Gamma-Ray Bursts

The Brightest Explosions in the Universe

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Springer

Published in association with
Praxis Publishing
Chichester, UK

PRAXIS

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SPRINGER–PRAXIS BOOKS IN ASTRONOMY AND PLANETARY SCIENCES
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ISBN 978-3-540-39085-5 Springer Berlin Heidelberg New York

Springer is part of Springer-Science + Business Media (springer.com)

Library of Congress Control Number: 2008934911

Printed in Germany

Cover design: Jim Wilkie
Project copy editor: Mike Shardlow
Typesetting: OPS Ltd, Gt Yarmouth, Norfolk, UK

Printed on acid-free paper

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Preface

The Editor proposed us to write this book in may 2004, few months before the launch of Swift. After some thoughts we responded positively to this request because we were really enthusiastic about relating the remarkable GRB story and providing in a single place basic observational and theoretical facts about gamma-ray bursts. The book is organized along these two lines.

Chapters 1 to 4 relate the GRB story in chronological sequence. They describe how observational progress have led a serendipitous discovery to become important domain of astrophysics, with the understanding that gamma-ray bursts are powerful stellar explosions producing a short-lived ultra-relativistic jet directed towards us. Chapters 5 to 8, discuss our basic understanding of gamma-ray bursts. The theoretical description of GRBs involves the evolution of relativistic fireballs and their impact on their environment, and the physical processes at work in astrophysical jets. These questions are addressed in Chapters 5, 6, and 7. Chapter 7 also shows the crucial need for multi-wavelength (X-rays to radio) time-resolved observations, and how the scarcity of these observations currently limits our understanding of gamma-ray bursts. Chapter 8 is about the GRB sources. It discusses exploding stars, like the collapsars leading to newly born fast-rotating black holes (and possibly short-lived magnetars), and various types of compact star mergers. It mentions some methods to distinguish between these two types of progenitors, and their difficulties. Chapter 9 briefly explore the possible future developments of the field. It explains the connection of GRBs with many present-day astronomical issues, like the history of star formation, the production of cosmic rays, and the detection of gravitational waves, and comments on how these events are participating in the better understanding of our Universe. ‘Gamma-Ray Bursts’ is intended for scientists and students who are interested in the main concepts of the quickly evolving field of GRB studies. It describes the main observational and theoretical work which have led to our present understanding, and it provides considerable bibliography. The curious reader (not necessarily scientist) may also be interested in the GRB story starting with the serendipitous discovery of these events in Chapter 1 and ending in Chapter 9 with a discussion of the many connections of GRBs with other fields of astrophysics.

When we started this venture, we were aware of three major difficulties of the task: our English was poor, the field was evolving very quickly (at least as fast as we could write!), and it was not possible in a single book to address all the astrophysical issues connected with GRBs. Regarding the first point we ask for the indulgence of the reader. The other points explain why we have focused this book on GRBs observations, theory and progenitors, with few excursions outside these issues (in Chapter 9). We have also tried to stay on firm grounds (as far as we can judge), avoiding going into the details of questions which remain speculative, but trying to list them. Moreover, we rapidly realized another complication which we had not anticipated: we had to face a vast bibliography preventing us from completeness, even with a total of more than 1700 references listed at the end of each chapter. We have attempted to provide a set of references sufficient to allow the detailed exploration of the subjects tackled in the book, but we definitely apologize for the references that have escaped our attention. We have used some reviews extensively, when this is the case this is mentioned in the text, and we take advantage of this preface to thank the authors of these reviews.

We have included in the book various features that could help the reader. The chapters are mostly independent and their content is outlined in the introduction. The last section of each chapter is a short summary of its content. Cross-references between sections are provided when this is required. An index of the main concepts is given at the end of the book, and, following a long-lasting tradition among GRB researchers, this index also contains references to the individual GRBs mentioned in the book, allowing anyone to search where and why we have mentioned his/her favourite GRB.

Finally, many thanks are due to Kevin Hurley who has accepted to go through the manuscript and has corrected many mistakes. We fully endorse the remaining errors and inaccuracies and we apologize for them. We also thank the Editor for offering us the opportunity to present the richness of a scientific field that we love and to tell the story of a serendipitous discovery that became in a quarter of a century an extremely active domain of research, contributing to a better understanding of our Universe.

