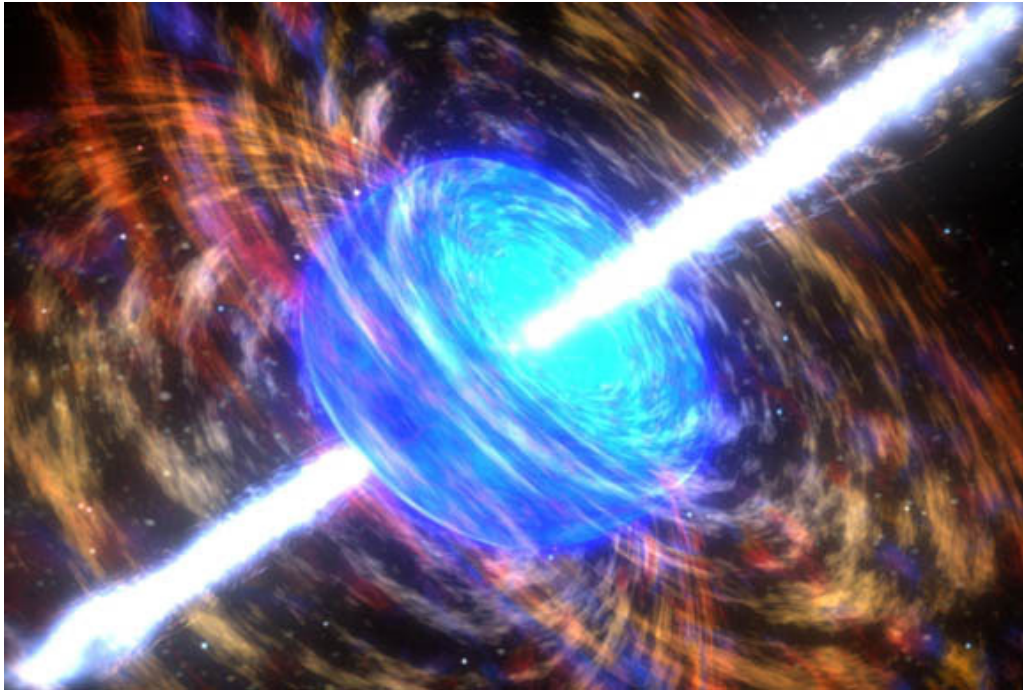


Gamma-Ray Bursts and Their Hosts: A Multi-Wavelength Exploration



Ph.D. Dissertation

by

PÁLL JAKOBSSON

Niels Bohr Institute
Faculty of Science
University of Copenhagen

Gamma-Ray Bursts and Their Hosts: A Multi-Wavelength Exploration

Ph.D. Thesis by
Páll Jakobsson
pallja@astro.ku.dk
Niels Bohr Institute
University of Copenhagen
Juliane Maries Vej 30
2100 Copenhagen Ø
Denmark

Supervisors:

Jens Hjorth
jens@astro.ku.dk
Niels Bohr Institute
University of Copenhagen
Juliane Maries Vej 30
2100 Copenhagen Ø
Denmark

Gunnlaugur Björnsson
gulli@raunvis.hi.is
Science Institute
University of Iceland
Dunhagi 3
107 Reykjavík
Iceland

June 2005

Contents

Preface	iii
1 Introduction	1
1.1 A Brief History of GRB Observations	1
1.2 The Fireball Model	6
1.2.1 The Compactness Problem	6
1.2.2 External & Internal Shocks	8
1.2.3 The Afterglow	11
1.2.4 Collimated Outflows & Beaming Effects	13
1.2.5 The Central Engine & Progenitors	15
1.2.6 Summary & Open Issues	17
1.3 GRB Host Galaxies	20
2 Dark Gamma-Ray Bursts	25
2.1 A Brief Introduction & Summary	25
2.2 Recent <i>Swift</i> Results	28
2.3 Individual Dark GRBs	29
2.3.1 GRB 970828	29
2.3.2 GRB 990506	29
2.3.3 GRB 990704	30
2.3.4 GRB 001025A	30
2.3.5 GRB 001109	30
2.3.6 GRB 050401	30
2.3.7 GRB 050408	30
2.3.8 GRB 050412	31
2.3.9 GRB 050607	31
3 Lyα Emission from GRB Hosts	33
3.1 Introduction	33
3.2 Main Results	34
4 GRB Light Curve Bumps	37
4.1 Introduction	37
4.2 Main Results	37
4.3 GRBs as Tools in Cosmography	38

5 Outlook & Future Prospects	43
A Papers	59
A.1 Paper I	59
A.2 Paper II	65
A.3 Paper III	75
A.4 Paper IV	81
A.5 Paper V	91
A.6 Paper VI	101
A.7 Paper VII	111

Preface

There is something happening in our Universe, and that something is the source of gamma-ray bursts. There may be more than one something.

NASA

The work presented in this thesis has been carried out in partial fulfillment of the requirements for the Ph.D. degree in astronomy from the Niels Bohr Institute, University of Copenhagen. During the time I worked on this thesis (May 2002 – May 2005), I was supervised by Jens Hjorth and Gunnlaugur Björnsson.

Thesis Outline & Main Results

As the field of gamma-ray bursts (GRBs) is in a rapid state of development, the topic of this thesis has partly twisted and turned away from its original path. The starting point was aimed at exploring GRBs as tools in cosmology. Of course it depends on what one assumes cosmology to encompass, but I would say roughly half the contents of this thesis are related to cosmology in one way or another.

The thesis is divided into four parts. There is a relatively short background and introduction part (Chapter 1). I have refrained from giving an exhaustive review of the history and detailed physics of GRBs. Instead I have chosen to point the reader to standard works. The second part of the thesis is dedicated to dark GRBs (Chapter 2) and is based on the following two papers:

Paper I: P. Jakobsson, J. Hjorth, J. P. U. Fynbo, et al. “Swift Identification of Dark Gamma-Ray Bursts.” 2004, *ApJ Letters*, **617**, L21–L24.

Paper II: P. Jakobsson, D. A. Frail, D. B. Fox, et al. “The Radio Afterglow and Host Galaxy of the Dark GRB 020819.” 2005, *ApJ*, **629**, 45–51.

In the former paper, we propose an operational definition of dark bursts: those bursts that are optically subluminal with respect to the fireball model, i.e. that have an optical-to-X-ray spectral index $\beta_{\text{OX}} < 0.5$. Out of a sample of 52 GRBs we identify 5 dark bursts. Part of the latter paper deals with GRBs localized with the Soft X-ray Camera (SXC) on-board the *High Energy Transient Explorer 2 (HETE-2)*. The high optical recovery rate among that sample (12/14) is used to argue that the fraction of truly dark bursts is $\sim 10\%$, consistent with the results from Paper I.

The third part (Chapter 3) addresses Ly α emission from GRB host galaxies. The groundwork for this part is laid out in: q

Paper III: J. P. U. Fynbo, P. Jakobsson, P. Møller, et al. “On the Ly α Emission from Gamma-Ray Burst Host Galaxies: Evidence for Low Metallicities.” 2003, *A&A Letters*, **406**, L63–L66.

Paper IV: P. Jakobsson, G. Björnsson, J. P. U. Fynbo, et al. “Ly α and UV Emission from High-Redshift GRB Hosts: To What Extent Do GRBs Trace Star Formation?” 2005, *MNRAS*, in press.

Here we suggest, based on five Ly α detections from GRB hosts out of five possible, a preference for GRB progenitors to be metal-poor, as expected in the collapsar model. We also demonstrate that a scenario where GRBs trace star formation in an unbiased way is compatible with current observational constraints.

The fourth part (Chapter 4) is mainly concerned with “wiggles” in GRB light curves, i.e. deviations from the common smooth power-law decay. The foundation for this work is:

Paper V: P. Jakobsson, J. Hjorth, J. P. U. Fynbo, et al. “The Afterglow and the Host Galaxy of GRB 011211.” 2003, *A&A*, **408**, 941–947.

Paper VI: P. Jakobsson, J. Hjorth, E. Ramirez-Ruiz, et al. “Small-Scale Variations in the Radiating Surface of the GRB 011211 Jet.” 2004, *New Astronomy*, **9**, 435–442.

Paper VII: P. Jakobsson, J. Hjorth, J. P. U. Fynbo, et al. “The Line-of-Sight Towards GRB 030429 at $z = 2.66$: Probing the Matter at Stellar, Galactic and Inter-galactic Scales.” 2004, *A&A*, **427**, 785–794.

The main result from this work is that for GRB 011211, the wiggles in the optical light curve are the result of spherically asymmetric density or energy variations. In addition, if the wiggles in the X-ray light curve are real, it would imply that the energy content across the jet-emitting surface is not uniform. We note that GRB 030429 also showed evidence for a bump in its optical light curve (Paper VII), but lacking multi-wavelength observations we were unable to distinguish between the possible explanations.

Although I have decided to split the thesis up like this, I would like to emphasize that the three topics (Chapters 2, 3 and 4) should not necessarily be viewed as separate entities. As an example, the first two topics are closely linked: Some of the dark bursts are the result of dust obscuration in their host galaxies. The presence of dust is extremely hazardous for Ly α photons; due to resonant scattering these photons face a large probability of being absorbed by dust particles. Hence, detection of Ly α emission implies little or no dust (and a metal-poor environment). Another

way to link the topics is to look at GRB 011211. This is an example of a burst that can be used to explore the multitudinous facets of astronomy. In Paper III, it is used to draw conclusions about the host galaxy metallicity, in Paper V the immediate surroundings of the progenitor is explored, while implications for the jet structure are put forward in Paper VI. In addition, there is a Nature paper on GRB 011211 by Reeves et al. (2002) reporting the first detection of multiple X-ray emission lines from a GRB afterglow.

Papers I–VII are located in Appendix A. After reading the Introduction (Chapter 1), the optimum way to read this thesis is to read the papers belonging to a specific topic and then the corresponding chapter. I have written each chapter to summarize the results from the papers and, if necessary, update and expand on the relevant topic.

Acknowledgements

The work presented in this thesis has involved numerous people, without whom it could never have been realized. First of all, I would like to thank my local supervisor, Jens Hjorth*, for invaluable advise, providing inspiration and for always¹ taking time for discussions. He has recently, and most deservedly, been ‘upgraded’ to a Professor, and together with some of his Danish/Swedish collaborators, has received a healthy fund from the National Danish Research Foundation to establish an astronomical research centre in Copenhagen for dark matter and energy. I wish him all the best in coming up with an appropriate acronym².

I am also hugely indebted to the other half of my supervision team, Gunnlaugur Björnsson*. He has not only frequently made me see the lighter side of the astronomy business/politics with his constant good spirit, but has also financed roughly 50% of this project. There is a good chance that my academic career would have been directed into a non-astronomical course without his support. Although not my official supervisor, Johan P. U. Fynbo* (a.k.a. Jóhann Pétursson) has certainly acted as one. Somehow he has managed to withstand my overwhelming barrage of daily questions without once losing patience. I suspect this is partly due to his fanatical interest in the Icelandic language, although he only seems to be able to pronounce two words correctly: *meiriháttar hádegismatur*³, which will forever echo in the corridors of the Rockefeller Complex.

Approximately once per week I have a nagging urge to discuss football, either to complain about the incompetence of mighty Liverpool, or to enjoy the downward spiral of manchester united. For this purpose, Darach Watson* has served me well. Even though he is a manchester united supporter, he is quite a decent chap. I first met him during my 5 months stay (latter half of 2002) at the University of Leicester, which kindly provided me with office space and computer facilities.

*Persons marked with an asterisk provided valuable comments to an earlier version of this thesis.

¹That is, when I could locate him in his office.

²Apparently, a bottle of a 21-year old, extra-smooth, single-malt scotch whisky is up for grabs for an ingenious suggestion.

³Fantastic lunch.

My former office-mate, Jesper Rasmussen, is gratefully acknowledged for perpetually spicing up my spirit at work, e.g. by demanding fredagsøl on various weekdays. He and my fellow students and collaborators at the Niels Bohr Institute (NBI) are responsible for countless good laughs. Many thanks to the staff at the NBI; the secretaries (especially Randi Møller and Marianne Bentsen) have frequently gone out of their way to assist me. I am deeply grateful to The Instrument Center for Danish Astrophysics (IDA) and NBI for funding dozens of observational trips, workshops and conference meetings I have participated in. In this respect, Jens Viggo Clausen is thanked for his patience and flexibility.

I spent last February at Caltech, thanks to a generous invitation from Shri R. Kulkarni. This was a highly productive period, resulting in Paper II being written from scratch, mainly due to the assistance and availability of Derek B. Fox⁴. My local guide while staying in Pasadena was S. Bradley Cenko; thanks for showing me what a typical American bowling alley looks like (no words can describe it). My Caltech office-mate was Kristin Kruse Madsen; I very much enjoyed her mumbling. I will also never forget the 5 hour trip with her significant other, Thomas R. Greve, to downtown L.A. to buy black-market tickets for a Lakers - Celtics NBA game. The L.A. transportation system really does suck.

Finally, I wish to thank my family and longtime friends, which I have only scarcely seen during the past five years. My parents have always been extremely supportive, acknowledging the importance of education. Last, but definitely not least, I must thank my girlfriend Linda. Not only has she tolerated my complete lack of time for her during the last month, but all in all she is an exceptionally encouraging, positive and thoughtful soul.

Páll Jakobsson
Copenhagen, May 2005

⁴Formerly known as Derek W. Fox, a cause of confusion in countless references. . .

Chapter 1

Introduction

A thorough treatment of all aspects of the science of gamma-ray bursts (GRBs) would be impractical and outside the scope of this thesis. This chapter is intended to provide the reader with a brief overview of the history and progress of GRB studies. It is loosely based on the excellent reviews by Piran (1999), Mészáros (2002) and Zhang & Mészáros (2004).

1.1 A Brief History of GRB Observations

GRBs are γ -ray flashes detected with space-based detectors in the range 0.1–100 MeV, with typical flux levels of 10^{-7} – 10^{-4} erg cm $^{-2}$ s $^{-1}$ and durations of 10^{-3} – 10^3 s. Their light curves range from smooth, fast-rise and quasi-exponential decay, through curves with several peaks, to variable curves with many peaks. The pulse distribution is complex, and the time histories of the emission as a function of energy can provide clues for the geometry of the emitting regions (e.g. Fenimore et al. 1999). This wide range of diversity has been summarized in the maxim “When you’ve seen one GRB, you’ve seen one GRB.” For the last four decades, scientists have been trying to solve the conundrum concerning the origin and cause of these GRBs. The first known GRB event was a fortuitous discovery in 1967 by nuclear test detection instruments flown on the American Vela satellites, although the discovery was not published until six years later (Klebesadel et al. 1973). Contrary to popular mythology, security considerations played no role in the delay before the findings were made public; the authors simply wanted to be sure that the flashes of light came from somewhere in space (Hjorth et al. 2004).

The study of the high-energy radiation can tell us much about the physical processes that produce the radiation, but they tell us little about what caused those processes to begin with, and they are notoriously hard to localize. However, it was soon recognized that the difference between the arrival times of a given burst at various GRB detectors yielded information about the location of the burst origin. This triangulation method has been used over the last thirty years to obtain rough GRB positions, taking advantage of detectors placed on Solar System satellite missions that form the Interplanetary Network (IPN). The main drawback of the IPN technique is that it takes a long time to produce a localization; data must be telemetered

from satellites and coordinated between different projects and countries. Even today, with fast and reliable Internet connections, IPN positions are often only available a few days after the initial event. Early efforts yielded catalogs that were published up to years after the GRB events (e.g. Atteia et al. 1987). Catalogs like these provided localizations for a few hundred GRBs over the decades since 1967, but only around forty error boxes with an area less than 100 arcmin^2 . Deep searches for counterparts at other wavelengths (commonly referred to as afterglows) such as radio (Schaefer et al. 1989), infrared (Schaefer et al. 1987), optical (Motch et al. 1985) and X-ray (Murakami et al. 1990) were unsuccessful (to name only a few of many efforts). The success of afterglow hunting, especially in the optical, was crucial in order to nail down the GRB distances via spectroscopy; ordinary atoms produce no spectral lines in γ -rays¹.

Due to the lack of key observational data, real progress in the GRB field only began in 1991 when the *Compton Gamma-Ray Observatory* (*CGRO*) was launched. On board was the Burst And Transient Source Experiment (BATSE), which eventually was able to localize GRBs with an accuracy of roughly one degree. Typically, one burst per day was detected by the BATSE instrument before it was safely de-orbited and re-entered the Earth's atmosphere in 2000. Analysis of the BATSE data showed that the bursts exhibited a bimodal distribution divided between short ($t < 2 \text{ s}$) and hard bursts, and longer ($t > 2 \text{ s}$) and softer bursts (Kouveliotou et al. 1993)². Here, the hardness of the burst is estimated by measuring the ratio of 100–300 keV counts to those in the 50–100 keV range. More importantly, with over 2700 GRBs accumulated over nine years of observations, the BATSE catalog showed a clear isotropic celestial distribution (Fig. 1.1); a result which had been previously hinted at (e.g. Strong et al. 1974; Fishman et al. 1978; Atteia et al. 1987).

The distribution of GRBs on the sky was shown to be isotropic long before the question of their distance was settled. In principle, such isotropy is consistent with many possible source populations, e.g. (i) the cloud of comets that fill the outer Solar System. This is a rather far-fetched idea, simply because no one ever invented a plausible explanation of how comets can make GRBs. (ii) The Solar neighborhood, the interstellar space at distances less than the thickness of the Galactic disk (of the order of 200 pc). Harwit & Salpeter (1973) suggested a model where a comet falls on a neutron star (NS) and that this impact would make a GRB. Although not going into details of how this model works, the real difficulty lay in deciding if it could really make a GRB with the observed properties. Obstacles arose, such as initial conditions and turbulence: would there be a suitable source of matter to accrete at the right rate and would a turbulent flow give the right variability to produce the observed behavior. (iii) A distribution of sources in the Galactic halo. It would have to be large enough to render the dipole moment, associated with our off-center

¹Here we will not dwell upon the statistical significance of controversial cyclotron spectral lines possibly observed in a few GRB spectra. See Katz (2002) for a detailed review.

²Thus far, mainly due to technical difficulties, it has only been possible to accurately localize bursts from the long-duration population which, in turn, allows multi-wavelength follow-up. Since only one short burst X-ray afterglow has been detected thus far (GRB 050509B), this thesis only concerns long GRBs (but see a short discussion in Sect. 1.2.6 and Chapter 5).

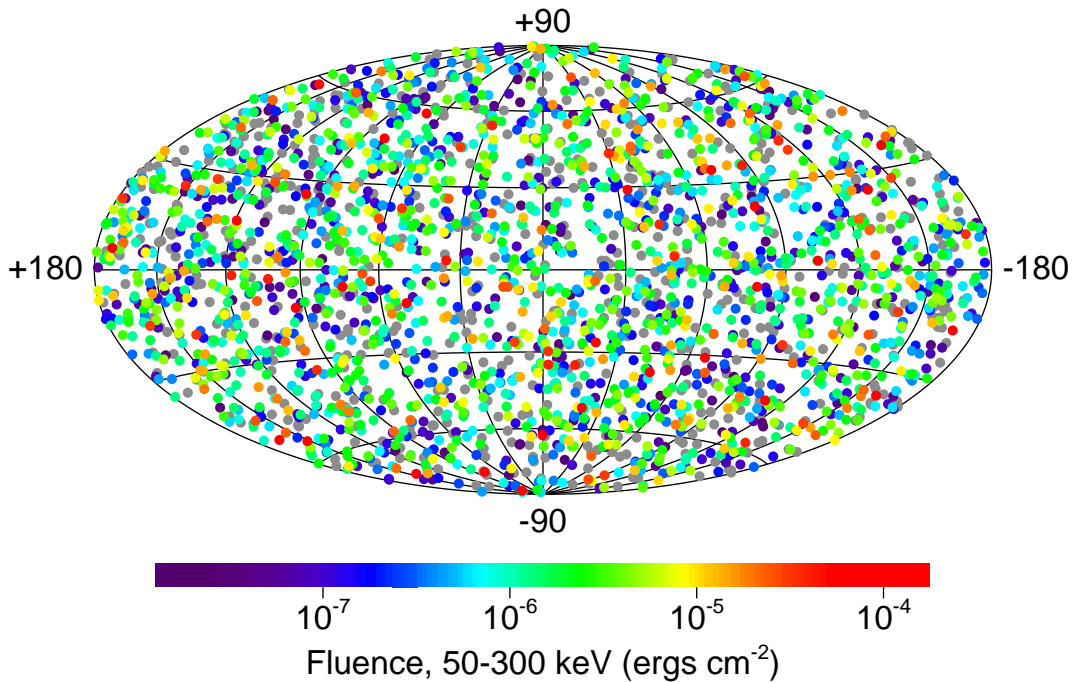


Figure 1.1: This map shows the locations of a total of 2704 GRBs recorded with BATSE on board the CGRO during its nine year mission. The projection is in galactic coordinates; the plane of the Milky Way Galaxy is along the horizontal line at the middle of the figure. The burst locations are color-coded based on the fluence, which is the energy flux of the burst integrated over the total duration of the event. Grey is used for bursts for which the fluence cannot be calculated due to incomplete data.

location, unnoticeable (i.e. greater than ~ 200 kpc). On the other hand, it could not be too large or we would have observed bursts from nearby galaxies (e.g. the Andromeda galaxy), which presumably are also surrounded by burst sources. This is not a crazy idea; it has been discovered in recent decades that most galaxies contain much more invisible mass (dark matter) than is present in visible stars. Ostriker et al. (1974) and Einasto et al. (1974) proposed that there are large amounts of dark matter around isolated galaxies and argued that the dark matter in spiral galaxies is located in giant halos, extending to several times the radius of the luminous matter and containing most of the total galaxy mass. Although the nature of the matter in the halos is unknown, they might contain the sources of GRBs (e.g. Lamb 1995). (iv) A cosmological distribution similar to that of the distant galaxies and clusters, i.e. hundreds of Mpc away. This possibility was first mentioned in print in a review by Ruderman (1975), and the first explicit advocacy of cosmological distances appears to have been in two papers by the Soviet astrophysicist Vladimir Usov and his colleagues (Usov & Chibisov 1975; Prilutski & Usov 1975).

