova ejection). Dynamical interactions may result in collisions and subsequent mergers, with newly formed very massive stars being ejected at high velocities and rapidly rotating. Some current models of GRBs, such as the collapsar model (MacFadyen & Woollsey 1999), require massive stars that are rapidly rotating, such as those produced in dense stellar regions, to enable the GRB explosion.

In this case it is possible that the progenitor of GRB060607 originated in such a dense star forming region, and was then at some stage ejected from the stellar cluster to a position many 100s of parsecs away from its original position. As the highest redshift system will no doubt be the system of the GRB, if the GRB was ejected in such a direction that the line of sight of the emitted radiation no longer passed through the rich galactic environments of its host, then the observed spectra may indeed be uncomplicated, with few metal absorption features. It should be noted that the region in which the GRB was discovered was itself a star-forming region (Fynbo et al. 2001), so a need to explain it's occurrence outside the Wolf-rayet region described is not necessary.

With three intervening systems at a relatively close distance to that of the GRB host, there is a possibility of a connection between these systems. The redshift difference between the two highest redshift system at $z=3.074$ and $z=3.048$ is $\Delta z \sim 0.03$, which when translated in actual distance is ~ 120 Mpc. The difference between the GRB host and the intervening system at $z=2.933$ is $\Delta z \sim$

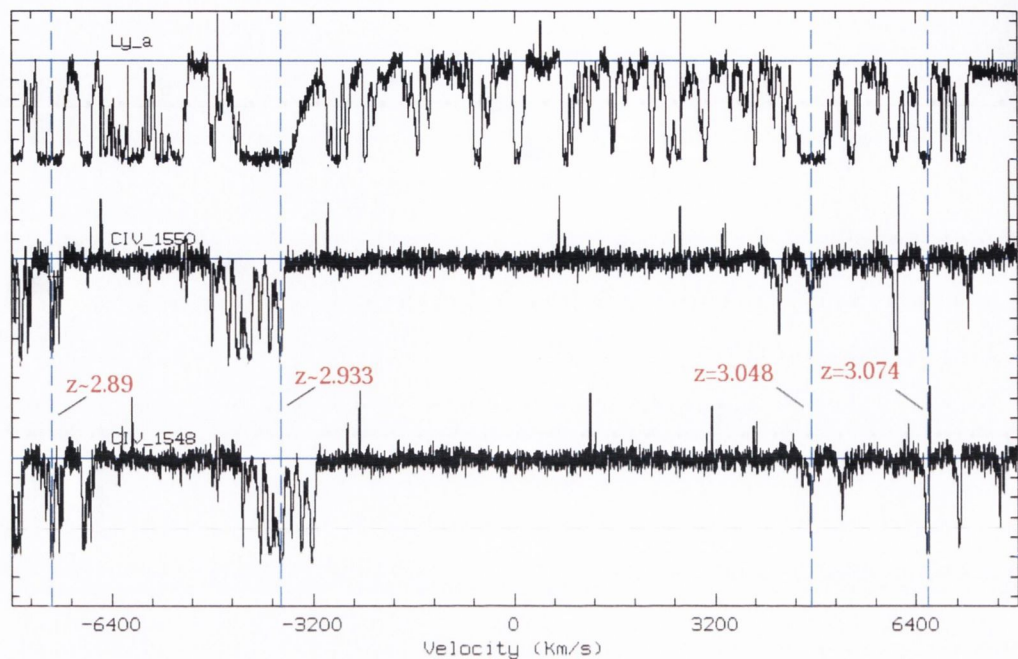


Figure 6-17: Relative velocity difference between the four highest redshift systems.

0.14, which works out at ~ 600 Mpc. This is larger than the typical size of a galaxy (the radius of the Milky Way is ~ 15 kpc), so is suggestive of separate galactic systems along the line of sight.

If one considers the possibility that the material causing the absorption is travelling at large velocities relative to the GRB then the velocity differences for the three highest intervening redshift systems at $z=3.048$, 2.933 and 2.89 are $\Delta v \sim 1500 - 13000$ km/s (see Figure 6-17). One possible progenitor of a GRB is a peculiar type Ibc supernova (Foley et al. 2003), which is characterised by high expansion velocity of the ejecta up to $30\,000$ km/s, which is well covered by the range of velocities observed here. In Chapter 4, in an analysis of the UVES spectra of GRB021004, we found the presence of a number of components spanning ~ 3000 km/s. The largest velocity difference between two components in this case is larger than that if the systems at $z=3.074$ were moving relative to the system at 3.048 for GRB060607. Nevertheless, in the case of GRB060607, there is a wide range of metals found in each system, which each have corresponding Lyman α absorption, so in all likelihood these intervening systems are not as a result of high-velocity ejecta from the GRB explosion but are intervening galaxies along the line of sight.

7

GRB / Supernova Connection: K-Correction of Supernovae

7.1 GRB / Supernova connection

7.1.1 Introduction

It has long been suggested that there is a connection between supernovae and GRBs. The nature of GRBs energetics, and subsequent observations, suggest that at least some long duration GRBs are the result of the death of a massive star (Klebesadel 1990; Dezalay et al. 1992; Kouveliotou et al. 1993). Direct evidence is provided by a handful of SN-GRB associations such as: SN 1998bw/GRB980425 (Galama et al. 1998), SN 2003dh/GRB030329 (Stanek et al. 2003, Hjorth et al. 2003), SN 2003lw/GRB031203 (Malesani et al. 2004), SN 2002lt/GRB021211 (Della Valle et al. 2003), XRF020903 (Soderberg et al. 2005), GRB050525A (Della Valle et al. 2006) and GRB060218 (Campana et al. 2006; Pian et al. 2006).

Some GRB light curves have shown some late-time rebrightening (see Figure 7-1). These

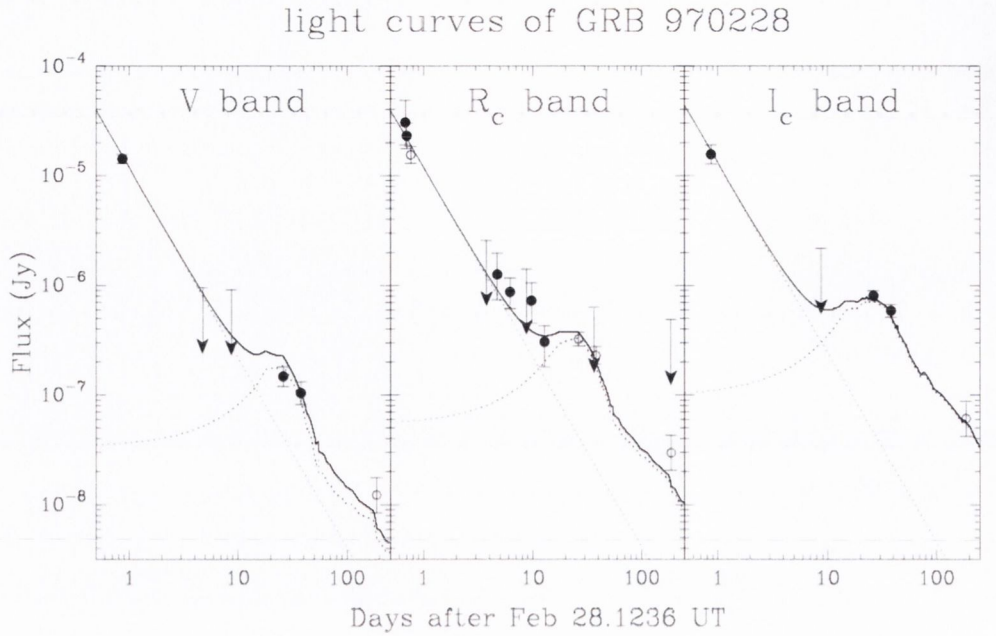


Figure 7-1: Supernova contribution to GRB970228 light curve, Galama et al. 2000

“bumps” are interpreted as the contribution of the supernova emerging out of the GRB afterglow (Bloom et al. 1999).

The first direct evidence for the SN/GRB connection was SN 1998bw, which occurred at the same time and position as GRB980425 (Galama et al. 1998). SN 1998bw was discovered in the nearby galaxy ESO 184-G82 at $z = 0.0085$, and was identified as a type Ic SN.

The discovery of this object suggested a new class of type Ic SNe, aptly name Hypernovae. SN 1998bw was exceptional for a SN Ic in that it was extremely energetic with a peak luminosity, $10^{43} \text{ erg s}^{-1}$, about 10 times brighter than typical SNe Ib/Ic (Clocchiatti & Wheeler 1997), and as luminous at peak as a SN Ia. Therefore suggesting that a large amount of ^{56}Ni must have been synthesized in the SN explosion (Iwamoto et al. 1998; Woosley, Eastman & Schmidt 1999).

The analysis of these various objects suggests that the KE may be related to the progenitors main-sequence mass, which was $\sim 40 M_{\odot}$ for SN 1998bw (Mazzali et al. 2006). These values place Hypernovae at the high-mass end of SN progenitors. It is not yet clear whether the large mass is the discriminating factor for the birth of a Hypernova or the connection with a GRB.

The aim of this study is to explore whether potentially other SN types than 1998bw may be responsible for such “bumps” in GRB light curves. We will show, by determining the K-correction for various SNe types, that the magnitude correction due to the K-correction can be significant.

7.1.2 Supernova Classification

The classification of supernovae is based primarily on their spectra near maximum light. Although the classification is mainly spectroscopic, there are some underlying similarities between the progenitors responsible for the different SN types.

SNe are broken down into two main groups based on the presence or absence of Hydrogen Balmer lines in their spectra at maximum brightness. Those without Balmer lines are classified as type I and those with Balmer lines are classified as type II. In recent years important subdivisions of these two types have been developed. Type I are divided into type Ia, Ib and Ic; and type II are divided into type II Plateau (SN IIP) and Linear (SN IIL).

Type I supernovae can be classified by their helium content. Type Ia contains no helium, type Ib is helium rich and type Ic helium poor. Type Ia also exhibit strong Si 6150Å lines. For type Ia SNe accreting white dwarfs have been considered to be promising candidates for progenitor stars. Most type Ib and Ic SNe are associated with star-forming regions, i.e. they are preferentially found in the arms of spiral galaxies. This has led to the currently popular idea that the progenitors of type Ib and Ic are helium stars more massive than $\sim 3M_{\odot}$, that have lost their hydrogen-rich envelope by strong winds, as in Wolf-Rayet stars, thereby initiating a supernova explosion by the iron core collapse (Ryder et al. 2004).

Type II supernovae are identified by the presence of hydrogen. In essence their progenitors have retained the hydrogen envelope. This type of SN is found only in spiral galaxies and mostly in the spiral arms. There are two main light curve types, SN IIP and SN IIL. However there are many subclasses of these two types.

SN IIP are thought to arise from explosions in stars with extended hydrogen-rich envelopes. These envelopes are heated by the shock waves of the explosions, and the diffusion of this radiant heat is thought to power the plateau of the light curve. Other SN type II light curves decline nearly exponentially from maximum light and are called SN IIL (linear).

7.1.3 Corrections to the Supernova Light Curve

A SN contribution to a GRB light curve will manifest itself as a bump in the light curve. When a bump is present in a GRB light curve, we can test to see whether or not there is the possibility that a SN is present, and which SN type it may be. This is done using either a template light curve for different SN types or individual SN light curves, which we then superimpose on the GRB light curve to see if the bump coincides with the peak of the SN light curve. For this we will use five

SN template lightcurves taken from the literature (see fig 7-2). Using these and also a number of individual light curves from SNe associated with GRBs (these light curves were compiled with the help of M.C. Rebelo and D. Malesani), we can decide which types may or may not be present in a GRB light curve. One application of such rebrightenings is as a means to estimate distance (Bloom et al. 1999). Supernovae explosions are many orders of magnitude dimmer than GRBs. Therefore the likelihood of detecting a SN bump decreases the higher the redshift of the GRB.

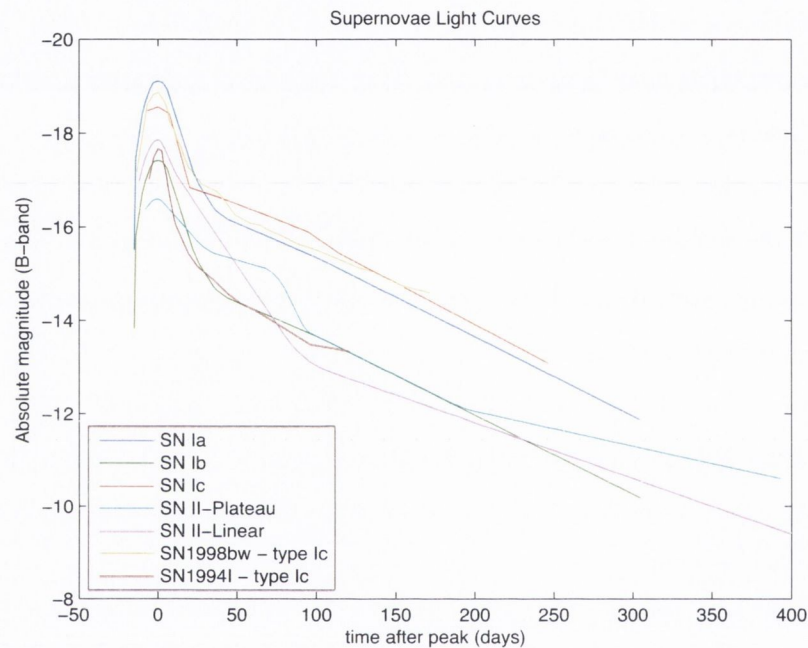


Figure 7-2: Supernova template light curves, taken from M.C. Rebelo 2003. ¹ Ia Dogget & Branch 1985, ² Ib equal to SN Ia but 1.69mag fainter, ³ Ic Clocchiatti 1997, ⁴ IIP Dogget & Branch 1985, ⁵ IIL Dogget & Branch 1985, ⁶ 98bw Galama et al. 1998, ⁷ SN 1994I Richmond et al. 1996.

Because we are dealing with a cosmological phenomenon special attention must be given to parameters which are affected by cosmological effects, such as distance modulus, time dilation and K-correction. Distance modulus and time dilation are effects that can be determined through the redshift of the object.

The distance modulus is the difference between the apparent and absolute magnitude. The observed apparent magnitude, m , of the star depends on its absolute magnitude, its distance and on extinction. We define the absolute magnitude, M , of an object by imagining it to be displaced from its true distance to a standard distance of 10pc. The distance modulus follows from the actual distance to an object. Ordinarily, for cosmological objects, we deal with redshift rather than distance.

To determine the actual distance we need to know not only the redshift, but also we must decide on a cosmological model to use to describe the geometry of the expanding universe. Cosmological models relate distance, d , to redshift by (in first order approximation):

$$d = \frac{c \times z}{H_o} \left[1 + \frac{1}{2}(1 - q_o) \times z \right] \quad (7.1)$$

where c is the velocity of light, z is the redshift, H_o is the Hubble constant and q_o is the deceleration parameter of the expansion of the universe. H_o and q_o follow from the choice of cosmological model.

Time dilation is again a cosmological effect whereby the time of the SN is dilated by a factor of $(1 + z)$ thus stretching the light curve. Leibundgut et al. (1996) show that SN 1995K, a type Ia supernova at redshift $z=0.479$, resembles local type Ia supernova when its light curve is dilated by a factor of $(1 + z)$, as suggested by cosmological expansion.

There are a number of other factors which we also need to take into account, including extinction due to dust (in the GRB host galaxy and in our own galaxy), and the choosing of appropriate values for H_o and q_o , but the primary focus of this study is the accurate determination of the K-correction and its effect on the redshifted light curve (see next section). Recent studies of GRB/Supernova light curves have shown that various tweaking effects are necessary to make the SN and GRB lightcurves coincide. These include varying the magnitude of the SN, stretching the light curve by additional factors and altering the time at which the SN occurs after the GRB in order to make the SN peak coincide with the bump. The K-correction is an effect that is intrinsic to the spectral shape of the supernova, and therefore should take a lot of consideration and care.