Acknowledgments

Gamma-Ray Bursts is the result of a collective effort and we would like to thank here all those who have contributed to bring this book to life.

First, Clive Horwood, Publisher, Praxis, whose confidence put us on the way in May 2004, while we were far from realizing the size of the task ("The journey of a thousand miles starts with a single step"—Lao Tseu). Clive was also very patient and comprehensive when we accumulated delays in chapter delivery. One benefit of these delays has been the possibility to fully take into account the beautiful discoveries of Swift. By chance, and in contrast with the predictions of some of our colleagues, they were not long enough to include the first results of the nicely working GLAST/Fermi mission.

We are also grateful to the referees who recommended this project, with excellent advice on the opportunity and content of the book, and to the colleagues who have read and corrected parts of the book, especially A. Blanchard. During the production process, we have discovered a number of persons who all contributed to the realization of the book, Dr John Mason, the Science Editor, Mike Shardlow, the Copy Editor, and Neil Shuttlewood, the Typesetter, who took into consideration all our requests during the stage of proof corrections, we warmly acknowledge their work. Many thanks are also due to our families who supported us during this long, and sometimes difficult, project. Finally we are indebted to the GRB community at large whose work is at the centre of this book. *Gamma-Ray Bursts* is a tribute to all the researchers and engineers who have contributed to the blossoming of this area of Astrophysics.

Special thanks are due to two colleagues R. Mochkovitch and K. Hurley. R. Mochkovitch, a well-known expert in GRB theory, kindly supervised the theoretical chapters of the book on GRB models and progenitors. K. Hurley, who started his research on γ-ray bursts at the CESR in Toulouse 30 years ago, is an active GRB scientist and a very regular and reliable partner. He has accepted to revise the nine chapters, which is a considerable amount of work, and an invaluable contribution to the book. These two colleagues contributed significantly to improve the quality of the book.

Foreword

The history of cosmic gamma-ray bursts, although relatively short by astronomical standards, has been a very eventful one. In the space of a few decades, they have gone from a curiosity, thought to be related to small energy releases involving Galactic neutron stars, to the most powerful cosmological explosions known. At the same time, they have become tools for the study of stellar evolution, supernovae, galactic structure, the intergalactic medium, and relativistic plasmas, to name only a few subjects. Well over 9,000 papers have now been published on gamma-ray bursts, and a new one appears every day or so, a rate which is about equal to that of the detection of new bursts. The authors of this book have both witnessed and been directly involved first-hand in this remarkable story. Gilbert Vedrenne was there at the beginning; as vice-director of the CESR (Toulouse), he was in a unique position to put the resources of the laboratory to work in studying gamma-ray bursts by building some of the first dedicated satellite experiments, which were launched on Russian spacecraft. Jean-Luc Atteia arrived on the scene only slightly later as a graduate student, and began his career by analyzing the resulting data. Both authors have continued to be deeply involved in the unfolding story over the years.

Although other books have now been written on the subject of gamma-ray bursts, this one is unique. It starts by tracing the history of the subject in detail, and then delves into the complex physics of the phenomenon. The first part of this book can be read as a history of the subject by anyone with a minimum of scientific training. The second part is suitable for advanced undergraduates and graduate students, and will also be useful as a reference for researchers in the field. It arrives at a moment when the major mystery—burst distances—has been resolved, and a flood of new data is demanding ever-more clever and detailed explanations, and forcing us to abandon some old preconceptions. *Gamma-Ray Bursts* captures the excitement, the changing ideas, and the cutting-edge physics of an extraordinary astrophysical phenomenon.