To this day, after the detection of several thousand bursts, and despite efforts to show the contrary (e.g. Quashnock & Lamb 1993), no deviation from an isotropic distribution in the directions of GRBs on the sky has been convincingly demonstrated. Studies of GRB brightnesses alone can also yield equally important spatial informa-

tion. In particular, comparing the numbers of bright and faint GRBs, without any knowledge of where they are on the sky, permits us to compare their density near us to that in more distant space. The argument is based on simple geometry. Firstly, the volume (V) of a sphere (or any other three-dimensional object) is proportional to the cube of its radius (R). If the number density of GRBs is uniform in space, their total number follows $N \propto V \propto R^3$. Secondly, we have the inverse square law: if the radiation passes through space without absorption (which is a valid assumption for γ -rays) the brightness obeys $S \propto R^{-2}$. Combining these simple geometrical laws, we can estimate the number of identical objects³ that appear brighter than some minimum brightness: $N(>S) \propto S^{-3/2}$. This is commonly referred to as a Euclidean distribution and, among other things, indicates that increasing the sensitivity of an astronomical instrument tenfold is predicted to increase the number of objects detected by a factor of about thirty. Any quantity that follows the inverse square law dependence on distance may be used for S . For GRBs, S is usually the fluence, i.e. the cumulative radiation received throughout the burst.

Early results from balloon flights and spacecrafts (Fishman et al. 1978; Mazets et al. 1981) indicated that the predicted $-3/2$ power-law in the N vs. S relation was not observed. The expected faint GRBs were absent or observed much less often than predicted. This was later confirmed by BATSE, which demonstrated that the deficiency of faint bursts was unquestionable⁴ (Meegan et al. 1992). The deficiency of faint GRBs can be explained if they are cosmological: the most distant bursts should be the most affected by cosmological energy redshift and time dilation. In addition, there could be an intrinsic difference between the younger and more distant regions of the Universe and those near us; in the remote past the Universe might have produced fewer/more bursts per galaxy.

The BATSE results tilted the scales toward cosmological distances for GRBs. This was nearly a consensus position by 1995, but not all astronomers were convinced. Sources in the Galactic halo could not be completely ruled out and an interest in them was still at hand, particularly in the context of the then newly discovered high-velocity NSs (e.g. Lyne & Lorimer 1994). In an event reminiscent of the Great Debate of 1920 between Heber Curtis and Harlow Shapley (the distance scale of the Universe, e.g. Trimble 1995), Donald Lamb and Bohdan Paczyński debated “The Distance Scale to Gamma-Ray Bursts” in April 1995 (Fishman 1995; Lamb 1995; Paczyński 1995; Rees 1995). Debates do not tend to settle scientific disagreements and the Great Debate of 1995 was somewhat of an anticlimax. The protagonists restated their positions in a controversy that most astronomers had considered settle a couple of years earlier. In most of their minds it was only a question of time when a cosmological origin would be confirmed.

After firmly establishing the isotropy of the GRB distribution, the focus of the BATSE GRB observations changed to providing positional information for GRBs

³This result is simplest to derive, as is done here, if all sources radiate the same amount of radiation. It can be shown that the same result applies even if the sources produce different amount of radiation, or if their radiation is beamed in random directions.

⁴It should be noted that Tavani (1998) has shown that long/soft BATSE bursts do not deviate significantly from the Euclidean distribution.

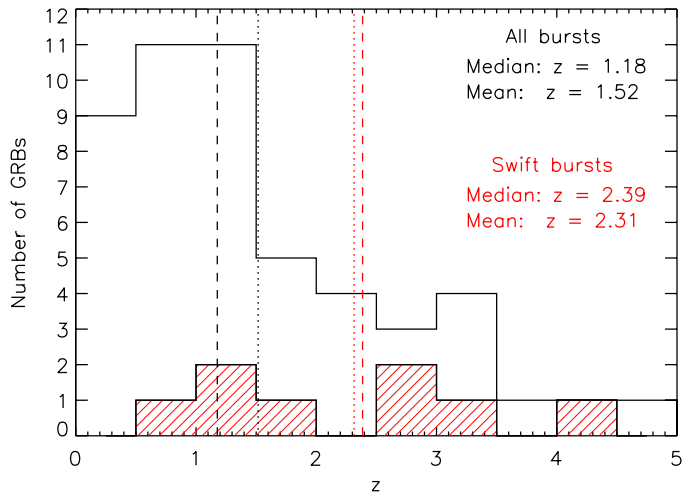


Figure 1.2: A histogram showing the distribution of GRB redshifts known to date (8 June 2005). The median value of the 50 redshifts is indicated by the black dashed line, while the mean value is shown with the black dotted line. The red striped bins show redshifts determined for Swift bursts. The median value of these 8 redshifts is indicated by the red dashed line, while the mean value is shown with the red dotted line. Taken and updated from Paper VII.

as quickly as possible over the newly formed GRB coordinate network (GCN). This service is intended to distribute GRB location information worldwide as quickly and efficiently as possible. Although BATSE alerted the scientific community of a GRB within seconds of the onset of the event, the radii of the error circles were tens of degrees in the first reports. Further processing after the events reduced the radii for the brightest bursts to a few degrees, but even such circles were far too large for most optical searches.

In 1997, the Italian-Dutch satellite *BeppoSAX* revolutionized our understanding of GRBs by localizing them quickly and precisely on the sky. On 28 February 1997, a GRB serendipitously fell within the field of view of the Wide-Field Camera on *BeppoSAX*. The X-ray flash associated with the GRB was localized to within a circle of $3'$ in radius. Eight hours later this circle was imaged with the higher sensitivity narrow-field instruments on *BeppoSAX*. A fading X-ray source was found and localized to within a circle of $50''$ in radius (Costa et al. 1997); the first direct observation of the afterglow of a GRB was realized. Both of these positions were widely disseminated among the astronomical community within a few hours, resulting in the first report of a contemporaneous detection of an optical counterpart of a GRB source (van Paradijs et al. 1997). The first radio afterglow was reported for GRB 970508 by Frail et al. (1997).

Further fast accurate positions, provided by *BeppoSAX*, *Rossi X-ray Timing Explorer (RXTE)*, *High Energy Transient Explorer 2 (HETE-2)*, *INTErnational Gamma-Ray Astrophysics Laboratory (INTEGRAL)* and the recently launched *Swift*, have led to many more identifications of GRB afterglows at longer wavelengths. This paved the way for the measurement of redshift distances; the wealth of data has en-

abled astronomers to firmly establish the cosmological origin of GRBs. The current number of reported GRB redshifts is 50 (Fig. 1.2), with the first redshift ($z = 0.835$) reported for GRB 970508 (Metzger et al. 1997). The mean redshift is around 1.5 with 19 GRBs at $z > 1.5$. These redshifts are determined either via absorption lines from the fading optical counterpart, or emission lines from the proposed host galaxy (see Sect. 1.3 for discussion on host properties). The aforementioned *Swift* satellite will not only (at least) double the redshift sample, but promises to provide approximately $5''$ radius error circles (from X-ray observations), resulting in the construction of an objectively selected and complete GRB afterglow sample.

1.2 The Fireball Model

A plethora of GRB observations is of course all good and well, but relatively useless without a proper model to account for the measurements. The early lack of observational breakthroughs for GRBs left ample freedom for modelers to play around. In fact, the models dedicated to interpret GRBs were so numerous, they may have outnumbered the total number of known GRBs at some point. Too many models are also problematic, but as long they can be disproven/strengthened with a ‘simple’ observation, it is a logical step forward in solving a problem. The fatal blow to the majority of the models was the confirmation that GRBs were at cosmological distances. In this section, the standard theoretical framework, namely the fireball shock model, will be briefly reviewed. Numerous alternative models still exist, e.g. cannonballs from supernovae (SNe) (Dado et al. 2002), precessing jets from pulsars (Blackman et al. 1996) and supermassive black hole formation (Fuller & Shi 1998), which will not be discussed in this thesis.

1.2.1 The Compactness Problem

At cosmological distances, the observed GRB fluxes imply energies of up to approximately 10^{54} erg if the emission is isotropic. Since subpulses from GRBs can last less than a millisecond (e.g. McBreen et al. 2001), the source region emitting this radiation cannot be larger than the distance light travels in this time. This corresponds to a size smaller than approximately 100 kilometers. It should not come as a surprise that a great deal of theoretical work on quasars has been applied to GRBs, since both are small, energetic and rapidly varying. The first instance of this was the compactness problem.

The radiation emitted by quasars is largely emitted by a process known as synchrotron radiation. When charged particles, especially electrons due to their small masses, move through a magnetic field their paths are bent, i.e. they are accelerated, and this bending produces radiation. Synchrotron radiation is weak if the electrons are moving slowly, but if they are moving at nearly the speed of light (c) it becomes significant, increasing as the square of the energy of the electrons. The radiated power is drawn from the energy of the electrons, which gradually slow down, as if emitting radiation were a form of friction. Quasars radiate huge amount of energy

from a small-sized region, i.e. their intensity must be very great. In fact, the calculated intensity is so high that another physical process takes over: inverse Compton scattering, where electrons collide with radiation. If an electron is very energetic, moving nearly at c , the collision transfers energy from the electron to the radiation. The more radiation is present, the more likely an electron is to collide with it, and the faster it loses energy.

In some quasars, the radiation intensity is so high that the electrons lose much more energy, and the radiation gains more energy, by inverse Compton scattering than in the synchrotron radiation. Hoyle et al. (1966) pointed out that a chain reaction would take place: the inverse Compton scattered radiation, with its multiplied energy, would gain more energy in a second round of scattering. Then a third round would extract even more energy and so on. This became known as the Compton catastrophe. It is so rapid that the electrons lose their energy before they can fill the volume from which the synchrotron radiation is observed. Basically, the model contradicts itself. It begins by asserting that electrons from a central engine fill a radiating region of a certain size (inferred from observed variability). But then it leads to the conclusion that the electrons lose their energy before they can do so.

Woltjer (1966) solved the problem when he found a flaw in the assumptions behind the Compton catastrophe. If the radiating electrons were rushing outward, away from the central engine in which they are energized, then their synchrotron radiation would also be beamed outward. If the electrons were streaming out nearly as fast as the radiation, with a Lorentz factor of $\Gamma \equiv (1 - (v/c)^2)^{-1/2} \sim 1000$, electrons and radiation would undergo inverse Compton scattering much less often than if they were moving randomly in all directions as had been assumed. There would be no head-on, or even broadside, collisions. Woltjer (1966) showed that this reduced the energy transferred by inverse Compton scattering by an enormous factor. The Compton catastrophe did not need to take place after all.

The compactness problem appeared again for GRBs. At cosmological distances they are up to million times brighter than quasars and, since they show variations on millisecond time-scales, are more than million times smaller than quasars. The compactness problem took a different and more general form for GRBs. There was no direct evidence that synchrotron radiation was the source of the emitted radiation of bursts, but Cavallo & Rees (1978) and Schmidt (1978) discovered a compactness paradox based only on the fact that GRBs emit γ -rays. According to Einstein's equation, $E = mc^2$, two colliding γ -rays may produce a mass m . The least massive known particles are electrons and positrons (e^\pm), each with a mass corresponding to 0.511 MeV of energy. Because electric charge is never created or destroyed, electrons and positrons can only be created in pairs. Two γ -rays, each with an energy of 0.511 MeV or more, colliding head-on, can therefore produce an e^\pm pair. If the collision is not head-on, then the necessary energy is greater. If the γ -rays have more energy than the minimum required, the extra appears as kinetic energy in the e^\pm pair.

At cosmological distances, the compactness parameter (proportional to the ratio of the luminosity to the radius) of GRBs would easily exceed one. By definition, this implies that the more energetic γ -rays collide with each other (since they are

so tightly packed into a small volume) and produce e^\pm pairs before they can escape. The GRB spectra would be expected to drop precipitously above 0.511 MeV. No such deficiency of the more energetic γ -rays could be found in the GRB data. A logical explanation (at that time) was that GRBs were comparatively close to us, certainly not at the other end of the Universe. However, there was a loophole in the compactness argument, just as for the quasars earlier. If the γ -rays were directed almost exactly outward, the minimum energy they must have to create an e^\pm pair would be much greater. The γ -ray energy at which the GRB spectra were expected to drop could be much higher, even outside the range of the current observations. In a nutshell, the head-on collision assumption in the compactness argument, was not accurate and could be entirely wrong.

In addition, there was an error in the argument used to set an upper bound on the GRB source size; the argument assumed that the source was at rest. If, however, the matter was moving outward at nearly c , then the actual size of the emitting region could be much larger. Such rapidly moving matter beams its radiation into a narrow cone in its direction of motion (see a more detailed discussion in Sect. 1.2.4 and Fig. 1.6). An observer sees only that tiny portion of the entire source that is moving almost exactly toward him. Any bound he sets on the size of the source only applies to this portion, and the complete source may be much larger. Hence, almost any luminosity was possible, as long as this (e^\pm, γ) fireball was moving fast enough. Put another way: the requirement that GRBs should be optically thin to high-energy photons yielded a lower limit on Γ of the expansion.

In independent, closely related and contemporaneous calculations, Paczyński (1986) and Goodman (1986) examined what would happen if an enormous amount of energy, far exceeding the compactness limit, was released in a small NS-sized region of space. A highly relativistic expanding (e^\pm, γ) fireball was predicted to form, converting its heat to the energy of outward motion. As it cooled, the energy of the average particle and the average γ -ray would decrease, until the γ -rays were no longer energetic enough to make new e^\pm pairs to replace those lost by annihilating into γ -rays. Eventually, far from the source, only γ -rays would be streaming nearly radially outward.

The simplicity of the original fireball picture, however, led to some severe difficulties. It was possible to calculate the appearance of such an event. It would have a Planck (blackbody) spectrum with a comparatively narrow spectral peak at a few MeV. The predicted γ -ray pulse would consist of a single short (millisecond) pulse. These theoretical predictions (the spectrum, duration and time dependence) disagreed with the observed properties of GRBs. In conclusion, at the risk of sounding too negative, the compactness argument, when examined in detail, showed that nobody knew how GRBs with the observed properties were actually made.

1.2.2 External & Internal Shocks

As is discussed in Sect. 1.2.5, long/soft bursts are thought to be created when a very massive star collapses. Thus, it is natural to assume that the properties of a fireball produced by the release of radiation energy (Paczyński 1986; Goodman

1986) does not reflect the properties of observed GRBs. The fireball is most likely “contaminated” by ordinary matter in the form of protons and electrons. Shemi & Piran (1990) were the first to make this theoretical step forward; effectively adding hydrogen to the fireball. Other elements, with heavier nuclei and more electrons, would have similar effects.

Even a small amount of hydrogen makes a big difference, because while e^\pm pairs completely annihilate into γ -rays, protons remain forever. The total number of electrons in the fireball includes both those created when γ -rays make e^\pm pairs and those that came along with the protons. After all the positrons have been annihilated, a few electrons will be left over, exactly as many as there are protons. The protons and the surviving electrons form the debris of the fireball. As previously discussed, a fireball without protons would entirely turn into freely escaping γ -rays. With protons present, the γ -rays are trapped within the cloud of leftover electrons: the electrons are accelerated forward via Compton scattering.

The fireball debris is a plasma consisting of charged particles. Soon the energy of the fireball is transferred to this debris, which accelerates to nearly c . How fast it travels depends on how much debris there is and how much energy. Typical estimates correspond to a Lorentz factor in the range $\Gamma \approx 100$ – 1000 (e.g. Krolik & Pier 1991; Lithwick & Sari 2001). Such a high Lorentz factor means that the rest mass energy (m_0c^2) is insignificant; nearly all the total energy (E) is kinetic energy (K):

$$K \equiv E - m_0c^2 = m_0c^2(\Gamma - 1) \Rightarrow \Gamma - 1 = \frac{K}{m_0c^2} . \quad (1.1)$$

Hence, if matter is added to a fireball, nearly all the energy of the fireball is converted to kinetic energy of the fireball debris. Almost none emerges as radiation. The kinetic energy of the debris is, in principle, available to make radiation, but cannot do so if the debris simply coasts through the vacuum of space.

The difficulty was now explaining how GRBs could radiate energies up to 10^{54} erg in pure γ -rays. The fact that just the γ -rays from GRBs were observed to be contain so much energy was the main problem for theorists. Rees & Mészáros (1992) and Mészáros & Rees (1993) presented the next step in the understanding of GRBs. The energetic protons and electrons accelerated by the pressure of the fireball will not travel freely forever. They will most likely run into the surrounding interstellar medium (ISM) of the host galaxy or a precursor wind from the GRB progenitor. In the latter case, a circumburst density of $n(R) \propto R^{-2}$ is expected. Even though the medium is very dilute, the fireball debris, moving almost at c , soon sweeps up enough mass to affect its motion.

This “sweeping up” is not a simple matter of elastic collisions. The fireball debris is a dense plasma and when it enters another plasma, such as the ISM, plasma waves are created. These waves involve a partial separation of the positively charged protons and the negatively charged electrons, and large electric fields pulling them back together. Large magnetic fields may also be present. It is not known in detail what happens when two plasmas collide at relativistic speed. The result is probably a plasma turbulence, i.e. when the fields are all tangled up and interfere with each other (e.g. Mitra 1996). Since plasma turbulence is all but incalculable, a shock is

generally assumed to be formed. This assumption is made since it is a great simplification; it permits replacing the original problem by relatively simple statements on each side of the shock. Basically, a shock is defined as an abrupt jump in the density, temperature, pressure, velocity and other physical properties (e.g. Mitra 1996; Gallant & Achterberg 1999). In order to produce a GRB the following is believed to take place.

The fireball debris and the ISM collide at nearly c . The immense kinetic energy of the protons in the debris is converted to random motion. Initially, nearly all this energy resides in the protons, simply because $m_p/m_e \approx 2000$. Next, the energy of the protons is shared with the electrons. Since the electrons are so light and their kinetic energy will be similar to that of the protons, Eq. (1.1) shows that the Γ_e may exceed Γ_p by a factor of m_p/m_e . Therefore, Γ_e might approach a million. Finally, some of the energy is expected to be converted to magnetic fields. Accepting these assumptions, consisting of straightforward steps building on the results of Shemi & Piran (1990), synchrotron radiation theory predicts an emission in soft γ -rays with roughly the energy required to make a GRB.

What about the complex and diverse time dependence of GRBs? Rees & Mészáros (1992) pointed out that if the expanding shell of fireball debris strikes a clumpy ISM, γ -rays would emerge at high-density sites while little radiation would be produced in-between. This appeared to solve the problem of how a single brief fireball could produce a long GRB containing dozens of subpulses. The diversity of burst time histories was roughly consistent with the anticipated ISM structure: in some places homogeneous, in others clumpy, with a very wide range of density. However, it was difficult to explain the spiky multi-peaked GRBs unless the ISM clouds were very small and widely separated, so that the individual subpulses were brief and separated by long intervals in which little energy was released. The clouds would have to be so sparse that most of the debris would never strike a cloud at all; a highly inefficient process possibly rendering bursts too faint to be observed at cosmological distances (Sari & Piran 1997).

Another scenario was soon suggested to produce the time dependence of the multi-peaked GRBs. If the central engine produced a time-varying outflow, successive shells could be ejected with different Γ and multiple shocks form as faster shells overtake slower ones (e.g. Rees & Mészáros 1994). Numerical simulations (Kobayashi et al. 1997) have shown that these internal shocks can produce the highly variable temporal structure observed in most bursts and the observed light curve peaks are in almost one-to-one correlation with the activity of the emitting source. A distinction is made between these different kind of shock models. External shocks result when a relativistic debris shell strikes interstellar matter. Internal shocks arise from the flow interacting with itself; separate relativistic debris shells, produced by the central engine of fluctuating power, strike each other. The internal/external shock scenario predicts that there should be no direct correlation between the γ -ray fluxes (from internal shocks) and the afterglow fluxes (from external shocks; see Sect. 1.2.3). Extrapolation from X-ray afterglow fluxes generally do not fit the γ -ray fluxes, in nice agreement with the predictions.