7.2 Measuring the K-correction

7.2.1 What is the K-correction?

K-correction deals with the observational effects of measuring the magnitude of a source at high redshift through a fixed bandpass. For a given classification, say that of a supernova type Ia (see Figure 7-5), the SED distribution is not uniform with wavelength. Measuring the R magnitude, through a fixed R bandpass filter, at $z=0$ will give a different result than a measurement in the same R bandpass filter of that same supernova Ia at $z=0.5$, since for the supernova at $z=0.5$ the R filter is not covering the same wavelength range anymore. This is because the spectrum of a very distant source is stretched as well as shifted towards the red.

To compare the brightness of a SN Ia at high redshift to one that is local requires a K-correction to correct for these observational effects. For a distant object it often makes sense to measure its brightness through a different bandpass, which is namely closer to the spectral region where now the redshifted R band would be located. In that case we need a cross-filter K-correction.

7.2.2 Simple K-correction

For measurements involving a single bandpass, "x", the standard K-correction, K_x , is used to calculate the apparent magnitude in that "x" filter band of an object at redshift z according to the equation (following the description by Kim et al 1996):

$$m_x(z, t_{obs}) = M_x(t_{rest}) + \mu(z) + K_x(z, t_{rest}) \quad (7.2)$$

where μ is the distance modulus, M_x is the absolute magnitude for filter "x" at rest wavelength at t_{rest} , t_{obs} is the time in the observer frame. The K correction, therefore, relates nearby and distant magnitudes measured with the same filter:

$$K_x = 2.5 \log(1 + z) + 2.5 \log\left(\frac{\int F(\lambda) S_x(\lambda) d\lambda}{\int F(\lambda/(1 + z)) S_x(\lambda) d\lambda}\right) \quad (7.3)$$

where $F(\lambda)$ is the spectral energy distribution at the source, and $S_x(\lambda)$ is the x'th filter transmission (Oke and Sandage 1968).

7.2.3 Cross-filter K-correction

It is possible to generalise the K-correction to account for measurements made in different bands than the one required (Nugent et al. 2002). For an absolute magnitude observed in a certain band x, one can obtain the apparent magnitude in the desired band y, with the knowledge of the appropriate cross-filter corrections. Equation 7.2 then becomes:

$$m_y(z, t_{obs}) = M_x(t_{rest}) + \mu(z) + K_{xy}(z, t_{rest}) \quad (7.4)$$

where K_{xy} is the K-correction from the rest frame x band to the redshifted y band. The apparent magnitude, m_y , is therefore expressed in terms of M_x , the rest frame absolute magnitude, K_{xy} , the cross-filter K-correction, and μ , the distance modulus. In this case the cross-filter K-correction becomes:

$$K_{xy} = -2.5 \log\left(\frac{\int \lambda Z_x(\lambda) S_x(\lambda) d\lambda}{\int \lambda Z_y(\lambda) S_y(\lambda) d\lambda}\right) + 2.5 \log(1 + z) + 2.5 \log\left(\frac{\int \lambda F(\lambda) S_x(\lambda) d\lambda}{\int \lambda F(\lambda/(1+z)) S_y(\lambda) d\lambda}\right) \quad (7.5)$$

The main difference between equation 7.3 and 7.5 is that an extra term has been added that accounts for the difference in the filter zeropoints of the magnitude systems we are using. $F(\lambda)$ is the spectral energy distribution of the supernova. $S_x(\lambda)$ and $S_y(\lambda)$ are the effective transmissions of the x and the y filter bands respectively, and $Z_x(\lambda)$ and $Z_y(\lambda)$ are the zeropoint transmission functions for the photometric system we are using.

Determination of the K_{xy} relies on three terms.

- **Zero Magnitude Term:** The first term, $2.5 \log\left(\frac{\int \lambda Z_x(\lambda) S_x(\lambda) d\lambda}{\int \lambda Z_y(\lambda) S_y(\lambda) d\lambda}\right)$, accounts for the difference in the transmission of filter x and y, canceling out the magnitude difference between the x band and the y band at zero magnitudes. It should be noted that if filters x and y come from the same photometric system then $Z_x(\lambda)$ and $Z_y(\lambda)$ are the same spectrum (see Figure 7-6). If we do not account for this effect and leave out the zero magnitude term the K-correction will be offset by a certain amount. Hsiao et al. (2003) show an illustration of this by calculating the K-correction using two different filter sets, Johnson filters and CFH12K filters. The results shows the two K-corrections diverging. With the inclusion of the zero magnitude term the two results converge (see Figure 7-4).
- **Bandwidth Term:** The second term, $2.5 \log(1 + z)$, accounts for the fact that the redshifted supernova spectrum is stretched but the observation is done through a fixed bandpass. This effect can be included in the selective term by stretching the redshifted spectrum itself.
- **Selective Term:** The third term, $2.5 \log\left(\frac{\int \lambda F(\lambda) S_x(\lambda) d\lambda}{\int \lambda F(\lambda/(1+z)) S_y(\lambda) d\lambda}\right)$, relies on the supernova spectrum itself and accounts for the magnitude difference between the rest-frame spectrum measured through filter x and the observed spectrum measured through filter y. If the spectrum were flat then the K-correction would be zero, but due to the nonlinear shape of the spectrum term 3 is required.

The cross-filter K-correction was derived by Nugent et al. (2002), using template SN Ia spectra, where he plotted the cross filter K-correction, K_{BR} with redshift (see Figure 7-3). The next section details our method to determine K_{BR} using the same template spectra.

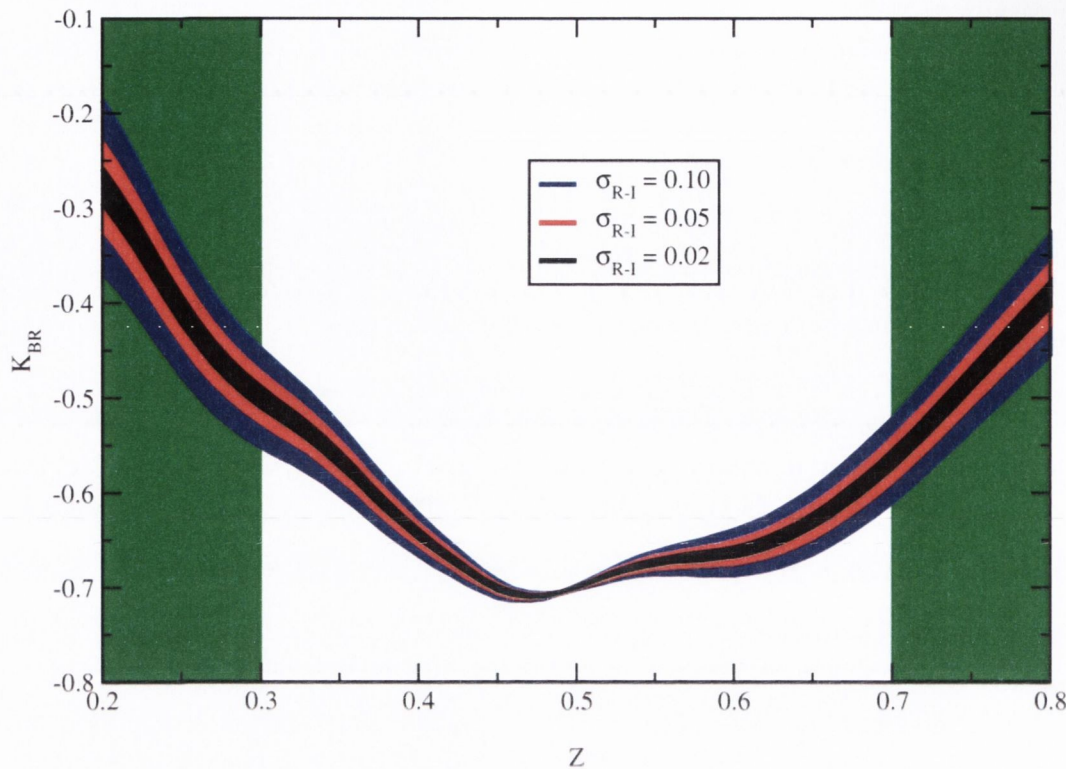


Figure 7-3: K_{BR} as measured by Nugent et al. (2002) for a SN Ia spectrum.

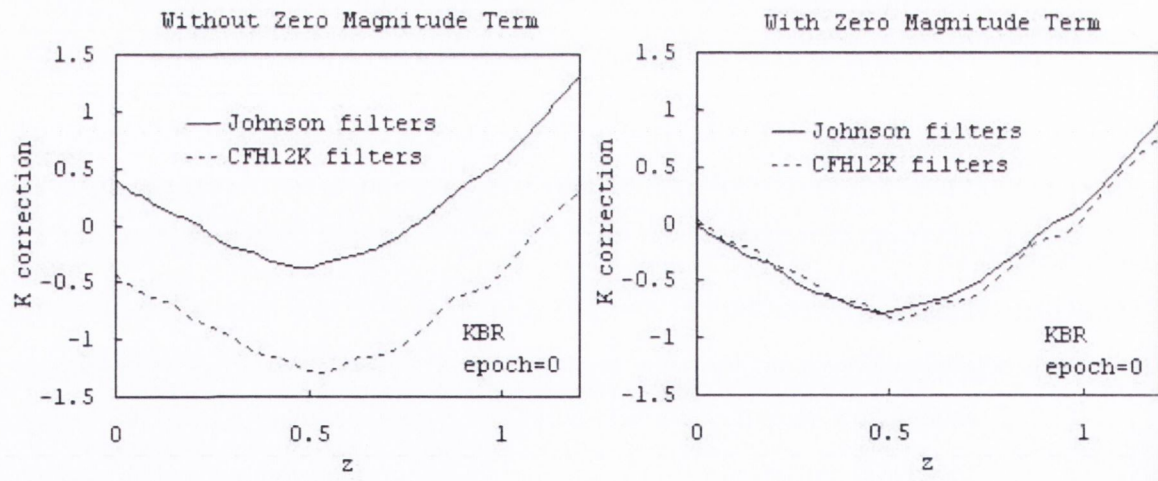


Figure 7-4: Taken from Hsiao et al 2003, shows the K -correction without the inclusion of the zeropoint term for two different filter sets.

7.3 Method

7.3.1 Preparing the spectrum

The preceding description shows that cross-filter K -corrections are likely to yield more accurate results. To calculate the K -correction using equation 7.5 we firstly need a spectrum. The third term

in equation 7.5 relies mainly on the observed supernova spectrum, and so this section will detail obtaining the spectrum and using it to calculate term 3.

The spectra of supernova type Ia are often used as standard candles. As a result they are the easiest to build a standard template spectrum for. This was done by Peter Nugent, who has made the template spectra available on his website as tables of flux vs. wavelength. He has built a number of template spectra for various epochs of the supernova. Firstly we must retrieve the tables containing the flux vs. wavelength for all epochs and build spectra for each, which we will do using the ESO MIDAS data reduction package.

The initial tables are simple text files from which we must first build a MIDAS readable table with wavelength and flux as the x and y values. Then a reference image must be created from which the table can then be transformed to a MIDAS image. The final image is just a normal spectrum which can then be outputted as a FITS file to be read by any other data reduction package.

This was done for $t=1, 2, 3, 5, 10, 15, 20, 30$ and 40 days after the supernova. The corresponding spectra showing the rise and fall of the flux are shown in Figure 7-5. The maximum brightness occurs at ~ 20 days after the supernova. Nugent et al. (2002) show that the K-correction measurement does not depend significantly on the epoch of the supernova. As most supernovae spectra are best studied at or around maximum brightness this spectrum was used to calculate the K-correction.

7.3.2 Calculating the Zero Point Term

The zeropoint term was calculated using the photometric system in Figure 7-6. Firstly we had to build a spectrum for the zeropoint transmission function $Z(\lambda)$. The spectrum was built using the same method used for the SN Ia spectrum and using values from Bessel et al (1990).

The spectra for the B and R filter transmission functions, $S_B(\lambda)$ and $S_R(\lambda)$, were then built, again using the same method as before. Using the B filter as the rest-frame x filter, and the R filter as the observed y filter, the first term from equation 7.5 becomes.

$$2.5 \log\left(\frac{\int \lambda Z(\lambda) S_B(\lambda) d\lambda}{\int \lambda Z(\lambda) S_R(\lambda) d\lambda}\right) \quad (7.6)$$

We can then calculate the transmission of the two filters, B and R, through the given photometric system by multiplying spectrum of each filter, $S_B(\lambda)$ and $S_R(\lambda)$, by the spectrum of the photometric system, $Z(\lambda)$, and integrating across each of the resulting spectra. This yields a value of [0.595] for the zero magnitude correction.

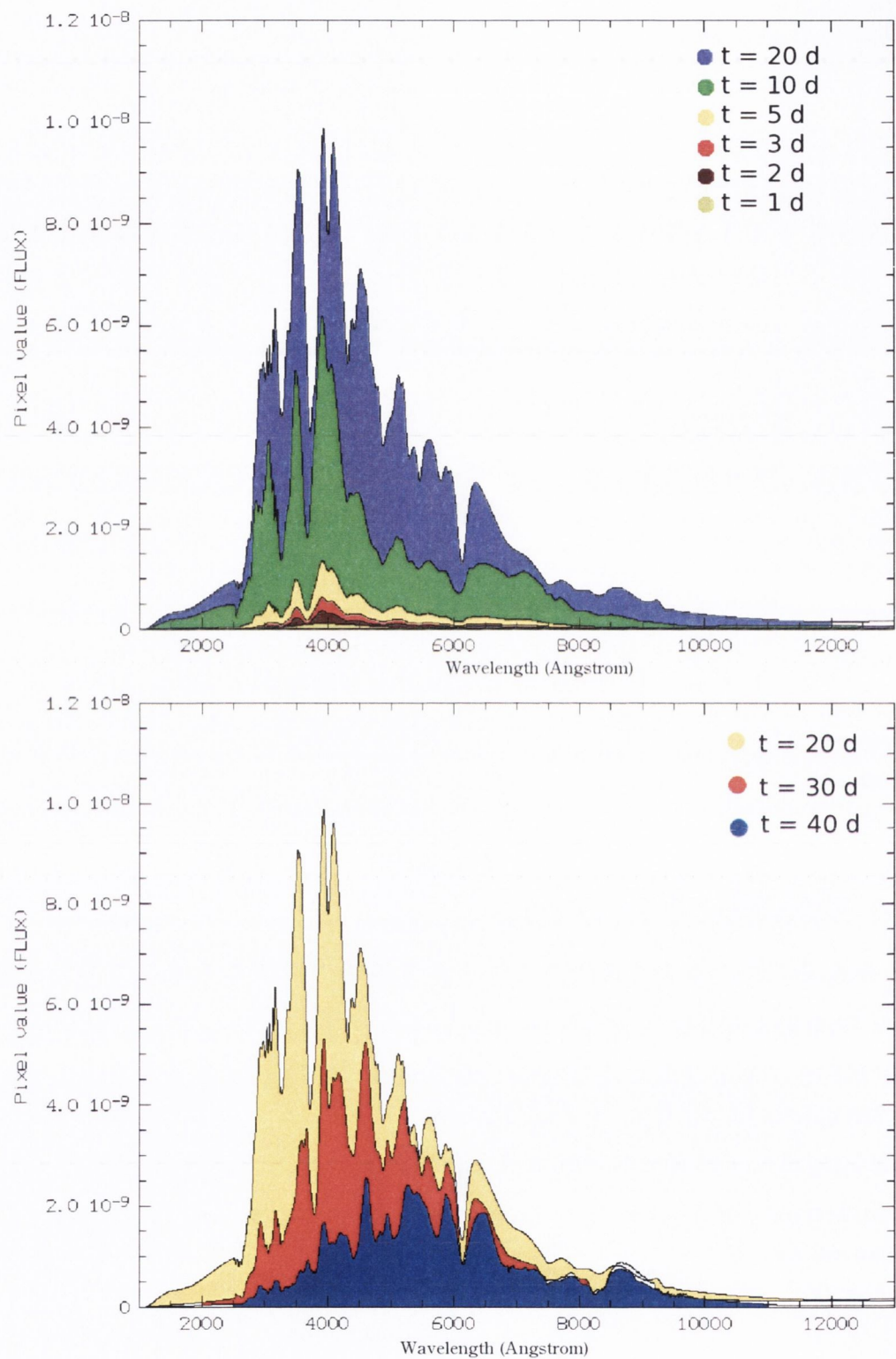


Figure 7-5: (Top) The rise in the supernova Ia brightness from $t = 1 - 20$ days. (Bottom) The fall in the supernova Ia brightness from $t = 20 - 40$ days