Kevin Hurley
November 2008

J-L.A dedicates the book to Sylvie
and
G.V. dedicates the book to his family

Figures

(figures marked with an asterisk also appear in the color section)

Tables

Introduction

The fascinating gamma-ray burst (GRB) story started in 1973 with the report of the discovery of unexpected bursts of gamma-rays detected by military satellites. It then took decades before this topic of the young high-energy astronomy field became an important area of astrophysics, involving a large and very active scientific community. Having participated in the birth of this field in the 1970s and 1980s, we were enthusiastic when the editor proposed that we should relate the fabulous story of these gamma-ray bursts. We say fabulous because it presents all the ingredients of a fortuitous discovery which, after a long period of gestation, became a major scientific topic. Naturally, we accepted this demand even though the work was considerable because of the multiple developments of this domain, brought about by the continuous succession of GRB missions, particularly the very successful Swift satellite, still in orbit. Without being exhaustive we have tried to present the major milestones of the GRB saga and our understanding of this field in 2008.

The GRB saga started with an exciting pioneering period marked by an explosion in the number of bursts observed with a growing number of satellites; but there was no decisive progress in discovering the real sources of these explosions. In the 1980s, nearby galactic neutron stars were considered to be the most probable candidates to explain GRBs, by analogy with the models explaining most of the galactic X-ray sources. In these early times, the number of models was comparable with the number of bursts. We describe in Chapter 1 the long period of investigation that was dedicated to the study of the temporal and spectral characteristics of gamma-ray bursts. As they were unpredictable in time and direction, the best way of detecting a large number of them was to use omnidirectional gamma-ray detectors. The determination of GRB characteristics included the measurement of their light-curves—to search for possible periodicities—and the study of their spectra—to establish if they were thermal or non-thermal and to search for possible spectral features. After a few years a large sample of bursts was available, often obtained easily, with very different gamma-ray detectors working in space above ten or a few tens of kiloelectronvolts. But these data were insufficient to fully understand the physics of GRBs and to identify the sources of these emissions. Some similarity could be found with X-ray bursts seen at lower energy and already associated with accreting neutron stars in our galaxy. But this analogy did not answer the question of the origin of GRBs.

The need to localize and identify the sources of these sporadic emissions was very much present from the beginning, but this was difficult as the sources did not repeat and occurred randomly on the sky. The accurate timing of GRBs detected with omnidirectional detectors on at least three satellites had appeared very early to be the best way to localize GRB sources with the best precision: this is the triangulation method. Another method was also used to provide coarse GRB positions: the detection of GRBs with several large-field-of-view detectors on the same satellite with different orientations covering the entire sky. Very quickly, using this last technique, an all-sky map of the sources was obtained by the Leningrad group led by E. Mazets. The GRB distribution appeared to be isotropic, without the concentration in the Galactic Plane that was observed for most Galactic populations. This result led to the conclusion that the sources were Galactic but in our close proximity, with a distance scale smaller than the scale height of the Galactic Disk. The triangulation method used for another sample of GRBs led to similar results. This isotropy was, however, puzzling for Galactic sources and M. Schmidt proposed using the $\langle V/V_{\max}\rangle$ test to measure the homogeneity of the sources in the radial direction. This test computes, for each GRB, its relative position within the volume accessible to the instrument. For homogeneous sources one expects $\langle V/V_{\max}\rangle = 0.5$. The results for GRBs were marginally below 0.5, suggesting a deficit of faint bursts. At that time the apparent contradiction between the isotropy and the non-homogeneity of the sources was not considered to be too dramatic, because localizations were usually obtained for the brightest GRBs seen by several detectors, while the $\langle V/V_{\max}\rangle$ test involved all GRBs, including the faintest. Most researchers were expecting that more sensitive instruments would find faint sources concentrated in the Galactic Plane. Some of them, however, considered this isotropy as a sufficiently serious constraint to propose extragalactic and cosmological models. This possibility was defended, for instance, by B. Paczyński and his colleagues from the middle of the 1980s. In the end, the searches for counterparts at all possible wavelengths—optical, radio, and X-rays—using the best localizations obtained by triangulation, were all negative, conserving the mystery of the nature of these sources.