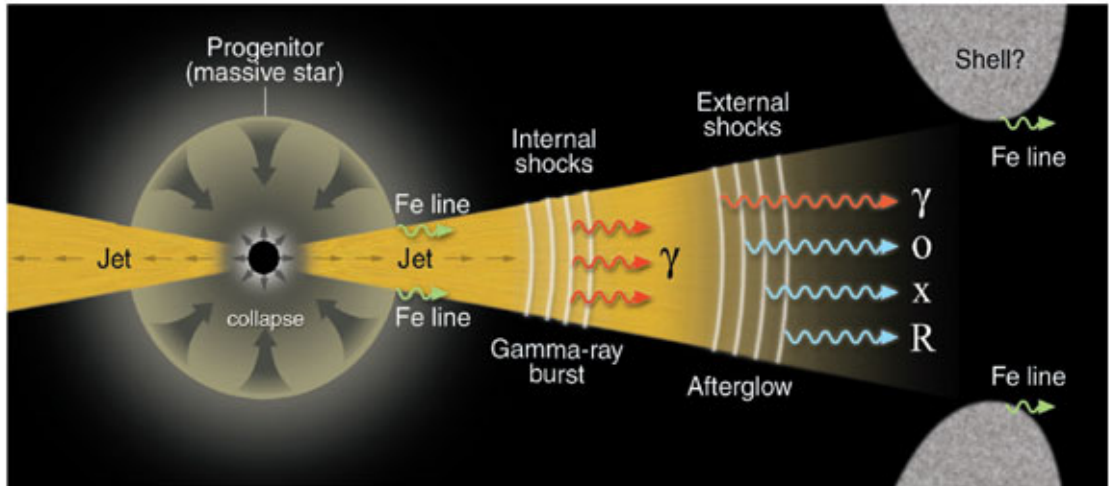


Figure 1.3: A schematic GRB from a massive stellar progenitor, resulting in a ultra-relativistic jet that undergoes internal shocks, producing a burst of γ -rays, and (as it decelerates through interaction with the external medium) an external shock afterglow, which leads successively to γ -rays, X-rays and optical and radio emission. Iron lines (or lines from lighter metals) may also arise from X-ray illumination of a pre-ejected shell, e.g. a supernova remnant (Vietri & Stella 1999), or from continued X-ray irradiation of the outer stellar envelope (Rees & Mészáros 2000). Taken from Mészáros (2001).

1.2.3 The Afterglow

The common consensus is that the GRBs originate from the internal shocks, but their afterglows in external shocks (Fig. 1.3). Internal shocks can dissipate only a fraction of the kinetic energy, therefore they must be accompanied by external shocks that follow and dissipate the remaining energy. The theory did make definite predictions about the spectral energy distribution (SED) of the external shocks. The electrons have different Lorentz factors. Assuming they are distributed as a power-law, $N(\Gamma) \propto \Gamma^{-p}$ (where p is the electron energy index, e.g. Rybicki & Lightman 1979), the resulting emitted spectrum is also a power-law (Sari et al. 1998): $F \propto t^{-\alpha} \nu^{-\beta}$, where α is the decay index and β is the spectral index⁵.

The aforementioned predictions were different for GRBs than for other astronomical sources of synchrotron radiation. This was due to their relativistic motions and relativistic shocks. The main differences between the predicted GRB SEDs and those originating from other synchrotron sources, were the values of α and β . As an example, cosmic rays are believed to be accelerated within non-relativistic shocks in SN remnants, often referred to as a Fermi acceleration (e.g. Fermi 1949; Blandford & Eichler 1987; Gaisser 1991). Here, only a tiny fraction of the charged particles are accelerated. In contrast, a fireball debris moving at nearly c and interacting with interstellar gas, will result in nearly all of its particles acquiring $\Gamma \gg 1$. These differences between non-relativistic and relativistic shocks affect the synchrotron

⁵Unfortunately α and β are sometimes defined including the minus sign, causing a slight confusion (Papers I and V use these different definitions). Even worse, in some papers the spectral index is denoted with α , usually earmarked for the GRB afterglow decay index.

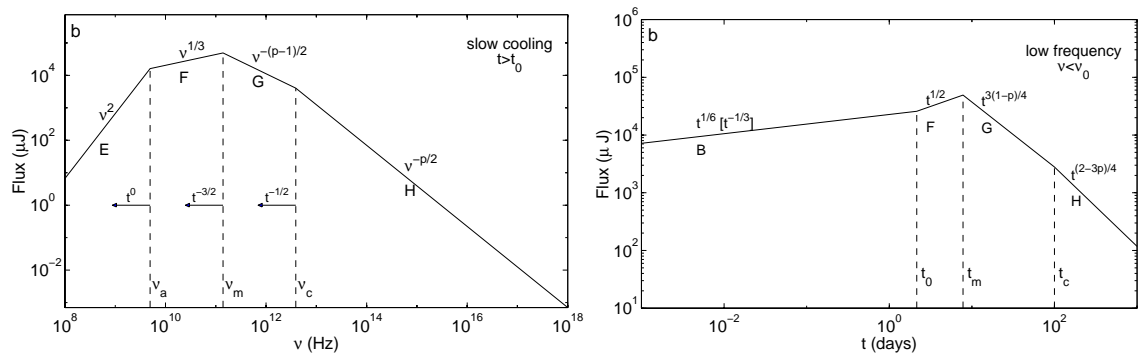


Figure 1.4: **Left:** a synchrotron spectrum of a relativistic shock with a power-law electron distribution. The panel shows the slow cooling case, which is expected at late times. **Right:** the corresponding synchrotron light curve (ignoring self-absorption). Both panels assume a constant-density (rather than stellar wind-like) external environment, and are taken from Sari et al. (1998).

radiation of the electrons they accelerate.

As the fireball ploughs ahead, it sweeps up an increasing amount of external medium resulting in a decrease in Γ . Depending on the nature of the ambient medium, Γ will decrease as a power of the time, asymptotically as $t^{-3/8}$ (ISM) or $t^{-1/4}$ (wind) in the adiabatic limit (Sari et al. 1998; Chevalier & Li 2000). As a consequence, the spectrum softens in time as the synchrotron peak frequency (ν_m) decreases. Thus, the GRB radiation, which started out concentrated in the γ -ray range during the burst, is expected to progressively evolve into an afterglow radiation that peaks in the X-rays, then UV, optical, infrared and radio (e.g. Mészáros & Rees 1997a).

A typical snapshot spectrum of the standard model at a given time is displayed in the left panel of Fig. 1.4. In general, many different possible broadband synchrotron spectra are possible. Which one is valid at any given time depends on miscellaneous factors, such as if “typical” electrons cool on a hydrodynamic timescale or not (fast cooling vs. slow cooling). The SED also depends on if the system is adiabatic or radiative; the adiabatic approximation is valid for most of the duration of the afterglow. Finally, the ambient medium (ISM or wind) shapes the resulting SED.

The SED in Fig. 1.4 consists of four power-law segments with three breaks. At low frequencies there is a steeply rising synchrotron self-absorbed spectrum ($\beta = 2$) up to a self-absorption break (ν_a), followed by a shallower slope ($\beta = 1/3$) up to ν_m . Above this break, the spectrum slope changes signs ($\beta = -(p-1)/2$) and finally takes the value $\beta = -p/2$ above the cooling break (ν_c), where the electron cooling time becomes short compared to the expansion time. In addition, at a given observer frequency, after ν_m has decreased below it, the observed flux is predicted to decrease as a power-law in time (right panel of Fig. 1.4). A good overview of relevant $\alpha(p)$ and $\beta(p)$ relations is given in table 1 in Zhang & Mészáros (2004). Note that in reality, smoother spectra and light curves are expected near the break frequencies (Granot & Sari 2002). GRB afterglow observations have provided convincing support for this generic fireball shock model; see e.g. Fig. 1.5 and dozens of GRB afterglow

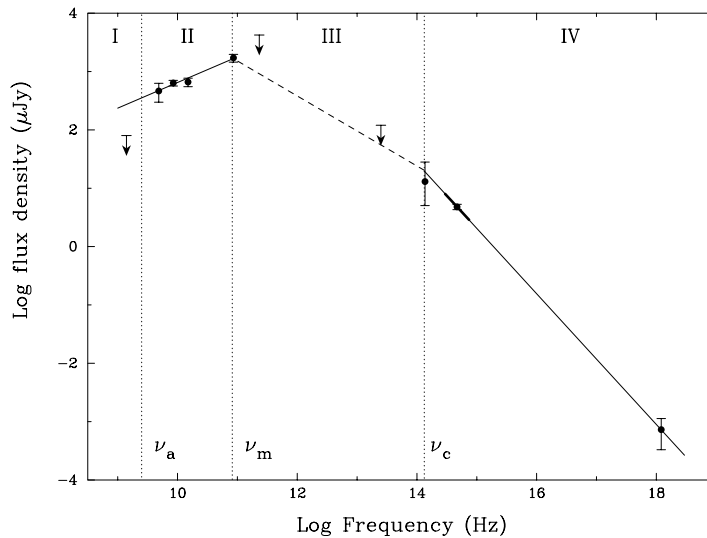


Figure 1.5: *The X-ray to radio spectrum of GRB 970508 on May 21.0 UT (12.1 days after the event). The fit to the low-frequency part is shown as well as the extrapolation from X-ray to optical (solid lines). The local optical slope (2.1–5.0 days after the event) is indicated by the thick solid line. Also displayed is the extrapolation $F \propto \nu^{-0.6}$ (dashed line). Indicated are the rough estimates of the break frequencies ν_a , ν_m and ν_c for May 21.0 UT. Taken from Galama et al. (1998c).*

light curves in the literature. However, strong evidence for departures from this simple standard model is provided by bumps and wiggles in afterglow light curves as discussed in Chapter 4 (and Papers V–VII). These deviations from a common smooth power-law decay may be explained by a variable external density, refreshed shocks from the central engine and/or a non-uniform jet structure.

Finally, a so-called reverse shock, moving into and heating the fireball ejecta, is expected to be produced in the external shock model (e.g. Mészáros & Rees 1997a; Wang et al. 2001; Nakar & Piran 2004). It is predicted that during the short phase in which the reverse shock exists, it should produce a powerful optical flash. This flash could coincide with the late part of the GRB. Kobayashi (2000) has calculated the light curves and typical frequencies of the reverse shock for a variety of conditions. The best observational evidence for this phenomenon comes from the optical/NIR light curves of GRB 021004 (Fox et al. 2003c), GRB 021211 (Fox et al. 2003b) and GRB 041219A (Blake et al. 2005).

1.2.4 Collimated Outflows & Beaming Effects

An issue raised by the GRB cosmological distance result, was that the measured γ -ray fluences implied a total photon energy of approximately $10^{52}–10^{54} \times (\Omega_\gamma/4\pi)$ erg, where Ω_γ is the solid angle into which the γ -rays are beamed. For a solar-mass object, this implies that an unusually large fraction of the energy is converted into γ -ray photon energy, assuming an isotropic energy release ($\Omega_\gamma = 4\pi$). A collimated outflow (jet; Rhoads 1999), where the relativistic matter is ejected into a cone of opening angle θ_{jet} , alleviates the energy requirements. Observational evidence for

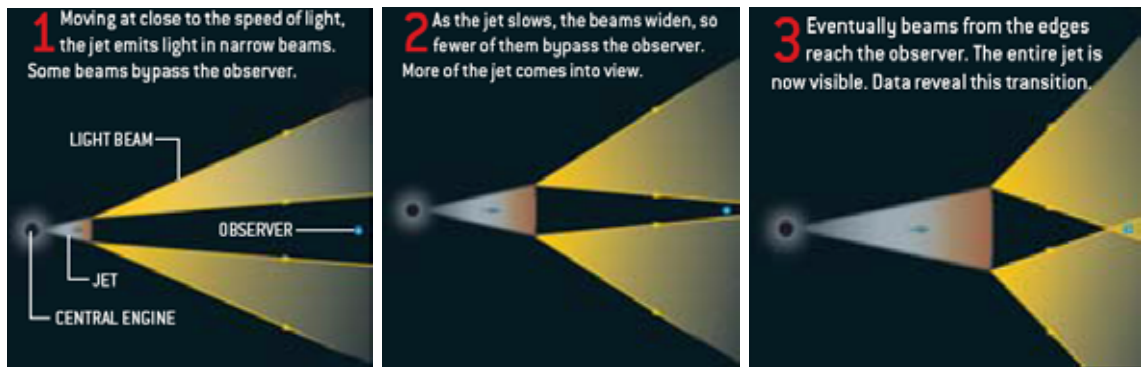


Figure 1.6: An illustration showing the effect of a collimated outflow (jet) and relativistic beaming. Taken from Gehrels et al. (2002).

this property are breaks in afterglow light curves (e.g. Kulkarni et al. 1999; Holland et al. 2000, Paper V, Paper VII), i.e. the rate of dimming increases suddenly. This is referred to as the jet break time, t_{jet} . Because of a relativistic effect, the observer sees more and more of the jet as it slows down. This is due to the radiation being beamed locally into a cone with an opening angle $1/\Gamma$. As the jet slows down, Γ decreases, resulting in an increase of this beaming angle. When $\Gamma \sim \theta_{\text{jet}}^{-1}$ there is no more to be seen, and the apparent brightness begins to fall off more rapidly.

Fig. 1.6 shows a schematic of this effect, with the line-of-sight of an observer parallel to the jet axis. The jet break appears sharper and occurs at a slightly earlier time for this observer, compared to an observer who does not fulfill this symmetric setup (but is still within θ_{jet} , e.g. Granot et al. 2001). For an observer located outside θ_{jet} , the GRB jet scenario predicts an afterglow not associated with prompt GRB emission, i.e. an orphan afterglow. The search for orphan afterglows is an observational challenge. Unlike afterglow searches that are triggered by a well-located GRB, there is no information on where to search for an orphan afterglow and confusion with other transients is relatively easy. Thus far, there have been no detections of any orphan afterglows at any wavelength.

For bursts displaying jet breaks in their light curves, the inferred θ_{jet} is typically a few degrees. This can be estimated by using equation (1) in Frail et al. (2001):

$$\theta_{\text{jet}} = 0.057 \left(\frac{t_{\text{jet}}}{1 \text{ day}} \right)^{3/8} \left(\frac{1+z}{2} \right)^{-3/8} \left(\frac{E_{\text{iso}}(\gamma)}{10^{53} \text{ erg}} \right)^{-1/8} \left(\frac{\eta_{\gamma}}{0.2} \right)^{1/8} \left(\frac{n}{0.1 \text{ cm}^{-3}} \right)^{1/8} \quad (1.2)$$

where $E_{\text{iso}}(\gamma)$ is the isotropic equivalent γ -ray energy and η_{γ} is the efficiency of the fireball in converting the energy in the ejecta into γ -rays. The jet reduces the overall energy emitted by the burst by a factor of several hundred (assuming a double-sided jet):

$$\frac{\Omega_{\gamma}}{4\pi} = 1 - \cos \theta_{\text{jet}} \approx \frac{\theta_{\text{jet}}^2}{2} \approx 3.8 \times 10^{-3} \quad (\theta_{\text{jet}} = 5^{\circ})$$

and increases the implied GRB rate by the same factor since only if the jet is aimed along our line-of-sight do we see the burst. Frail et al. (2001) suggested that the true rate is larger by a factor of 500 than the observed isotropic estimate rate. However,

Guetta et al. (2005) repeated this calculation, performing a careful average over the luminosity function, and found a true rate of only a factor of ~ 75 times the isotropic estimate.

There is another effect resulting in a light curve break at a similar time (when $\Gamma \sim \theta_{\text{jet}}^{-1}$): sideways propagation of the jet. Before that time, the matter in the jet is not affected by the non-spherical geometry and the blast wave behaves as if it were a part of a sphere. When $\Gamma \sim \theta_{\text{jet}}^{-1}$ the ejecta, now encountering more surrounding matter, decelerates faster than in the spherical case. If the lateral spreading of the jet is close to c , both transitions (the other one being the beaming transition in Fig. 1.6) would take place at the same time (Sari et al. 1999). If the sideways expansion is at the sound speed, the beaming transition would take place first and only later would the hydrodynamical transition occur (Panaitescu & Mészáros 1999). This would cause a slower and wider transition with two distinct breaks, first a steep break when the edge of the jet becomes visible and later a shallower break when the sideways expansion becomes important. This is further discussed in Sect. 4.3.

The final stage of a GRB resembles a SN remnant, in which a sub-relativistic debris shell sweeps up interstellar matter. This is often called the Newtonian transition (e.g. Frail et al. 2000). Since the velocities are at most mildly relativistic, there are no beaming effects and the afterglow will be observed from all viewing angles. A concluding remark is that neither a “fireball” nor a “jet” is the most appropriate jargon to be used. The width of the jet (in the direction parallel to the motion) is orders of magnitude smaller than the radius where the jet is located. The phrase “flying pancake” is a better description of the jet, although not as suitable for varied uses.

1.2.5 The Central Engine & Progenitors

The fireball model tells us how GRBs operate. However, it is largely independent of the details of the central engine, i.e. it does not provide an answer to the question: What produces the GRBs? Which astrophysical process generates the energetic ultrarelativistic flow needed for the fireball model? Fortunately, observational clues exist which can help us navigate to a likely answer.

The total energy involved is quite large, $\sim 10^{51}$ erg, a significant fraction of the binding energy of a stellar compact object. The central engine must be able to generate this energy and accelerate $\sim 10^{-5} M_{\odot}$ to ultra-relativistic velocities (e.g. Piran 2005). The central engine must also be able to collimate the relativistic flow. The GRB rates must be reproducible. Although uncertain, GRBs are expected to take place once per $\sim 10^5$ years per galaxy (e.g. Piran 2005). Hence, they are very rare, about 1/3000 the rate of SNe. Finally, the overall duration of GRBs and their variability timescales have to be taken into consideration. The former (typically of the order of tens of seconds for long/soft bursts) hints at a prolonged activity. The latter (as short as a millisecond) suggests a compact object.

These clues, especially the last one, indicate that GRBs arise due to accretion of a massive ($\sim 0.1 M_{\odot}$) disk onto a compact object, most likely a newborn black hole (BH). A compact object is required due to the short variability timescales. Accre-

tion is needed to produce the two different timescales, in particular the prolonged activity. A massive disk is required because of the energetics, and can form only simultaneously with the formation of a compact object. All this leads to the conclusion that GRBs accompany the formation of BHs. The temporary debris torus can provide a sudden release of gravitational energy sufficient to power a burst. Another large reservoir of energy is the rotational energy of the BH (Blandford & Znajek 1977). Exactly how these two energy reservoirs are converted into γ -rays is not fully understood. It is possible that a magnetic field builds up during the formation of the disk. In doing so, it heats the disk to such high temperatures that it unleashes a (e^\pm, γ) fireball which is funneled into a pair of narrow jets that flow out along the rotational axis (Mészáros & Rees 2001; Zhang et al. 2003). Such jets are not unprecedented; similar beaming is observed in quasars and other objects powered by accretion onto a BH.

The nature of the progenitor that collapses to form the BH/accretion system is unclear. Currently, the most popular view is that GRBs occur in a small fraction of stars that experience a cataclysmic energy release event at the end of their evolution. One class of candidates involves the core collapse of a single massive star (Woosley 1993; Paczyński 1998; MacFadyen & Woosley 1999), often referred to as a collapsar (variations of this model exist where the star is merging with a companion, e.g. Fryer et al. 1999). The star is believed to have a mass of a few tens times M_\odot and cannot contain a significant hydrogen (and even helium) envelope; otherwise the jet would slow down too quickly in order to produce the observed emission. Such stars are thought to end their lives as Type Ibc SNe. Due to the high mass of the progenitor, the resulting SN is predicted to be very energetic and often referred to as a hypernova. Another class of candidates consists of NS binaries or NS/BH binaries (e.g. Eichler et al. 1989; Mészáros & Rees 1997b; Rosswog & Ramirez-Ruiz 2003), which lose orbital angular momentum by gravitational wave radiation and undergo a merger. Narayan et al. (2001) have shown that accretion theory suggests that collapsars produce long bursts but NS/NS or NS/BH mergers short bursts.