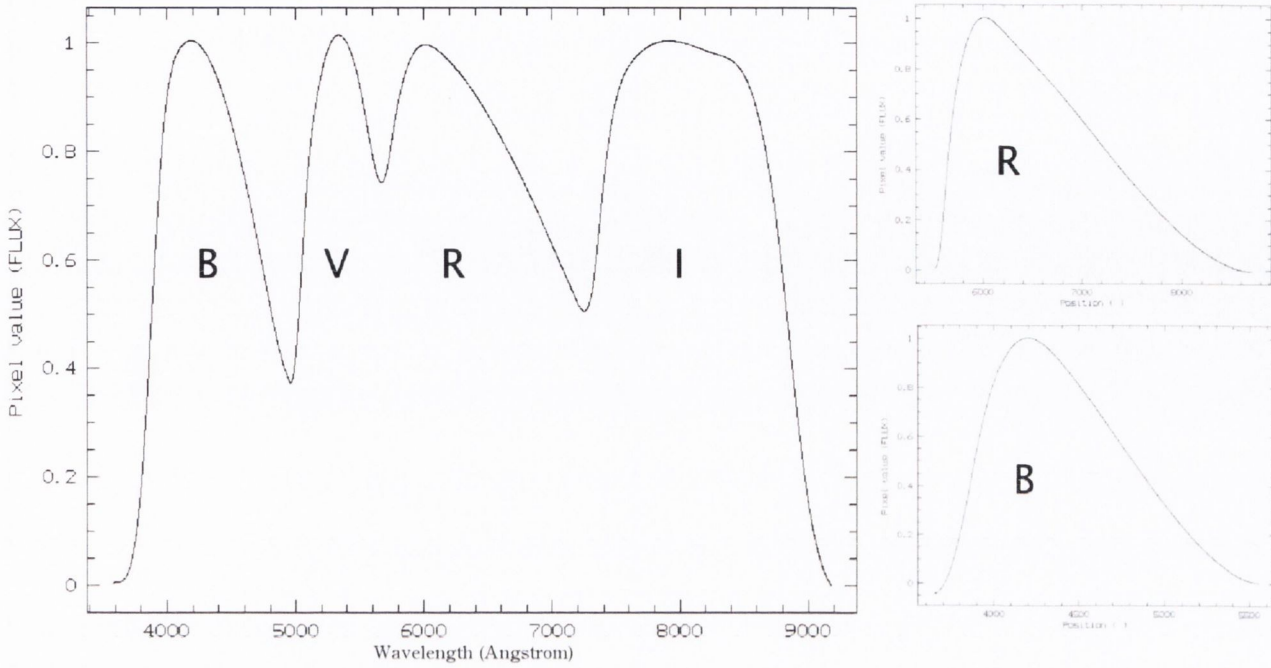


Figure 7-6: (left) The colour system used to calculate the zero magnitude (right) R and B filter transmission functions

7.3.3 Calculating the Selective Term

Term 3 in equation 7.5 can now be calculated, for which we use the template spectrum for $t=20$ days. The $\int \lambda F(\lambda) S_x(\lambda) d\lambda$ expression in term 3 (which we will designate here by EXP 1) deals with the rest-frame supernova spectrum, where the magnitude is measured through the x, or in this case B, filter. The $\int \lambda F(\lambda/(1+z)) S_y(\lambda) d\lambda$ expression (EXP 2) in term 3 deals with the observed spectrum, the magnitude of which is measured through the y, or in this case R, filter. Therefore the value of EXP 1 remains the same for all measurements of K_{BR} , as it is not the expression relying on redshift. EXP 2 will change with each increment of redshift because the spectrum itself should be stretching and shifting with redshift.

To accurately measure EXP 2, for each redshift increment, the original rest-frame spectrum must be redshifted and stretched by the appropriate value. This was done with the data reduction package IRAF using the routine NEWREDSHIFT. This routine artificially redshifts a spectrum by the desired increment. It does not, however, stretch the spectrum. This accounts for the bandwidth term in equation 7.5 and is done, again using MIDAS, by rebinning the spectrum by a factor of $\frac{1}{(1+z)}$. The R filter transmission function, S_R is then multiplied by the SN spectrum at a given redshift,

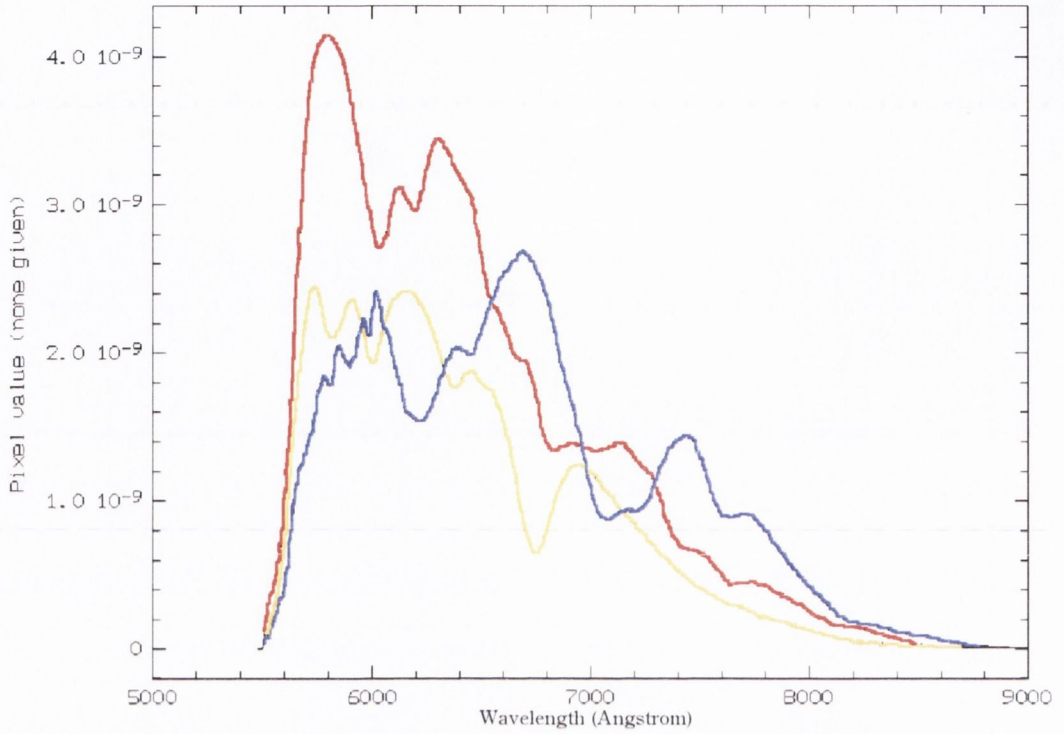


Figure 7-7: The R transmission of the supernova at redshift $z=0.1$ (yellow), 0.4 (red) and 0.9 (purple)

$F(\lambda/(1+z))$, in order to calculate what the transmission through filter R of the SN at redshift z will be. As the SN spectrum is redshifted to different values of z the region of the spectrum coinciding with filter R will change, therefore the transmission through filter R will change also (see Figure 7-7).

With the B filter as the rest-frame x filter, and the R filter as the observed y filter, the third term from equation 7.5 becomes:

$$2.5 \log \left(\frac{\int \lambda F(\lambda) S_B(\lambda) d\lambda}{\int \lambda F(\lambda/(1+z)) S_R(\lambda) d\lambda} \right) \quad (7.7)$$

For this equation EXP 1 and EXP 2 can then be calculated with the template spectrum at $t=20$, $F(\lambda)$, the B filter transmission function, $S_B(\lambda)$, and the R filter transmission function, $S_R(\lambda)$. The results of this are detailed in the next section.

REDSHIFT	Zero Mag.	EXP 1	EXP 2	$2.5 \log \frac{EXP1}{EXP2}$	K_{BR}
0.0	0.595	0.614	0.326	0.687	0.092
0.1	-	-	0.403	0.457	-0.138
0.2	-	-	0.459	0.316	-0.279
0.25	-	-	0.500	0.223	-0.372
0.3	-	-	0.538	0.143	-0.452
0.35	-	-	0.569	0.083	-0.512
0.4	-	-	0.616	-0.004	-0.599
0.45	-	-	0.661	-0.080	-0.675
0.475	-	-	0.671	-0.096	-0.691
0.5	-	-	0.669	-0.093	-0.688
0.55	-	-	0.651	-0.064	-0.659
0.6	-	-	0.648	-0.059	-0.654
0.7	-	-	0.630	-0.028	-0.623
0.8	-	-	0.565	0.090	-0.505
0.9	-	-	0.505	0.212	-0.383
1.0	-	-	0.441	0.359	-0.241

Table 7.1: Values calculated for the three terms used to evaluate the K-correction K_{BR} , and the subsequently derived values for K_{BR} .

7.4 Results

As the K-correction calculations were carried out using the supernova type Ia template created by Peter Nugent, the aim was to derive first a plot of the K-correction, K_{BR} , versus redshift in order to compare it with the plot obtained by Nugent et al 1995 (Figure 7-3).

With the method outlined in the previous section the obtained values for K_{BR} are given in Table 7.1 for redshift $0 < z < 1$. Particular attention was paid to the region of the plot between $0.2 < z < 0.6$ in order to find as closely as possible the shape of the curve. In this region of the plot made by Nugent we see a minimum at $z \sim 0.48$, followed by a shallow rise at $0.55 < z < 0.65$, then followed by a steep rise at $z > 0.65$. Figure 7-8 shows the derived plot of K_{BR} vs. redshift for SN type Ia. A comparison with the plot obtained by Nugent et al. (inset of Figure 7-8) demonstrates that a comparable result can be obtained using our method. Now that a reliable method for calculating the K-correction has been verified, it can be applied to other supernova types. In our case we expand the results from $0 < z < 0.8$ to $0 < z < 1$. It should also be noted that future work exploring K-correction measurements further than $z=1$ should consider using a different filter for x i.e. a filter that when redshifted will coincide with the R filter.

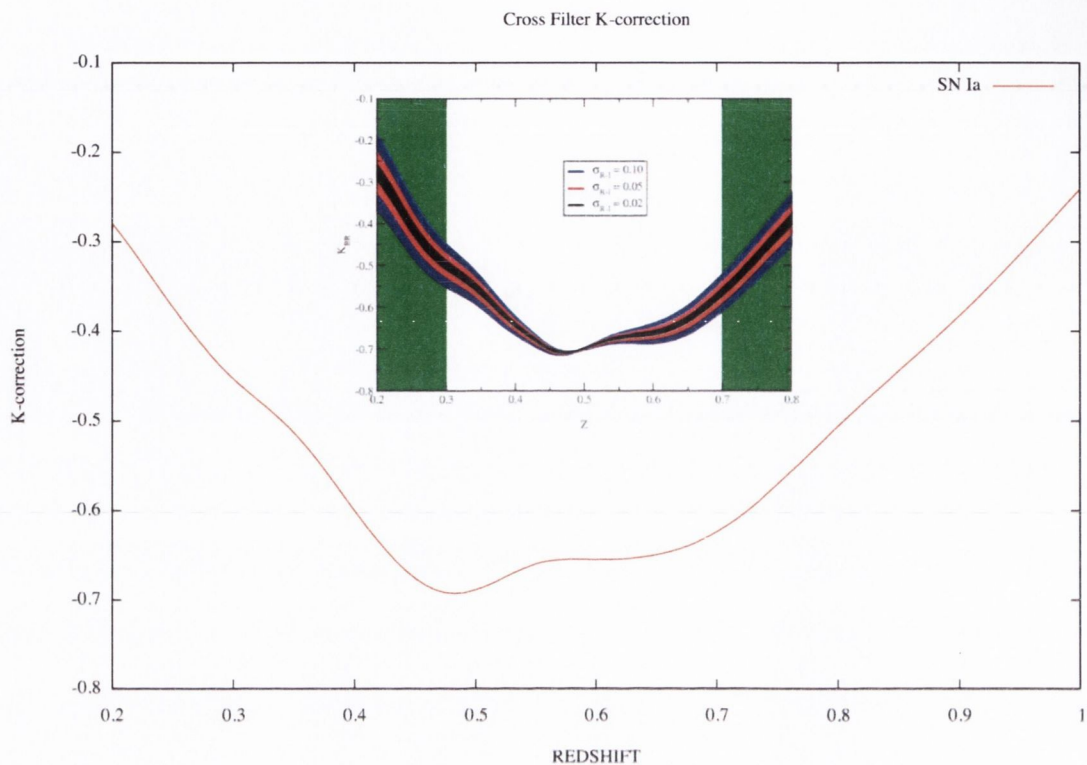


Figure 7-8: (Blue) The K-correction K_{BR} of SN Ia. Inset: K_{BR} from Nugent et al.

7.4.1 Expanding the method to include other supernova types

The main purpose of this exercise is examine the effect of the various SN contributions to GRB light curves. Therefore we must have K-corrections for as many SN types as possible. Using templates created by Peter Nugent, K-corrections were subsequently calculated for other supernova types, namely types Ib/c, Ib/c (Hypernovae), IIP and IIL. The templates for these supernovae were taken from Peter Nugents website (supernova.lbl.gov/~nugent/nugent_templates.html). From these template spectra were built using the same method as for the SNIa. The spectra created are shown in Figure 7-9.

The same method was used as in the previous section, using the same photometric system and filter transmission curves. The K-corrections determined for each supernova type are shown in Figure 7-10 and the values obtained are summarised in Table 7.2. As the difference between the measured K-corrections for type IIP and IIL was negligible, we have used one curve to show both of their K-corrections.