Hence after more than 15 years (1973–1991) of investigation a large sample of GRBs was accumulated with a large diversity of instruments on many satellites, often dedicated to X-ray or gamma-ray astronomy, and on planetary probes. They made it possible to collect a large sample of light-curves with rapid variability at the level of milliseconds, but with no convincing periodicities. When measured, the time-resolved spectra during the burst were often quite variable. Moreover lines were detected at ~400 keV, interpreted as originating from the annihilation of e^+/e^- at 511 keV, redshifted to 400 keV by the gravitational field of the compact source. Absorption lines at 20–40 keV were also observed by the KONUS instrument and convincingly confirmed by Ginga for a few GRBs. These lines were taken as an indication that GRBs were produced by strongly magnetized neutron stars (NS). These features were indisputably considered to be strong arguments for the association of GRBs with nearby Galactic neutron stars, isolated or in binary systems. The absence of counterparts for sources situated at few hundred parsecs (to accommodate the observed isotropy) was compatible with isolated NS or with NS in a binary system with a faint companion and a low accretion rate. The energy involved in GRBs was reasonable (10^{38} erg) due to the proximity of the sources and the sources had to emit 10^3–10^5 bursts to explain the observed rate of a few $\times\ 10^2$ GRBs per year. So by the end of this period NS models had been developed which explained the sources of GRBs reasonably well. The difference between GRBs and X-ray bursts was attributed to the lower accretion rate of GRB sources possibly accompanied by a higher magnetic field. It is finally interesting to note that the issues that would become crucial for cosmological models were already being addressed at that early time: photon–photon opacity and the non-thermal shape of the spectrum, fast variability, the nature of the radiation mechanism, and so on.

In 1991 NASA launched an ambitious mission, called the Compton Gamma-Ray Observatory (CGRO), which was quite successful. CGRO was so big (17 tons) that it had to be launched from the space shuttle. Planned for launch in 1986, it was delayed until 1991 after the tragic Challenger accident in January 1986. CGRO carried four science instruments, among them BATSE which improved the sensitivity to GRBs by about an order of magnitude. We analyze the major breakthroughs made possible by BATSE on CGRO in Chapter 2. Thanks to the sensitivity and to the long operating time of BATSE an unprecedented number of bursts (nearly 3000) was observed *with the same instrument*. The major properties of GRBs: duration, rapid variability, lack of periodicities, existence of two classes of GRBs, short and long, were completely confirmed. The non-thermal nature of their energy spectra and the spectral variability within a burst were confirmed and well studied. On the other hand, one very important result which had strongly influenced the neutron star paradigm described in Chapter 1, the presence of absorption lines at 20–40 keV, was not confirmed in any of the GRB spectra.

The isotropy of the angular distribution already observed before BATSE was quickly confirmed for hundreds of crudely localized GRBs. The sensitivity of the BATSE detectors, which allowed sampling GRBs five to six times more distant than previous detectors (a volume 100 to 200 times larger) and the large size of the sample made it possible to demonstrate the isotropy of weak GRBs. The $\langle V/V_{\max}\rangle$ test performed on BATSE GRBs demonstrated without any doubt a deficit of faint sources. The conjunction of the indisputable isotropy of the GRB distribution and the non-homogeneous distribution of these bursts is the most remarkable result of BATSE. This result presented decisive arguments for rejecting a GRB origin linked to nearby neutron stars in the Galactic Disk. This had dramatic consequences for the GRB energy scale. For a disk population at typically 100 pc the energy requirement per burst was 10^{38} erg. With BATSE this possibility was rejected and the minimum distance scale compatible with the isotropy of the sources was 100 kpc, corresponding to an extended corona around our Galaxy. In this case the energy released reaches $\sim 10^{44}$ erg. But even extended Galactic Halo models were having difficulties with BATSE results. Hence the idea that GRBs could be at cosmological distance (a few gigaparsecs) with enormous energies liberated in the GRB sources (beyond 10^{52} erg) was increasingly accepted.

Cosmological sources would obviously explain the isotropy of the angular distribution, the non-homogeneous distribution of sources and the lack of quiescent counterparts. But the non-thermal nature of the emission and the energy released remained crucial issues. The problem of cosmological models was the very large $\gamma\gamma$ opacity in the source, which would quench high-energy emission. Fortunately solutions were proposed early on involving the relativistic expansion of the source (the fireball). In the absence of counterparts many authors studied the statistical properties of the large GRB sample provided by BATSE in detail. The main purpose of these studies was the search for the expected consequences of the expansion of the Universe on cosmological GRBs: time dilation, spectral softening, and the flattening of the intensity distribution. These studies compared bright and faint GRBs, assuming that the faintest GRBs were on average the most distant. Unfortunately the intrinsic luminosity function of GRBs is so broad (and the range of redshift comparatively small, about a factor of 10) that it was not possible to disentangle cosmological effects from intrinsic properties convincingly.