For the long GRBs, where deep optical searches have been performed, a host galaxy has been identified in almost all cases. Usually the GRB is slightly offset from the host galaxy center; from a sample of 20 GRBs, Bloom et al. (2002a) find a median physical offset of 1.3 kpc, providing a strong observational constraint against delayed merging remnants as the progenitors of long bursts. They also find a strong connection of GRB locations with the UV light of the hosts, suggesting an association between GRBs and star formation. Further evidence linking long GRBs to regions of active star formation, necessary for the presence of a young and massive progenitor star, has been slowly mounting over the years (e.g. Paczyński 1998; Fruchter et al. 1999; Fynbo et al. 2000; Hjorth et al. 2000). However, the crucial milestone was the discovery of the GRB/SN connection. The evidence was originally based on the probable association of one unusual GRB with a SN (GRB 980425/SN 1998bw: Galama et al. 1998b), but was later supported by the appearance of SN-like bumps in the optical light curves of several bursts (e.g. Bloom et al. 1999, 2002b; Garnavich et al. 2003; Fynbo et al. 2004). The decisive observations were obtained by Hjorth et al. (2003b) and Stanek et al. (2003), who spectroscopically confirmed

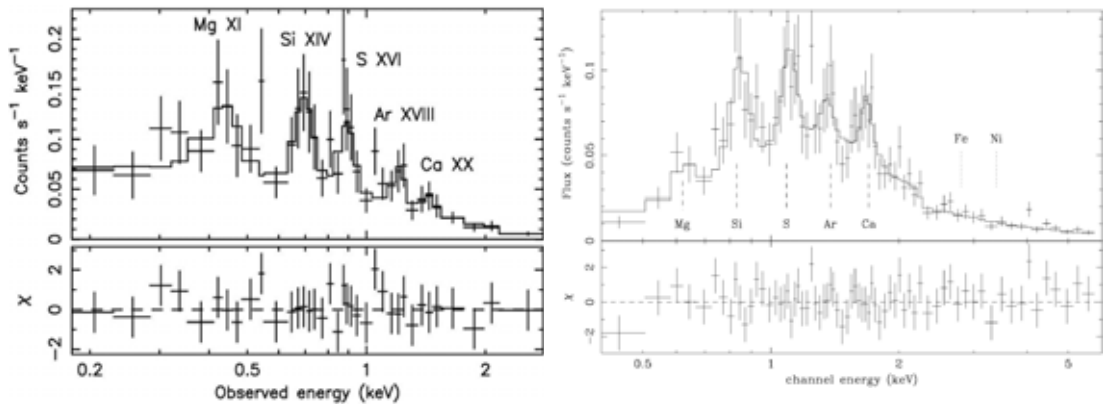


Figure 1.7: **Left:** The XMM-Newton spectrum of the GRB 011211 afterglow. The upper panel shows the observed count rate spectrum, whilst the lower panel plots the residuals of a thermal model compared with the data points. Taken from Reeves et al. (2002). **Right:** The XMM-Newton spectrum of the GRB 030227 afterglow. The data are fitted with an absorbed power-law and five Gaussian emission lines. Taken from Watson et al. (2003).

a very energetic SN (hypernova) temporally and spatially coincident with a burst (GRB 030329/SN 2003dh). Thus, current evidence suggests that core-collapse events can give rise to long GRBs, thereby favoring the collapsar model.

Another method to obtain information on GRB progenitors is X-ray spectroscopy, which can reveal the details of the environment of the burst explosion. Observations of some X-ray afterglows have indicated the presence of strong emission lines, often identified as Fe $K\alpha$ (Piro et al. 1998, 2000; Antonelli et al. 2000; Yoshida et al. 2001, but see Sako et al. (2005) who attribute the proposed lines to statistical fluctuations). Lines of freshly synthesized hydrogen- and/or helium-like elements (Si, S, Ar, Ca and Mg) have also been observed in the spectra of a few X-ray afterglows (Reeves et al. 2002; Watson et al. 2003; Butler et al. 2003, see the most convincing cases in Fig. 1.7), although the statistical significance and reality of these lines have been debated (Borozdin & Trudolyubov 2003; Rutledge & Sako 2003; Reeves et al. 2003). The line observations appear to support models where the burst explodes into an enriched and high-density medium, favoring a massive stellar progenitor for long GRBs. One possible source of the lines is in a shell of distant material ejected from a supernova (the supranova model, see below). Alternatively, the lines could be produced as a strong post-GRB source is reflected off the internal edges of a cavity evacuated in the star by the GRB jet (Rees & Mészáros 2000; Zhang et al. 2003; Watson et al. 2003). Both of these possibilities are indicated in Fig 1.3. But the jury is still out on the interpretation of these lines, e.g. it is not trivial to explain why neither Fe, Co nor Ni, elements that power SN light curves, are observed together with the lighter metals.

1.2.6 Summary & Open Issues

The formation of a GRB is hypothesized to begin either with the collapse of a massive star (a long/soft burst) or a with a NS/NS or NS/BH merger (a short/soft burst).

Both these events create a BH with a disk of material around it. This accreting system, in turn, pumps out a jet of material at close to the speed of light, commonly referred to as a fireball. The initial γ -ray emission is most likely the result of internal shocks within this expanding fireball. Those shocks are set up when faster blobs in the expanding material overtake slower blobs. The fireball continues to expand, and eventually it encounters and sweeps up surrounding gas. Another shock forms, this time at the boundary between the fireball and the external medium, and persists as the fireball slows down. This external shock accounts for the GRB afterglow emission and the gradual degradation of this emission from γ -rays to X-rays to visible light and, finally, to radio waves.

A few years ago, the majority of GRB papers contained the almost mandatory “GRBs are one of the most mysterious explosions in the Universe” sentence. The field has experienced a series of breakthrough years and astronomers no longer talk of bursts as utter mysteries. However, that does not mean the puzzle is completely solved and many open questions remain to be answered. A few of them are listed below.

X-ray flashes (XRFs) are transient sources distributed isotropically on the sky. They have a similar temporal structure as GRBs but lower typical energies. Heise et al. (2001) discovered XRFs based on data from *BeppoSAX* and introduced an operational definition for them: a fast transient source with duration less than 1000 s in the Wide Field Camera (covering 2–25 keV) that did not trigger the Gamma Ray Burst Monitor (covering 40–700 keV). This implies that these flashes do not have any hard component and most of their flux is in the X-ray region of the spectrum. Heise (2003) found that the observed XRF frequency is approximately half of the GRB frequency. Barraud et al. (2003) analyzed 35 bursts detected by *HETE-2* and found a continuity between XRFs and GRBs.

A natural explanation of XRF and GRB properties is that XRFs are GRBs at high- z . However, the detection of a few XRF afterglows and a host candidate at $z = 0.251$ for XRF 020903, makes this rather unlikely as discussed in Sect. 2.1. In addition, the lack of excessive time dilation compared to GRBs argues against this interpretation. The current view is that XRFs might be a geometrical effect, i.e. normal GRBs seen off-axis with the viewing angle larger than θ_{jet} (Woods & Loeb 1999; Yamazaki et al. 2002, 2003). This model predicts that XRFs will be too dim to observe at $z > 0.2$. XRFs can also be understood in terms of a picture in which GRB jets are structured (see next paragraph for a further discussion), with a mild variation of energy inside and a rapid decrease of energy outside of a characteristic angle (Zhang et al. 2004). Another possibility is that XRFs are dirty fireballs, i.e. relativistic jets with a larger baryon load and hence (assuming external shocks; see Sect. 1.2.2) lower Γ than those of normal GRBs (e.g. Dermer et al. 1999).

An alternative interpretation of the observed afterglow light curve breaks, is that we are viewing an universal angle-dependent structured jet from different viewing angles (Lipunov et al. 2001; Rossi et al. 2002; Zhang & Mészáros 2002). The observed break in this model does not correspond to θ_{jet} (as given in Eq. 1.2), but to the viewing angle. This interpretation means that θ_{jet} is quite large. Therefore, the GRB rate is smaller and the GRBs more energetic than what is implied by the usual

beaming factor. Unfortunately, the afterglow light curves predicted for a structured jet are hardly distinguishable from those of a homogeneous jet (see figure 2 in Rossi et al. 2002). On the other hand, the predicted polarization from a structured jet is drastically different from that of a uniform jet, providing an excellent comparison between the two models (Rossi et al. 2004).

A few other viable central engines (and progenitors) have been suggested to produce a GRB. An important alternative to accretion was suggested by Usov (1992, 1994), in which the relativistic flow is mostly Poynting flux, driven by the magnetic and rotational energies of a newborn, rapidly rotating and highly magnetized NS. Energy considerations require an extremely large magnetic field of the order of 10^{15} G within such sources. Mészáros & Rees (1997b) discuss a related idea with regards to the formation of a Poynting flux dominated flow within a BH/accretion model. The so-called supranova model (Vietri & Stella 1999) is a two-step event. First a SN explodes which may be more energetic than an average one. A supermassive NS is formed. A few weeks/months later this NS collapses, producing a GRB. This model makes several predictions which are different from that of the collapsar model. SN bumps on the afterglow light curves are not expected unless the time delay is a few days. The supranova model also naturally explains the Fe X-ray lines (if real): the SN shell was ejected several weeks/months before the GRB, providing time for the iron to be synthesized. Is there any solid observational evidence in favour of this model? Reeves et al. (2002) estimated a minimum time delay of about 4 days between GRB 011211 (the subject of Papers V–VI) and an associated SN. The association of GRB 030329 with SN 2003dh (Hjorth et al. 2003b; Stanek et al. 2003), on the other hand, is incompatible with the supranova model. Proponents of that model argue, however, that there might be a distribution of delay times between the first and second collapse.

An intriguing question is whether the long-duration bursts arise from a different population than the short-duration bursts. There is strong evidence supporting that long bursts originate in the collapsar scenario, whereas it is predicted that NS/NS and NS/BH mergers might give rise to short bursts. From evolutionary arguments alone, it is expected that the actual merger would take place far from the formation site of the binary system, where the surrounding environment has very low density. Thus, a very faint afterglow would be expected in this case. However, recent NS/NS merger models suggest much shorter lifetimes for the binary system, in which case the mergers would take place well within the parent galaxy (e.g. Dewi & Pols 2003). It has also been speculated that short bursts might be generated through a mechanism similar to long GRBs (e.g. Zhang et al. 2003; Yamazaki et al. 2004). Due to the lack of accurate localizations for short bursts we do not yet know if they are commonly accompanied by afterglows⁶. This remains one of the holy grails in GRB astronomy, hopefully attainable with the new *Swift* satellite.

⁶GRB 050509B is, thus far, the only short burst with a detected (X-ray) afterglow (Gehrels et al. 2005). See Chapter 5 for a further discussion.

1.3 GRB Host Galaxies

There are numerous good reasons to study GRB host galaxies. One of the most straightforward argument is to obtain the host redshift, in cases where the redshift was not measured while the optical afterglow (OA) was bright. Since the hosts can be quite faint (see below), spectroscopy may require long integration times on even the largest telescopes. The redshift is essential for, e.g. the calculation of the GRB energy budget, which lately is becoming crucial in attempts to use GRBs to constrain cosmological parameters (Sect. 4.3).

Another good reason to systematically search for and analyze GRB hosts, is that the selection mechanism, compared to other galaxy selection mechanisms, is not flux limited. For instance, Lyman-break selection (Shapley et al. 2003) is continuum flux limited and Ly α selection (e.g. Ouchi et al. 2003; Fynbo et al. 2003) is line flux limited. Hence, GRB-selected galaxies permit us to probe the faint end of the luminosity function (LF) currently inaccessible to other techniques. GRB hosts span a wide range of apparent magnitudes, from $R = 14.3$ (GRB 980425: Fynbo et al. 2000) to $R > 29.5$ (GRB 020124: Berger et al. 2002), with a median around $R \approx 25$ (Djorgovski et al. 2003b). A major contribution to this magnitude diversity is of course the redshift distribution (Fig. 1.2).

The evidence presented in Sect. 1.2.5, i.e. the GRB/SN connection and association with star-forming regions, indicates that hosts should on average display properties synonymous with star formation. What are the general characteristics of GRB hosts? They are predominately sub-luminous galaxies with very blue colors (Fruchter et al. 1999; Le Floch et al. 2003; Christensen et al. 2004a). Their morphologies are often compact and sometimes suggestive of a merging system (e.g. GRB 980613: Hjorth et al. 2002; Djorgovski et al. 2003a). Merging galaxies are excellent star-formation nurseries; the gas content of the colliding galaxies rapidly falls into the combined potential well, which sets off a burst of massive star formation. Fig. 1.8 shows a mosaic of 18 GRB host galaxies, imaged with the *Hubble Space Telescope* (*HST*). It clearly shows their morphological variety and demonstrates that they do not fit into one clear single morphological class.

Spectroscopic measurements also provide direct estimation of recent star formation in GRB hosts. This is based on luminosities of emission lines such as the [O II] $\lambda 3727$ doublet (e.g. Bloom et al. 2003a), the Ly α line (e.g. Kulkarni et al. 1998; Møller et al. 2002; Vreeswijk et al. 2004) and the Balmer lines (e.g. Christensen et al. 2004b). All of these estimators are susceptible to internal host extinction and geometry; the observed unobscured star-formation rates (SFRs) range from a few tenths of, to a few $M_{\odot} \text{ yr}^{-1}$. Applying reddening corrections, e.g. derived from the OA SED (and further assuming that they are representative of the mean extinction of the corresponding host), increases these numbers by a factor of a few in most cases. The resulting values are typical for a normal field galaxy population at comparable redshifts. However, GRB hosts are most likely similar to the field galaxies with the largest specific SFRs, i.e. the most efficient star-forming objects (Christensen et al. 2004a; Courty et al. 2004).

The interpretation of the observed SFRs is vastly complicated by the (often)

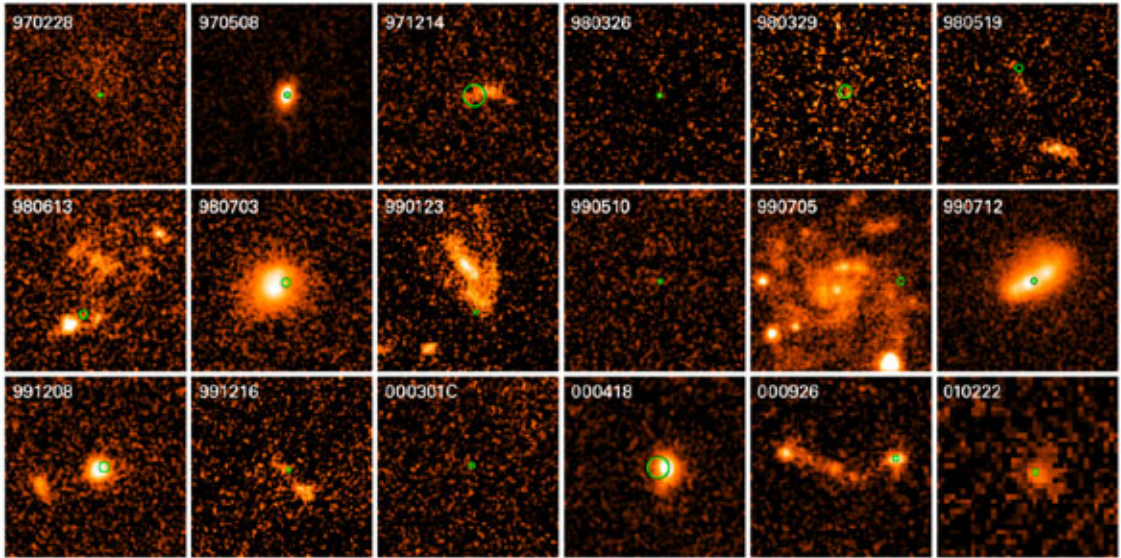


Figure 1.8: *HST* images of 18 GRB host galaxies for which an accurate projection of the early afterglow position is possible (shown with a green circle). The images are $2''.5$ on a side, except for GRB 000926, which is $3''.75 \times 3''.75$. This mosaic shows that GRB host galaxies display a wide range in magnitude and morphology. Taken from Fruchter et al. (2005, to be submitted).

unknown amount and geometry of extinction. In visible light, the observed quantities trace only the unobscured stellar component, or components seen through optically thin dust. Constituents hidden by optically thick dust cannot be estimated from these data; they require radio or submm observations. Submm observations are not without their own observational bias: a lack of sensitivity means that these measurements uncover only the most prodigiously star-forming galaxies, the so-called ultraluminous infrared galaxies (ULIRGs) with $\text{SFR} \gtrsim 500 M_{\odot} \text{ yr}^{-1}$. To date, submm emission powered by obscured star formation has been detected from 3 GRB hosts (GRBs 000418, 000210 and 010222) from a sample of roughly 20 (Barnard et al. 2003; Berger et al. 2003; Tanvir et al. 2004). This relatively small number statistics tentatively implies that 10%–20% of GRB hosts are objects of this ultra-luminous type. Another interesting result is that GRB hosts (including those detected in the submm) have significantly bluer $R - K$ colors as compared with galaxies selected in the submm and radio in the same redshift range (Fig. 1.9). This might indicate that the stellar populations in GRB hosts are on average younger, supporting the collapsar scenario for GRBs, but it is also possible that GRB hosts are on average less dusty. The fact that the submm-detected GRB hosts are bluer than typical submm-selected galaxies, suggests that GRB selection may be probing a previously unrecognized population of dusty star-forming galaxies.

Absorption line spectroscopy of GRB OAs is gradually becoming a powerful probe of the ISM in evolving galaxies, complementary to the traditional studies of QSO absorption line systems. The key point here is that GRBs, since they seem to be related to sites of ongoing or recent star formation, probe the sightlines to

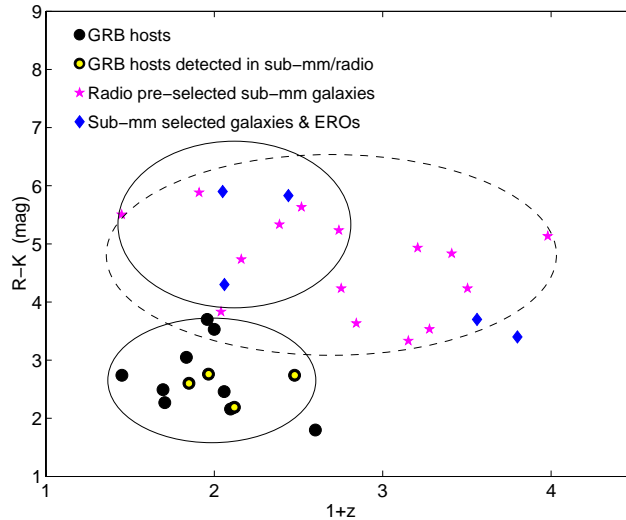


Figure 1.9: $R-K$ color as a function of redshift for GRB host galaxies and radio-preselected submm-selected galaxies. The solid ellipses are centered on the mean color and redshift for each population of galaxies in the redshift range $z < 1.6$, and have widths of 2σ . The dashed ellipse is the same for the submm population as a whole. Clearly, the GRB hosts are significantly bluer than the submm galaxies in the same redshift range, indicating a possible preference for younger star-formation episodes in GRB-selected galaxies. Taken from Berger et al. (2003).

dense and central regions of their host galaxies⁷. GRB absorption systems show exceptionally high column densities of gas when compared to the typical QSO absorption systems; only the highest column density systems, the so-called damped Ly α absorbers (DLAs), come close (Fig 1.10). This strongly suggests that GRBs explode in galaxies, or regions within galaxies, with high neutral hydrogen densities. The HI gas responsible, could be related to the site of the GRB explosion, e.g. part of the star-forming region in which the GRB occurred, but could also be gas that is not associated with the GRB, further away in the host galaxy. The column densities are in fact lower limits as the GRB itself occurs within the galaxy that is associated with the DLA system; if the GRB sightlines would have been probed with background QSOs, their column densities would have been on average a factor of two larger (Vreeswijk et al. 2004). Intriguingly, when an independent extinction measurement is available, the resulting gas/dust ratio is much higher than in the Milky Way (MW), but similar to that found in the Small Magellanic Cloud (SMC). The SMC has lower abundances of heavy elements and dust than the MW, resembling galaxies at high redshifts, which are presumably in the early stages of chemical enrichment. Taken at face value, these results (see table 3 in Hjorth et al. 2003a, and Paper VII) indicate that the GRB surroundings are low in dust, because of low metallicity and/or because of a low dust-to-metal ratio.

With regards to GRB host galaxies, one of the most interesting use of GRBs

⁷ Lower redshift, intervening absorbers are also frequently seen (e.g. Paper VII). Their properties appear to be no different from those of the QSO absorbers.

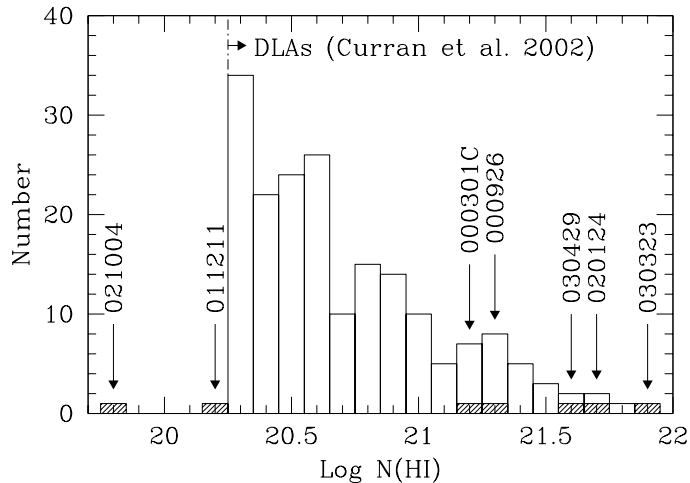


Figure 1.10: Histogram of the column densities of DLA systems measured through the damping wings of $\text{Ly}\alpha$ discovered in the spectrum of a background QSO. The shaded histogram shows measurements in GRBs for which the redshift was large enough to detect $\text{Ly}\alpha$. Out of 7 GRBs, 5 show neutral hydrogen column densities above the DLA definition of $2 \times 10^{20} \text{ cm}^{-2}$ ($\log N(\text{H I}) = 20.3$). In fact, a refined analysis (Vreeswijk et al. 2005) has shifted GRB 011211 to the right of the DLA definition. Taken from Vreeswijk et al. (2004).

is to probe the early phases of star and galaxy formation, and the resulting re-ionization of the Universe at $6 \lesssim z \lesssim 30$ (e.g. Loeb & Barkana 2001; Kogut et al. 2003). If GRBs reflect the deaths of massive stars, their very existence and statistics would provide a superb probe of the primordial massive star formation and even the initial mass function (ISM). Direct observations of galaxies and QSOs at $z > 6$ have proven difficult, not only due to the large luminosity distances, but to rapidly declining number densities of bright sources. GRBs offer an exciting alternative tool; the prompt and afterglow emission from GRBs in contrast, is bright enough to be detected by *Swift*, and followed from the ground, out to $z \approx 20$ (Gou et al. 2004).