It is clear from Figure 7-10 that the contribution of the K-correction for each SN type is signif-

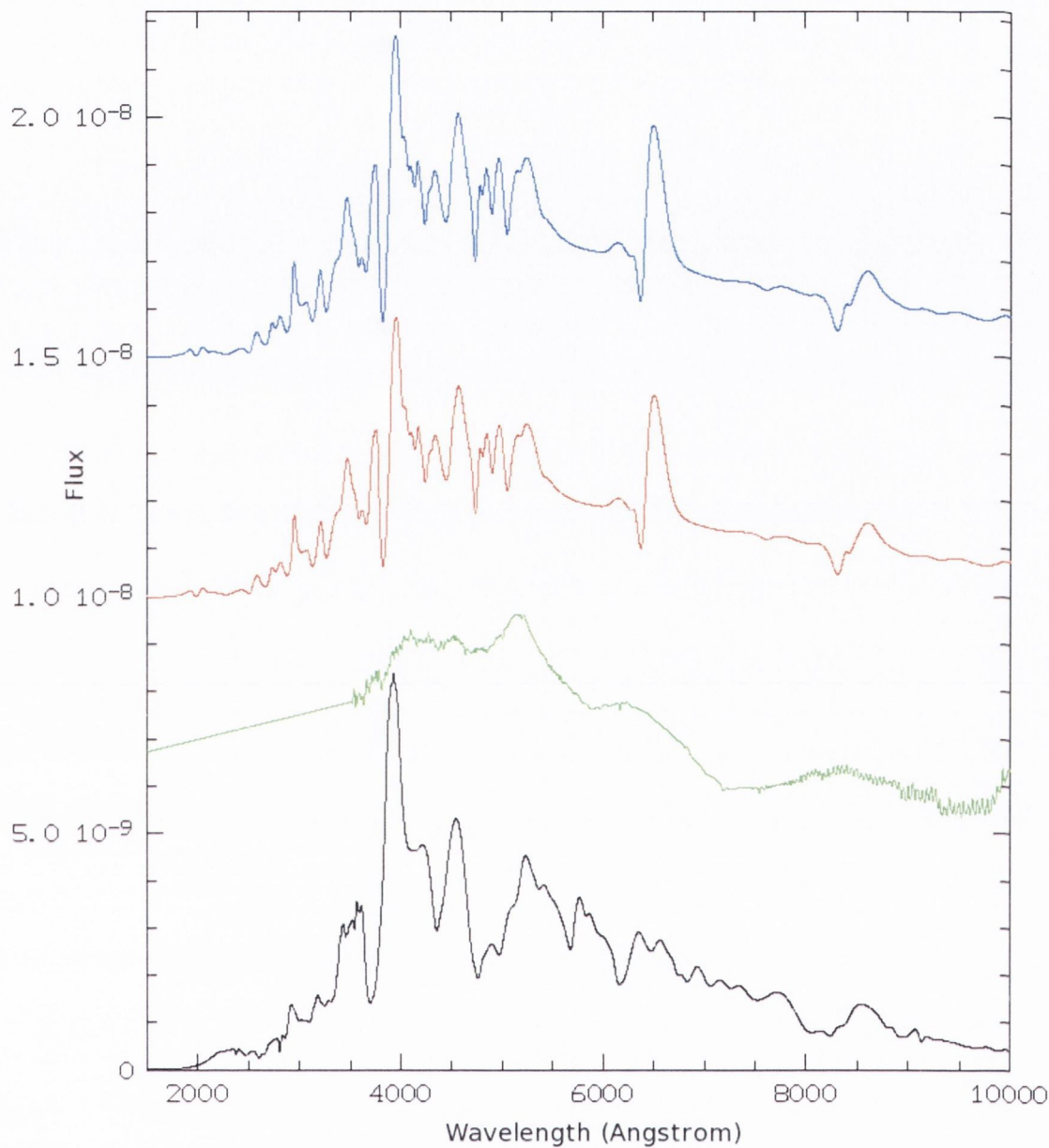


Figure 7-9: Spectra for SN types Ib/c (black), Ib/c (Hypernovae) (green), IIL (red) and IIP (blue). The relative fluxes of the spectra have been scaled.

icant and varies greatly depending on SN type and redshift. We can also see that the four curves corresponding to the four K-correction measured seem to converge at $z \sim 0.5$. This is due to the fact that at $z \sim 0.5$ a redshifted B filter will coincide with the R filter i.e. the same region of the spectrum going through filter B at $z = 0$ will be going through filter R at $z \sim 0.5$, and as such the third term in equation 7.5 will get close to zero.

REDSHIFT	K_{SNIa}	$K_{SNIb/c(Hyp)}$	$K_{SNIb/c}$	K_{SNIIL}	K_{SNIIP}
0.0	0.092	-0.443	-0.461	-0.541	-0.535
0.1	-0.138	-0.681	-0.624	-0.629	-0.631
0.2	-0.279	-0.800	-0.573	-0.676	-0.674
0.3	-0.452	-0.803	-0.592	-0.705	-0.705
0.4	-0.599	-0.769	-0.619	-0.692	-0.691
0.5	-0.688	-0.681	-0.719	-0.686	-0.686
0.6	-0.654	-0.542	-0.587	-0.534	-0.532
0.7	-0.623	-0.388	-0.436	-0.370	-0.372
0.8	-0.505	-0.238	-0.193	-0.130	-0.130
0.9	-0.383	-0.101	0.110	0.144	0.145
1.0	-0.241	0.024	0.431	0.426	0.426

Table 7.2: K-Corrections for SN types Ia, Ib/c (Hypernovae,) Ib/c, IIP and. IIL

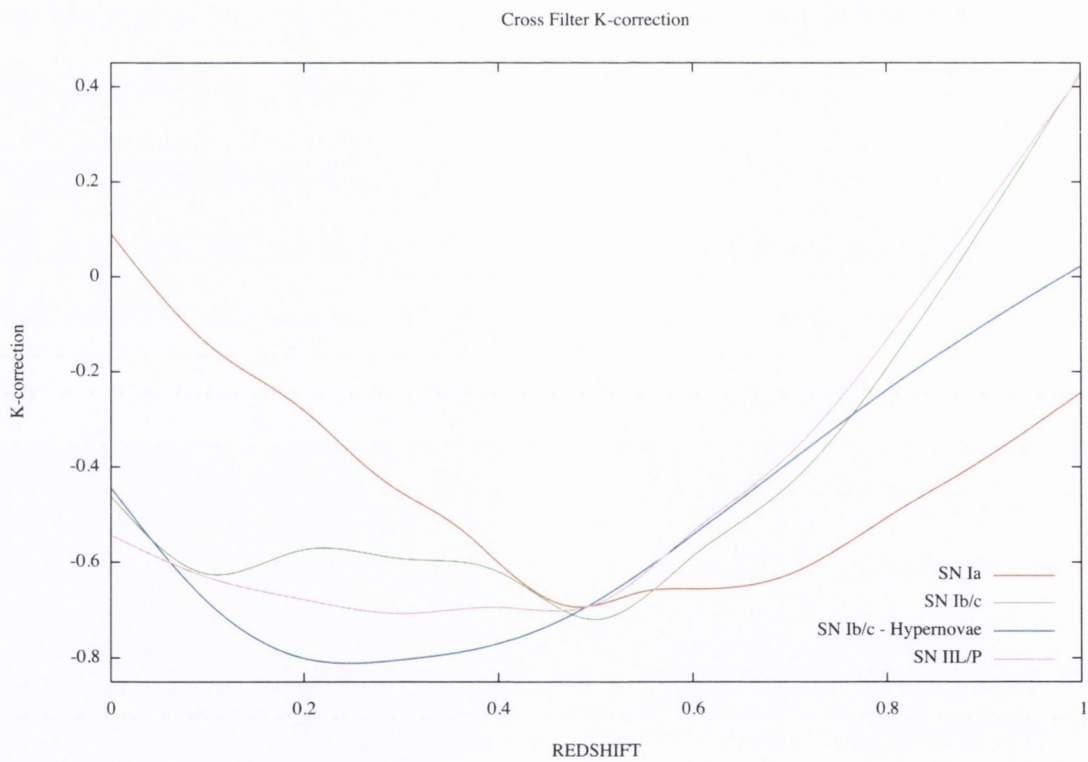


Figure 7-10: K-Corrections for SN types Ia, Ib/c (Hypernovae), Ib/c, and IIP together with IIL

7.5 GRB / Supernova Light Curves

Now that we have developed a means to determine a cross-filter K-correction for each supernova type for redshift values of $0 < z < 1$, we can make the appropriate corrections to our template supernova lightcurves before superimposing them on the GRB light curves.

We use Figure 7-10 to determine the K-correction for each SN type at the redshift of the given GRB. We must also correct for extinction due to both our Galaxy and the host galaxy. In some cases the host extinction is not known and so we just take the extinction to be that of our Galaxy. The values used are summarised in Table 7.3.

Now we must choose the GRB light curves with which to test. Table 7.3 shows the sample of 8 GRBs we have chosen, all of which have either coincided with SNe or whose light curve shows a rebrightening at some epoch after the GRB. This usually occurs ~ 10 -30 days after the burst. Besides SN template light curves for types Ia, Ib, Ic, IIP and IIL (see Figure 7-2), we also use light curves for a number of SNe previously associated with GRBs and other type Ic Hypernovae, namely SNe 1998bw, 1994I, 2002ap and 2006aj. The composite lightcurves were then fit using a spline of the GRB and SN lightcurves. This was done using a MATLAB script adapted from one originally created by M.C. Rebelo (Meurs & Rebelo, 2004). A more in depth explanation of the fitting procedures used is given in Appendix A.2. Before the two light curves are superimposed the SN light curve was redshifted to the redshift of the GRB and correction was made for extinction. In some cases it was possible to estimate the contribution of the host galaxy (where stated); in the rest of the cases a previously published value is used. The best fit SN light curves are those that fit within the error bars of the GRB light curve, or those that come the closest to fitting the GRB light curve.

GRB	Redshift	Extinction	K_{SNIa}	$K_{Ib/c}$	$K_{IIP/L}$	K_{Hyp}
GRB970228	0.695	0.96	-0.6225	-0.4375	-0.3759	-0.3930
GRB980326	1.0*	0.22	-0.2349	0.4330	0.4330	0.0323
GRB990712	0.434	0.06	-0.6572	-0.6572	-0.6983	-0.7428
GRB021211	1.010	0.06	-0.2212	0.4604	0.4604	0.0494
GRB030329	0.168	0.07	-0.2295	-0.5891	-0.6645	-0.7775
GRB041006	0.716	0.06	-0.6019	-0.3964	-0.3347	-0.3587
GRB050525A	0.606	0.25	-0.6534	-0.5712	-0.5233	-0.5233
XRF060218	0.0331	0.50	0.00323	-0.5345	-0.5756	-0.5345

Table 7.3: Using Figure 7-10 we calculated the K-correction for the values supernova types at the redshifts of the GRBs in our sample.* This was the value estimated by Bloom et al. (1999).

7.5.1 GRB970228

GRB970228 was the first GRB for which an afterglow was discovered. Subsequent work on the late time afterglow identified a rebrightening in the lightcurve. After the discovery of GRB980425 and SN 1998bw the possibility of a SN contribution in the afterglow of GRB970228 was re-examined. Reichart et al. (1999) and Galama et al. (2000) reported that the brightening that occurs at ~20 days after the burst can be explained by the presence of type Ic supernova like SN 1998bw. Figure 7-11 shows our plots of GRB970228, using the R band data published by Galama et al. 2002 (these plot have been published previously without the appropriate K-correction or host galaxy contribution by Meurs & Rebelo (2004)), with both template (right) and individual (left) SN light curves splined with the afterglow power law decay.

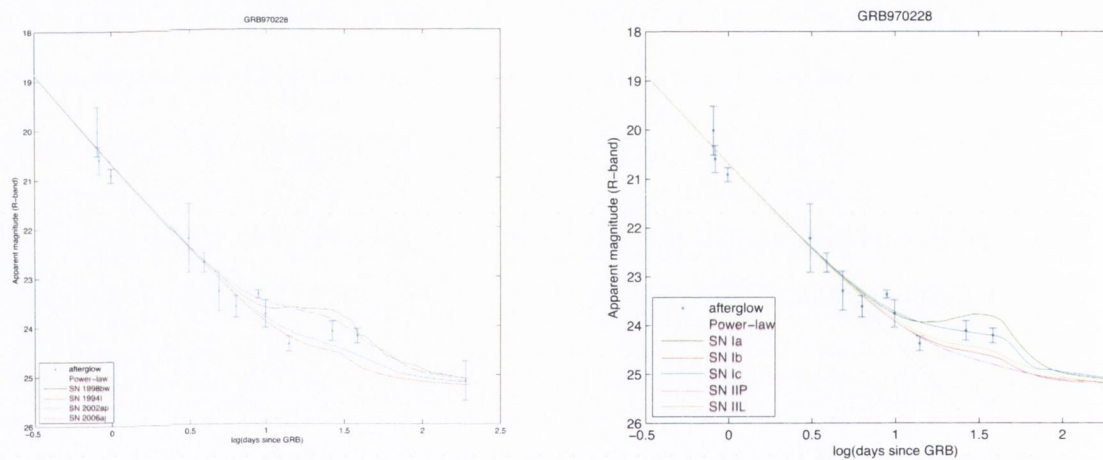


Figure 7-11: Superimposed over the light curve of GRB970228 are the SN template light curves (right) and the lights curves of individual supernovae (left).

From the light curves of individual SNe, those associated with GRBs (all type Ic) and the templates of the other types, our results show that all but SN 1994l can fit the bump in the light curve. It should be noted that SN 1994l and 2002ap is subluminous compared to the other two Hypernovae, SNe 1998bw and 2006aj. From the five template lightcurves we can see also that the SN type that best fits the bump is the type Ic.

7.5.2 GRB980326

GRB980326 also displayed evidence of an underlying SN contribution. In this case however the redshift was not known. Bloom et al. (1999) showed that by artificially redshifting the SN 1998bw light curve by various redshift increments, and judging which most closely fit the GRB light curve,

it was possible to use the SN bump as a way to estimate the distance of the GRB (see Figure 7-12). Their results suggested that the redshift of the burst was $z \sim 1$.

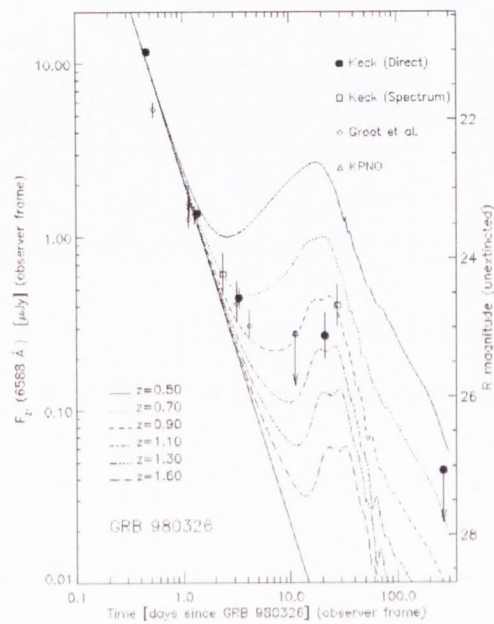


Figure 7-12: Taken from Bloom et al. (1999). The lightcurve of SN 98bw has been artificially redshifted by a range of values in order to obtain an estimate for the redshift for the GRB.

Using the same set of R filter observations used by Bloom et al., we repeated the procedure of artificially redshifting the SN 1998bw light curve to see which redshift is the closest fit to the GRB light curve. For our plots, however, we include the K-corrections calculated in the previous section. Figure 7-13 shows a series of our plots ranging from $0.7 < z < 1.0$, as our results for the K-correction only go to redshift 1. Our results would suggest the redshift is more likely $z \sim 0.85$, as this is the curve which fits the data points the most accurately.

Using $z=0.85$ as an estimate for the redshift of the GRB, we can test for the suitability of other SN types by applying the same redshift and relevant K-correction to each SN light curve. Evidently the best fit to the curve is the light curve of SN 1998bw. Of the other individual SN lightcurves SN 2006aj fits all but one of the data points, while SN 1994l and SN 2002ap are not as close (see Figure 7-14). For the template lightcurves the only SN type that fits the data points well is a SN Ia.

It should be noted, we have tried to modify the SN lightcurves as little as possible, instead relying on the physical parameters needed to alter the position of the peak i.e. K-correction, redshift. In some cases in the literature the SN spectrum is modified in order to make the GRB bump and SN

peak coincide. Such modifications include altering the magnitude of the SN contribution and off-setting the time at which the SN occurs after the GRB event, as well as stretching the SN lightcurve in time.