Finally, despite the beautiful results of BATSE, the absence of counterparts at all wavelengths did not allow GRB sources to be identified. The major questions asked by B. Paczyński and others in 1992 were: How far away are GRBs? What are they? How do they generate gamma-rays?, and they remained without response.

Fortunately a new satellite devoted to X-ray and gamma-ray astronomy was launched in 1996. This Italian–Dutch mission, BeppoSAX, made it possible to detect and locate GRBs, to perform deep X-ray observations of them in the hours following detection, and eventually to discover their X-ray afterglows. This was a major breakthrough because, for the first time, the GRB localizations available in few hours were precise enough to use the largest ground-based telescopes, allowing the GRB afterglow at optical and radio wavelengths to be detected. Hence BeppoSAX solved the GRB mystery: the counterparts of GRBs were found, their distances measured, and their host galaxies identified. These explosions are really at cosmological distances, often at redshift $z = 1$ or more. BeppoSAX opened a brilliant new era for our understanding of GRBs. For these remarkable achievements the BeppoSAX team was awarded the Rossi prize of the American Astronomical Society in 1998 and the Descartes prize of the European Communiy in 2002.

In Chapter 3 we report the major results of BeppoSAX, which have been so important in elucidating some of the GRB mysteries. First, BeppoSAX made it possible to discover the X-ray afterglow of GRBs, which had been foreseen by theoreticians, and to provide precise GRB localizations in the hours following the burst. The afterglows, which remain detectable for hours and sometimes days, allowed us for the first time to study GRBs with the classical tools of astronomy: large optical and radio telescopes on the ground and X-ray telescopes in space. During the famous ‘GRB year’ 1997 several GRBs were discovered and rapidly followed up by multiwavelength observations, and their redshifts were measured thanks to optical spectroscopy with large ground-based telescopes, showing that GRBs take place at cosmological distances (i.e. gigaparsecs), with the consequence of a considerable energy release. At these distances GRBs are the most powerful explosions in the Universe, and over tens of seconds they liberate an energy equivalent to that produced by the Sun during its entire lifetime ($\sim 10^{10}$ years). In the same year one burst was detected at a large redshift, $z = 3.42$. The host galaxy was an actively star-forming galaxy which had produced a GRB at a time when the Universe was only 2 billion years old. Later, with Swift, GRBs would be observed at even larger redshifts. We have emphasized the energy problem; it is real because in some cases the GRB energy is found to be comparable with the energy associated with the rest mass of a NS if one assumes isotropic emission. This led very early to the introduction of the possibility of collimation of the GRB emission. If it is significant this can reduce the amount of emitted energy by two or three orders of magnitude, increasing the number of GRBs that have to be produced by the same factor. GRB collimation is extremely important and the ways to measure the collimation angle were widely discussed in this epoch. Achromatic breaks in the afterglow light-curves were expected if the bursts were collimated. These breaks have been observed in many visible afterglows, but the X-ray observations were often too scarce to confirm their achromaticity over a broad range of wavelengths. This critical issue would be reconsidered after the launch of Swift. The breaks observed in the visible afterglows permitted a measurement of the jet opening angle for several GRBs, and measurement of the true energy released in gamma-rays after correction for the beaming factor. Typical beaming angles range from 1° to 10°, implying that on average only one GRB out of a hundred or more has its jet directed towards the Earth.