Spectroscopy of GRB afterglows at such high redshifts would provide a crucial and unique information about the physical state and evolution of the primordial ISM during the era of re-ionization. In this context, GRBs are more useful than QSOs for several reasons. In the first place, GRBs might exist at high redshifts where no comparably luminous QSOs reside. Secondly, afterglow spectra are featureless power-laws, without complications caused by the broad $\text{Ly}\alpha$ line in QSOs. Finally, they would provide a genuine snapshot of the intervening ISM since GRBs do not have any long-term effect on their neighborhood; the continuous luminous output of QSOs, on the other hand, makes them a significant ionization sources in their own right (e.g. Lazzati et al. 2001; Barkana & Loeb 2004). In conclusion, the plausible existence of high- z GRBs carries a lot of potential, but is, as of yet, unfulfilled. A detection requires a rapid search for afterglows, as well as a high-resolution follow-up optical and NIR spectroscopy. However, the considerable scientific rewards will be well worth the effort.

Chapter 2

Dark Gamma-Ray Bursts

This chapter is based on Papers I and II, available in Appendices A.1 and A.2. Below, the major conclusions will be highlighted, and the content of the papers updated using recent *Swift* results. Finally, the properties of each individual burst classified as dark will be considered.

2.1 A Brief Introduction & Summary

Already within months of the first GRB afterglow detections, a few well-localized bursts lacked an OA despite deep and rapid searches; the prototype dark burst being GRB 970828 (Djorgovski et al. 2001). Various explanations have been put forward in order to explain non-detections of OAs.

In the obscuration scenario, the failed OA detection is ascribed to extinction, i.e. the optical light is extinguished by dust, either within the immediate environment of the burst or elsewhere along the line-of-sight. In the high-redshift scenario, as some fraction of bursts will be located beyond $z \gtrsim 5$, the UV light, which is strongly extinguished by absorption in the Ly α forest, is redshifted into the optical band. This scenario would naturally explain the properties of the XRFs. Here the peak of the γ -ray spectrum would be redshifted into the X-ray band. This reasoning, though, has been severely dented with the detection of six¹ XRF optical/NIR afterglows: XRF 020903 (Soderberg et al. 2004b), XRF 030723 (Fox et al. 2003a), XRF 040916 (Kosugi et al. 2004), XRF 050215B (Tanvir et al. 2005), XRF 050406 (Berger et al. 2005e) and XRF 050509C (Gorosabel et al. 2005). In addition, XRF 020903 has been associated with a probable host galaxy at $z = 0.251$ (Soderberg et al. 2004b), and Fynbo et al. (2004) have put a firm upper limit of $z \lesssim 2.3$ on the redshift of XRF 030723 from the afterglow spectrum. Finally, optical faintness can arise if the GRB afterglow is intrinsically dark as may happen, e.g. if a relativistic ejecta is decelerated in a low-density ambient medium.

The dark burst fraction has remained uncertain over the years, mainly due to a lack of a proper physical definition. Remarkably, however, GRBs have been con-

¹Another conceivable XRF with a detected OA is 031203; however it is yet to be concluded if this is the case (e.g. Watson et al. 2004; Sazonov et al. 2004; Watson et al. 2005).

sidered dark in many cases if no OA was detected, irrespective of how inefficient the search was. Despite this, current statistical samples have been used to make far-reaching conclusions. For instance, the dark burst fraction has been used as a potentially important tracer of the fraction of obscured star formation in the Universe (e.g. Ramirez-Ruiz et al. 2002). In Paper I we propose an operational definition of dark bursts as those bursts that are optically subluminal with respect to the fireball model, i.e., which have an optical-to-X-ray spectral index $\beta_{\text{OX}} < 0.5$.

The upper panel in Fig. 2.1 plots the optical flux versus the X-ray flux for all known GRBs for which an X-ray afterglow has been detected (see next section for details on recent *Swift* bursts not included in the original diagram in Paper I). Lines of constant β_{OX} are also shown, making the diagram a simple and quick diagnostic tool for identifying dark GRBs based on limited information. In the lower panel of Fig. 2.1 we plot an equivalent version of the diagram: the optical flux versus β_{OX} . The current sample consists of 72 GRBs, out of which we identify nine² certain dark bursts. This implies a dark burst fraction of approximately 13%.

Before jumping to conclusions with regards to the implications for the obscured star formation in the Universe, it is crucial to realize what the 13% fraction encompasses. There are at least four factors to consider. (i) Since approximately half of the sample includes optical upper limits, 13% is a lower limit on the dark burst fraction. Rephrasing the previous sentence: only 13% have optical limits deep enough to establish them as dark bursts. Similarly, the optical detections located above the line of constant $\beta_{\text{OX}} = 0.5$ in Fig. 2.1 sets an upper limit on the dark burst fraction of around 50%. (ii) To answer the question why a specific burst is dark, it must be modeled in detail; Fig. 2.1 is just a quick diagnostic tool. Lacking additional information makes it impossible to determine if a burst is affected by extinction, is at high- z , has $p < 2$ or has an excessive X-ray flux. (iii) As emphasized in Paper I, using this definition of dark bursts, there is no guarantee that all obscured or high- z bursts are caught. If, for instance, for a particular burst $p = 2.5$ and ν_c is located below the optical, it will have a high intrinsic β_{OX} value and there is no assurance that high redshift or optical obscuration will shift β_{OX} below 0.5. (iv) Finally, GRBs may be able to destroy dust in their immediate vicinity. If the rest of the optical path through their hosts is dust-free, the OA would not be significantly affected by dust extinction. Such a geometrical arrangement could position a GRB above the line of constant $\beta_{\text{OX}} = 0.5$ in a highly dust obscured host galaxy.

As mentioned above, around half the sample of the 72 GRBs contains optical upper limits, which in many cases are neither very deep nor the result of a rapid search effort. In that sense, the sample is far from being homogeneous and well-studied. With the *Swift* satellite now distributing rapid and accurate positions and follow-ups with the X-Ray Telescope (XRT) and UltraViolet/Optical Telescope (UVOT), a large homogeneous afterglow sample is finally being realized. Before *Swift*, the most uniform sample available was that provided by the Soft X-ray Camera (SXC) on *HETE-2*. In Paper II we have constructed a sample of all SXC bursts (i) which are localized to better than $2'$ radius (such that the error-circles fit inside the field-of-

²Assuming the *Swift* X-ray information provided in GCNs is accurate.

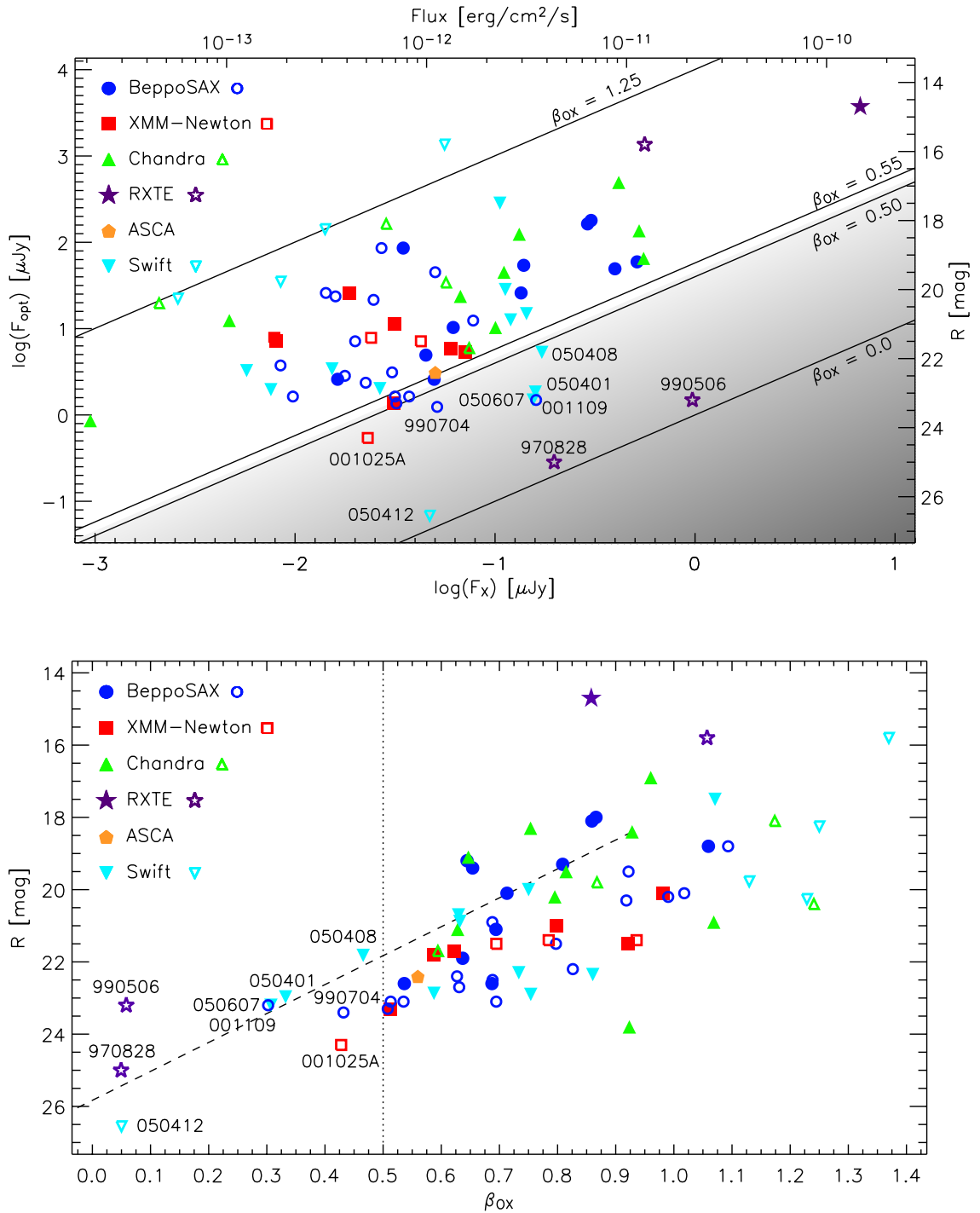


Figure 2.1: **Top:** the optical flux vs. the X-ray flux diagram taken from Paper I, but here reproduced in colour and including Swift bursts. It has also been updated to include other bursts recently reported (see main text for details). **Bottom:** an equivalent representation of the diagram above. Here we plot the optical flux vs. β_{OX} . The dashed line shows the effect of adding host extinction to GRB 021004.

view of large telescopes), (ii) whose small error-circles are made available within a few hours, and (iii) which have a rapid optical follow-up (within 3 hr). The sample contains 14 GRBs and only two of them lack an OA detection. One of these non-detections, GRB 020819, is also the subject of Paper II. There we show, using radio afterglow observations, that only a modest host extinction is required to suppress the optical flux below our *R*-band upper limits. In conclusion, the non-detections in the SXC sample, are fully consistent with the dark burst fraction derived in Paper I.

2.2 Recent *Swift* Results

Swift was launched on 20 November 2004, but during the first 4.5 month commissioning phase, the instrument teams were understandably busy conducting the initial in-flight calibrations and focused on shaking out the bugs in the system. However, during this phase *Swift* managed to detect over 20 GRBs. Unfortunately, until 5 April 2005, the data were not public. Thus, attempts to take advantage of the new dark burst definition relied on very limited information provided in GCNs from the *Swift* instrument teams. Thus far (8 June 2005), *Swift* has detected 30 long GRBs that have been localized with the XRT. Only 16 of those have sufficient X-ray and optical afterglow information to tentatively locate them on the dark burst diagram (Fig. 2.1)³. These bursts are GRB 041223 (Burrows et al. 2005a; Berger et al. 2005a), GRB 050124 (Berger et al. 2005a), GRB 050126 (Berger et al. 2005a), GRB 050128 (Monfardini et al. 2005; Antonelli et al. 2005), GRB 050215B (Mason et al. 2005; Goad et al. 2005), GRB 050306 (Klotz et al. 2005; Mangano et al. 2005b), GRB 050318 (McGowan et al. 2005; Markwardt et al. 2005), GRB 050401 (D'Avanzo et al. 2005; Berger et al. 2005c), GRB 050406 (Berger et al. 2005d; Capalbi et al. 2005), GRB 050408 (Milne et al. 2005; Chincarini et al. 2005), GRB 050412 (Kosugi et al. 2005; Mangano et al. 2005a), GRB 050416A (Berger et al. 2005c), GRB 050421 (Blustin et al. 2005; Godet et al. 2005), GRB 050520 (Allen et al. 2005; Perri et al. 2005), GRB 050603 (Berger & McWilliam 2005; Grupe et al. 2005) and GRB 050607 (E. Rol, private communication; D. Watson, private communication). In addition, we have added bursts to the diagram, using *XMM* observations of GRB 040827 (De Luca et al. 2005b) and GRB 050326 (Holland et al. 2005; De Luca et al. 2005a), *Chandra* observations of GRB 050509C (Fox 2005; Gorosabel et al. 2005) and *ASCA* observations of GRB 970815 (Mirabal et al. 2005; Soderberg et al. 2004a).

One of the major advantages of Fig. 2.1 is that, as long as the optical and X-ray flux is estimated at a similar epoch, a GRB can be quickly located in the diagram. A new feature has been added to Fig. 2.1, compared to the one published in Paper I: the upper abscissa now displays the X-ray flux (the X-ray flux density is plotted on the lower abscissa). Since GCNs frequently report the flux, not the flux density, this facilitates the usage of the diagram. We note that there is not a one-to-one correspondence between the flux and flux density, but we have calculated the 0.5–10 keV flux, corresponding to the energy range usually quoted by the XRT team GCNs.

³The diagram will be kept updated on <http://astro.ku.dk/~pallja/dark.html>.

The dark burst definition is based on the simple external (forward) shock fireball model, i.e. a synchrotron spectrum displayed in the left panel of Fig. 1.4. However, GRB afterglows can display a wealth of other interesting features, such as the signature of a reverse shock (GRB 021211: Fox et al. 2003b) or a prompt optical emission (GRB 990123: Akerlof et al. 1999). Recently, GRB 041219A showed signs of both of these effects (Blake et al. 2005; Vestrand et al. 2005). Although extremely intriguing by themselves, such features can “contaminate” the employment of the dark burst definition. For instance, if *Swift* slews quickly to a relatively long burst, the afterglow observations can be dominated by the prompt emission. This was the case for the X-ray flux of GRB 050117; hence it is not plotted in Fig. 2.1.

2.3 Individual Dark GRBs

Here we take a closer look at the properties of the nine dark GRBs. An attempt is made to determine the cause of their darkness, or at least rule out certain scenarios.

2.3.1 GRB 970828

The question whether a high redshift results in this burst being classified as dark, is easily answered by the results of Djorgovski et al. (2001). They measure a redshift of $z = 0.96$ for the proposed host; a typical value for a GRB (Fig. 1.2). Barnard et al. (2003) are unable to significantly detect the host in submm; hence it is not a ULIRG. However, the submm observations do not rule out significant host extinction. In fact, using the X-ray afterglow to predict the OA flux, Djorgovski et al. (2001) estimate that at least $A_R = 6.5$ mag (observer frame) is required to satisfy the optical upper limits. This extinction interpretation is supported by the morphology of the host; the position of a radio transient associated with the burst is consistent with a possible dust lane intersecting the host.

2.3.2 GRB 990506

The situation is similar for this burst as for GRB 970828: it is located at a moderate redshift of $z = 1.31$ (Bloom et al. 2003a) and its host remains undetected in the submm (Barnard et al. 2003). In addition, Taylor et al. (2000a) detect a rapidly fading radio afterglow; ν_m is estimated to have passed through the radio frequency considerably earlier than typically seen in other radio afterglows. Using a similar procedure as presented in Paper II, they use this fact to predict the optical flux at various epochs when OA searches were performed. They find there is no need to invoke dust extinction to account for the lack of an OA detection; the radio and optical observations are consistent within the fireball model. The relatively poorly sampled radio light curve and the corresponding radio decay index imply that $2.1 < p < 3.7$. Why is this burst classified as dark? The most likely reason is an excessive X-ray flux, but as the X-ray data have not been analyzed in detail we are unable to confirm this interpretation.

2.3.3 GRB 990704

Apart from optical upper limits and a radio afterglow non-detection reported in GCNs, the most significant facts regarding GRB 990704 are published in Feroci et al. (2001). They describe the burst as the most X-ray rich BeppoSAX GRB (at least until 2000). As this relates to the prompt emission, it does not shed much light on the burst darkness, whose origin remains ambiguous.

2.3.4 GRB 001025A

GRB 001025A did not take place in a ULIRG; the host is not submm luminous (Tanvir et al. 2004). Pedersen et al. (2005) propose that this burst appears optically dark because its (X-ray) afterglow is faint and ν_c is located close to the X-ray band. Although this might explain its optical faintness, it does not elucidate its membership in the new dark burst club. Watson et al. (2002) detected broadened soft X-ray emission lines in the burst afterglow, and found that a thermal plasma model fit the data significantly better than an absorbed power-law. Hence, similar to GRB 990506, β_{OX} might be shifted below 0.5 due to an excessive X-ray flux.

2.3.5 GRB 001109

A radio source was found within the BeppoSAX errorbox (Taylor et al. 2000b). It is coincident with a galaxy at $z = 0.40$ with a best-fit SED of $A_V = 1.4$ mag (Castro Cerón et al. 2004). However, Berger & Frail (2001) did not detect a decrease in the radio flux over a period of 390 days. It is thus unlikely that this galaxy is the GRB 001109 host. It remains uncertain why this burst is dark.

2.3.6 GRB 050401

It might seem paradoxical at first that this burst is classified as dark since it has an OA. However, the dark burst definition does not impose an optical non-detection constraint on GRBs classified as dark. For instance, if GRB 030329 (filled 5-pointed star in Fig. 2.1) had been subjected to five magnitudes of extinction, its OA would still have been quite bright but the burst identified as dark. This fact underlines the purpose of the new dark burst definition, i.e. to flag bursts that are guaranteed to be special⁴. Not much information is available on GRB 050401, but at least a high-redshift scenario can be ruled out ($z = 2.90$: Fynbo et al. 2005).

2.3.7 GRB 050408

As for the previous burst, it might seem paradoxical that this burst is classified as dark since it is one of the 12 SXC bursts in Paper II that have a detected OA. We refer to the previous subsection for clarification. Regarding GRB 050408, not much

⁴Although “dark bursts” are not necessarily optically dark using this definition, it seems wiser to stick to a jargon firmly rooted in the GRB community than to invent another slang.

information is available (but $z = 1.24$: Berger et al. 2005b) and its dark burst identity relies on preliminary X-ray analysis. Since $\beta_{\text{OX}} = 0.47$, a refined examination might easily shift the burst out of the dark burst category.

2.3.8 GRB 050412

This GRB is firmly classified as dark, with $\beta_{\text{OX}} < 0.05$. There is neither a redshift available nor any information about possible host dust extinction. However, Mangano et al. (2005a) report an X-ray spectral index of $\beta_{\text{X}} = 0.35$. Depending on the ν_{c} location, this implies $p = 0.7$ or $p = 1.7$. Thus, it is viable that its darkness is due to a low $p < 2$.

2.3.9 GRB 050607

This is the most recent GRB classified as dark, with $\beta_{\text{OX}} = 0.31$. It has the faintest optical afterglow ever detected at an equivalent time, or $R \approx 23.2$ @ 1 hr (corrected for Galactic extinction, see figure 5 in Berger et al. 2005c). As for GRB 050412, neither a redshift nor any information about possible host dust extinction is available.

Chapter 3

Ly α Emission from GRB Hosts

This chapter is predicated on Papers III and IV, available in Appendices A.3 and A.4. It starts with a brief introduction to the topic of star-forming galaxies and their relation to Ly α emission. The most substantial results of the papers are then emphasized.

3.1 Introduction

The so-called Lyman-break galaxies (LBGs) have often been used in synonymy with high- z starburst galaxies. LBGs are selected by performing deep imaging in three broadband filters (UGR) as illustrated in Fig. 3.1 (see also Steidel & Hamilton 1992, 1993; Steidel et al. 1995). Star-forming galaxies at $z > 2.5$ will be very faint or absent in the U -band. This is due to same effect that render GRBs dark in the high-redshift scenario (Sect. 2.1).

By definition, LBGs are starbursts that are extremely luminous in the UV. Hence, they do not give a complete census of all the star formation at high- z . The current magnitude limit in LBG ground-based surveys is $R_{AB} = 25.5$ (Steidel et al. 2003), but the LBG LF has been extended to $R_{AB} \approx 27$ based on data from the Hubble Deep Fields (Adelberger & Steidel 2000). The LBG LF faint end slope is very steep, $\alpha \approx -1.6$, indicating that more than 70% of the light is emitted by galaxies fainter than $R_{AB} = 25.5$.

How is it then possible to locate and study high- z starburst galaxies that are missed by the Lyman-break technique? There are at least four methods available. (i) The most vigorous starbursts at high- z are often obscured in the restframe UV, the so-called ULIRGs (e.g. Chapman et al. 2003, 2004). (ii) Absorption selection of galaxies. The few galaxy counterparts that thus far have been identified with DLAs, found in QSO spectra, appear to be star-forming galaxies (e.g. Møller et al. 2004; Weatherley et al. 2005). However, the majority of DLAs are not detected in emission and they seem to be significantly less luminous than LBGs (e.g. Fynbo et al. 1999). (iii) Selection of Ly α emitting galaxies via deep narrow-band imaging. Since Ly α emission is produced when hydrogen recombines, Ly α is a sign of the presence of hydrogen-ionizing sources in a gas-rich galaxy. These sources are mainly short-lived and massive O and B stars. In other words, Ly α emitting galaxies must

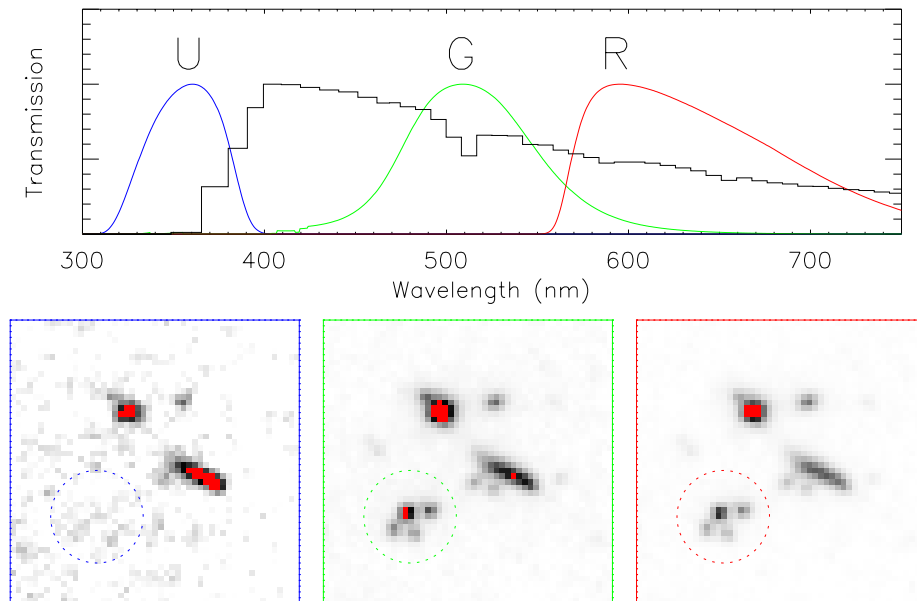


Figure 3.1: An illustration of the Lyman-break technique. The upper panel shows an LBG spectrum with the transmission curves of three broadband filters overplotted. The lower three panels show the corresponding broadband images (based on HST observations). The LBG is shown in the dashed circle: it is detected in the G- and R-band, but not in the U-band.

be in a state of active star formation unless powered by an AGN. These galaxies are sometimes referred to as Ly α emitting galaxy-building objects (LEGOs: Møller & Fynbo 2001). For ground-based telescopes, this technique only works for objects at $z \gtrsim 2$; the Ly α line has to be redshifted into the optical regime. LEGOs tend to be extremely faint; Fynbo et al. (2003) find that around 85% of a sample of 20 spectroscopically confirmed LEGOs are fainter than the LBG flux limit. (iv) GRB-selected galaxies. As discussed extensively in Sect. 1.3, GRBs are associated with star formation and often occur at high- z (Fig. 1.2).

3.2 Main Results

It is of course possible to combine galaxy selection methods, as we do in Papers III and IV. There we report the result of a search for Ly α emission from the hosts of four GRBs and other galaxies in their surrounding field. Apart from revealing the star-formation activity of the hosts, these observations provide information about their immediate environment. In fact, the latter property is relevant with regards to the often asked question: Do GRBs trace star formation? If GRB hosts are predominantly found in crowded groups/clusters of galaxies, they are prone to gravitationally- and/or merging-induced star formation. This research does not find an excessive number of LEGOs in the fields of three GRB hosts (broadband observations were lacking for the fourth host). Although some GRB hosts show signs of a disturbed morphology, many GRB host observations are not constraining enough to draw a concrete conclusion for the GRB host population as a whole.

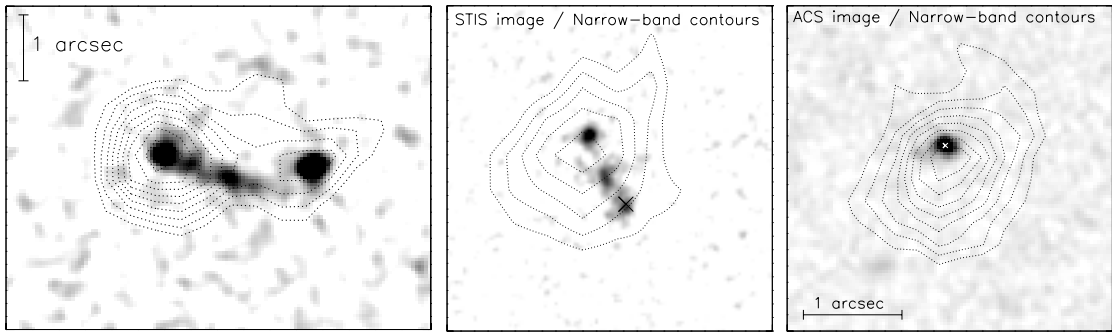


Figure 3.2: *HST* images centered on the host galaxies of GRB 000926 (left), GRB 011211 (middle) and GRB 021004 (right). The contours show the morphology of Ly α emission as measured from ground-based narrow-band imaging (Fynbo et al. 2002; Paper III; Paper IV). GRB 000926 occurred near the center of the right-most knot. The locations of GRB 011211 and GRB 021004 are marked with crosses. The field size is the same for GRB 011211 and GRB 021004.

The most remarkable result from our investigation is that all current evidence is consistent with the conjecture that GRB host galaxies, at least at high- z , are Ly α emitters. In Fig. 3.2 we plot the contours of the Ly α emission on top of *HST* images. This is done for the three hosts that have been detected in the Ly α narrow-band. What does this result imply? Ly α photons face a large probability of being absorbed by dust particles due to resonant scattering. Therefore, Ly α emitting galaxies are often considered to contain little or no dust and to have low metallicity (Charlot & Fall 1993; Heckman et al. 1998). However, a number of local metal-poor galaxies with active star formation show little signs of Ly α emission (e.g. Mas-Hesse et al. 2003; Hayes et al. 2005). This indicates that dust and metallicity are not the only factors affecting the escape of Ly α photons; kinematical and geometrical properties of the ISM may also play a major part (e.g. Neufeld 1991; Giavalisco et al. 1996). Assuming, however, the validity of the Charlot & Fall (1993) relation between metallicity and Ly α emission (see their figure 8), implies a preference for GRB progenitors to be metal poor. In the collapsar model, a strong stellar wind, which is the consequence of a high metallicity, makes it difficult to produce a GRB due to mass loss and loss of angular momentum. Therefore, a preference for GRB hosts to be metal poor is a clear prediction of the collapsar model.

As noted above, GRB hosts seem to be LEGO-like entities. But how do GRB hosts compare to LBGs? Thus far, the redshift has been measured for 16 GRBs at $z \gtrsim 2$, see table 4 in Paper IV (it does not include the recently discovered GRB 050603). As explained in that paper, we have fitted the $z = 3$ magnitudes to the Schechter (1976) LF, assuming GRBs trace the UV luminosity. The result is shown in Fig. 3.3. We find a characteristic magnitude of $24.6^{+0.6}_{-0.7}$ mag and a faint end slope of $\alpha = -1.55^{+0.24}_{-0.16}$. We compare this to the R -band LF, corresponding to the restframe UV LF, for LBGs at $z = 3$. The LBG LF has a characteristic magnitude of 24.54 ± 0.14 mag and a faint end slope of $\alpha = -1.57 \pm 0.14$ (Adelberger & Steidel 2000). Hence, there is consistency between the properties of the GRB host

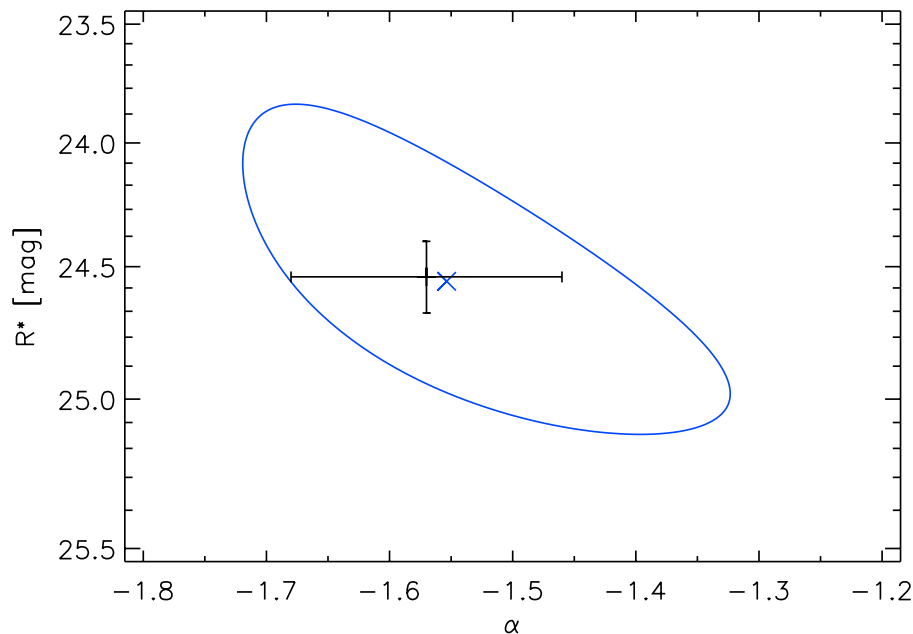


Figure 3.3: The 1σ confidence contour for the characteristic magnitude (R^*) and faint end slope (α) fitted under the assumption that GRBs trace star formation. The \times indicates the best fit. The point with errorbars marks the R^* and α range for LBGs. Taken and updated from Paper IV.

and LBG LFs, implying that GRBs are consistent with tracing the UV luminosity. This result seems to contradict the fact that only $\sim 33\%$ of the $R_{\text{AB}} < 25.5$ LBGs are Ly α emitters with a restframe equivalent width (EW) larger than 10 \AA (Shapley et al. 2003). It is also pointed out in Paper III that GRB hosts are inconsistent with being drawn randomly from the same Ly α EW distribution as the LBGs at the 99.8% level. However, if the fraction of Ly α emitters with $\text{EW} > 10 \text{ \AA}$ is higher than 33% at fainter magnitudes, this could be consistent with the high fraction of Ly α emitters among GRB hosts.

Taking at face value the evidence presented above, it is possible that faint LEGO-like galaxies account for the majority of the star formation at $z \gtrsim 3$. Nevertheless, this argument hinges upon whether the UV luminosity on average is proportional to the SFR. Locally, such a correlation has been established (Kennicutt 1998), but it is known that for some starburst galaxies, most of the UV emission is absorbed and re-radiated by dust (e.g. Chapman et al. 2003, 2004). However, Chary & Elbaz (2001) argue that the contribution to the total SFR density at $z = 3$ from dust-enshrouded ULIRGs is most likely less than 30%. Therefore it is a good first approximation to assume that the UV luminosity, for the bulk of the star-forming galaxies, is proportional to the SFR at $z = 3$. In conclusion, the available data do not exclude GRBs as star-formation tracers, but additional observations are clearly required to settle the issue.

Chapter 4

GRB Light Curve Bumps

Papers V-VII, located in Appendices A.5, A.6 and A.7, are the underpinning of this chapter. As usual it begins with a short introduction to the relevant subject, followed by a summary of the main results. Finally, afterglow light curve variations are discussed in the context of GRBs being used as tools in cosmology.

4.1 Introduction

As previously discussed, deviations from the assumed smooth power-law decay in GRB light curves, are not uncommon. For some bursts, a SN-like bump appears within 2–4 weeks from the onset of the burst (e.g. Bloom et al. 1999, 2002b; Garavich et al. 2003; Fynbo et al. 2004). There is also a possibility that emission from the reverse shock, or even the internal shock, contributes to the early light curve (Blake et al. 2005). These phenomena are not the subject of this chapter; rather the appearance of bumps (or “wiggles”) at intermediate times.

Such undulations, typically taking place a few hours or a few days after the burst, have been observed previously in GRB light curves: GRB 970508 (e.g. Galama et al. 1998a), GRB 000301C (e.g. Jensen et al. 2001; Gaudi et al. 2001), GRB 021004 (e.g. Lazzati et al. 2002; Fox et al. 2003c) and GRB 030329 (e.g. Lipkin et al. 2004). Explanations include (i) the relativistic jet impacting an external medium of variable density, (ii) a non-uniform jet structure, (iii) energy injections from the central engine, and (iv) a microlensing event. To distinguish between the above scenarios, simultaneous multi-wavelength observations can be of great assist (e.g. Nakar & Piran 2003; Nakar et al. 2003). For instance, scenario (i) has a very weak impact on flux emitted above ν_c . Hence, if ν_c is located in-between the optical and X-ray bands, contemporaneous observations at these frequencies might constrain the possible interpretations.

4.2 Main Results

We have discovered fluctuations in the afterglow light curves of GRB 011211 and GRB 030429. Lacking multi-wavelength afterglow observations of the latter burst,

we are unfortunately unable to distinguish between the possible scenarios listed above. Nonetheless, GRB 030429 was immensely valuable in many other respects and demonstrates what a powerful tool a GRB can be. It was used to probe sub-pc scales (progenitor environment), kpc scales (host galaxy properties) and Gpc scales (an intervening Mg II absorber). The proximity of the burst and Mg II absorber was even used to estimate the probability of a strong gravitational lensing. We refer to Paper VII for further scrutiny.

The GRB 011211 optical light curve displayed an unprecedented short-term, wave-like behaviour. Scenario (iii) is immediately ruled out as refreshed shocks can only increase the blast wave energy, and therefore cannot account for the rapid decay seen in the optical data. Irrespective of which scenario is valid, (i) or (ii), a firm conclusion based on the optical observations, is that the wiggles are the result of spherically asymmetric variations. This is because the observed timescale of the variations (around 1 hr) is much shorter than the overall elapsed time after the burst trigger (around 12 hr), when angular smoothing would have smeared out the light curve variations.

Additionally, there is evidence for fluctuations in the GRB 011211 X-ray light curve. If real, the oscillations are not in phase with the optical (time difference of at least 0.7 hr). Since ν_c is located in-between the optical and X-ray frequencies (Paper V), scenario (i) predicts a much stronger correlated optical fluctuation. This is not observed. Hence, scenario (ii) is a likely possibility: energy variations within the expanding jet, i.e. the energy content of the jet varies strongly as a function of angle (hot spots). As discussed in Paper VI, uncorrelated fluctuations at different energy bands can be produced by such hot spots. This is due to the fact that both the energy and Γ strongly affect ν_m ; Fig. 4.1 is intended to supplement this logic. Interestingly, Ioka et al. (2004) arrive at a similar conclusion regarding the bumps/dips in the GRB 011211 light curve: the jet must have a temporal anisotropy with a small angular structure.

4.3 GRBs as Tools in Cosmography

The usage of Type Ia SNe has revolutionized cosmology. These SNe are theorized to result from the thermonuclear explosion of a carbon-oxygen white dwarf which has accreted material until it reaches the Chandrasekhar limit. If true, the uniformity of mass and similarity of chemical composition for SN Ia progenitors could explain why these SNe are particularly good standard candles in optical light. With a relatively simple light curve correction (e.g. Phillips 1993; Riess et al. 1996; Perlmutter et al. 1997) they can be standardized to high enough precision to probe the matter/energy content of the Universe. In fact, this led to the discovery that dark energy dominates the presently accelerating Universe (Riess et al. 1998; Perlmutter et al. 1999).

As summarized in Sect. 1.2, GRBs are most likely more powerful explosions than SNe Ia, which allows studies at even higher redshifts. In contrast to SNe Ia where the rate is unknown at $z \gtrsim 1.5$ (Dahlen et al. 2004, suggest a decrease in Type Ia rate with redshift), GRBs are known to exist at high- z (e.g. Andersen et al. 2000,

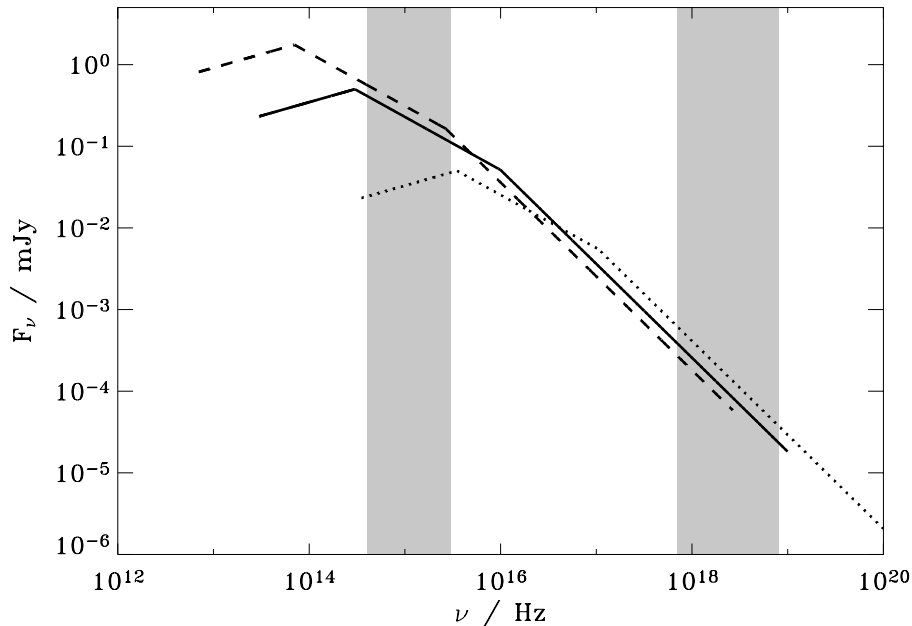


Figure 4.1: A model SED of a GRB afterglow (solid curve). The dashed curve shows a hot spot spectrum with a slightly smaller Γ and higher energy than the afterglow SED. The dotted curve shows a hot spot with a slightly higher Γ and similar energy with respect to the afterglow SED. The shaded regions correspond approximately to the optical and X-ray frequencies.

see also Fig 1.2). Moreover, γ -rays can penetrate dust that attenuates optical light; see Östman & Mörtzell (2005) for a discussion on the effect of extinction on SN Ia measurements. The potential of using GRBs as tools in cosmology is therefore quite considerable.

The prospect of using GRBs to estimate cosmological parameters, such as Ω_m and Ω_Λ , relies on GRBs being standard candles, or more precisely, being standardizable in a manner similar to the stretch-luminosity relation for Type Ia SNe. Evidence for GRBs as standard energy reservoir, when corrected for the effects of beaming, was first reported by Frail et al. (2001) and later updated by Bloom et al. (2003b). More recently, Ghirlanda et al. (2004a) discovered a tight correlation between the GRB restframe peak energy (E_{peak}) and the restframe beaming-corrected γ -ray energy release (E_γ), displayed in Fig 4.2. The origin of this correlation is not yet fully understood, but might be due to viewing angle effects (e.g. Levinson & Eichler 2005). The correlation gives rise to an empirical correction to the determined luminosity distance for each burst, analogous to the stretch-luminosity correction applied to Type Ia SNe. The result is a measurement of the luminosity distance, independent of a GRB redshift. Finally, if a redshift is available, a Hubble diagram can be created (including Type Ia SNe) and a cosmological model fitted to the data.