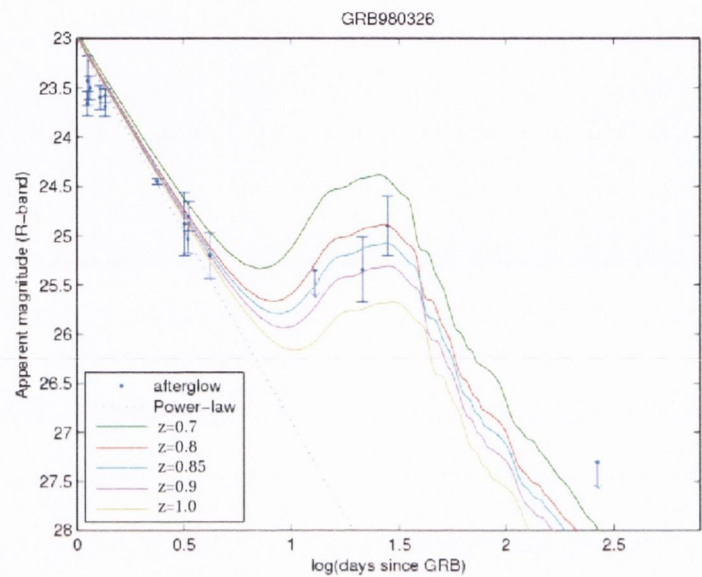


Figure 7-13: The lightcurve of GRB980326 combined with the lightcurve of SN 1998bw. The lightcurve of SN 1998bw has been redshifted by a range of values. The value that best fits the data points is $z \sim 0.85$

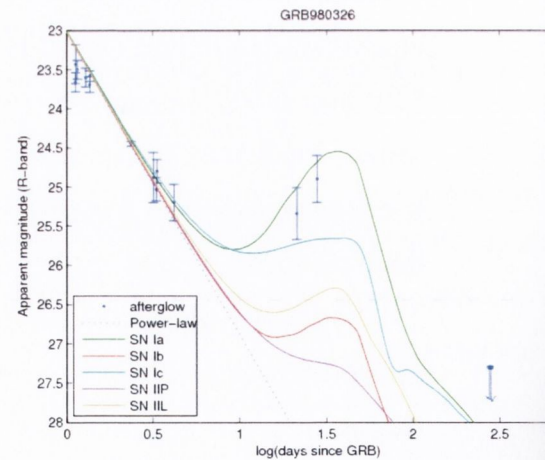
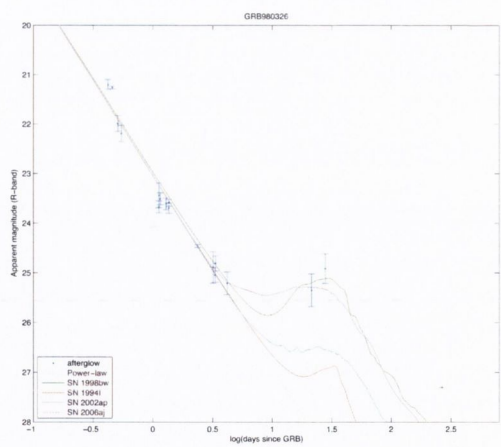


Figure 7-14: The light curve of GRB980326, with various SN light curves superimposed and redshifted to $z=0.85$.

7.5.3 XRF060218 - Connection with GRB980425 and GRB031203

Of the GRBs with SN contributions the light curves of GRB980425, GRB031203 and XRF060218 show some strong similarities. Intrinsic spectral properties of GRBs had previously been explored and showed that almost all GRBs fit a relationship developed by Amati et al. (2002) GRB980425 and GRB031203 were surprisingly underluminous bursts, however, which put them as outliers to this Amati relationship. Unlike GRB980425 and GRB031203, the other bursts so far associated with a supernova event obey the Amati relation. The two outliers are comparatively close to Earth, with redshifts of $z = 0.0085$ (GRB980425, Tinney et al. 1998) and $z = 0.106$ (GRB031203, Prochaska et al. 2004). Both show an optically weak GRB followed by a large rebrightening, now attributed to a coinciding SN explosion. In Table 7.3, we show the GRBs which display late time rebrightenings in their light curves. We have not included GRB980425 or GRB031203 because their lightcurves comprise mainly of a SN component.

As the template for most other GRBs with SN contributions, SN 1998bw and GRB980425 constitute an important example to understand. Is SN 1998bw indicative of all Hypernovae?, and if so why does its light curve differ so much from most other bursts?

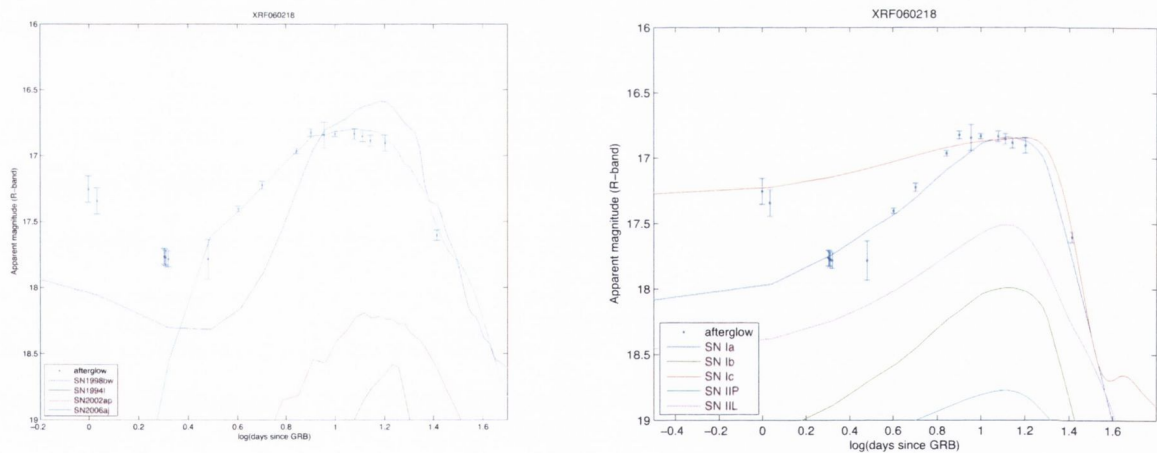


Figure 7-15: The large GRB / SN bump of XRF060218, with our template (right) and individual (left) light curves superimposed.

With the discovery of XRF060218, it has now been suggested (Ghisellini et al. 2006) that what was observed for the prompt emission of GRB980425 and GRB031203 was only a small part of much longer duration burst and that the real prompt emission of these bursts was subject to a relatively strong hard to soft spectral evolution, meaning their true total energy was much larger than previously thought. XRF060218 had a prompt emission that lasted ~ 3000 s, which allowed

for more direct information of the high and low energy spectral components to be obtained. Using GRB060218 as a template Ghisellini et al. show how GRB980425 and GRB031203 can be made more consistent with the Amati relation if these changes are taken into account.

To test which SN types may be possible for XRF060218, we again superimpose our sample of SN lightcurves on the GRB lightcurve. Figure 7-15 shows the light curve of XRF060218 with both the individual (left) and template (right) light curves redshifted to the redshift of the burst, and with relevant K-corrections applied. Of course SN 2006aj, the SN associated with XRF060218, is a perfect match. In addition our results show the next closest match is not SN 1998bw but a SN type Ia. For this case we have fit not a power law to the weak beginning of the afterglow, but instead have concentrated on the SN dominated late time afterglow. This was done because the part of the lightcurve with which we are interested is the SN contribution, in most cases as a late rebrightening. However, in this case the SN contribution is far more significant. Therefore, for the purposes of this analysis we did not fit the early time powerlaw decay of the GRB lightcurve.

7.5.4 GRB990712

Sahu et al. (2000) detected another SN contribution in the late-time light curve of GRB990712 peaking at ~ 11 days after the burst (see Figure 7-16). Again they use a SN 1998bw type Hypernovae as a template for the SN contribution.

We find, although most of the Hyperovae come quite close to fitting the curve, that the SN type that fits the light curve the best is a type Ia SN (see Figure 7-17). It should be noted that by modifying the light curve of SN 1998bw (or the other Hypernovae), more specifically by changing the time difference between GRB explosion and SN, a better fit to the curve would be found. However one of the main purposes of this exercise is not to see how closely we can make a specific SN type could fit the GRB light curve, through arbitrarily modifying their parameters, but rather to see which, if any, fit the curve as is.

7.5.5 GRB021211

GRB 021211 was detected by the HETE2 satellite (Crew et al. 2003), which allowed the localization of its optical afterglow (Fox et al. 2003) and the measurement of the redshift $z = 1.006$ (Vreeswijk et al. 2002). A rebrightening is apparent, starting ~ 15 days after the burst (Della Valle et al. 2003). Della Valle et al. suggest the presence of a SN, SN 2002lt, as the likely explanation for the rebrightening. The authors suggest that this, however, is not a Hypernovae like previous SNe

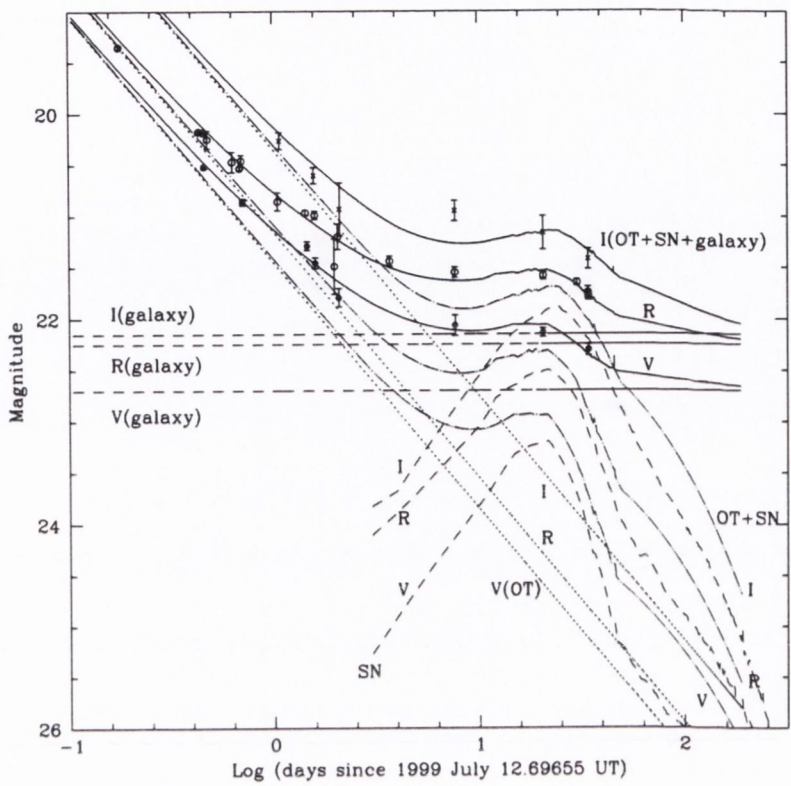


Figure 7-16: Multi-band light curve of GRB990712 taken from Sahu et al. (2000).

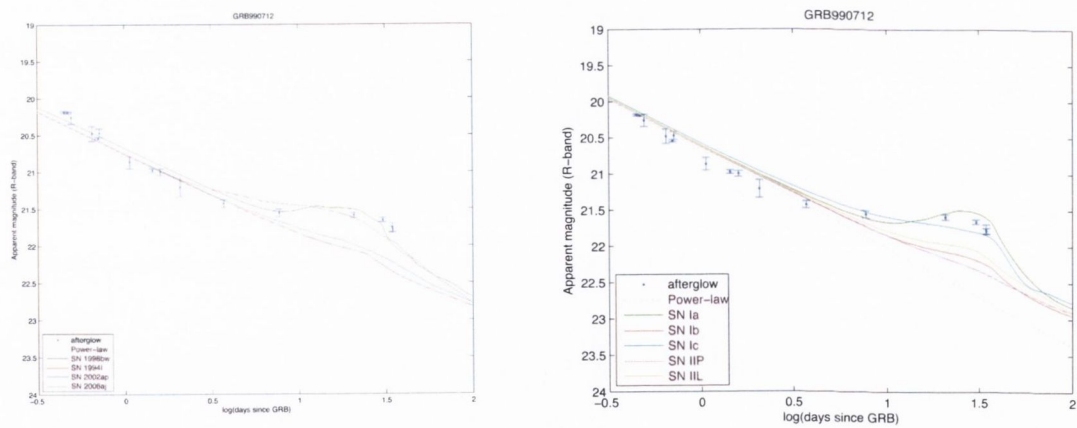


Figure 7-17: Our fit to the lightcurve of GRB990712, with the two sets of SN lightcurves superimposed.

associated with GRBs, but more similar to a normal type Ic SN. In their paper they give SN 1994l, dereddened by $A_V = 2$, as a template to the type of underlying SN (see fig 7-18).

However, unlike other such cases where a SN is detected, this GRB is quite distant, at redshift $z \sim 1$. Our results show that the Hypernova type light curves such as SN1998bw do fit the GRB

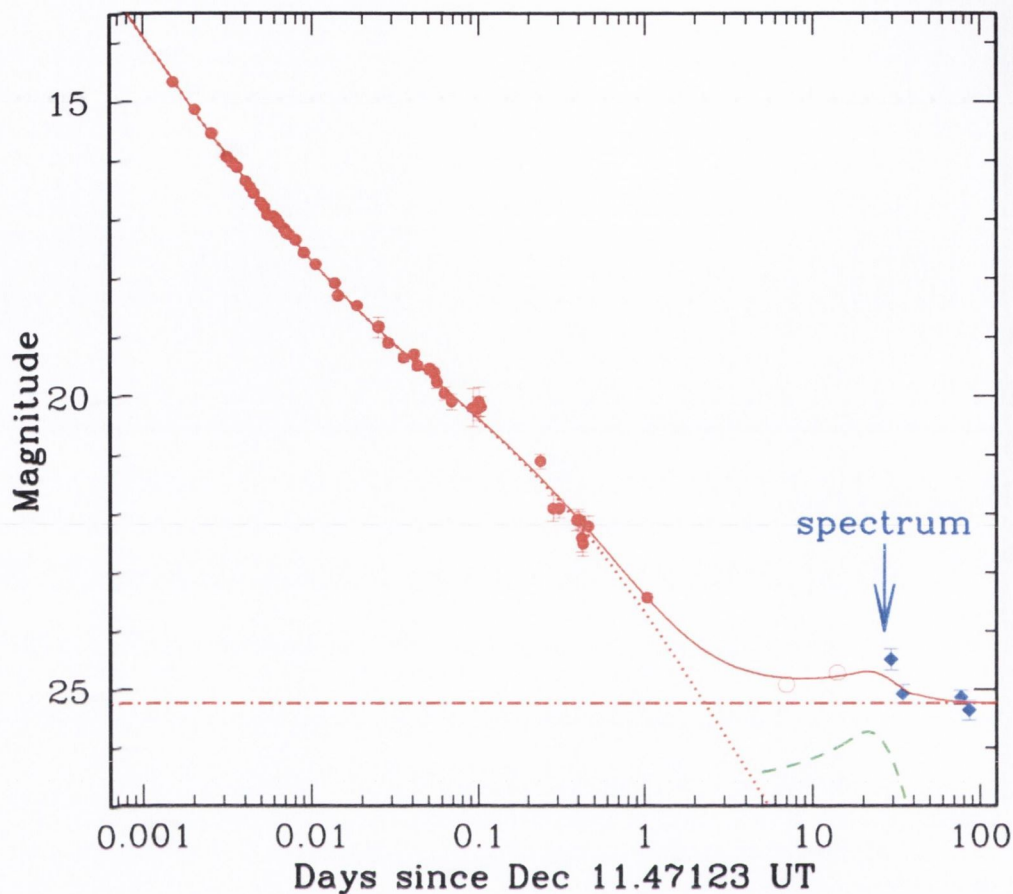


Figure 7-18: The light curve of GRB021211 taken from Della Valle et al. (2003).

light curve, with the exclusion of one data point (at $t \sim 10^{1.5}$ days) and SN 1994l does not (see Figure 7-19). One possible reason for this is that the values for K-correction used may differ. The K-corrections we use for determining the composite light curves are shown in Table 7.3, and were computed from suitable template spectra. Della Valle et al. (2003) use U-band data of SN 1994l for their K-correction, but the exact method they use is unclear. In addition, using the template SN lightcurves we get the best fit with a SN Ia and SN Ic, also with the exclusion of the same data point.

Della Valle et al. also use the late time observations to estimate the contribution of the host galaxy, as seen by flattening of the light curve after the SN bump. They estimate a value of $R=25.22$ as the galactic contribution (seen as the dotted line in Figure 7-18). For our plots the galactic contribution is best described using a value of $R=25.62$, as seen by the horizontal line in Figure 7-19.