BeppoSAX also provided crucial information on the progenitors of GRBs. The accurate astrometry of GRB afterglows within their host galaxies with the Hubble Space Telescope showed that GRBs occur in star-forming regions of star-forming galaxies. Since these regions harbor young massive stars which probably end up as black holes, models invoking the emission of relativistic jets by newly born stellar black holes were quickly favored. In 1998 BeppoSAX provided the first clue of a possible connection between a supernova (SN) and a GRB. It was noticed that the error box of the long GRB 980425 contained a new supernova SN 1998bw, whose time of explosion, measured to 1–2 day accuracy, was compatible with the time of the GRB. This important observation shed some light on the possible progenitors of GRBs. This SN–GRB connection, which would be confirmed later by HETE-2 and Swift, has been very useful in supporting the collapsar model, which is analyzed in Chapter 8; this model is based on the explosion of a massive star of Wolf–Rayet (WR) type leaving behind a black hole (BH) with a transient accretion disk as the source of the relativistic fireball. This GRB–SN association was an extraordinary revelation. Supernovae were mentioned when the enormous energy associated with a GRB was established, but after the discovery of this possible association GRBs really appeared to be connected with the explosions of massive stars. But of course special conditions were needed because the vast majority of supernovae do not emit the relativistic jet needed to produce a GRB (or at least the jet cannot escape from the star). This is illustrated by the fact that supernovae occur at a rate of about one per second in the observable Universe while GRBs occur at a rate of one per day (or one every 1000 seconds, correcting for beaming).

To fully appreciate the diversity and richness of the BeppoSAX results, the reader should also be aware that this mission has led to the discovery of many new features of gamma-ray bursts:

- The confirmation of the existence of a new sub-class of GRBs, called X-ray flashes (XRF), which emit the bulk of their energy around a few kiloelectronvolts, at energies significantly lower than classical GRBs. Apart from the softness of their emission the basic properties of XRFs have been found to be similar to those of classical 'hard' spectrum GRBs. This class of GRBs is analyzed in Chapter 4.
- The discovery of 'dark bursts' which have bright X-ray afterglows but no detectable optical afterglows. These dark bursts represent a significant fraction of BeppoSAX GRBs.
- The discovery of a correlation between the isotropic equivalent energy radiated by GRBs and the peak energy of their νF_ν spectrum. This correlation, and others discovered later, opened the possibility to use GRBs as cosmic rulers, as discussed in the final chapter (Chapter 9).

Clearly BeppoSAX was a watershed mission, which solved a significant part of the GRB mystery. With BeppoSAX it was not possible, however, to localize GRBs in seconds and to localize short GRBs. This would be the job of HETE-2 and particularly Swift, the following dedicated GRB missions that would reduce the time for GRB localizations to tens of seconds.

The beautiful results of Swift are reported in Chapter 4. Another mission, the small HETE-2 satellite dedicated to GRBs, had been launched before Swift. It has been quite successful because it was the first mission capable of distributing relatively precise GRB positions in several seconds, allowing the very early follow-up of the visible afterglow with robotic telescopes. As was to be the case for Swift, GRB data were analyzed on-board by powerful processors to determine the GRB position on the sky. In a few seconds this position was transmitted to the ground via a network of VHF receivers distributed along the Earth's equator. Hence the scientific community was alerted within tens of seconds of the trigger. These fast alerts made it possible to uncover the complexity of the early optical afterglow.

The connection of long GRBs with supernovae was fully confirmed in March 2003, when HETE-2 detected an extremely bright GRB associated with a supernova at redshift $z = 0.17$. In July 2005, a HETE-2 alert led to the discovery of the first optical afterglow of a short GRB, which was soon followed (two weeks later) by a second observation triggered by Swift. These observations opened the window on the study of short GRBs, their energetics, their host galaxies, and their possible progenitors. Finally, the study of many X-ray flashes with HETE-2 showed that they are nothing other than soft GRBs. Thus, while confirming the link of long GRBs with supernovae, HETE-2 observations opened the field up by showing that short GRBs and XRFs share the basic properties of long GRBs, raising the question of what the progenitors of these events were. The models which have been proposed to explain the observed large diversity of GRBs (see Chapter 5) suggest that the emission of relativistic jets by dying stars, mergers, or magnetars might be a very general mechanism which would explain classical GRBs, XRFs, and short GRBs. Before analyzing the very ambitious Swift mission, Chapter 4 presents a remarkable contribution of the INTEGRAL ESA mission: the spectacular X-ray halos observed around GRB 031203 due to a large cloud of dust in our Galaxy located along the line of sight of the distant GRB. This is another illustration of the power of GRBs for the study of all the matter along the line of sight, from our Galaxy to the most distant host galaxies, through gigaparsecs of intergalactic medium.