This proposed use of GRBs in cosmology has caused a heated debate in the GRB community (e.g. Ghirlanda et al. 2004b; Dai et al. 2004; Firmani et al. 2005; Xu 2005; Xu et al. 2005; Friedman & Bloom 2005; Mörtzell & Sollerman 2005), mainly due to the presently limited sample of well-studied GRBs. It is not the purpose of

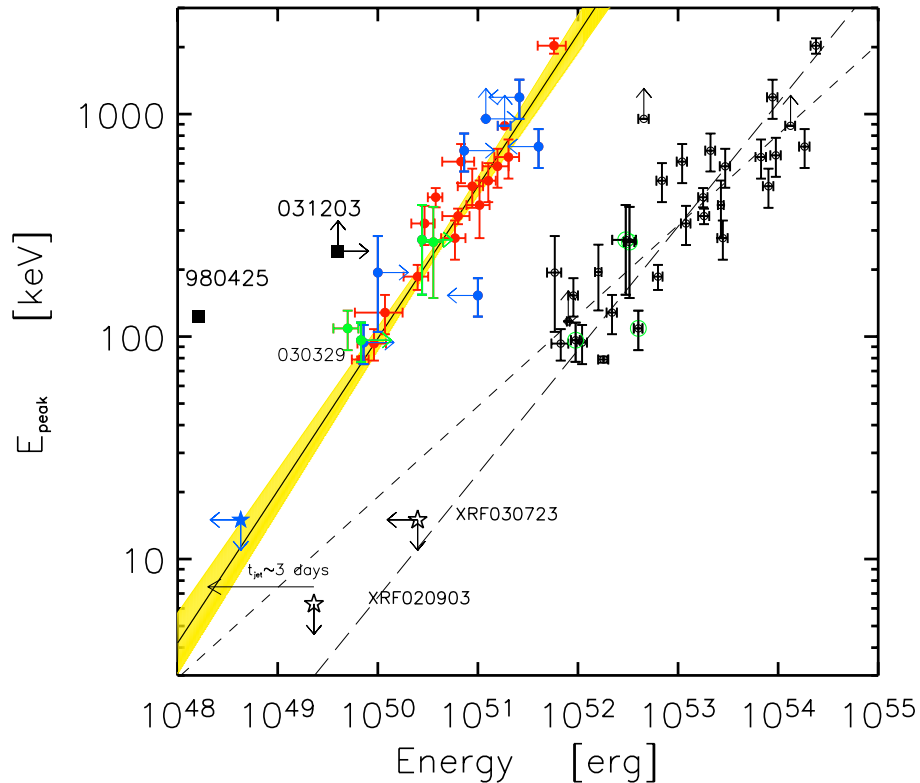


Figure 4.2: *Restframe peak energy versus γ -ray energy for the GRB sample with measured redshifts. The black open circles on the right represent the equivalent isotropic energy, with the dashed lines indicating the best fit to the points. The bursts are shifted to the left (filled circles) after correcting the energy using the jet opening angle (estimated from t_{jet}). The solid line is the best fit to these points. Red circles are the fifteen GRBs that have a measured t_{jet} , blue circles GRBs that have a lower/upper limit on E_{γ} , while the four green circles are the newest addition to the plot. Taken from Ghirlanda et al. (2005).*

this section to detail the pros and cons of each of the methods used in the references cited above. It is rather to urge caution when collecting data from the literature, e.g. if parameters and their quoted uncertainties are reliable. It is clear that the results of fitting a cosmological model to the GRB sample are crucially dependent on the choice of, in some cases poorly known, input parameters. The major concern arises from the beaming correction; as can be seen from Eq. (1.2) the jet opening angle estimation depends on (i) the efficiency, η_{γ} , of the fireball in converting the energy in the ejecta into γ -rays, (ii) the mean circumburst density n , and (iii) the jet break time t_{jet} . The former two parameters are indirect observables, not tightly constrained for most bursts. Numbers typically used are $\eta_{\gamma} \gtrsim 0.2$ (e.g. Beloborodov 2000) and $0.1 \lesssim n \lesssim 10 \text{ cm}^{-3}$ (e.g. Panaitescu & Kumar 2001).

In theory, the jet break time should be quite easily estimated by observing a break in a relatively densely sampled light curve. In practice, several factors make this procedure considerably more complicated. First of all, as has been demonstrated in Papers V–VII, light curves are not always smooth. Bumps and deviations from the theoretical synchrotron light curve can make it non-trivial to locate t_{jet} . The

GRB 011211 light curve wiggles did not, at least not in a significant way, affect the t_{jet} location. On the other hand, GRB 030429 serves as an excellent example of how a sparsely sampled light curve could lead to an error in the t_{jet} estimation. As can be seen in figure 3 and table 3 in Paper VII, without the observations obtained around 1.8 days after the burst, the break time would have been erroneously estimated at around 3 days instead of at approximately 1 day. Even for densely sampled light curves, carefulness is advised, as was shown in the case of GRB 021004. For this burst, repeated energy injections slowed the early light curve decay and delayed the appearance of the steepening until after the last injection. A broken power-law thus underestimates the pre-break decay slope and overestimates the jet break time (Björnsson et al. 2004). Finally, a SN bump, contemporaneous with the break time, can conceal the light curve break (GRB 030329: Lipkin et al. 2004).

Utilizing GRBs to correctly constrain cosmological parameters, not only rests on t_{jet} but also on its uncertainty. Is there a way to correctly estimate this uncertainty? It is a common practice to fit GRB afterglow light curves with broken power-laws, which is a good first approximation for a sharp jet ploughing through a uniform circumstellar environment. However, for a wind-like external medium the break is expected to be much smoother and extend over a longer period in time (e.g. Kumar & Panaitescu 2000). In addition, a sideways expansion of the jet is also expected to take place at approximately t_{jet} . As discussed in Sect. 1.2.4, this causes a change in its hydrodynamic behaviour and hence another break in the light curve. This could cause a slower and smoother transition. Various other parametrized functions have been used to fit light curves to account for this (e.g. Stanek et al. 1999; Rhoads & Fruchter 2001). Since a “correct” theoretical analytical function does not exist for observers to fit their light curves to, it is hard to estimate “correct” errorbars for t_{jet} . As an example, Ghirlanda et al. (2004a) have modified $t_{\text{jet}} = 1.56 \pm 0.02$ days, estimated for GRB 011211 in Paper V, to $t_{\text{jet}} = 1.50 \pm 0.15$ days. Although increasing the uncertainty to 10% is completely arbitrary, the new errorbar is not unreasonable as the original one was calculated assuming a broken power-law. Another option to estimate t_{jet} is via polarimetry; the polarization angle is predicted to change by 90° at that time (e.g. Ghisellini & Lazzati 1999).

Chapter 5

Outlook & Future Prospects

It would be inappropriate, in the concluding chapter, not to discuss the bright future of GRB astronomy provided by the *Swift* mission (Gehrels et al. 2004). This multi-wavelength GRB observatory is an autonomous rapid-slewing satellite that promises to observe more than 100 bursts yr^{-1} . It detects GRBs with the Burst Alert Telescope (BAT) and then proceeds to perform detailed X-ray and UV/optical afterglow observations spanning timescales from a minute to several days after a burst. A few open issues, that *Swift* might help elucidate, are listed below.

It is clear from Fig. 1.2 that *Swift* is, on average, finding more distant bursts. The redshift median of *Swift* bursts ($z = 2.39$) is more than one higher than the redshift median for all bursts ($z = 1.18$). The higher sensitivity and accurate positions of *Swift* seem to result in a better representation of the true GRB redshift distribution. This is also true for the brightness distribution, Berger et al. (2005c) find that the optical/NIR afterglows of *Swift* events are on average 1.7 mag fainter at 12 hr than those of previous missions, with the X-ray afterglows similarly fainter compared to those of pre-*Swift* bursts.

These important results might have implications for the true fraction of dark bursts. Paper I reported a dark burst fraction of 10%. In Chapter 2, recent *Swift* bursts were added to the sample, resulting in a slight increase of this fraction (13%). If we **only** include *Swift* bursts from the dark burst diagram (Fig. 2.1), the fraction increases further, to more than 20%. Note that not all the GRBs marked with the blue upside down triangles in Fig. 2.1 are *Swift* bursts; rather their X-ray flux is obtained from the XRT. Hence, there are at present three dark *Swift* bursts (GRB 050408 was detected by *HETE-2*). Why is the *Swift* dark burst fraction higher? As detailed in the previous paragraph, *Swift* seems to be probing higher redshifts. Therefore, more $z > 5$ bursts might emerge in the dark burst diagram. The number of *Swift* bursts with a reported X-ray flux is still relatively small, but these early results indicate that the dark burst fraction is higher than reported in Paper I.

The number of high- z bursts *Swift* appears to be detecting, will shed light on the early Universe, e.g. provide input to the ongoing discussion on the subject of “GRBs as tracers of star formation”. In particular, since March 2005, *Swift* has increased the number of $z \gtrsim 2$ bursts by almost 50% compared to the pre-*Swift* sample (Fig. 1.2).

A similar rate of high- z GRB detections will very quickly increase the sample in table 4 in Paper IV and decrease the 1σ confidence contour in Fig. 3.3. Hence, we will soon be able to confirm (or rule out) the apparent consistency between the properties of the GRB host and LBG LFs.

Around 25% of the BATSE bursts were short/hard (Kouveliotou et al. 1993), but none of them were accurately located, leaving the question of where they come from unanswered. However, this is not the ratio of the real rates between short and long bursts as (i) the BATSE detector is less sensitive to short bursts than to long ones; and (ii) the true rate depends on the spatial distribution of the short bursts (which is uncertain due to the lack of redshifts). There are indications that the $\log N$ - $\log S$ relation (Sect. 1.1) for short bursts is closer to the Euclidean value than for long bursts (e.g. Guetta & Piran 2005). Although this could be explained by the different BATSE thresholds for detecting long and short bursts, it might also indicate that short bursts are nearer to us than the long ones, possibly with all observed short bursts at $z < 0.5$. What has *Swift* already informed us about short bursts? It has detected 41 bursts (8 June 2005), out of which two are short, i.e. a short burst fraction of 5%. The difference between this and the BATSE fraction, most likely, has two explanations. Firstly, BAT has a softer energy range (15–150 keV) than BATSE and is therefore less sensitive to triggering short/hard bursts. Secondly, since BAT is supposedly more sensitive than BATSE, it might be probing a turn-over in the $\log N$ - $\log S$ plot for short bursts, implying a Galactic origin. GRB 050509B is, thus far, the only short burst with a detected (X-ray) afterglow (Gehrels et al. 2005) and a bright elliptical galaxy ($z = 0.22$) is within its error-circle (Bloom et al. 2005). A crucial test for distinguishing between a NS/NS (NS/BH) merger and a collapsar scenario for short/hard bursts is to look for possible SN signatures in their afterglows. Hjorth et al. (2005) demonstrated that if GRB 050509B took place at $z = 0.22$, any SN-like event accompanying the GRB would have to be much fainter than a normal SN. Clearly, more short GRB afterglows have to be discovered before the issue can be settled.

Due to its rapid-slewing capability, *Swift* can observe bursts within a minute of their onset. This will advance our understanding of the prompt/afterglow emission transition phase, and explain away light-curve bumps seen in the early stages. Although UVOT does not seem to be detecting as many bursts as was predicted (a combination of *Swift* bursts being on average optically fainter, and shallower UVOT limiting magnitudes), the XRT is performing marvelously, exploring hitherto uncharted early time domains in GRB X-ray light curves (e.g. XRF 050406 and GRB 050502B: Burrows et al. 2005b).

Since GRBs and SNe seem to be inextricably linked, *Swift* might turn out to be an excellent SN hunting machine. Some of the faint bursts that *Swift* will detect are likely to be seen off-axis at modest distances (XRFs: Sect. 1.2.6). If SNe accompany such bursts (as they seem to do: Soderberg et al. 2005), the SNe will not be hidden by a bright afterglow. It should therefore be relatively easy to study how SNe evolve in the first few minutes, days and months after the burst.

It is apparent that the potential for *Swift* to deliver cutting edge science is at hand. However, as for many previous great scientific discoveries, including the GRBs

themselves, serendipity might be the keyword here. A totally unexpected finding, perhaps that has little to do with GRB research, might be one of the most noteworthy results coming from *Swift*. Only time will tell.

Bibliography

- Adelberger, K. L. & Steidel, C. C. 2000, *ApJ*, 544, 218
- Akerlof, C., Balsano, R., Barthelemy, S., et al. 1999, *Nature*, 398, 400
- Allen, D., Rodgers, C., & Canterna, R. 2005, *GCN Circ.* 3439
- Andersen, M. I., Hjorth, J., Pedersen, H., et al. 2000, *A&A*, 364, L54
- Antonelli, L. A., Campana, S., Tagliaferri, G., et al. 2005, *GCN Circ.* 2991
- Antonelli, L. A., Piro, L., Vietri, M., et al. 2000, *ApJ*, 545, L39
- Atteia, J.-L., Barat, C., Hurley, K., et al. 1987, *ApJS*, 64, 305
- Barkana, R. & Loeb, A. 2004, *ApJ*, 601, 64
- Barnard, V. E., Blain, A. W., Tanvir, N. R., et al. 2003, *MNRAS*, 338, 1
- Barraud, C., Olive, J.-F., Lestrade, J. P., et al. 2003, *A&A*, 400, 1021
- Beloborodov, A. M. 2000, *ApJ*, 539, L25
- Berger, D. & McWilliam, A. 2005, *GCN Circ.* 3511
- Berger, E., Cowie, L. L., Kulkarni, S. R., et al. 2003, *ApJ*, 588, 99
- Berger, E., Fox, D., Kulkarni, S. R., et al. 2005a, *ApJ*, submitted [astro-ph/0502468]
- Berger, E. & Frail, D. A. 2001, *GCN Circ.* 1168
- Berger, E., Gladders, M., & Oemler, G. 2005b, *GCN Circ.* 3201
- Berger, E., Kulkarni, S. R., Bloom, J. S., et al. 2002, *ApJ*, 581, 981
- Berger, E., Kulkarni, S. R., Fox, D. B., et al. 2005c, *ApJ*, submitted [astro-ph/0505107]
- Berger, E., Oemler, G., & Gladders, M. 2005d, *GCN Circ.* 3185
- Berger, E., Oemler, G., & Gladders, M. 2005e, *GCN Circ.* 3185
- Björnsson, G., Gudmundsson, E. H., & Jóhannesson, G. 2004, *ApJ*, 615, L77

- Blackman, E. G., Yi, I., & Field, G. B. 1996, *ApJ*, 473, L79
- Blake, C. H., Bloom, J. S., Starr, D. L., et al. 2005, *Nature*, in press [astro-ph/0503508]
- Blandford, R. & Eichler, D. 1987, *PhR*, 154, 1
- Blandford, R. D. & Znajek, R. L. 1977, *MNRAS*, 179, 433
- Bloom, J. S., Berger, E., Kulkarni, S. R., Djorgovski, S. G., & Frail, D. A. 2003a, *AJ*, 125, 999
- Bloom, J. S., Frail, D. A., & Kulkarni, S. R. 2003b, *ApJ*, 594, 674
- Bloom, J. S., Kulkarni, S. R., & Djorgovski, S. G. 2002a, *AJ*, 123, 1111
- Bloom, J. S., Kulkarni, S. R., Djorgovski, S. G., et al. 1999, *Nature*, 401, 453
- Bloom, J. S., Kulkarni, S. R., Price, P. A., et al. 2002b, *ApJ*, 572, L45
- Bloom, J. S., Prochaska, J. X., Pooley, D., et al. 2005, *ApJ*, submitted [astro-ph/0505480]
- Blustin, A., Barbier, L., McGowan, K., et al. 2005, *GCN Circ.* 3307
- Borozdin, K. N. & Trudolyubov, S. P. 2003, *ApJ*, 583, L57
- Burrows, D. N., Hill, J. E., Chincarini, G., et al. 2005a, *ApJ*, 622, L85
- Burrows, D. N., Romano, P., Falcone, A., et al. 2005b, *Nature*, submitted [astro-ph/0506130]
- Butler, N. R., Marshall, H. L., Ricker, G. R., et al. 2003, *ApJ*, 597, 1010
- Capalbi, M., Perri, M., Romano, P., et al. 2005, *GCN Circ.* 3184
- Castro Cerón, J. M., Gorosabel, J., Castro-Tirado, A. J., et al. 2004, *A&A*, 424, 833
- Cavallo, G. & Rees, M. J. 1978, *MNRAS*, 183, 359
- Chapman, S. C., Blain, A. W., Ivison, R. J., & Smail, I. R. 2003, *Nature*, 422, 695
- Chapman, S. C., Smail, I., Windhorst, R., Muxlow, T., & Ivison, R. J. 2004, *ApJ*, 611, 732
- Charlot, S. & Fall, S. M. 1993, *ApJ*, 415, 580
- Chary, R. & Elbaz, D. 2001, *ApJ*, 556, 562
- Chevalier, R. A. & Li, Z. 2000, *ApJ*, 536, 195
- Chincarini, G., Romano, P., Campana, S., et al. 2005, *GCN Circ.* 3209

- Christensen, L., Hjorth, J., & Gorosabel, J. 2004a, *A&A*, 425, 913
- Christensen, L., Hjorth, J., Gorosabel, J., et al. 2004b, *A&A*, 413, 121
- Costa, E., Frontera, F., Heise, J., et al. 1997, *Nature*, 387, 783
- Courty, S., Björnsson, G., & Gudmundsson, E. H. 2004, *MNRAS*, 354, 581
- Dado, S., Dar, A., & De Rújula, A. 2002, *A&A*, 388, 1079
- Dahlen, T., Strolger, L., Riess, A. G., et al. 2004, *ApJ*, 613, 189
- Dai, Z. G., Liang, E. W., & Xu, D. 2004, *ApJ*, 612, L101
- D'Avanzo, P., Fugazza, D., Masetti, N., & Pedani, M. 2005, *GCN Circ.* 3171
- De Luca, A., Gotz, D., & Campana, S. 2005a, *GCN Circ.* 3293
- De Luca, A., Melandri, A., Caraveo, P. A., et al. 2005b, *A&A*, in press [astro-ph/0505261]
- Dermer, C. D., Chiang, J., & Böttcher, M. 1999, *ApJ*, 513, 656
- Dewi, J. D. M. & Pols, O. R. 2003, *MNRAS*, 344, 629
- Djorgovski, S. G., Bloom, J. S., & Kulkarni, S. R. 2003a, *ApJ*, 591, L13
- Djorgovski, S. G., Frail, D. A., Kulkarni, S. R., et al. 2001, *ApJ*, 562, 654
- Djorgovski, S. G., Kulkarni, S. R., Frail, D. A., et al. 2003b, in *Proceedings of the SPIE, Volume 4834 (Discoveries and Research Prospects from 6- to 10-Meter-Class Telescopes II)*, ed. P. Guhathakurta, 238
- Eichler, D., Livio, M., Piran, T., & Schramm, D. N. 1989, *Nature*, 340, 126
- Einasto, J., Kaasik, A., & Saar, E. 1974, *Nature*, 250, 309
- Fenimore, E. E., Ramirez-Ruiz, E., & Wu, B. 1999, *ApJ*, 518, L73
- Fermi, E. 1949, *PhRv*, 75, 1169
- Feroci, M., Antonelli, L. A., Soffitta, P., et al. 2001, *A&A*, 378, 441
- Firmani, C., Ghisellini, G., Ghirlanda, G., & Avila-Reese, V. 2005, *MNRAS*, in press [astro-ph/0501395]
- Fishman, G. J. 1995, *PASP*, 107, 1145
- Fishman, G. J., Meegan, C. A., Watts, J. W., & Derrickson, J. H. 1978, *ApJ*, 223, L13
- Fox, D. B. 2005, *GCN Circ.* 3442

- Fox, D. B., Kaplan, D. L., Cenko, B., Kulkarni, S. R., & Nechita, A. 2003a, GCN Circ. 2323
- Fox, D. W., Price, P. A., Soderberg, A. M., et al. 2003b, ApJ, 586, L5
- Fox, D. W., Yost, S., Kulkarni, S. R., et al. 2003c, Nature, 422, 284
- Frail, D. A., Kulkarni, S. R., Nicastro, S. R., Feroci, M., & Taylor, G. B. 1997, Nature, 389, 261
- Frail, D. A., Kulkarni, S. R., Sari, R., et al. 2001, ApJ, 562, L55
- Frail, D. A., Waxman, E., & Kulkarni, S. R. 2000, ApJ, 537, 191
- Friedman, A. S. & Bloom, J. S. 2005, ApJ, submitted [astro-ph/0408413]
- Fruchter, A. S., Pian, E., Thorsett, S. E., et al. 1999, ApJ, 516, 683
- Fryer, C. L., Woosley, S. E., & Hartmann, D. H. 1999, ApJ, 526, 152
- Fuller, G. M. & Shi, X. 1998, ApJ, 502, L5
- Fynbo, J. P. U., Jensen, B. L., Hjorth, J., et al. 2005, GCN Circ. 3176
- Fynbo, J. P. U., Ledoux, C., Möller, P., Thomsen, B., & Burud, I. 2003, A&A, 407, 147
- Fynbo, J. P. U., Möller, P., Thomsen, B., et al. 2002, A&A, 388, 425
- Fynbo, J. P. U., Sollerman, J., Hjorth, J., et al. 2004, ApJ, 609, 962
- Fynbo, J. U., Holland, S., Andersen, M. I., et al. 2000, ApJ, 542, L89
- Fynbo, J. U., Möller, P., & Warren, S. J. 1999, MNRAS, 305, 849
- Gaisser, T. K. 1991, Cosmic Rays and Particle Physics (Cambridge:Cambridge University Press)
- Galama, T. J., Groot, P. J., van Paradijs, J., et al. 1998a, ApJ, 497, L13
- Galama, T. J., Vreeswijk, P. M., van Paradijs, J., et al. 1998b, Nature, 395, 670
- Galama, T. J., Wijers, R. A. M. J., Bremer, M., et al. 1998c, ApJ, 500, L97
- Gallant, Y. A. & Achterberg, A. 1999, MNRAS, 305, L6
- Garnavich, P. M., Stanek, K. Z., Wyrzykowski, L., et al. 2003, ApJ, 582, 924
- Gaudi, B. S., Granot, J., & Loeb, A. 2001, ApJ, 561, 178
- Gehrels, N., Barbier, L., Barthelmy, S. D., et al. 2005, Nature, submitted [astro-ph/0505630]

- Gehrels, N., Chincarini, G., Giommi, P., et al. 2004, *ApJ*, 611, 1005
- Gehrels, N., Piro, L., & Leonard, P. J. T. 2002, *Scientific American*, 536, 84
- Ghirlanda, G., Ghisellini, G., & Lazzati, D. 2004a, *ApJ*, 616, 331
- Ghirlanda, G., Ghisellini, G., Lazzati, D., & Firmani, C. 2004b, *ApJ*, 613, L13
- Ghirlanda, G., Ghisellini, G., Lazzati, D., & Firmani, C. 2005, in *Il Nuovo Cimento (4th Workshop Gamma-Ray Bursts in the Afterglow Era)*, in press [astro-ph/0504184]
- Ghisellini, G. & Lazzati, D. 1999, *MNRAS*, 309, L7
- Giavalisco, M., Koratkar, A., & Calzetti, D. 1996, *ApJ*, 466, 831
- Goad, M., Page, K., Osborne, J. P., et al. 2005, *GCN Circ.* 3034
- Godet, O., Goad, M., Page, K., et al. 2005, *GCN Circ.* 3301
- Goodman, J. 1986, *ApJ*, 308, L47
- Gorosabel, J., Jensen, B. L., Galaz, G., et al. 2005, *GCN Circ.* 3425
- Gou, L. J., Mészáros, P., Abel, T., & Zhang, B. 2004, *ApJ*, 604, 508
- Granot, J., Miller, M., Piran, T., Suen, W. M., & Hughes, P. A. 2001, 312–314
- Granot, J. & Sari, R. 2002, *ApJ*, 568, 820
- Grupe, D., Retter, A., Burrows, D., Kennea, J., & Gehrels, N. 2005, *GCN Circ.* 3519
- Guetta, D. & Piran, T. 2005, *A&A*, 435, 421
- Guetta, D., Piran, T., & Waxman, E. 2005, *ApJ*, 619, 412
- Harwit, M. & Salpeter, E. E. 1973, *ApJ*, 186, L37
- Hayes, M., Östlin, G., Mas-Hesse, J. M., et al. 2005, *A&A*, in press [astro-ph/0503320]
- Heckman, T. M., Robert, C., Leitherer, C., Garnett, D. R., & van der Rydt, F. 1998, *ApJ*, 503, 646
- Heise, J. 2003, in *AIP Conf. Proc.* 662 (*Gamma-Ray Burst and Afterglow Astronomy*), ed. G. R. Ricker & R. K. Vanderspek (Melville: AIP), 229
- Heise, J., in't Zand, J., Kippen, R. M., & Woods, P. M. 2001, in *Gamma-ray Bursts in the Afterglow Era*, ed. E. Costa, F. Frontera & J. Hjorth (Berlin: Springer), 16
- Hjorth, J., Holland, S., Courbin, F., et al. 2000, *ApJ*, 534, L147

- Hjorth, J., Kouveliotou, C., & Woosley, S. 2004, *Physics World*, 17, 35
- Hjorth, J., Møller, P., Gorosabel, J., et al. 2003a, *ApJ*, 597, 699
- Hjorth, J., Sollerman, J., Gorosabel, J., et al. 2005, *ApJ*, submitted [astro-ph/0506123]
- Hjorth, J., Sollerman, J., Møller, P., et al. 2003b, *Nature*, 423, 847
- Hjorth, J., Thomsen, B., Nielsen, S. R., et al. 2002, *ApJ*, 576, 113
- Holland, S., Björnsson, G., Hjorth, J., & Thomsen, B. 2000, *A&A*, 364, 467
- Holland, S. T., Still, M., Landsman, W., et al. 2005, *GCN Circ.* 3150
- Hoyle, F., Burbidge, G. R., & Sargent, W. L. W. 1966, *Nature*, 209, 751
- Ioka, K., Kobayashi, S., & Zhang, B. 2004, [astro-ph/0409376]
- Jensen, B. L., Fynbo, J. U., Gorosabel, J., et al. 2001, *A&A*, 370, 909
- Katz, J. I. 2002, *The Biggest Bangs* (New York: Oxford University Press)
- Kennicutt, R. C. 1998, *ARA&A*, 36, 189
- Klebesadel, R. W., Strong, I. B., & Olson, R. A. 1973, *ApJ*, 182, L85
- Klotz, A., Boer, M., Atteia, J. L., & Stratta, G. 2005, *GCN Circ.* 3084
- Kobayashi, S. 2000, *ApJ*, 545, 807
- Kobayashi, S., Piran, T., & Sari, R. 1997, *ApJ*, 490, 92
- Kogut, A., Spergel, D. N., Barnes, C., et al. 2003, *ApJS*, 148, 161
- Kosugi, G., Kawai, N., Aoki, K., et al. 2005, *GCN Circ.* 3253
- Kosugi, G., Kawai, N., Tajitsu, A., & Furusawa, H. 2004, *GCN Circ.* 2726
- Kouveliotou, C., Meegan, C. A., Fishman, G. J., et al. 1993, *ApJ*, 413, L101
- Krolik, J. H. & Pier, E. A. 1991, *ApJ*, 373, 277
- Kulkarni, S. R., Djorgovski, S. G., Odewahn, S. C., et al. 1999, *Nature*, 398, 389
- Kulkarni, S. R., Djorgovski, S. G., Ramaprakash, A. N., et al. 1998, *Nature*, 393, 35
- Kumar, P. & Panaitescu, A. 2000, *ApJ*, 541, L9
- Lamb, D. Q. 1995, *PASP*, 107, 1152
- Lazzati, D., Ghisellini, G., Haardt, F., & Fernández-Soto, A. 2001, in *Gamma-Ray Bursts in the Afterglow Era*, ed. E. Costa, F. Frontera, & J. Hjorth (Berlin: Springer), 236

- Lazzati, D., Rossi, E., Covino, S., Ghisellini, G., & Malesani, D. 2002, *A&A*, 396, L5
- Le Floch, E., Duc, P.-A., Mirabel, I. F., et al. 2003, *A&A*, 400, 499
- Levinson, A. & Eichler, D. 2005, *ApJ*, submitted [astro-ph/0504125]
- Lipkin, Y. M., Ofek, E. O., Gal-Yam, A., et al. 2004, *ApJ*, 606, 381
- Lipunov, V. M., Postnov, K. A., & Prokhorov, M. E. 2001, *Astronomy Reports*, 45, 236
- Lithwick, Y. & Sari, R. 2001, *ApJ*, 555, 540
- Loeb, A. & Barkana, R. 2001, *ARA&A*, 39, 19
- Lyne, A. G. & Lorimer, D. R. 1994, *Nature*, 369, 127
- Mészáros, P. & Rees, M. J. 2001, *ApJ*, 556, L37
- MacFadyen, A. I. & Woosley, S. E. 1999, *ApJ*, 524, 262
- Mangano, V., Capalbi, M., Pagani, C., et al. 2005a, *GCN Circ.* 3263
- Mangano, V., Cusumano, G., Mineo, T., et al. 2005b, *GCN Circ.* 3086
- Markwardt, C. B., Boyd, P., Gehrels, N., et al. 2005, *GCN Circ.* 3112
- Mas-Hesse, J. M., Kunth, D., Tenorio-Tagle, G., et al. 2003, *ApJ*, 598, 858
- Mason, K., Schady, P., Ivanushkina, M., et al. 2005, *GCN Circ.* 3037
- Mazets, E. P., Golenetskii, S. V., Ilinskii, V. N., et al. 1981, *Ap&SS*, 80, 1
- McBreen, S., Quilligan, F., McBreen, B., Hanlon, L., & Watson, D. 2001, *A&A*, 380, L31
- McGowan, K., de Pasquale, M., Boyd, P., et al. 2005, *GCN Circ.* 3115
- Meegan, C. A., Fishman, G. J., Wilson, R. B., et al. 1992, *Nature*, 355, 143
- Mészáros, P. 2001, *Science*, 291, 79
- Mészáros, P. 2002, *ARA&A*, 40, 137
- Mészáros, P. & Rees, M. J. 1993, *ApJ*, 405, 278
- Mészáros, P. & Rees, M. J. 1997a, *ApJ*, 476, 232
- Mészáros, P. & Rees, M. J. 1997b, *ApJ*, 482, L29
- Metzger, M. R., Djorgovski, S. G., Kulkarni, S. R., et al. 1997, *Nature*, 387, 878

- Milne, P. A., Williams, G. G., & Park, H.-S. 2005, GCN Circ. 3258
- Mirabal, N., Halpern, J. P., Gotthelf, E. V., & Mukherjee, R. 2005, ApJ, 620, 379
- Mitra, A. 1996, A&A, 313, L9
- Møller, P., Fynbo, J. P. U., & Fall, S. M. 2004, A&A, 422, L33
- Møller, P., Fynbo, J. P. U., Hjorth, J., et al. 2002, A&A, 396, L21
- Møller, P. & Fynbo, J. U. 2001, A&A, 372, L57
- Monfardini, A., Tanvir, N., Smith, R., et al. 2005, GCN Circ. 3001
- Mörtsell, E. & Sollerman, J. 2005, A&A, submitted [astro-ph/0504245]
- Motch, C., Ilovaisky, S. A., Chevalier, C., et al. 1985, A&A, 145, 201
- Murakami, T., Nishimura, J., Kawai, N., Cooke, B. A., & Katoh, M. 1990, A&A, 227, 451
- Nakar, E. & Piran, T. 2003, ApJ, 598, 400
- Nakar, E. & Piran, T. 2004, MNRAS, 353, 647
- Nakar, E., Piran, T., & Granot, J. 2003, New Astronomy, 8, 495
- Narayan, R., Piran, T., & Kumar, P. 2001, ApJ, 557, 949
- Neufeld, D. A. 1991, 370, L85
- Östman, L. & Mörtsell, E. 2005, JCAP, 2, 5
- Ostriker, J. P., Peebles, P. J. E., & Yahil, A. 1974, ApJ, 193, L1
- Ouchi, M., Shimasaku, K., Furusawa, H., et al. 2003, ApJ, 582, 60
- Paczynski, B. 1986, ApJ, 308, L43
- Paczynski, B. 1995, PASP, 107, 1167
- Paczynski, B. 1998, ApJ, 494, L45
- Panaitescu, A. & Kumar, P. 2001, ApJ, 554, 667
- Panaitescu, A. & Mészáros, P. 1999, ApJ, 526, 707
- Pedersen, K., Hurley, K., Hjorth, J., et al. 2005, ApJ, submitted
- Perlmutter, S., Aldering, G., Goldhaber, G., et al. 1999, ApJ, 517, 565
- Perlmutter, S., Gabi, S., Goldhaber, G., et al. 1997, ApJ, 483, 565

- Perri, M., Capalbi, M., Giommi, P., et al. 2005, GCN Circ. 3443
- Phillips, M. M. 1993, ApJ, 413, L105
- Piran, T. 1999, PhR, 314, 575
- Piran, T. 2005, Reviews of Modern Physics, 76, 1143
- Piro, L., Amati, L., Antonelli, L. A., et al. 1998, A&A, 331, L41
- Piro, L., Garmire, G., Garcia, M., et al. 2000, Science, 290, 955
- Prilutski, O. F. & Usov, V. V. 1975, Ap&SS, 34, 387
- Quashnock, J. M. & Lamb, D. Q. 1993, MNRAS, 265, L45
- Ramirez-Ruiz, E., Trentham, N., & Blain, A. W. 2002, MNRAS, 329, 465
- Rees, M. J. 1995, PASP, 107, 1176
- Rees, M. J. & Mészáros, P. 1992, MNRAS, 258, 41
- Rees, M. J. & Mészáros, P. 1994, ApJ, 430, L93
- Rees, M. J. & Mészáros, P. 2000, ApJ, 545, L73
- Reeves, J. N., Watson, D., Osborne, J. P., Pounds, K. A., & O'Brien, P. T. 2003, A&A, 403, 463
- Reeves, J. N., Watson, D., Osborne, J. P., et al. 2002, Nature, 416, 512
- Rhoads, J. E. 1999, ApJ, 525, 737
- Rhoads, J. E. & Fruchter, A. S. 2001, ApJ, 546, 117
- Riess, A. G., Filippenko, A. V., Challis, P., et al. 1998, AJ, 116, 1009
- Riess, A. G., Press, W. H., & Kirshner, R. P. 1996, ApJ, 473, 88
- Rossi, E., Lazzati, D., & Rees, M. J. 2002, MNRAS, 332, 945
- Rossi, E. M., Lazzati, D., Salmonson, J. D., & Ghisellini, G. 2004, MNRAS, 354, 86
- Rosswog, S. & Ramirez-Ruiz, E. 2003, MNRAS, 343, L36
- Ruderman, M. 1975, in Proceedings of the New York Academy Sciences, Volume 262 (Seventh Texas Symposium on Relativistic Astrophysics), 164
- Rutledge, R. E. & Sako, M. 2003, MNRAS, 339, 600
- Rybicki, G. B. & Lightman, A. P. 1979, Radiative Processes in Astrophysics (New York:JWS)

- Sako, M., Harrison, F., & Rutledge, R. 2005, ApJ, submitted [astro-ph/0406210]
- Sari, R. & Piran, T. 1997, ApJ, 485, 270
- Sari, R., Piran, T., & Halpern, J. P. 1999, ApJ, 519, L17
- Sari, R., Piran, T., & Narayan, R. 1998, ApJ, 497, L17
- Sazonov, S. Y., Lutovinov, A. A., & Sunyaev, R. A. 2004, Nature, 430, 646
- Schaefer, B. E., Cline, T. L., Atteia, J.-L., et al. 1989, ApJ, 340, 455
- Schaefer, B. E., Cline, T. L., Desai, U., et al. 1987, ApJ, 313, 226
- Schechter, P. 1976, ApJ, 203, 297
- Schmidt, W. K. H. 1978, Nature, 271, 525
- Shapley, A. E., Steidel, C. C., Pettini, M., & Adelberger, K. L. 2003, ApJ, 588, 65
- Shemi, A. & Piran, T. 1990, ApJ, 365, L55
- Soderberg, A., Djorgovski, S. G., Halpern, J. P., & Mirabal, N. 2004a, GCN Circ. 2837
- Soderberg, A. M., Kulkarni, S. R., Berger, E., et al. 2004b, ApJ, 606, 994
- Soderberg, A. M., Kulkarni, S. R., Fox, D. B., et al. 2005, ApJ, submitted [astro-ph/0502553]
- Stanek, K. Z., Garnavich, P. M., Kaluzny, J., Pych, W., & Thompson, I. 1999, ApJ, 522, L39
- Stanek, K. Z., Matheson, T., Garnavich, P. M., et al. 2003, ApJ, 591, L17
- Steidel, C. C., Adelberger, K. L., Shapley, A. E., et al. 2003, ApJ, 592, 728
- Steidel, C. C. & Hamilton, D. 1992, AJ, 104, 941
- Steidel, C. C. & Hamilton, D. 1993, AJ, 105, 2017
- Steidel, C. C., Pettini, M., & Hamilton, D. 1995, AJ, 110, 2519
- Strong, I. B., Klebesadel, R. W., & Olson, R. A. 1974, ApJ, 188, L1
- Tanvir, N., Pak, S., Priddey, R., et al. 2005, GCN Circ. 3031
- Tanvir, N. R., Barnard, V. E., Blain, A. W., et al. 2004, MNRAS, 352, 1073
- Tavani, M. 1998, ApJ, 497, L21
- Taylor, G. B., Bloom, J. S., Frail, D. A., et al. 2000a, ApJ, 537, L17

- Taylor, G. B., Frail, D. A., & Bloom, J. S. 2000b, GCN Circ. 880
- Trimble, V. 1995, PASP, 107, 1133
- Usov, V. V. 1992, Nature, 357, 472
- Usov, V. V. 1994, MNRAS, 267, 1035
- Usov, V. V. & Chibisov, G. V. 1975, Soviet Astronomy, 19, 115
- van Paradijs, J., Groot, P. J., Galama, T., et al. 1997, Nature, 386, 686
- Vestrand, W. T., Wozniak, P. R., Wren, J. A., et al. 2005, Nature, in press [astro-ph/0503521]
- Vietri, M. & Stella, L. 1999, ApJ, 527, L43
- Vreeswijk, P. M., Ellison, S. L., Ledoux, C., et al. 2004, A&A, 419, 927
- Vreeswijk, P. M., Smette, A., Fruchter, A. S., et al. 2005, A&A, submitted
- Wang, X. Y., Dai, Z. G., & Lu, T. 2001, ApJ, 546, L33
- Watson, D., Hjorth, J., Levan, A., et al. 2004, ApJ, 605, L101
- Watson, D., Reeves, J. N., Hjorth, J., Jakobsson, P., & Pedersen, K. 2003, ApJ, 595, L29
- Watson, D., Reeves, J. N., Osborne, J., et al. 2002, A&A, 393, L1
- Watson, D., Vaughan, S. A., Willingale, R., et al. 2005, ApJ, submitted
- Weatherley, S. J., Warren, S. J., Møller, P., et al. 2005, MNRAS, 358, 985
- Woltjer, L. 1966, ApJ, 146, 597
- Woods, E. & Loeb, A. 1999, ApJ, 523, 187
- Woosley, S. E. 1993, ApJ, 405, 273
- Xu, D. 2005, [astro-ph/0504052]
- Xu, D., Dai, Z. G., & Liang, E. W. 2005, [astro-ph/0501458]
- Yamazaki, R., Ioka, K., & Nakamura, T. 2002, ApJ, 571, L31
- Yamazaki, R., Ioka, K., & Nakamura, T. 2003, ApJ, 593, 941
- Yamazaki, R., Ioka, K., & Nakamura, T. 2004, ApJ, 607, L103
- Yoshida, A., Namiki, M., Yonetoku, D., et al. 2001, ApJ, 557, L27
- Zhang, B., Dai, X., Lloyd-Ronning, N. M., & Mészáros, P. 2004, ApJ, 601, L119

Zhang, B. & Mészáros, P. 2002, *ApJ*, 571, 876

Zhang, B. & Mészáros, P. 2004, *Int. J. Mod. Phys. A*, 19, 2385

Zhang, W., Woosley, S. E., & MacFadyen, A. I. 2003, *ApJ*, 586, 356

Appendix A

Papers

This appendix contains the seven papers that form the basis of this Ph.D. thesis. They are not listed in a chronological order, rather in the order explained in the Preface. They have all been published in refereed journals, except Paper IV which is in press.

A.1 Paper I

Swift Identification of Dark Gamma-Ray Bursts

by

P. Jakobsson, J. Hjorth, J. P. U. Fynbo, et al.

Astrophysical Journal Letters, **617**, L21–L24 (2004)

A.2 Paper II

The Radio Afterglow and Host Galaxy of the Dark GRB 020819

by

P. Jakobsson, D. A. Frail, D. B. Fox, et al.

Astrophysical Journal, **629**, 45–51 (2005)

A.3 Paper III

On the Ly α Emission from Gamma-Ray Burst Host Galaxies:
Evidence for Low Metallicities

by

J. P. U. Fynbo, P. Jakobsson, P. Møller, et al.

Astronomy & Astrophysics Letters, **406**, L63–L66 (2003)

A.4 Paper IV

Ly α and UV Emission from High-Redshift GRB Hosts:
To What Extent Do GRBs Trace Star Formation?

by

P. Jakobsson, G. Björnsson, J. P. U. Fynbo, et al.

Monthly Notices of the Royal Astronomical Society, in press (2005)

A.5 Paper V

The Afterglow and the Host Galaxy of GRB 011211

by

P. Jakobsson, J. Hjorth, J. P. U. Fynbo, et al.

Astronomy & Astrophysics, **408**, 941–947 (2003)

A.6 Paper VI

Small-Scale Variations in the Radiating Surface of the GRB 011211 Jet

by

P. Jakobsson, J. Hjorth, E. Ramirez-Ruiz, et al.

New Astronomy, **9**, 435–442 (2004)

A.7 Paper VII

The Line-of-Sight Towards GRB 030429 at $z = 2.66$:
Probing the Matter at Stellar, Galactic and Intergalactic Scales

by

P. Jakobsson, J. Hjorth, J. P. U. Fynbo, et al.

Astronomy & Astrophysics, **427**, 785–794 (2004)