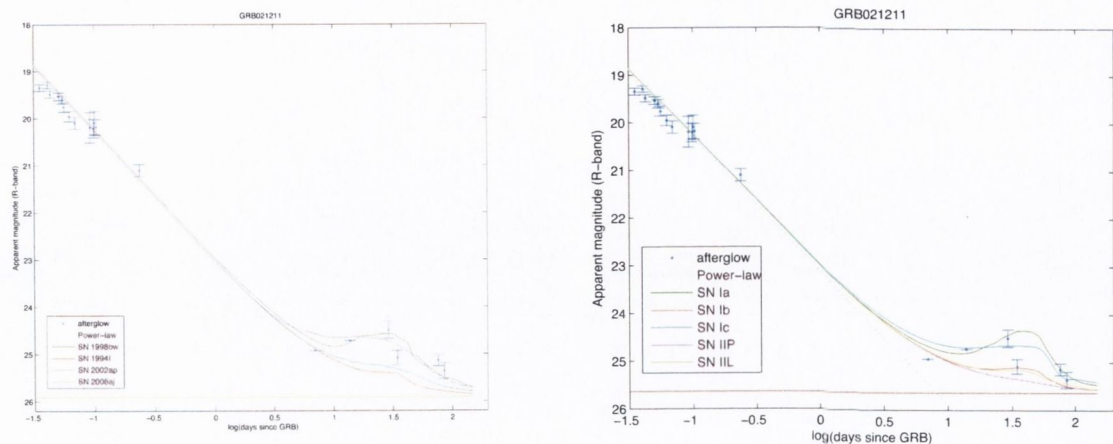


Figure 7-19: Our fit to the light curve of GRB021202. The left panel shows the individual light curves of the five SN Ic we have used, which all fit well to the GRB light curve; with the exception of SN1994l. The right panel shows the various SN template light curves.

7.5.6 GRB030329

The breakthrough in the study of the GRB/SN association arrived with the bright GRB 030329. This burst, again discovered by the HETE2 satellite, was found at a redshift $z = 0.1685$ (Greiner et al. 2003), relatively nearby, therefore allowing detailed photometric and spectroscopic studies. SN features were detected in the spectra of the afterglow by several groups (Stanek et al. 2003, Hjorth et al. 2003; see also Kawabata et al. 2003; Matheson et al. 2003a) and the associated SN (SN 2003dh) bump looked strikingly similar to SN 1998bw (Figure 7-20). The gamma-ray and afterglow properties of this GRB were not unusual among GRBs, and therefore, the link between GRBs and SNe was eventually established to be general.

Figure 7-20 shows the light curve of GRB030329 with the template (right) and individual (left) SN lightcurves superimposed. In this case the light was more complex than the previous examples and could not be fit with a simple power law. We therefore fit a spline to the afterglow component and used this to spline with the SN light curve. Because we cannot fit a simple power law, to determine the contribution of the GRB to the lightcurve we used SN1998bw as a template with which to fit the GRB/SN lightcurve; giving the contribution of the GRB lightcurve (~ 2 mags). Using this correction we could then fit the other SN light curves to determine which of them fit the data points most accurately. The GRB light curve itself is very bright and the SN component is only barely visible. As with the other cases the SN that fits the data points the best is SN1998bw.

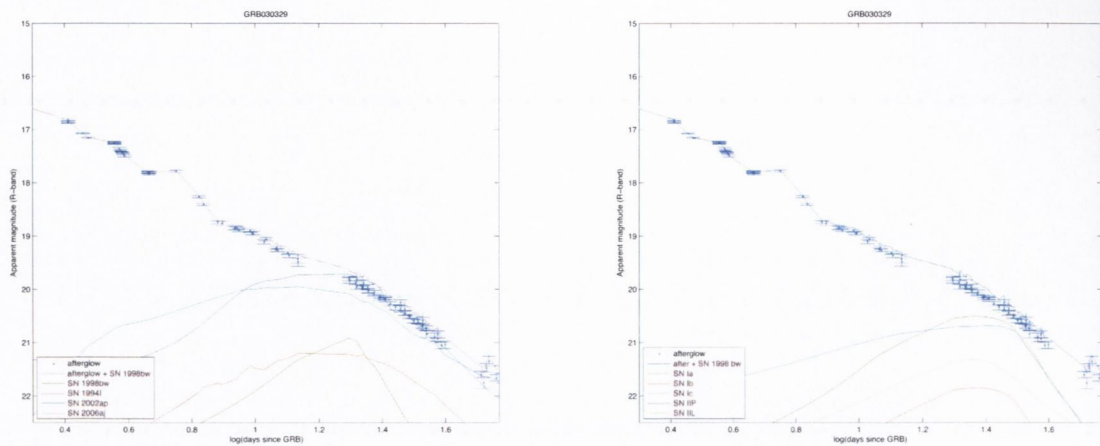


Figure 7-20: Our K-corrected SN template lightcurves (right) and individual SN lightcurves (left) splined with the light curve of GRB030329.

7.5.7 GRB041006

Stanek et al. (2005) presented photometric data of GRB041006 spanning 65 days from the burst. They found a rebrightening at ~ 30 days after the burst. They attribute this to a type Ic supernova, using the lightcurve of SN 1998bw as a template (see Figure 7-21). It should be noted that in producing their composite GRB / SN lightcurve the authors apply extra corrections on the light curve of SN 1998bw, reducing its R magnitude by -0.30 mag and stretching its light by a factor of 1.38 additional to cosmological stretching. They also apply a K-correction but do not give details of its value or determination.

Our results for GRB041006 are shown in Figure 7-22. As with the other bursts in our sample we have produced composite light curves using the light curve of GRB041006 (Stanek et al. 2005) and our sample of SN light curves. No additional stretching was included in time evolution of the SN light curves. Also, Stanek et al. use a number of other points taken from GCN reports (seen as open points in Figure 7-21), but we use just their data set (seen as filled red points in Figure 7-21)

We find, as before, that all the SNe associated with GRBs with the exception of SN1994l could account for the bump, indicating that it is most likely a SN type Ic emerging from the GRB light curve. Of the other SN types various additions could be made to their light curves to fit them to the bump, but still the most likely candidate is a type Ic.

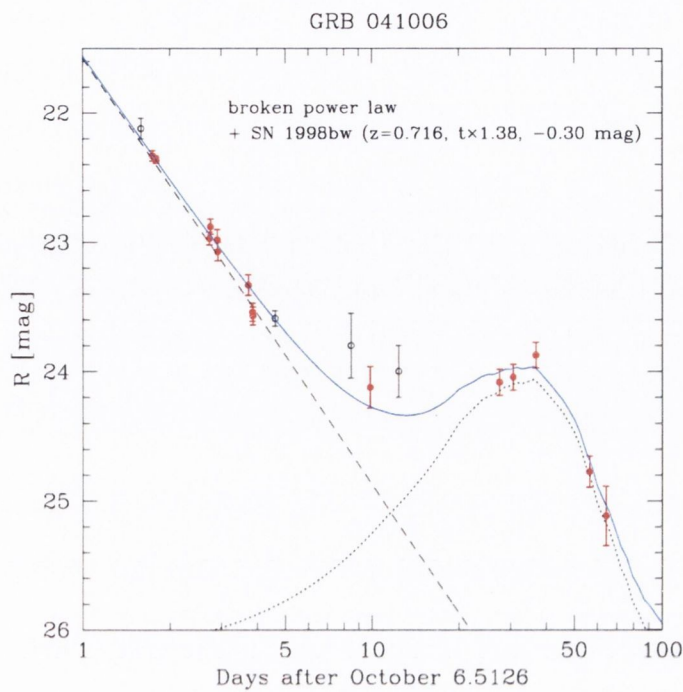


Figure 7-21: Light curve of GRB041006 from Stanek et al. (2005).

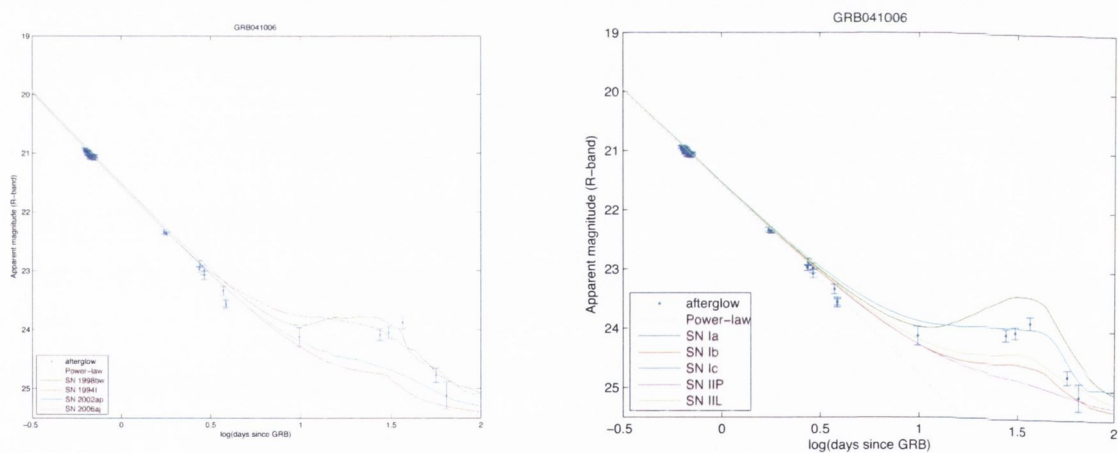


Figure 7-22: Our fit of the lightcurve of GRB041006 with the superimposed template SN lightcurves (right) those of individual SNe (left).

7.5.8 GRB050525A

On the discovery of GRB 050525A both the magnitude and the shape of the light curve suggest that a supernova was emerging during the late decay of the afterglow (Della Valle et al. 2006). This supernova was dubbed SN2005nc.

In their paper the authors suggest the possible supernova type, not only based on templates

of previous GRB associated SNe, but also by comparing the spectrum of the GRB with that of SN 1998bw. While their photometric data alone are consistent with different SN morphologies (based on either SN 1998bw, SN 2002ap, or SN 1994l templates (see Figure 7-23)), the analysis of the spectrum gave SN 1998bw as the best match (possibly dimmed by ~ 0.3 mag). In making their plots they apply a number of corrections to the SN lightcurves in order to obtain a better fit, for example SN 2002ap and SN 1994l are brightened by 1.3 mag and 1.8 mag respectively. The authors obtained an upper value limit for the galactic contribution of $R=25.2$, which we use also.

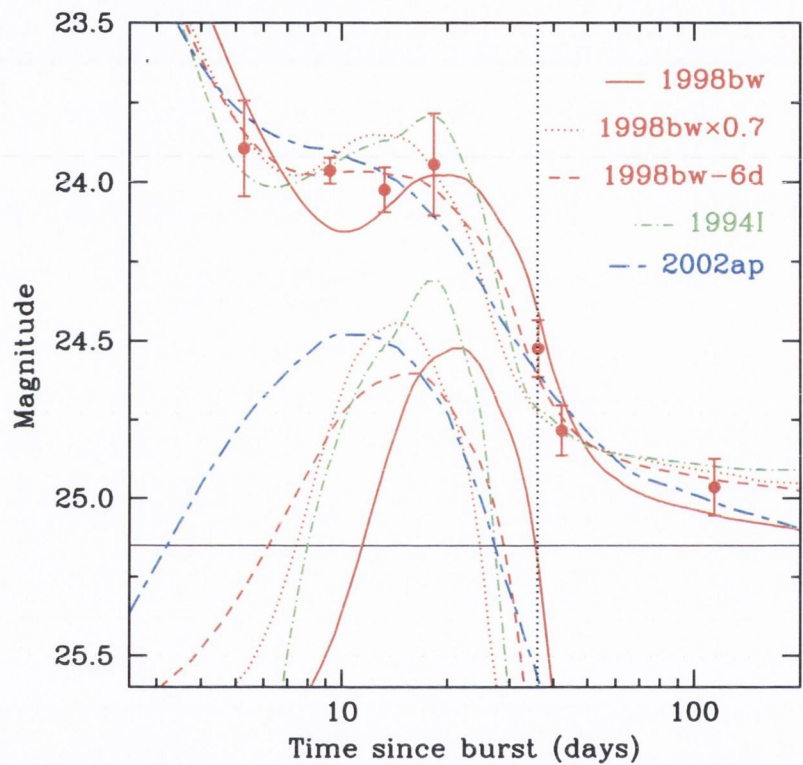


Figure 7-23: Light curve of GRB050525A taken from Della Valle et al. (2006).

Our findings show a similar result. The most likely candidates in our case are SN 1998bw, SN 2002ap and SN 2006aj. Again, this is a clear indication that SN2005nc is probably a type Ic supernova and at least very similar to the SNe associated with other GRBs.

The light curves of the other SN types do not coincide with SN2005nc, but may be possible with some added effects i.e. additional temporal stretching, dimming or brightening.

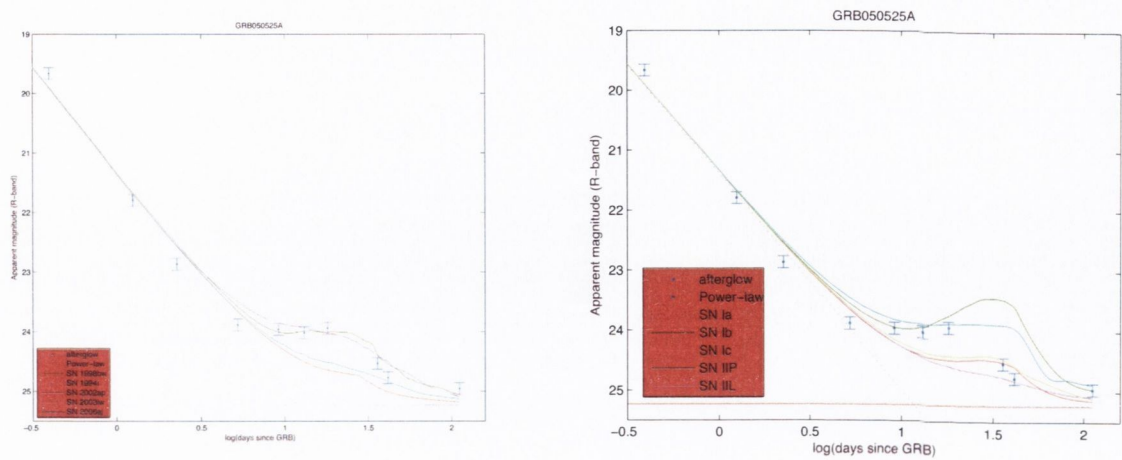


Figure 7-24: Superimposed over the light curve of GRB050525A are the SN template light curves (right) and the lights curves of individual supernova (left).

7.6 Discussion

Our results show that the most likely candidate for SNe connected with GRBs is a type Ic, more specifically Hypernovae. One of the main purposes of this study was to explore the possibility that the light curves of other supernova types may fit the late time rebrightening. Of the SN types other than type Ic, it is type Ia that has the closest fit to the GRB light curves.

The progenitors of SN Ia are white dwarfs whose collapse is due to the accretion of matter from a companion. This scenario is not compatible with the current model of GRB emission. The most likely progenitor is the core collapse of a massive star, quite unlike a SN Ia. The most likely candidates are SN Ib/c.

However the early to mid time light curve of a SN Ia is dominated by the radioactive decay of Ni^{56} (see Figure 7-25). The radioactive decay of nickel-56 through cobalt-56 to iron-56 produces high-energy photons which dominate the energy output of the ejecta at intermediate to late times (W. Hillebrandt & J. C. Niemeyer, 2000).

It has been suggested (MacFadyen & Woosley 1999, McLaughlin & Wimers 2002, Zhang, Woosley, & MacFadyen 2002) that nickel is produced in the GRB explosion. In fact, extensive numerical modeling of light curves and spectra of hypernovae (see Nomoto et al. 2004 for a recent review) suggest the need of an atypically high mass of nickel ($\sim 0.1 - 0.5 M_{\odot}$), for core-collapse SNe, to be present in the ejecta in order to explain the observed hypernova properties. The rapid rise in the observed light curve of SN 1998bw requires a substantial amount of Ni^{56} to be present near the surface. This strongly indicates the important role of mixing during the explosion as nickel is

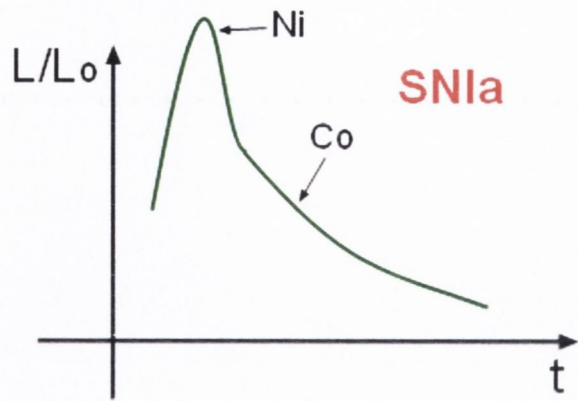


Figure 7-25: The light curve of a SN Ia is dominated by the radioactive decay of Ni_{56} , and then by the radioactive decay of Co_{56} .

synthesized in deep layers during a spherical explosion. Therefore, it is likely that the observed trend for SN Ia light to fit the bumps in the late time GRB curves is due to the high amount of nickel being produced in the GRB explosion.