The second part of Chapter 4 is entirely devoted to several major breakthroughs from the Swift satellite, launched in November 2004 and still in operation in 2008, with a typical rate of two GRBs detected per week (compared with two GRBs per month for BeppoSAX and HETE-2). The major advantage of Swift is its unique autonomous rapid slewing capability to track GRBs and their afterglows with minimum dead time. X-ray afterglows are observed as early as 50–70 s after the trigger and can be followed for days to weeks; this delay is only slightly longer for the Ultra-Violet/Optical Telescope (UVOT). The large effective area of its Burst Alert Telescope ($5000\,\mathrm{cm}^2$) gives an excellent sensitivity and allows the detection of GRBs at higher redshifts, which explains why the mean redshift of Swift GRBs ($\langle z \rangle \sim 2.75$) is more than twice as large as that of pre-Swift bursts.

Swift's fast response has led to a completely new view of the early X-ray afterglow with well-defined phases which were previously unknown: after the prompt emission there is a phase of rapid decline which is followed by a late shallow phase preceding the standard decay, observed by BeppoSAX a few hours after the burst. In addition, about half the Swift GRBs exhibit late X-ray flares superimposed on the smooth decay. This newly discovered behavior is analyzed in Chapter 7, with proposed explanations. It seems in particular that the shallow phase and the X-ray flares suggest a long-lasting activity of the central engine (several hours). In Chapter 7 we also revisit the critical issue of the existence of achromatic breaks in the afterglows, which could be interpreted as jet breaks. The excellent coverage of X-ray afterglows with Swift led to the conclusion that truly achromatic breaks are rare, casting some doubt on the jet interpretation of the breaks seen in optical afterglows. This was another unexpected finding of Swift.

The report of Swift results would not be complete without the analysis of some exciting bursts that were detected by this satellite. We discuss four of them in detail. GRB 060218 was a low redshift X-ray flash ($z = 0.033$) whose supernova was studied in great detail, with the detection of the shock when the supernova broke out from the upper layers of the star. GRB 050904 at $z = 6.3$ is one of the most distant GRBs. It exploded when the Universe was ~900 million years old, almost at the end of the epoch of re-ionization. Given the brightness of GRBs, these detections provide a unique way of probing the Universe when the first stars were formed. GRB 061007 is one of the brightest bursts detected by Swift, and it had excellent follow-up observations at all wavelengths. GRB 060614 is a nearby long GRB ($z = 0.125$) with no associated supernova, which raises questions on the diversity of GRB progenitors.

Finally, the discovery of several afterglows of short GRBs is a major Swift breakthrough. The initial sample, still limited, suggests that these bursts might have progenitors different from those of long GRBs. Even though the classification of long and short GRBs may be too simple, it nevertheless seems that the presence of two kinds of progenitors, corresponding to the deaths of massive stars and to the coalescence of compact objects, is required. These progenitors are extensively analyzed in Chapter 8.

The observational discoveries reported in Chapters 1–4 were accompanied by the development of GRB models explaining their main properties. Among them the GRB internal–external shock model has received a lot of attention and it rapidly became the "standard" model for GRB. In Chapters 5 and 6 we outline its main characteristics. In Chapter 5, we examine how internal shocks can explain the prompt emission starting from the behavior of relativistic fireballs. Since the photospheric emission of such fireballs cannot explain GRB non-thermal emission, shocks were rapidly added to the model: internal shocks and external shocks, which explain the prompt emission and the afterglow, respectively. We first present some basic elements of this standard model: the content of the fireball with its particles and magnetic fields, the shocks associated with ultra-relativistic fireballs, the acceleration of electrons in relativistic shocks and the resulting electron spectrum. The presence of these accelerated electrons and magnetic fields leads naturally to the consideration of the production of photons by synchrotron and/or synchrotron self-Compton emission. The characteristics of the resulting photon spectra, which can explain the GRBs and their afterglows, are briefly presented.