8

Conclusions

The results of the work in this thesis show not only the diverse and complex nature of GRBs and their progenitors, but also the many changes in the field over the last few years. The study of GRBs is still in many ways quite a new field. There are many aspects of these phenomena that are still not yet well understood. Their cosmological nature was first proven only 10 years ago, and it has only been made possible to perform a number of the observations in this thesis since the launch of the Swift satellite.

Although many theories have been put forward as to what the progenitors of GRBs are, there is still not enough observational evidence to prove convincingly which scenarios are most likely. There are a number of key aspects to understanding how GRBs form and what types of progenitors may be possible. One such way is by studying the environments directly affected by the GRB. Through the study of the early time afterglow with robotic facilities such as REM it is possible to view the afterglow prior to its power law decay giving vital information about the initial conditions of the blast wave. It is clear from the findings of REM that in order to observe such events, it is imperative to have a facility with the ability to observe the GRB within 10s of seconds of the burst trigger. The introduction of fully autonomous observations has shown that the need for human

intervention, which may cost vital minutes, is no longer a necessity.

Through observations of the early light curve of GRB060418 and GRB060607, the initial lorentz factor of the GRB explosion has been directly measured. This was achieved by measuring the peak arising before the lightcurves begin their power law decay. The value found for both bursts is $\Gamma_0 \sim 400$. REM has also proved successful as a fully autonomous robotic telescope, detecting 9 GRB afterglows since it began operations, in some cases beginning observations just tens of seconds after the initial trigger, meaning REM has managed to capture the early stages of what was once of the most elusive of astrophysical phenomena.

Through the contained study of detailed spectroscopy, a better understanding of the GRB environment, and subsequently the progenitor, can be found. This, along with a better theoretical understanding of the physical conditions both in the GRB progenitor and the host galaxy, will hopefully lead to a more complete picture of what GRBs are. High resolution spectroscopic observations of GRB afterglows are at the cutting edge of GRB research. While high resolution spectra have been obtained before, it is still quite a new field coming into its own in terms of resources and technological advances. Observations of GRB afterglows beginning just minutes after the alert have only been made possible in the last 3 years since the launch of the GRB dedicated Swift satellite, allowing for burst positions to be obtained within tens of seconds after the burst. These positions can then be relayed to larger ground based telescopes such as the VLT. With the introduction of the rapid response mode on the VLT it is now possible to begin spectroscopic observations within minutes of the burst. For the first time we can probe the circumburst region with high resolution precision on such a short time scale. Continued observations allows for the possible detection of variability in the absorption features showing directly the influence of the GRB explosion on its surroundings.

We have shown with observations of GRB021004, GRB050922C and GRB060607 the diverse and unpredictable environments in which GRBs occur. The observations of GRB021004, one of the first bursts for which high resolution spectra were obtained, showed for the first time an environment resembling that of a stellar wind, with multiple components spanning ~ 3000 km / s. This has been attributed to a clumpy environment, possibly from shells emitted from the GRB progenitor. The relatively high velocity of some of the components suggest that these were moving at such velocities prior to the GRB explosion. Through a comparison of the column density ratios with those predicted by photoionisation code CLOUDY, it has been shown that ionisation parameters appear to lie in a relatively small range, again indicative of a wind environment.

The spectra of GRB050922C showed an even more complex environment, with seven components making up the redshift system of the GRB. Through the presence of fine structure transitions we have compared column density ratios with those expected for two different excitation mechanisms, the most likely of which we find to be UV pumping. We also detect numerous low and high ionisation lines, some of which appear to trace different regions in the circumburst environment. One important result is the detection of a component that appears just for the low ionisation lines, which we interpret as a feature of the host galaxy, (relatively) unaffected by the GRB. In contrast, the component for which we detect the highest column density for the fine structure transitions does not appear for some low ionisation species, such as MgI. MgI has a first ionisation energy below the 1Ryd threshold and would be easily ionised by the strong radiation from the GRB. This is a good indication that this component is closest to the site of the GRB and has been completely ionised.

The spectrum of GRB060607, in contrast to those of GRB021004 and GRB050922C, show a GRB host uncomplicated by absorption features. In the highest redshift system, that of the GRB host, we detect only SiIV and CIV absorption features. The intervening systems along the line of sight, however, show some highly complex environments. The lack of features present in the system of the GRB host may be as a result of the line of sight. The light from the GRB may just not be passing through as much galactic material as with other GRBs. Another possibility is that the GRB has been ejected from the star forming region in which it was born, and may be as a result of a runaway star. Previous examples, such as GRB980425 (Hammer et al. 2006), have shown such cases where the GRB has occurred ~ 250 pc from star forming regions.

As research continues to explain GRB progenitors better, one key observational aspect is the discovery of late-time rebrightenings in GRB afterglows. These have been attributed to SN explosions emerging from the GRB lightcurve, lending much weight to the collapsar model of GRBs. Where no accompanying SN can be verified, the late time lightcurve bump can be fitted with lightcurves of previous SN, such as SN 1998bw. This can be a useful method to test for the presence of an underlying SN. Given that the SN lightcurves being used originated from a different explosion, with different conditions and at a different redshifts, the best we can hope to do is compare the brightness of the late GRB bump and SN template lightcurve, and the time at which the peak occurs. It is therefore important to correct for any cosmological effects that may alter the peak magnitude of the SN lightcurve.

One such effect is K-correction, which we have shown will affect the brightness of an artificially redshifted SN lightcurve. We have shown that, using derived K-corrections for each SN type, the

number of SNaE that can fit the latetime GRB bump increases. Most noticeable is the correlation with SN Ia lightcurves. It is unlikely that GRBs will occur from a SN Ia explosion, but the nature of the SN Ia lightcurve indicates that GRB SNaE may have similar properties, such as a high content of Nickel.

9

Future Work

- Although GRB research has come a long way in the last ten years it is clear that there is still a lot of unanswered questions. Through early time observations of GRBs, made possible only by Swift, we are now able to observe GRBs on sufficiently short time scales to probe directly the effects on the circumburst environment, and to obtain both photometric and spectroscopic observations within seconds to minutes from the burst.
- My aims for future research are to continue studies of early time observations of GRBs through both spectroscopy and photometry. I also hope to expand my theoretical knowledge of the physical processes involved with early time behavior of the burst, and the excitation mechanisms by which the circumburst environment is affected.
- Using early spectroscopic data (in the case of GRB060607A, ~ 7.5 minutes after the burst trigger from Swift) it is possible to obtain vital information on the kinematics, structure and ionisation state of the medium directly affected by the burst. Multiple observations can detect variability in the column densities of the absorption features. In the case of GRB060418 (Vreeswijk et al. 2007), spectroscopic observations began ~ 10 mins after the Swift trigger.

They detected variability in a number of transitions, which suggests the most likely mechanism for excitation as UV pumping.

- I also plan to continue my research on SN / GRB connections with a focus on observational signs of an underlying SN and cosmological effects such as K-correction. Further to this, understanding the nature of the SN contributions to GRB lightcurves may show that these bumps are not purely as a result of simultaneous SN event, but possibly intrinsic to the GRB progenitor itself.

A

APPENDIX

A.1 Appendix 1 - Using Jet Breaks to Estimate GRB Distances

In Chapter 2 I reviewed a number aspects of distance determinations and estimations for GRBs. Included in this Chapter was an overview of a potential distance estimator by Atteia et al. (2003). In this appendix I will outline a basic distance estimator based on the constraining of E_γ as a constant. The sample of bursts used in this study are pre-Swift bursts, and the values for each burst property are taken from the review by Friedman et al. (2005).

Of the two distinct categories of GRBs, long ($>2s$) and short ($<2s$), it is the long GRBs which have become relatively well understood. This is primarily due to the afterglow which can linger for up to several weeks after the burst. The value for the isotropic equivalent energy output of a GRB, E_{iso} , in a given bandpass is found by:

$$E_{iso} = S_\gamma \frac{4\pi d_L^2}{(1+z)} k \quad (A.1)$$

where S_γ is the fluence received in the observed band pass and d_L is the luminosity distance at redshift z . The quantity k is the k-correction.

However, it has been shown that true energy release, E_γ , of a GRB is in fact much less than this when the burst is beamed into a collimated jet of half opening angle θ_j . The relationship between E_γ and E_{iso} is:

$$E_\gamma = (1 - \cos(\theta_j))E_{iso} \approx \frac{\theta_j^2}{2}E_{iso} \quad (A.2)$$

The beaming fraction can also be described as the ratio of the true energy release and isotropic equivalent energy; $\frac{E_\gamma}{E_{iso}} \approx \frac{\theta_j^2}{2}$ and therefore:

$$\theta_j \approx \left(\frac{2E_\gamma}{E_{iso}}\right)^{1/2} \quad (A.3)$$

A.1.1 Jet Breaks

One signature of such a jet is a broadband break in the power-law decay of the afterglow emission. This break happens for two reasons. Firstly, there is an edge effect that occurs at a time t_j when the bulk Lorentz factor of the blast wave (Γ) has slowed down to $\Gamma < \theta_j^{-1}$. The second effect is the lateral spreading of the jet when the ejecta decelerate faster as they encounter more circumburst material.

According to the formulation made by Sari et al. (1999), the time at which the break occurs is given by $t_j \approx 6.2 \left(\frac{E_{iso}}{n_1}\right)^{1/3} \left(\frac{\theta_0}{0.1}\right)^{8/3}$ days. This is derived from the spherical adiabatic evolution of the Lorentz factor $\gamma(t) \approx 6 \left(\frac{E_{iso}}{n_1}\right)^{1/8} t_j^{-3/8}$. Subsequently, if the break occurs when $\Gamma \approx \theta_j^{-1}$, from equation A.3 we find that $\left(\frac{2E_\gamma}{E_{iso}}\right)^{-1/2} \approx 6 \left(\frac{E_{iso}}{n_1}\right)^{1/8} t_{day}^{-3/8}$ which can be rearranged to give:

$$E_{iso} = 119(2E_\gamma)^{4/3}(n)^{-1/3}(t_j)^{-1}. \quad (A.4)$$

This, therefore, gives us a simple expression to calculate E_{iso} from the time at which the jet break occurs, the density of the circumburst medium and the beaming corrected.

A.1.2 Standard Candles

Previous work has suggested that Gamma Ray Bursts have the potential to be used as standard candles (Frail et al. 2001, Bloom et al. 2003). Although the current set of data is inadequate to build any realistic model for studying cosmology, it does give the opportunity to explore some interesting tests.

If GRBs are in fact standard candles then the value for E_γ can be estimated as a constant. Using this presumption we can use the two equations for E_{iso} to construct a relationship between intrinsic

burst parameters and the redshift. Equations A.1 and A.4 can therefore be used to give the following relationship.

$$\left(\frac{d_L^2}{1+z}\right) = Q_T(t_j, S_\gamma, n, k)E_\gamma^{4/3} \quad (\text{A.5})$$

Here we define $Q_T \equiv \frac{238.7}{t_j n^{(1/3)} S_\gamma k}$.

A.1.3 Results

We can now test this relationship using existing data. Table A.1 lists the parameters for the 12 bursts which we have used. For each of these bursts is given values for z , n , t_j , S_γ and k . These values are taken from Friedman et al. (2005) for GRBs which have measured values for each of the parameters. Subsequently for each burst we derive a value for Q_T .

GRB	z	$n \text{ [cm}^{-3}\text{]}$	$t_j \text{ [days]}$	$S_\gamma \text{ [10}^{-6} \text{ erg cm}^{-2}\text{]}$	k	$Q_T \text{ [10 cm}^3 \text{ erg}^{-1} \text{ s}^{-1}\text{]}$
GRB970508	0.8349±0.0003	1 ±0.5	25 ±5	1.8 ±0.3	1.55 ±0.08	0.3420 ±0.3140
GRB980329	2.95 ±0.95	29 ±10	0.29 ±0.2	65 ±5	0.97±0.09	0.4250 ±0.5120
GRB980703	0.9662±0.0002	28 ±10	3.4 ±0.5	22.6 ±2.26	0.94±0.08	0.1090 ±0.0751
GRB990510	1.6187±0.0015	0.29±0.15	1.57 ±0.03	19±2	1.29±0.03	0.9370 ±0.6548
GRB991208	0.7055±0.0	18 ±22	<2.1	100 ±10	1.09±0.03	0.0398 ±0.0537
GRB991216	1.02 ±0.02	4.7 ±6.8	1.2 ±0.4	194 ±19.4	0.88±0.09	0.0696 ±0.1379
GRB000301	2.0335±0.0003	26 ±12	7.3 ±0.5	2 ±0.6	1.37±0.36	0.4028 ±0.4402
GRB000418	1.1182±0.0001	27 ±256	25.7 ±5.1	20.00±2	1.00±0.02	0.0155 ±0.1519
GRB000926	2.0369±0.0007	27 ±3	1.8 ±0.1	6.20 ±0.62	3.91 ±1.33	0.1823 ±0.0548
GRB010222	1.4769±0.00005	1.7 ±0.85	0.93 ±0.15	120.00 ±3	1.03±0.04	0.1740 ±0.1261
GRB021004	2.3351±0.0	30 ±270	6.5 ±0.2	2.55 ±0.69	1.04 ±0.06	0.4456 ±4.1707
GRB030329	0.1685±0.000004	5.5 ±2.75	0.48 ±0.03	163.00±1.4	1.01±0.03	0.1711 ±0.1028

Table A.1: Derived values for Q_T . Values for z , n , t_j , S_γ and k are taken from Friedman & Bloom (2005).

If (initially) we ignore certain cosmological effects (such as acceleration/deceleration) the quantity Q_T will evolve with redshift z . Figure A-1 is plot of Q_T vs. z (logarithmic scale).

The dotted line represents the observed trend in the data points; the value for Q_T appears to increase with redshift. Amati et. al (2002) previously noticed a trend of E_{iso} to increase with z . The derived relationship is

$$Q_T = A \times z^\beta \quad (\text{A.6})$$

where $A \sim 0.1 \text{ cm}^3 \text{ erg}^{-1} \text{ s}^{-1}$ and $\beta=1.5$ (see Figure A-1). We therefore have a method for determining z^* , the estimated redshift, according the relationship derived from the plot in Figure A-1,

$$z^* = \left(\frac{Q_T}{0.1}\right)^{2/3} \quad (\text{A.7})$$

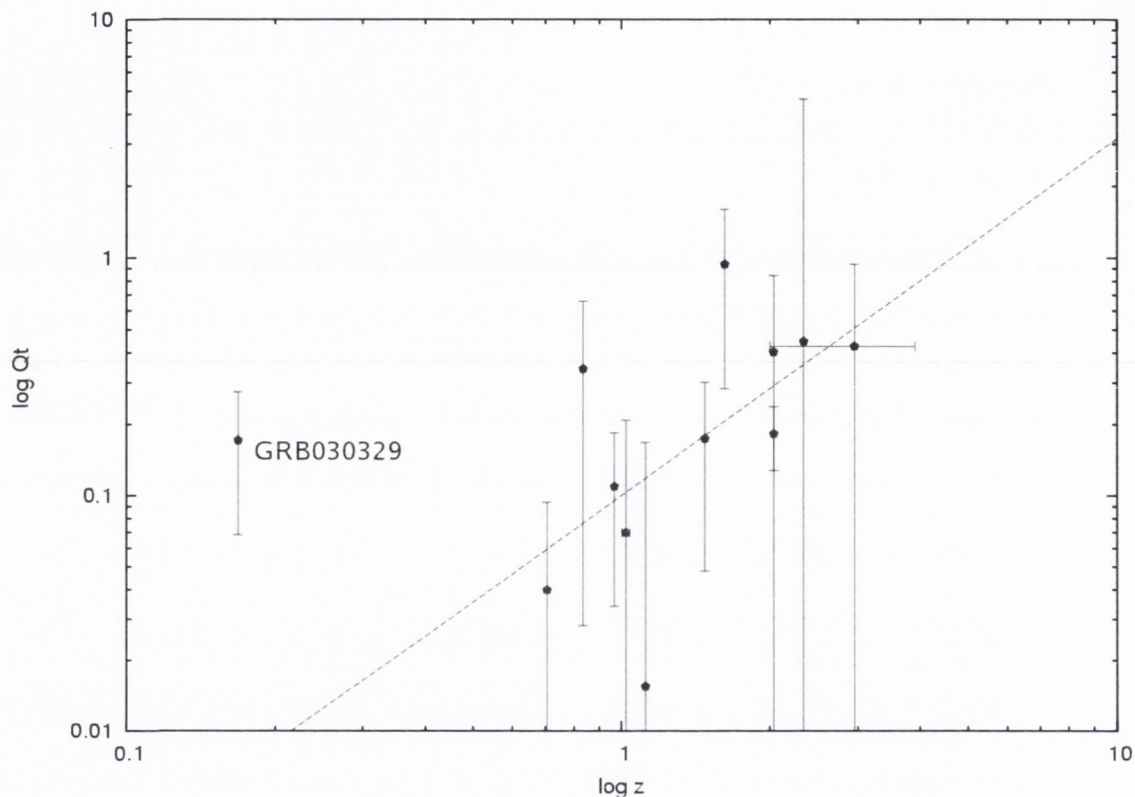


Figure A-1: A plot of $\log Q_T$ vs. $\log z$. We observe one main outlier to the relationship, GRB030329. This is the only GRB in our sample associated with a supernova, it has the highest fluence and is also the closest at $z=0.1685$.

Using equation A.7 we can determine the predicted redshift, z^* , for each of the twelve bursts. We can see the dependence of the relationship in equation A.7 on each of the burst parameters (see Figure A-2). The parameter which shows the dependence on z^*-z is t_j , (see Figure A-3). Table A.2 shows the derived values for z^* and z^*-z for each of the twelve bursts in the sample. There is a clear evolution of z^*-z with increased t_j , indicating the error in z^* will increase the longer the time after the burst when a break occurs. Figure A-3 shows a larger view of (z^*-z) vs. t_j .

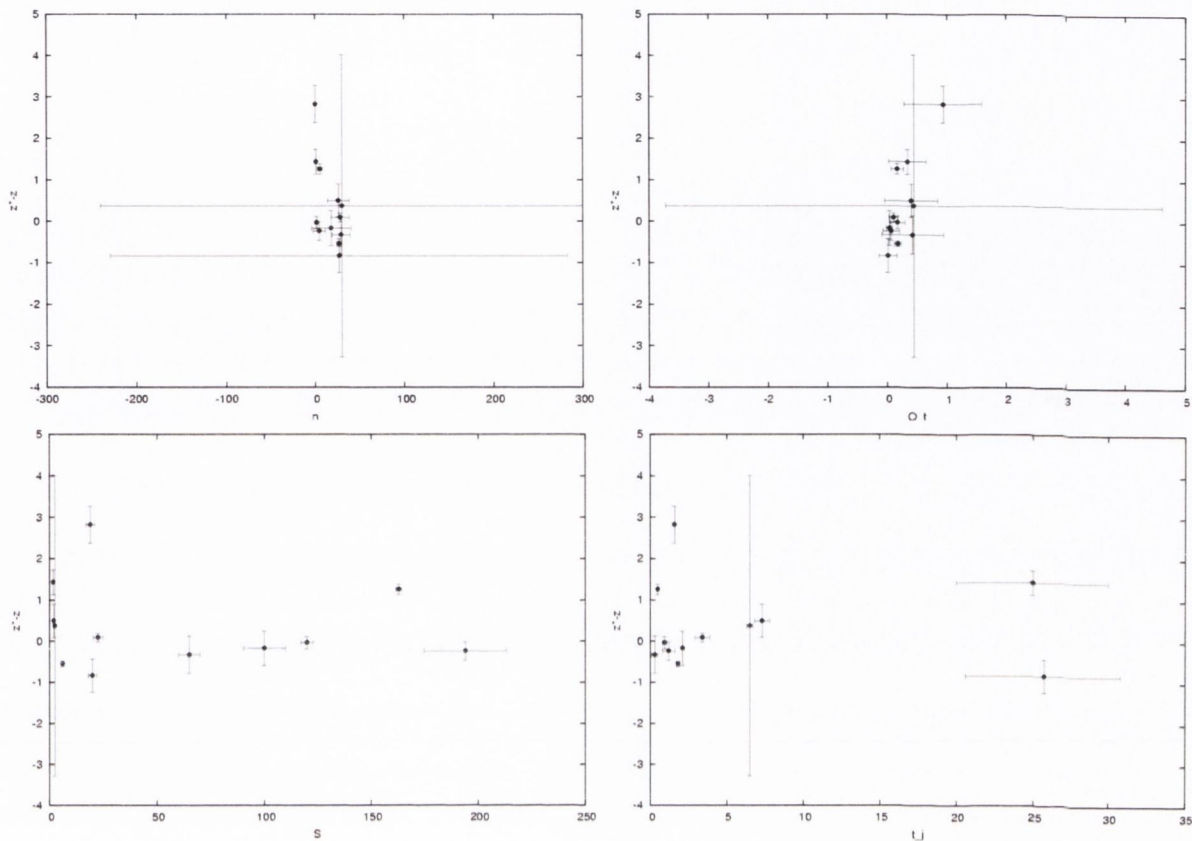


Figure A-2: Above we have plotted z^*-z vs. Q_I, S_γ, n and t_j

GRB	t_j [days]	z^*	z^*-z
GRB970508	25 ± 5.00	2.2700 ± 0.2993	1.4351 ± 0.2993
GRB980329	0.29 ± 0.20	2.6238 ± 0.4540	-0.3262 ± 0.4540
GRB980703	3.4 ± 0.50	1.0591 ± 0.1048	0.0929 ± 0.1048
GRB990510	1.57 ± 0.03	4.4445 ± 0.4461	2.8258 ± 0.4461
GRB991208	<2.1	0.5411 ± 0.4194	-0.1644 ± 0.4194
GRB991216	1.2 ± 0.40	0.7854 ± 0.2235	-0.2346 ± 0.2235
GRB000301	7.3 ± 0.50	2.5316 ± 0.3974	0.4981 ± 0.3974
GRB000418	25.7 ± 5.10	0.2886 ± 0.4062	-0.8296 ± 0.4062
GRB000926	1.8 ± 0.10	1.4923 ± 0.0644	-0.5446 ± 0.0644
GRB010222	0.93 ± 0.15	1.4467 ± 0.1506	-0.0302 ± 0.1506
GRB021004	6.5 ± 0.20	2.7080 ± 3.6403	0.3728 ± 3.6403
GRB030329	0.48 ± 0.03	2.3879 ± 0.1234	1.2620 ± 0.1234

Table A.2: The calculated values for z^* .

A.1.4 Distance Estimator

If the observed trends are indeed due to some intrinsic characteristic of the bursts, then the above method would be extremely useful not only as a redshift estimator but would also be a useful tool to fill in the many gaps in the current set of GRB results. It is clear however that more data are

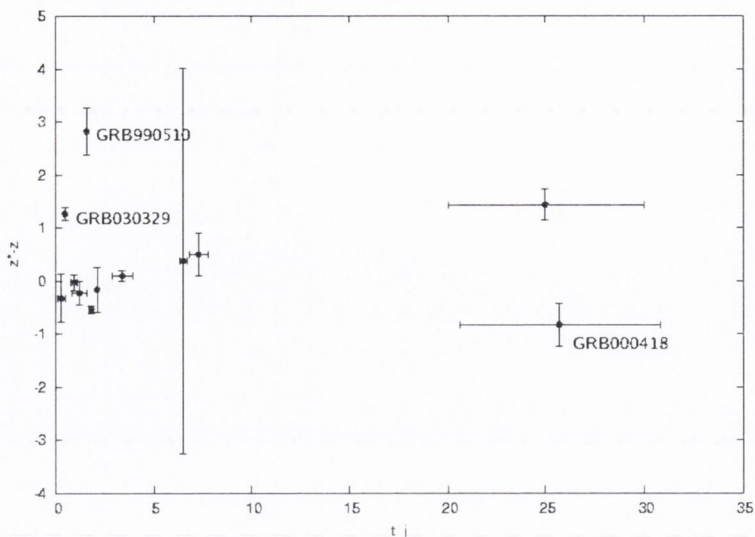


Figure A-3: A plot of t_j vs. z^*-z . The majority of the points show a linear dependency, however there are three main outliers: GRB030329, GRB990510 (this GRB has a very low value for n . This is two orders of magnitude below the average), 000418 (this GRB has a very large error in n , $\pm 270 \text{ cm}^{-3}$). If these three points are removed we obtain a Pearson correlation coefficient of $r=0.94$

required to understand fully both the nature of GRBs and their potential as probes of the high redshift universe. Continued research should include data mining of bursts with well established values for S_γ , n , t_j , and z . This would better provide a constraint to the relationship in equation A.7.

A.2 Appendix 2 - MATLAB fitting procedure

To fit the GRB / SN light curves I have used MATLAB. As an example of the fitting procedure I will use GRB050525A, outlining the script code used for specific tasks. In most cases, such as this, a powerlaw is fitted to the GRB afterglow. This is then splined with the light curve of a SN.

Firstly we define the GRB magnitude vs. time data using:

```
clear
day=[0.0708 0.3946 0.1364 1.2532 2.2684 5.2181 9.1589 13.052 18.0287 35.8502 41.4756 111.589 ]
[a b]=size(day)
tGRB=day
mm=[17.4090 19.6599 18.1848 21.7905 22.8613 23.8774 23.9539 24.0086 23.9321 24.5221 24.7625 24.9482]
erro=[.1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1 .1]
xx=log10(tGRB)
Galaxy=26.22
mGRB=2.5*log10(10.^(0.4*(mm))-1)
```

Where day, mm and erro correspond to the measured time, magnitude and error of the GRB afterglow. The magnitude contribution due to the host galaxy can also be defined here. Next we define the conditions under which the powerlaw is fit. In this case we do want to include the data points contributing to the SN bump to calculate the GRB powerlaw, so we define $tGRB < 8$.

```
j=1
for i=1:b
    if tGRB(1,i)<8
        if erro(1,i)<0.6
            tpl(1,j)=tGRB(1,i)
            mpl(1,j)=mGRB(1,i)
            erropl(1,j)=erro(1,i)
            j=j+1
        end
    end
end
end
```

Next we define the variables to be used in the powerlaw fit, p, fitting them (on a logarithmic scale) over the iterations defined by s; pl defines the powerlaw fit.

```
p=polyfit(log10(tpl),mpl,1)
s=0.1:112
sw=1:112
pl=polyval(p,log10(s))
```

Next, in order to calculate the equations for magnitude and to correct for our K-correction we need to define a number of constants such that:


```

c=3*10^5
Ho=70
qo=.2
z=0.606
Abs=0.6
Abs1=0.6
Kbrla=-0.6534
Kbrlbc=-0.5712
KbrHy=-0.5233
Kbrll=-0.5756
t=0

```

We then define the magnitude vs. time data for each of the supernova lightcurves. This was done for a number of SNa, below is the data for the SN Ia light curve used for the fitting.

```

tpa=20
da=[-20 -14 -12 -10 -9 -8 -6.6 -5 -3 -2 0 2 3 4 6 7 22 26 35 37 44 100 200 305]+tpa
ma=[3.6 1.62 1.14 .71 .58 .45 .28 .16 .04 .02 0 .02 .04 .08 .19 .31 1.89 2.2 2.68 2.76 2.94 3.76 5.4 7.25]
Mpa=-18.19+5*log10(Ho/100)
Ma=ma-min(ma)+Mpa

```

This same procedure was carried out for all of the other SN light curves also. We then must correct for the fact that the given SN lightcurve are at different redshifts. This requires a time dilation correction, giving t_{SN}^* . We also define the cosmology used, and using the constants we defined earlier, calculate the correctioned magnitudes for the SN lightcurves. This includes the K-corrections given by K_{br}^* . We can then fit the SN light curves, defined by y^* .

```

tSNa=(da+t)*(1+z)
tSNb=(db+t)*(1+z)
tSNc=(dc+t)*(1+z)
tSNd=(dd+t)*(1+z)
tSNe=(de+t)*(1+z)
tSNf=(df+t)*(1+z)
tSNg=(dg+t)*(1+z)
tSNh=(dh+t)*(1+z)
tSNI=(di+t)*(1+z)
tSNj=(dj+t)*(1+z)

dist=c*z*(1+.5*(1-qo)*z)/Ho

mSNa=Ma+26.2+5*log10(dist)+Abs+Kbrla
mSNb=Mb+26.2+5*log10(dist)+Abs+Kbrlbc
mSNc=Mc+26.2+5*log10(dist)+Abs+Kbrlbc
mSNd=Md+26.2+5*log10(dist)+Abs+Kbrll
mSNe=Me+26.2+5*log10(dist)+Abs+Kbrll
mSNf=Mf+26.3+5*log10(dist)+Abs+KbrHy
mSNg=Mg+26.2+5*log10(dist)+Abs1+KbrHy
mSNh=Mh+26.2+5*log10(dist)+Abs+KbrHy
mSNI=Mi+26.2+5*log10(dist)+Abs+KbrHy
mSNj=Mj+26.2+5*log10(dist)+Abs+KbrHy

ya=spline(tSNa,mSNa,s)
yb=spline(tSNb,mSNb,s)
yc=spline(tSNc,mSNc,s)
yd=spline(tSNd,mSNd,s)
ye=spline(tSNe,mSNe,s)
yf=spline(tSNf,mSNf,s)
yg=spline(tSNg,mSNg,s)
yh=spline(tSNh,mSNh,s)
yi=spline(tSNI,mSNI,s)
yj=spline(tSNj,mSNj,s)

```

We now combine the two lightcurves using the argument below. This involves the addition of the magnitudes of the two light curves, giving the final composite light curve defined by AA, BB etc.

```
AA=pl-2.5*log10(100.^((pl-ya)/5)+1)
BB=pl-2.5*log10(100.^((pl-yb)/5)+1)
CC=pl-2.5*log10(100.^((pl-yc)/5)+1)
DD=pl-2.5*log10(100.^((pl-yd)/5)+1)
EE=pl-2.5*log10(100.^((pl-ye)/5)+1)
FF=pl-2.5*log10(100.^((pl-yf)/5)+1)
GG=pl-2.5*log10(100.^((pl-yg)/5)+1)
HH=pl-2.5*log10(100.^((pl-yh)/5)+1)
II=pl-2.5*log10(100.^((pl-yi)/5)+1)
JJ=pl-2.5*log10(100.^((pl-yj)/5)+1)
```

We can then plot the light curves using the argument 'plot'.

```
plot(w,pl,'-',w,FF,w,GG,w,HH,w,II)
```

The final set of arguments define the labeling of the graph, as well the ranges of the x and y axis.

```
title('GRB050525A')
ylabel('Apparent magnitude (R-band)')
xlabel('log(days since GRB)')
h=legend('afterglow','Power-law','SN 1998bw','SN 1994I','SN 2002ap','SN 2003lw','SN 2006aj',3)
axis([-0.5 2.2 19.0 25.5])
```

In the above case the GRB afterglow is fitted with a powerlaw over a given range. This is then superimposed with SN light curve corrected for K-correction, time dilation and other cosmological effects. It should be noted that there are a number of other arguments, defining parameters such as the error, which I have not included in this brief overview.

B

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