The second part of Chapter 5 concentrates on internal shocks. These shocks were introduced when it appeared that it was difficult to explain the fast temporal variability (at the level of tens of milliseconds) found in many GRBs with external shocks. Internal shocks can appear within a relativistic outflow if the Lorentz factor of the wind is variable. In this case, successive shells can have large relative velocities and fast shells injected after a slower one will eventually catch up and collide with it. This is the origin of internal shocks, assumed to be the result of multiple two-shell interactions. Internal shocks occur close to the central engine (10^{14-15} cm) where the fireball is denser with higher magnetic field, producing synchrotron radiation in the X-ray and gamma-ray ranges. Many authors have studied the hydrodynamics of internal shocks and have shown that they can easily explain the multiple timescales observed in the GRB light-curves provided that the source itself is variable. In fact the observed temporal structure reflects the activity of the inner engine that drives the GRB. But internal shocks, even though they explain the properties of the GRB light-curves, meet with some difficulties. The two major issues are the compatibility of the spectral shape of the prompt emission spectra with the prediction of the synchrotron–shock model and the low radiative efficiency of internal shocks. We briefly mention the different solutions which have been proposed to resolve the first issue. The second point, concerning the efficiency of internal shocks, is more critical: the estimates of the ratio of the energy radiated in gamma-rays to the kinetic energy of the ejecta can sometimes reach 50%, while it is expected to be low, typically less than 10%. We analyze this question and the solutions which have been proposed to increase the radiative efficiency of internal shocks. The debate on this question remains, and it has been amplified by the results of Swift, which suggest that late energy injection could increase the required radiative efficiency. Despite these open issues the internal shock model remains the favorite to explain the prompt GRB emission. Nevertheless, this chapter closes with a short discussion of other models, proposed to explain the prompt GRB emission, which avoid internal shocks. We mention in particular the electromagnetic model, with its Poynting flux, as a very attractive way to carry the energy in the flow. The possibility of a fireball which is more or less dominated by Poynting flux certainly needs to be studied thoroughly in the future.

The first part of Chapter 6 deals with the analysis of GRB afterglows in the framework of the standard model. It is followed by a second part which introduces the additional complexity needed to achieve a better agreement between the model and the properties of the afterglows observed with BeppoSAX and later HETE-2. We have indicated that internal shocks appear when the fireball coasts with constant Lorentz factor $\Gamma \sim 100$. This shell is cold, because the initial internal energy has been transformed into bulk kinetic energy. At the beginning of the coasting phase the medium has no influence on the expanding shell. As the shell progresses, it drives a shock into the interstellar medium (ISM) or the circum-burst medium; behind the shock the ISM is heated. As the shell radius R increases, more ISM is shocked and the shell is progressively influenced by the ISM. This influence is significant when the energy of the heated ISM becomes comparable with the initial energy of the fireball. So the afterglow emission begins when most of the energy of the ejecta has been transferred to the shocked external medium.

The presence of an afterglow was anticipated when the fireball model was first proposed. It includes the forward and the reverse shock (which was not considered in the basic standard model). We indicate how the energy spectrum of the afterglow can be calculated assuming synchrotron emission and fast or slow cooling. The afterglow light-curves are also obtained for radiative and adiabatic evolution. The temporal decay index α and the spectral index β of the afterglow are related by 'closure relations', which are formulated for various conditions: fast or slow cooling, adiabatic or radiative evolution, and various environments (ISM or wind). After the discovery of the afterglows of a dozen GRBs the gross characteristics of their light-curves and spectra have confirmed that the fireball model is robust. But with the observation of more and more afterglow light-curves at different wavelengths it rapidly became clear that the basic standard model was too simple. Indeed it considers spherical fireballs with an impulsive energy input and a single value of the Lorentz factor. In addition the highly relativistic expansion of the fireball is assumed to occur in a homogeneous external medium and in the adiabatic regime. The shock acceleration parameters $p, \varepsilon_e, \varepsilon_B$, are assumed constant for a given GRB. Finally, as we have said, the reverse shock is not taken into account. Even though this basic model was successful in explaining the first BeppoSAX results, it quickly became necessary to consider more complex conditions. These conditions are presented in the second part of Chapter 6.

The following elements have been progressively added to complete the basic fireball model: