Doctoral Thesis in Physics

Investigating subphotospheric dissipation in gamma-ray bursts by fitting a physical model

Björn Ahlgren

Particle and Astroparticle Physics, Department of Physics, Royal Institute of Technology, SE-106 91 Stockholm, Sweden

Stockholm, Sweden 2019
Cover illustration: GRB Science flow chart. Figure produced by Björn Ahlgren.

Akademisk avhandling som med tillstånd av Kungliga Tekniska högskolan i Stockholm framlägges till offentlig granskning för avläggande av teknologie doktorsexamen fredagen den 29 mars 2019 kl 13:00 i sal FA31, AlbaNova Universitetscentrum, Roslagstullsbacken 21, Stockholm.

Avhandlingen försvaras på engelska.

ISBN 978-91-7873-140-4
TRITA-SCI-FOU 2019:14
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Printed by Universitetsservice US-AB
Abstract

Gamma-ray bursts (GRBs) are the brightest events in the Universe, exploding with isotropic equivalent luminosities up to $10^{54}$ erg s$^{-1}$. These events are related to supernovae and to mergers of compact objects in binaries. The origin of the so-called prompt emission in GRBs remains an unsolved problem, although progress is being made. Spectral analysis of prompt emission has traditionally been performed with the so-called Band function, an empirical model with no physical interpretation. It is just recently that physical models have started to be used in the analysis. This thesis presents spectral analysis of gamma-ray and X-ray observations of GRBs from the Fermi Gamma-ray Space Telescope and the Neil Gehrels Swift Observatory using a physical model for subphotospheric dissipation called DREAM (Dissipation with Radiative Emission As a table Model). The model is developed using a numerical code and implemented as a table model in XSPEC. The model begins as a proof-of-concept and is developed throughout the thesis. Time-resolved spectral analysis is performed using both frequentist and Bayesian methods. It is found that the physical scenario is capable of describing a large number of the analysed spectra, with the successfully fitted spectra covering the full range of observed spectral slopes. The major cause for inadequate fits is a high luminosity, meaning that the model is unable to account for the most energetic GRBs. This shows that if the prompt emission has a photospheric origin, the dissipation cannot only be by internal shocks. Modifications to the model are also discussed, as well as correlations between model parameters. These results illustrate the importance of fitting a physical model directly to data in order to make reliable inferences about the model scenario.
Sammanfattning


Artikel I beskriver hur tabell-modellen konstrueras, samt är en konceptvalidering för tabell-modeller inom spektralanalys för gammablixxar och för att anpassa data med en fysikalisk modell. I det här pappret anpassas modellen till data från två gammablixxar och resultaten jämförs med motsvarande anpassningar med Bandfunktionen. Slutsatsen är, förutom att demonstrera metoden, att modellen kan beskriva flera typer av spektrum, inklusive spektrum som inom ramen för Bandmodellen beskrivs med hjälp extra spektralkomponenter.

I artikel II utvecklas modellen för subfotosfärisk dissipering vidare, parameterrymden för modellen utvidgas och analysverktygen förbättrar. Dessutom introduceras adiabatisk kylning i modellen och en mer ingående analys av osäkerheter i modellen genomförs. En tidsupplöst spektralanalys görs på en samling av 36

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Introduction

Space, is big. Really big. You just won’t believe how vastly, hugely, mindbogglingly big it is. I mean, you may think it’s a long way down the road to the chemist’s, but that’s just peanuts to space (Adams, 1979). Despite this, people have been trying to make sense of it for as long as there have been people; from just looking up at the night sky and wondering about all those small shiny dots, and about the other really quite big one, to more recent queries regarding the properties of space-time in proximity of particularly exotic states of reality. One such relatively recent conundrum, probably located somewhere in between the two aforementioned questions, is the nature of gamma-ray bursts (GRBs).

GRBs are rare, cosmological events, isotropically distributed on the gamma-ray sky. Despite being rare on a cosmological level we are currently observing about one burst every day. This is because of the vast distances over which we can observe these events. A GRB is seen as the release of a tremendous amount of energy in gamma-rays, the isotropic equivalence of up to a solar mass of energy, in a time span of between a fraction of a second and a few minutes. The extreme luminosities, \( L \sim 10^{50-54} \text{ erg s}^{-1} \), for isotropic equivalent energies, make these events not only visible at cosmological distances, but also the most distant objects in the Universe that we are able to detect. Fig. 1 shows the distribution of observed GRBs as a function of redshift. The average redshift is \( \sim 2 \), which corresponds to a distance of about \( 5 \times 10^{10} \) light years.

GRBs were first observed in 1967, by the Vela satellites as brief flashes of gamma-rays of extraterrestrial origin. It was not until several years later, 1973, that the findings were published in Klebesadel, Strong, and Olson (1973). At this point it was completely unknown what these events were, as was their extragalactic origin. It was not until the 1990’s that it was concluded that the observed GRBs were indeed not from our own galaxy. One of the keys to this conclusion was their angular distribution. With the Burst and Transient Source Experiment (BATSE; Fishman et al., 1989), which was mounted on the Compton Gamma Ray Observatory (CGRO; Gehrels, Chipman, and Kniffen, 1994), it was possible to determine GRB positions precisely enough to infer that they are isotropically distributed across the sky (Briggs et al., 1996).

The Beppo-SAX satellite (Boella et al., 1997) was launched in 1997 and showed, by measurements of fading X-ray signals in some GRBs, that GRBs in addition to
their prompt gamma-ray emission (i.e. the early onset of high-energy emission) also have afterglows at longer wavelengths (Costa et al., 1997). X-ray afterglows often last long enough to conduct follow-up observations in optical and radio wavelengths. These observations in turn allowed for sufficiently precise localisations to identify host galaxies and their corresponding redshifts (Metzger et al., 1997). This settled the question of their extragalactic origin.

Today, more than two decades later, many questions regarding GRBs remain unanswered. One of them is the origin of the prompt emission, which is the topic of this thesis. The thesis is structured such that it starts with this general introduction, followed by six chapters introducing gamma-ray bursts (GRBs) and some of the key concepts of the work. Chapter 1 is devoted to giving an overview of GRBs, including their progenitors. In Chapter 2 I go through some of the basic theoretical concepts that lay the foundation for the work in the thesis, such as relativistic Doppler shift and frames of reference. I also give an overview of the GRB fireball model. Chapter 3 gives an overview of prompt emission, which is the part of GRBs mainly studied in this work. Chapter 4 describes the numerical implementation of the physical model which has been the primary product of this thesis, called the DREAM model. I also describe the numerical code from which the model is built. In Chapter 5 I briefly present the instruments with which the majority of the data examined here has been observed. In Chapter 6 I present the data analysis and review some of the statistical tools and concepts used in the thesis. Finally, Chapter 7 presents an outlook. This thesis is based on my previously published Licentiate thesis (Ahlgren, 2016).

The bulk of the work is presented in the form of three articles, appended at the back of the thesis, of which the first two articles are published and the third is a
draft which is soon to be submitted. These article are listed and summarised next in the next section.

Throughout the thesis, I use cgs units and all errors are 1σ unless otherwise stated. I have assumed standard Λ-CDM cosmology with $H_0 = 67.3$, $\Omega_\Lambda = 0.685$, and $\Omega_M = 0.315$ where it is relevant (Planck Collaboration et al., 2014).
List of publications

Publications included in the thesis

Paper I
Ahlgren et al. (2015), Confronting GRB prompt emission with a model for subphotospheric dissipation

Paper II
Ahlgren et al. (2019a), Testing a model for subphotospheric dissipation in GRBs: fits to Fermi data constrain the dissipation scenario

Paper III (Draft)
Ahlgren et al. (2019b), Searching for subphotospheric dissipation in prompt GRB emission using joint Fermi-Swift observations
Additional publications not included in the thesis

Paper IV
Iyyani et al. (2015), Extremely narrow spectrum of GRB110920A: further evidence for localized, subphotospheric dissipation

Paper V
Valan et al. (2018), Thermal components in the early X-ray afterglows of GRBs: likely cocoon emission and constraints on the progenitors
Author Contribution

Paper I

All coding, data reduction and analysis was done by me, except for creating the code that turns simulation output into a table model, which was created by Tanja Nymark. The manuscript was written by me, with comments from the co-authors. All the figures are created by me.

Paper II

I performed all coding, data reduction and analysis, except for:

- creating the original Monte Carlo code for assessing goodness of fit and systematic uncertainties, which was used in the initial evaluations of the model. This code was created by Erik Ahlberg.

- the post-processing of a spectrum in Fig. 3, which was performed by Christopher Lundman, using his simulation code. Additionally, it was he who suggested the idea of introducing the adiabatic cooling factor, \( a \).

The manuscript was written by me, with comments from the co-authors. All the figures are created by me.

Paper III

All coding, data reduction and analysis was performed by me. The manuscript was written by me, with comments from the co-authors. All the figures are created by me. I proposed the idea that we use Bayesian inference and customised the necessary software.

All work has been performed with the guidance of my supervisor, Josefin Larsson, and co-supervisor, Felix Ryde.
Acknowledgments

First, I would like to thank my supervisor, Josefin Larsson, for her support and patience, and for being so generous with her time, and my co-supervisor, Felix Ryde. I would also like to thank the people with whom I work, particularly Vlasta, for always listening to my complaints about endless programming and statistics related mysteries and discussing them with me, as well as for the great company. Also Rakhee and Nirmal for their kindness and constant positivity. Thanks to Mikael, for the help on all computer related matters (Alakazam would be in a sorry state without you), and even more so for the great lunch company and strolls.

Thanks also to the AlbaNova gym, without which I would have been both mentally and physically weaker. Nothing has cleared my mind from frustration and helped me solve problems as much as an hour or two in the gym. Of course, the experience would not have been half as fun without the small community of gym regulars. I have had some of my most enjoyable moments at AlbaNova in the welcoming and sweaty, although surprisingly well-ventilated, atmosphere of the AlbaNova gym. It is a special place, where you can discuss research while on the bench press, with people who are proficient in both aspects. It is also a place for improving your Russian through immersion, though I suspect with a biased vocabulary. These things are, I find, much harder in regular gyms.

To my family for their support. My mother, for always listening, and my father, for the peace I find in Klapparvik. Also, to my friends, particularly my Dalton brothers; Martin, Emil, and Axel. I don’t want to know where I would have been without you, but I know it would not have been half as enjoyable. And to the many others, you know who you are. Lastly, I would like to thank my wonderful fiancée, Nabila, a constant source of joy in my life, for always being there with support and love.
Chapter 1

Gamma-ray bursts

“In the beginning the Universe was created. This has made a lot of people very angry and been widely regarded as a bad move.”


Here I briefly present our current understanding of GRBs and outline some of the models used to describe the different phases of GRBs as well as some of the characteristic spectral features of the radiation. For a more complete overview of GRBs, see e.g. Piran (1998), Mészáros (2006), and Kumar and Zhang (2015).

1.1 Introduction

With the launch of BATSE in 1991, the number of detected bursts increased rapidly. By analysing burst durations, two classes of GRBs, long and short, were identified (Kouveliotou et al., 1993). The simplest way to illustrate this is to plot a histogram of burst durations in logarithmic scale where two populations are visible to the naked eye, with a divisor at \( \sim 2 \) seconds, which has been set as the delimiter between the two populations. See Fig. 1.1 for an example of such a plot. Since it might be ambiguous when a burst has ended, the \( T_{90} \) is used instead, which is defined as the time when 90 percent of the radiation has been observed. There have been claims of more than two populations (Howell and Coward, 2013), but there is no conclusive evidence and the statistical significance of an intermediate populations is negligible (Bhat et al., 2016). However, there have been a few observation of ultra-long GRBs, with durations on the order of 10 000 seconds (Levan et al., 2014). These bursts have been suggested to have different origins than long and short bursts. However, due to their small number the evidence for this is inconclusive (Zhang et al., 2014).

Long bursts have been found to be associated with high redshifts, typically 1–2, whereas the short bursts are predominantly found at lower redshifts. However, it is generally harder to measure the redshift for short bursts (Gehrels et al., 2003).
Furthermore, we observe a greater number of long bursts than short bursts and the short bursts also have an isotropic equivalent luminosity which is typically a few orders of magnitude lower than that of long bursts (Barthelmy et al., 2005a; Fox et al., 2005; Panaitescu, 2006).

1.2 Progenitors

Observations show that long GRBs are associated with core collapse supernovae. The first joint detection of a GRB with a supernova came in 1998 when a supernova was discovered together with GRB 980425 (Galama et al., 1998). This provided strong support for the connection between supernovae and GRBs. Since then there have been many joint observations of GRBs and supernovae, including spectroscopic analyses and measured redshifts, which have confirmed that the events are related. See Cano et al. (2017) for a recent review. Further analysis of long GRBs have revealed that they are mainly found in galaxies with high star forming rates (Krühler et al., 2015), which is also consistent with their relation to the death of massive stars.

Short GRBs were, until recently, a more elusive matter. Theoretical models suggested, and indirect observations later confirmed, that short GRBs are the result of compact object mergers (neutron star-neutron star or black hole-neutron star) (Berger et al., 2003). This was recently further confirmed through the direct detection of a neutron star-neutron star merger by the LIGO and Virgo collaboration, GW 170817 (Abbott et al., 2017a). Rapid follow up searches were conducted...
1.2. Progenitors

in all electromagnetic wavebands (Abbott et al., 2017). This lead to, amongst oth-
ers, that the expected signal from a kilonova, induced by an abundance of r-process
nucleosynthesis, could be identified, (Abbott et al., 2017a). Additionally, about 2
seconds after the GW signal, *Integral* (Winkler et al., 2003) and *Fermi* both de-
tected a short GRB from a position consistent with that of GW 170817 (Abbott
et al., 2017b).

Since long GRBs constitute the majority of observed GRBs (between 70-90
percent Tarnopolski, 2015) and have long durations, which facilitates follow up ob-
servations, they have been studied in greater detail than short bursts. However,
there have still been afterglows observed for short GRBs, which reveal that they
are found in a plethora of galaxies, not only in those with high star formation rate
(Bloom et al., 2006; Berger et al., 2007). Additionally, they can be found outside of
their host galaxies, which is consistent with the binary merger scenario (Narayan,
Paczynski, and Piran, 1992). For a review of short GRBs, see e.g. Berger (2014).

Regardless of the progenitor, the main source of the GRB energy likely comes
from accretion of matter onto a compact object, releasing gravitational energy.
This process is the most efficient means of releasing energy in the Universe, short
of matter anti-matter annihilation. For massive stars this is referred to as the
collapsar model (MacFadyen, Woosley, and Heger, 2001). Whether the progenitor
is a massive star or merging compact objects a black hole is expected to form,
along with an accretion disk. A fraction of the energy released by the gravitational
collapse of this disk yields the electromagnetic radiation we observe in the early
stages of the emission (i.e. the prompt emission). Furthermore, this is essentially
why we would not expect GRBs as a result of a binary black hole merger, as this
is believed to be a clean system with little matter to accrete. However, there
are models predicting GRBs from such systems (Loeb, 2016). Additionally, if the
progenitor is a massive star undergoing core collapse we expect the majority of the
energy to be released in the form of thermal neutrinos. In the event of compact
object mergers we would expect a significant fraction of the energy to be converted
into gravitational waves. As discussed above, this has recently been confirmed by
observations.

There is another model scenario, in which a rapidly rotating proto-neutron star
is created instead of a black hole. For a rotational period of ~ 1 ms and surface
magnetic fields on the order of $10^{15}$ G, this is known as a magnetar (Usov, 1992;
Thompson, 1994). In this scenario, the energy released in the collapse, or merger,
is converted into magnetic fields, which yield a Poynting flux dominated outflow.
This magnetic energy then propels the jet out from the magnetar (Uzdensky and
MacFadyen, 2007), leading to the observed prompt emission. One observational
justification for this model is a plateau like featured in the X-ray band observed
by the SWIFT satellite in some GRBs (Zhang et al., 2006; Nousek et al., 2006).
This behaviour can be explained for magnetically dominated outflow by letting
the plateau be the result of residual rotational or magnetic energy which may continue
to inject energy into the outflow at these later stages (Metzger et al., 2011).
1.3 Relativistic outflows in GRBs

The prompt emission is the early onset of high-energy emission observed from GRBs. The observed durations of prompt emission vary widely and span more than six decades in time, from 0.01 seconds for the shortest bursts up to several hours for the bursts with the longest durations, e.g., GRB 111209A, which has a duration of more than seven hours (Gendre et al., 2013). Burst duration is not the only temporal attribute to vary between bursts; the variability time is another useful concept in GRB physics and is usually derived from the width of the peaks in the lightcurve. Variability has been observed down to a level of milliseconds in some long bursts (Nakar and Piran, 2002). The observed variability sets powerful constraints on theoretical models as it limits the size of the emission region (Sari and Piran, 1997).

Due to the fast variability of GRBs we can conclude that the size of the emitting region must be small. The fastest variabilities observed at the ~ millisecond level correspond to an emitting region of ~ $10^7$ cm, approximately the same size as a Schwarzschild radius of a 30 solar mass black hole, in order for time delays from different regions of the source not to smear the signal. Given the small emission region and and the high isotropic equivalent luminosity of typical bursts, the radiation would be optically thick due to pair production of photon-photon interactions, leading to suppression of the high-energy emission. For the radiation to escape we infer relativistic outflows with high Lorentz factors, typically in excess of 100, meaning that the outflow is highly relativistic and beamed, see e.g. Lithwick and Sari (2001).

There are several additional arguments for why GRBs should emit in relativistic, collimated outflows, including observed jet-breaks in GRB afterglows (Sari, Piran, and Halpern, 1999). This effect is caused by two things, the first of which is that the edge of the jet becomes visible as it slows down by sweeping up material. This is a result of relativistic beaming (relativistic beaming is covered in Chapter 4). An observer located along the jet axis perceives the radiation to be isotropic from the source. As the Lorentz factor of the outflow decreases, more of the jet becomes visible to the observer due to the opening angle of the photon beaming increasing (i.e. the relativistic beaming decreasing), until photons from the entire width of the jet reaches the observer. When the Lorentz factor decreases further, the increased spreading of the photons from any given part of the jet is no longer compensated by more of the jet becoming visible, and there is a sudden drop in observed flux. Secondly, as the jet slows down it starts to spread laterally, causing a further decrease in the observed emission. This has been shown to occur at a similar time as the first effect (Sari, Piran, and Halpern, 1999, Rhoads, 1999).

Another feature of jetted emission is that it relaxes the energy requirements of bursts. As noted in the introduction, the isotropic equivalent energies released are huge, and challenging to model. When calculating the isotropic equivalent energy it is assumed that the energy released from the GRB is emitted equally in every direction (hence the name). Thus, if the bursts instead emit radiation in jets the
the total energy required may decrease by more than a factor of 100 (Harrison et al., 1993).

1.4 Emission phases and light curves

As previously mentioned, GRB emission is divided into two parts; prompt emission and afterglow, originating from different processes and locations in the GRB. Despite its short duration, the bulk of the emitted electromagnetic radiation lies in the prompt emission.

There are several features of prompt GRB emission, but perhaps the single most striking characteristic is that GRB lightcurves seem to be unique. There appears to be no systematic patterns in GRB prompt lightcurves, not in how long the emission lasts, how many peaks they have, or the properties of the peaks. Fig. 1.2 contains examples of 12 light curves, which clearly display this erratic behaviour. The prompt emission is sometimes foregone by a short precursor. This is seen in the lightcurve as a small, brief spike, usually a few seconds up to minutes prior to the bulk of the prompt emission (Bernardini, 2015). For long GRBs, jet breakouts from the stellar mantle (Ramirez-Ruiz, MacFadyen, and Lazzati, 2002), or central engine activity in the collapsar scenario (Wang and Meszaros, 2007) have been suggested as possible mechanisms for the precursor. For short GRBs, similar mechanisms have been suggested, where the precursor is a result of either central engine activity or interaction of the jet with a pre-ejected baryonic wind (Troja, Rosswog, and Gehrels, 2010).

Regardless of the underlying emission mechanisms of prompt emission and of progenitor we would expect the emerging jet to produce shocks as it collides in the surrounding medium. These shocks produce radiation at lower energies and longer time scales than the prompt emission and it is this emission which is known as the afterglow. When the afterglow was first discovered by Beppo-SAX it was in terms of fading X-emission from GRB 970228, found eight hours after the detection of the prompt emission, which later also led to the first optical afterglow (Costa et al., 1997). In general, the early X-ray emission of GRB afterglows is described by the canonical X-ray afterglow light curve, outlining up to five different phases of the X-ray afterglow (Zhang et al., 2006). This emission usually lasts up to a few days. The previously mentioned jet break typically occurs after about a day. Successively longer wavelengths persist after the X-ray emission has faded, with the optical emission typically lasting months and the radio emission lasting up to several years. However, only about 50% of all long GRBs have detected optical or radio afterglows (Greiner et al., 2011). GRB afterglows are relatively well understood compared to the prompt emission. The spectra are typically well represented by a power law or broken power law, and can be accounted for by the standard models of external shocks (Zhang, 2007). For particularly bright afterglow data, features beyond a power law can be distinguished, such as bumps in the spectrum which are not accounted for by the simplest afterglow models (Bernardini et al., 2010).

This thesis’ main concern is the origin of the GRB prompt emission.
Figure 1.2. Example of gamma-ray light curves of GRB prompt emission. The figure is made by Daniel Perley using data from the public BATSE archive, [http://gammaray.msfc.nasa.gov/batse/grb/catalog/](http://gammaray.msfc.nasa.gov/batse/grb/catalog/).
Chapter 2

Theory and modelling

“All you really need to know for the moment is that the universe is a lot more complicated than you might think, even if you start from a position of thinking it’s pretty damn complicated in the first place.”


In this chapter I briefly present some of the key concepts in GRB physics. More extensive descriptions of these concepts can be found in the reviews by e.g. Pe’er (2015), Piran (1999), Kumar and Zhang (2013), and Mészáros (2006).

2.1 Relativistic outflows and frames of reference

Working with velocities close to the speed of light, $c$, the theory of relativity and particular frames of reference become important. In this section I cover the Lorentz transformation, present the Doppler shift formula for relativistic outflows and discuss the most important frames needed. Starting from the theory of special relativity, the Lorentz transformation between two frames of reference, $K$ and $K'$, can be written as

$$t' = \Gamma \left( t - \frac{\beta}{c} x \right),$$  \hspace{1cm} (2.1)

$$x' = \Gamma (x - vt)$$ \hspace{1cm} (2.2)

where primed coordinates belong to the comoving frame, $K'$. This notation will be maintained throughout the thesis. It is assumed that $K'$ moves with a uniform
speed \( v \) along the \( x \) coordinate of \( K \) and that the origins of the two frames coincide at \( t = 0 \). Furthermore, \( \beta = v/c \) and \( \Gamma \) is the Lorentz factor, defined as

\[
\Gamma = \frac{1}{\sqrt{1 - \beta^2}}.
\]

This leads to the concept of length contraction, such that a rigid rod of length \( L' = x_1' - x_0' \), when travelling in the comoving frame \( K' \), has a length \( L = x_1 - x_0 = L' / \Gamma \) in \( K \), using Eq. 2.1 and 2.2. Hence the rod is shorter by a factor of \( 1/\Gamma \) when measured in a frame where it is perceived to be moving. Naturally, this effect is symmetrical between the two frames and hence an observer in the frame \( K' \) would likewise consider the same rod, now being at rest in frame \( K \) to be similarly contracted by the factor \( 1/\Gamma \). However, there is no paradox involved in this effect and the difference in perceived length is an effect of what is considered to be simultaneous events in the two frames. When a rod is measured in a frame, both ends of the rod are measured simultaneously in that frame, but not according to an observer in another frame. Similarly, time dilation obeys \( T = \Gamma T' \), where \( T \) and \( T' \) is the duration of a process as measured in the frames \( K \) and \( K' \), respectively. Thus, a process in the comoving frame lasts longer when measured in the rest frame.

When discussing these concepts in an astrophysical setting, there are a few standard frames of reference, pertaining to different situations. The lab frame for GRBs typically refers to the frame where the jet is moving at relativistic speeds, \( \beta \), and where the progenitor is non-moving, i.e. the stellar rest frame for our purposes. Additionally, there is the observer frame, which is the same as the lab frame, except for the cosmological redshift factor, associated with cosmological distances due to the expansion of the Universe. This induces a shift of energies by a factor \( 1/(1 + z) \) in the observer frame, i.e. \( E_{\text{obs}} = E_{\text{lab}}/(1 + z) \), where \( z \) is the cosmological redshift. There is also the rest frame, or sometimes the comoving frame, which in our case will usually refer to the rest frame of the emission region. This is typically some part of the GRB jet, often travelling with a Lorentz factor \( \Gamma >> 1 \) relative to the lab frame. This will be stated clearly if there is any risk of ambiguity.

Additionally, I will discuss photons from relativistic sources as observed in the lab frame. Although time dilation will make processes in \( K' \) appear longer than in \( K \) there is an additional effect to take into account when considering photons from sources propagating with relativistic velocities. If the source is assumed to propagate at an angle \( \theta \) and with a relativistic velocity \( \beta \), relative to the observer situated in the lab frame, a photon emitted at time \( t_0 \) and one emitted at \( t_1 \) are observed with a time difference of \( \Delta t'_{\text{obs}} = \Delta t' \Gamma (1 - \beta \cos \theta) = \Delta t' / \mathcal{D} \), where I have introduced the Doppler shift formula,

\[
\mathcal{D} = \frac{1}{\Gamma (1 - \beta \cos \theta)}.
\]

Similarly, the observed frequency of a photon emitted from a relativistic source is \( \nu = \mathcal{D} \nu' \). Additionally, the comoving temperature transforms as \( T = \mathcal{D} T' \).
It is illustrative to consider this Doppler factor for different angles, $\theta$. For $\theta = -\pi$, i.e. for a receding source, $D \sim 1/2\Gamma$, whereas for an approaching source, with $\theta = 0$, a series expansion of $\beta(\Gamma)$ yields $D \sim 2\Gamma$.

Additionally, when considering an isotropically emitting source, travelling at relativistic speeds towards an observer, the radiation is beamed towards the observer. Consider a photon which is emitted at a comoving angle of $\theta' = \pm \pi/2$, with respect to the direction of motion of the source. This angle is given by $\sin \theta = \pm 1/\Gamma$ in the lab frame, and for $\Gamma \gg 1$, this becomes $\theta \sim \pm 1/\Gamma$. This is known as relativistic beaming, and is, apart from being a fundamental feature of relativistic sources, important when considering e.g. jet geometries and variability time scales.

### 2.2 The fireball model

Here I present the schematics of the most popular GRB model; the fireball model (Goodman, 1984; Paczynski, 1986; Shemi and Piran, 1990; Rees and Meszaros, 1992). For recent reviews of the fireball model, see the references given at the beginning of this chapter. I outline the derivations of the scaling laws for the temperature of the plasma, as well as the Lorentz factor of the bulk outflow, and define the saturation radius and the photospheric radius.

Beginning from the arguments presented in Section 1.3, a huge energy, typically in excess of $10^{52}$ erg, is released in the collapse of a massive star, or through the merging of two compact objects. This energy is assumed to be released in a few milliseconds inside a volume approximately the size of a Schwartzchild radius. In the centre of the region, a compact object, either a black hole or a magnetar, is formed, onto which the surrounding material can accrete and possibly supply more energy to the GRB. However, the nature of this process is not well understood. The majority of the energy is converted into neutrinos and gravitational waves, which can escape the GRB unhindered. A small fraction, a few per mille to a few percent of the energy, forms an opaque fireball in the form of a plasma of $e^\pm$, photons and baryons. Due to the high opacity the fireball is in thermal equilibrium at this stage. Additionally, there are scenarios where the outflow may also carry magnetic fields with comparable energy content to that of the thermal energy of the fireball. The dynamics of the outflow, and thus the scaling laws presented below, depend on the magnetisation. Below I assume the fireball to be photon-dominated, a so-called "hot fireball", with low magnetisation. Conversely, an outflow dominated by magnetisation is known as a "cold fireball", and will not be covered here.

The fireball experiences a sufficiently high radiation pressure from the photons to counteract the gravitational pressure, meaning that it starts expanding. The threshold is given by the Eddington luminosity, $L_E = 4\pi GMm_p c/\sigma_T$ (with $G$ being the gravitational constant and $\sigma_T$ the Thomson cross section), which is the luminosity where radiation pressure balances gravitational pressure. For a one solar mass object this becomes $L_E(1M_\odot) \sim 10^{38}$ erg s$^{-1}$, orders of magnitude below observed GRB luminosities. As the plasma expands, it accelerates until some threshold velocity, after which it continues to propagate with a coasting Lorentz
Chapter 2. Theory and modelling

factor $\Gamma = \eta$, where $\eta \equiv L/\dot{M}c^2$ is the dimensionless entropy of the outflow. I motivate the value of this entropy below, when I discuss the saturation radius.

The temperature of the plasma at the base of the outflow is given by the energy density of the emitting region through Stefan-Boltzmann’s law as

$$aT_0^4 = L/(4\pi r_0^2 c), \quad (2.4)$$

where $a$ is the radiation constant, giving us a temperature of

$$T_0 = \left( \frac{L}{4\pi r_0^2 c a} \right)^{1/4}. \quad (2.5)$$

Note that the outflow is considered to be photon dominated and that photons outnumber leptons and baryons by several orders of magnitude.

To obtain the scaling laws of the fireball, conservation of energy and entropy is used, and the evolution of the temperature in the fireball is followed. Assuming that the energy is released and contained in a shell of width $\Delta r \sim r_0$, giving it a comoving volume of $V' = 4\pi \Delta r' r_0^2 = 4\pi r_0^2 \Gamma(r) r^2$, the observed total energy of the shell in the lab frame is

$$E_{\text{obs}} \propto \Gamma(r)V'(r)T'(r)^4 = \Gamma(r)^2 r^2 r_0 T'(r)^4, \quad (2.6)$$

which is constant due to conservation of energy. Considering entropy from the relation $dS = (dU + pdV)/T$, the entropy of the outflow in the comoving frame is found as $S' = V'(u' + p')/T'$, where $u$ and $p$ are the internal energy density and internal pressure, respectively. Note that the chemical potential has been set to zero since I consider a photon dominated outflow. Furthermore, in a radiation dominated outflow it holds that $p' = u'/3 \propto T'^4$, as given by Eq. 2.4. Hence,

$$S' = V' u' \frac{1 + \frac{3}{2} \Gamma(r)^2 r^2 r_0 T'(r)^3 = \text{const},} \quad (2.7)$$

where I have neglected the rest mass as well as the initial kinetic energy of the baryons, meaning that the entropy comes from the photons alone. Combining Eq. 2.6 and 2.7 results in an observed temperature $T(r) = \Gamma(r) T'(r) = \text{const}$. This is an expected result, meaning that as the comoving temperature decreases, the Lorentz factor of the outflow will increase. Hence, as the outflow expands, internal energy of the radiation will be converted into kinetic energy of the outflow. It is obvious that this expansion cannot go on forever and that there is a saturation radius, $r_s$, at which the Lorentz factor coasts, such that $r_s \equiv \eta r_0$, again with the previously defined $\eta \equiv L/\dot{M}c^2$. This means that the acceleration cannot continue, since the Lorentz factor per particle cannot increase beyond the initial value of internal energy per particle of the plasma. Alternatively, it can be understood as that the particles start out with individual Lorentz factors $\gamma \sim \eta$, with an isotropic velocity distribution, and that at $r_s$, the velocities are contained within an angle $r_s/r_0$. Note also that at $r_s$, most of the energy is in the form of kinetic energy of the baryons.
2.3. Dissipation mechanisms

Although the outflow ceases to accelerate it continues to expand and hence the temperature will decrease and Eq. 2.2 yields that $T'(r) \propto r^{-2/3}$. Summarising the scaling laws in the two different regimes discussed so far yields

\[
\Gamma(r) = \begin{cases} \frac{r}{r_0} & r < r_s \\ \eta & r > r_s, \end{cases}
\]

\[
T(r) = \begin{cases} T_0 & r < r_s \\ T_0(r/r_s)^{-2/3} & r > r_s, \end{cases}
\]

\[
V'(r) \propto \begin{cases} r^3 & r < r_s \\ r^2 & r > r_s, \end{cases}
\]

where $T(r)$ denotes the temperature in the lab frame, as seen by an observer.

In the above reasoning I have assumed that the plasma is optically thick as long as $r < r_s$ and that the energy is released momentarily in a shell of width $r_0$. For bursts of duration longer than $r_0/c$ the emission can be considered to consist of many sub-shells, each of width $r_0$ and follow the above reasoning. There are also several other approaches to derive the standard fireball scenario, but the method outlined above highlights some important aspects which are important for the work in this thesis and the discussions to follow.

Finally, the spectrum is released at the photosphere, which is the surface of last scattering, given by $\tau = 1$, with $\tau$ being the optical depth. For a relativistic outflow the optical depth at a given radius is given by $\tau = (L\sigma_T)/(8\pi r^2\Gamma^3 m_p c^3)$, where $\sigma_T$ is the Thomson cross section and $m_p$ is the proton mass (Abramowicz, Novikov, and Paczynski, 1991). Solving this equation for $r$ and setting $\tau = 1$ gives the photospheric radius as $r_{ph} = (L\sigma_T)/(8\pi \Gamma^3 m_p c^3)$.

If the radiation leaving the photosphere has been unaltered from the scenario described above, the observed prompt emission would be a Planck function, which is not the case. There are several ways to obtain non-thermal spectra. In the next section I will discuss dissipation, but there are also effects such as geometric broadening (Pe’er, 2008; Lundman, Pe’er, and Ryde, 2013), a fuzzy photosphere (Beloborodov, 2011; Bégue, Siutsou, and Vereshchagin, 2013) and other spatial effects (Lazzati, Morsony, and Begelman, 2009) which cause photospheric emission from a relativistic outflow to be non-thermal. I discuss the observational justification for considering photospheric emission in Chapter 4.

2.3 Dissipation mechanisms

There are several possible mechanisms to dissipate energy in a GRB outflow. Generally, dissipation means that energy is transferred to the electrons in the outflow by tapping energy from either the bulk kinetic energy of the baryons, or the magnetic fields present. Magnetic energy can be accessed through magnetic reconnection, where magnetic field lines of different magnetic domains meet and change their pattern of connectivity (Thompson, 1994). Kinetic energy of the bulk motion can
be dissipated by shocks, where shells of different velocities collide and transfer energy by Fermi acceleration (Kirk and Schneider, 1986). There are different types of shocks suggested for dissipation in GRBs: external shocks (Cavallo and Rees, 1978; Rees and Meszaros, 1992), hadronic collision shocks (Beloborodov, 2010) or internal shocks (Rees and Mészáros, 2005). Internal shocks denote shocks within the jet, caused by shells of different speeds. External shocks instead refer to shocks caused by a collision between the jet and the circumstellar medium. In this section I will discuss internal shocks and sketch the derivation of the central properties of a basic internal shock scenario, since this particular dissipation mechanism is assumed in the numerical code that has been employed in Paper I - III.

The internal shock scenario is derived from the fireball model, with additional assumptions. As stated in the previous section, continuous emission can be considered to consist of independent sub-shells, each typically of width \( \sim r_0 \). It is assumed that there are fluctuations in the central engine activity on the time scale of \( \delta t = r_0/c \), which is the observed variability time. The fluctuations in the outflow leads to the shells obtaining slightly different densities which results in different coasting Lorentz factors, usually assumed to be of order \( \Delta \Gamma \sim \eta \), where \( \eta \) is the typical value of the coasting Lorentz factor for the shells. This leads to a velocity spread of \( \Delta v \sim c/2\eta^2 \) between two shells. Hence, faster shells will catch up to slower shells ahead of them and create shocks that propagate into the colliding shells. A forward shock will propagate into the slower shell and a reverse shock will propagate into the faster shell. This converts kinetic energy of the bulk flow motion into internal energy of the outflow.

Given the shell width, \( \Delta r = r_0 \), and velocity of the shells, they will start to collide at a radius \( r_d = 2r_0\Gamma^2 \). The merger time for the two shells in the comoving frame is given by \( t_{\text{merge}}' = \Delta r'/c = \Gamma r_0/c \). In the lab frame this becomes \( t_{\text{merge}} = r_0/c = \Delta r_{\text{obs}}/c \), with \( \Delta r_{\text{obs}} \) being the observed variability time of the burst. Hence internal shocks give observed variability times on the same scale as the central engine activity. Note that it is possible for these shocks to take place below or above the photosphere.

It should be noted that internal shocks have a very limited efficiency. It is clear that the two colliding shells can dissipate no more energy than the differential kinetic energy between them. Consider two shells, with \( m_1, m_2 \) and \( \Gamma_1, \Gamma_2 \) as the respective shell’s mass and Lorentz factor. It was showed by Kobayashi, Piran, and Sari (1997), assuming \( \Gamma_1, \Gamma_2 \gg 1 \), that the resulting Lorentz factor of the merged shell becomes

\[
\Gamma_f = \left[ (m_1\Gamma_1 + m_2\Gamma_2)/(m_1/\Gamma_1 + m_2/\Gamma_2) \right]^{1/2}.
\]

This leads to an efficiency of

\[
e = 1 - \frac{(m_1 + m_2)\Gamma_f}{m_1\Gamma_1 + m_2\Gamma_2},
\]

which, together with Eq. (2.11) shows that, as expected, similar masses, \( m_1 \sim m_2 \) and a large difference in Lorentz factors, \( \Gamma_1 \gg \Gamma_2 \), is required for highest efficiency.
2.4. Emission processes

Using typical values of GRBs, and taking into consideration that a first shock with high efficiency leads to lower efficiency for subsequent collisions due to the high merged Lorentz factor, $\Gamma$, it has been shown that the typical total efficiency expected is $1 - 10\%$ (Mochkovitch, Maitia, and Marques, 1995; Kobayashi, Piran, and Sari, 1997; Panaitescu, Spada, and Mészáros, 1999; Lazzati, Ghisellini, and Celotti, 1999; Kumar, 1999).

The internal shock scenario’s strength is the model’s simplicity, as well as its ability to reproduce the fastest observed variability time scales. Its main weakness is the low efficiency, requiring large luminosities to produce the observed fluxes. Furthermore, it lacks predictive power since it does not make any predictions about the details of the emission; how long it will be, spectral features or amount of dissipated energy.

2.4 Emission processes

When considering GRB emission there are several relevant radiative processes to take into account, depending on what model is being considered. I will here outline a few of these. For a an in-depth coverage of all relevant processes, see e.g. Rybicki and Lightman (1979). For a comprehensive overview, see e.g. Kumar and Zhang (2013) and Pe’er (2013), which contain all the information given below.

2.4.1 Synchrotron radiation

Charged particles accelerated by magnetic fields radiate. This is referred to as cyclotron radiation for non-relativistic particles. However, for highly relativistic particles, the spectrum of the resulting radiation is more complex, and is instead referred to as synchrotron radiation. In GRBs we may expect both strong magnetic fields and highly relativistic particles, making synchrotron radiation a highly relevant radiation process. Additionally, synchrotron radiation is seen in several other astronomical systems, including active galactic nuclei (AGNs), and even GRB afterglows. Energetic electrons can be obtained e.g. through the aforementioned internal shocks (Rees and Meszaros, 1994; Daigne and Mochkovitch, 1998) or through acceleration in strong magnetic fields (Drenkhahn and Spruit, 2002). External shocks, where a forward shock propagates into the surrounding circumburst medium, have also been suggested as a source for synchrotron emission (Cavallo and Rees, 1978; Meszaros and Rees, 1993).

If we consider a single electron in a uniform magnetic field of strength $B$, with a Lorentz factor $\gamma_e$ and velocity $v_e$, Maxwell’s equations dictates that the electron will be moving orthogonally to the magnetic field direction. Larmor’s formula further gives that the electron radiates a power

$$P_{\text{sync}} = \frac{4}{3} \sigma_T c \beta^2 \gamma_e^2 \frac{B^2}{8\pi},$$
as the electron gyrate around the magnetic field lines. $\sigma_T$ is the Thomson cross section and the factor $\frac{B^2}{8\pi}$ the magnetic energy density. It is also useful to define a critical frequency,

$$\nu_{\text{crit}} = \frac{3}{2} \gamma_e^3 \nu_B \sin \alpha,$$

where $\alpha$ is the pitch angle between the magnetic field and the velocity and $\nu_B = \nu_B(\gamma_e, B)$ is the Larmor frequency (its gyration). This definition of $\nu_{\text{crit}}$ corresponds to the frequency at which the synchrotron power spectrum peaks. Below the peak the spectrum is approximately described by the power law $P(\nu) \propto \nu^{1/3}$. Above $\nu_{\text{crit}}$ the spectrum decreases exponentially. For a power law distribution of electrons, as one might expect from the previously mentioned acceleration mechanisms, the slope of the power law below $\nu_{\text{crit}}$ instead becomes

$$P(\nu) \propto \nu^{-\frac{p+1}{2}},$$

where $p$ is the power law index of the electron distribution.

The characteristic power law behaviour from an electron distribution is modified when synchrotron cooling is accounted for. As the electrons radiate they loose energy and thus the electron distribution will change, and the corresponding synchrotron spectrum with it. On the topic of synchrotron cooling, there are two regimes which are frequently discussed; the fast and slow cooling regime, respectively (Sari, Piran, and Narayan, 1998). Going back to the case of a single electron it is possible to find the cooling frequency $\nu_c = \nu(\gamma_c)$ such that $P(\nu) \propto \nu^{1/3}$ when $\nu < \nu_c$, which corresponds to where there is little to no effect from cooling on the spectral shape. Further, it turns out that $P(\nu) \propto \nu^{-1/2}$ when $\nu_c < \nu < \nu_{\text{crit}}$. Again, the spectrum falls off exponentially at $\nu > \nu_{\text{crit}}$.

If we instead consider a power law distribution of electrons, two possibilities present themselves, representing the case where $\gamma_m < \gamma_c$ and $\gamma_m > \gamma_c$, respectively. Here, $\gamma_m$ is the minimum Lorentz factor of the electron distribution. The case where $\gamma_m > \gamma_c$ is referred to as the fast cooling regime, since all electrons cool down to $\gamma_c$ quickly. In the case of $\gamma_m < \gamma_c$, only the electrons with $\gamma_e > \gamma_c$ cool, which yields a significantly different spectral shape. There are further effects which affect the synchrotron spectral shape, such as synchrotron self-absorption. Note that the above exposition applies to optically thin synchrotron.

### 2.4.2 Compton scattering

Compton scattering describes the process where a photon scatters on an electron. Usually, this denotes the scenario where the photon transfers some of its energy to the electron. Similarly, the process is usually referred to as Inverse Compton (IC) when energy is instead transferred from the electron to the photon. For a large number of scatterings, this will be the average outcome in the case where the electron energy is larger than that of the photon.
2.4. Emission processes

We consider the average photon to have a Lorentz factor $\gamma_e$, and additionally that we are in a regime where $E\gamma_e \ll m_e c^2$, where $E$ is the photon energy in the lab frame. This corresponds to a scenario where the electron has much more energy than the photon, and where the scattering can thus be considered to be elastic in the rest frame of the electron (i.e. where the electron gains negligible energy and momentum). Doppler boosting the photon to the electron frame and then performing a Lorentz transformation back after the scattering, it can be shown that the scattered photon obtains the energy

$$E_{1C} = E\gamma_e^2,$$

where $E_{1C}$ denotes the energy of the scattered photon in lab frame. In order to obtain the IC spectrum, the seed photon spectrum is needed. By convolving the seed photon spectrum with the electron distribution the observed photon spectrum is obtained.

When the photon energy in the electron rest frame is comparable to, or larger than, that of the electron rest mass $E\gamma_e \sim m_e c^2$ we refer to it as the Klein-Nishina regime. In this regime the scattered photons can obtain energies no larger than $\gamma_e m_e c^2$, due to conservation of energy. Additionally, the scattering cross section in this regime decreases as $E^{-1}$, which also impacts the spectral shape.

2.4.3 Photospheric emission

Finally, it may also be instructive to mention photospheric emission as a radiative process. It is not a physical process in the same way as synchrotron radiation or Compton scattering. However, since an idealised photosphere is the point of last scattering it does have certain properties. It is also of interest since the fireball model without any additional assumptions naturally predicts the presence of photospheric emission. As mentioned in Section 2.2, contrary to the naive approach, careful examination of the properties of photospheric emission in relativistic outflows has revealed that it is expected to be non-thermal. However, starting from pure blackbody emission, it has the shape of a Planck function. One of the most relevant features of this shape for GRB physics is the fact that it is asymptotically harder (has a steeper spectral slope), and is narrower, than what is possible to achieve with e.g. synchrotron radiation. Additionally, the fact that the shape of a Planck function only depends on the temperature makes it possible to make inferences about the emission region, e.g. about the Lorentz factor of the outflow, if a spectrum can be represented by a Planck function.

The simplest deviation from a blackbody spectrum is a multicolour blackbody spectrum. This is a slightly wider spectrum, consisting of several superimposed blackbody spectra at different energies, as depicted in Fig. 2.1. This is a possible scenario as soon as there is radiation from e.g. several regions of the outflow, where there are different temperatures. Thermal radiation is also relevant in that it may provide the seed photon distribution for e.g. IC. Additional scenarios where photospheric radiation is non-thermal are discussed in Chapter 3 and 4.
Figure 2.1. Schematic example of a multicolour blackbody (black line) as built up by several blackbody spectra at different temperatures, as indicated by the colours.
Chapter 3

Spectra of prompt emission

"They hung in the sky in much the same way bricks don’t."

In this chapter I discuss spectra of GRB prompt emission. I describe the main features of the emission and review some of the empirical functions commonly used to describe the spectra. I also provide observational justifications for considering subphotospheric dissipation as a source of prompt emission.

3.1 Empirical functions

GRB prompt emission spectra are usually described using the so called Band function (Band et al., 1993), which is a smoothly broken power law, defined as

\[
N(E) = \begin{cases} 
KE^\alpha \exp\left(-\frac{E}{E_0}\right), & \text{if } E \leq (\alpha - \beta)E_0 \\
K [\alpha - \beta) E_0]^{(\alpha - \beta)} E^\beta \exp (\beta - \alpha), & \text{if } E > (\alpha - \beta)E_0 
\end{cases}
\]

(3.1)

with \(N(E)\), being the photon number spectrum, \(\alpha\) the slope of the low energy power law, \(\beta\) the slope of the high energy power law, \(E_0\) the break energy, and \(K\) the normalisation parameter. The Band model is an empirical function and does not correspond to any physical scenario, even if some effort has been made to reconcile it with e.g. synchrotron radiation. The Band model is used in most GRB catalogues and is a standard point of reference in the field. Although the model lacks a physical interpretation, it does provide several interesting relations between its parameters and physical quantities. One example is the Amati relation (Amati et al., 2002), which shows a correlation between the lab frame peak energy, with the
peak energy being defined as 

\[ E_{\text{peak}}^{\text{lab}} \propto E_{\text{iso}}^\eta, \]

where \( \eta \) is a constant. However, there are indications that the Amati relation may be the result of functional correlations (Massaro et al., 2008) as well as selection effects (Kocevski, 2012). Another example is the Golenetskii correlation (Golenetskii et al., 1983),

\[ L \propto (E_{\text{peak}}^{\text{lab}})^{\gamma} \text{erg s}^{-1}, \]

where \( L \) is the observed luminosity, \( E_{\text{peak}}^{\text{lab}} \) is again the spectral peak of the spectrum in the stellar rest frame, defined as above, and \( \gamma \) is a constant. The biggest difference between this and the Amati correlation is that the Amati relation considers time integrated qualities, whereas the Golenetskii relation is applied to time-resolved analyses. It has been argued that this correlation might be used to determine the redshift of GRBs (see e.g. Guiriec et al., 2013). However, this idea has been criticised on the basis that the relation appears to be generated by several processes which are too disparate in order for this to be possible (Burgess, 2013).

Another commonly used empirical function is a cutoff power law (CPL). This is a power-law with a high-energy cutoff, defined as

\[ N(E) = A \left( \frac{E}{100 \text{ keV}} \right)^{\alpha} e^{-\left(\frac{\alpha+2}{E_p}\right)E_p}, \]

where, similarly to the Band function, \( \alpha \) is the low-energy spectral slope, \( E_p \) is the peak energy in \( \nu F_\nu \) and \( A \) is a normalisation constant with the units photons s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\). This function is used e.g. to describe time resolved spectra in Yu et al. (2016), where they also find that the cutoff power law is often better at describing the data than the Band function. However, Kaneko et al. (2006) and Goldstein et al. (2012) point out that this preference may be a result of poor count statistics at high energies.

In Fig. 3.1 I provide examples of the Band function, the CPL as well as a Planck function, plotted together for illustrative purposes. As discussed in section 2.4.3, the Planck function represents the emission from a perfect blackbody. This is not something we generally expect to find in prompt emission, since even pure photospheric emission is at least slightly broader than a pure Planck function in a relativistic outflow.

### 3.2 Observed spectral features

Using the functions presented in the previous section, it is possible to characterise GRB spectra by the model parameters. In Fig. 3.2 I present the distribution of \( E_{\text{peak}} \), \( \alpha \) and \( \beta \) for a large sample of GRBs. These distributions are made from a
3.2. Observed spectral features

![Graph of energy flux vs. energy](image)

**Figure 3.1.** Examples of some of the empirical functions often fitted to data. The Band function has $\alpha = -2/3$, $\beta = -3$ and $E_0 = 100$ keV. The CPL has $\alpha = 1/3/2$ and $E_0 = 200$. The Planck function has a temperature of 50 keV (i.e. $k_B T = 50$ keV, where $k_B$ is Boltzmann’s constant). The plot is presented in $EF_E$ space, i.e. energy flux multiplied by the energy and plotted against energy, which is a common way of showing model spectra.

...time-integrated analysis and change slightly if a time-resolved analysis is employed (see also discussion in Section 3.1). When performing a time-resolved analysis $E_{\text{peak}}$ tends to either decrease throughout the burst duration, or to track the intensity. The former is known as a hard-to-soft evolution (Norris et al., 1986). Additionally, values of $\alpha$ tend to increase (i.e. the low-energy part of the spectrum becomes steeper) in a time resolved analysis. $\beta$ is often poorly constrained due to the low signal at high energies. Some GRBs have been fitted with multiple-component models, such as fitting simultaneously with both a Band function and a Planck function (see also Section 3.3). There have also been emission detected at high energies ($\geq 100$ MeV), observed to decay as a power law in most cases (Ackermann et al., 2013). This high-energy emission is typically delayed with respect to the emission around the spectral peak, and is usually attributed to early afterglow. Conversely, there are also observed cases with a high-energy cutoff, such as GRB 100728B and GRB 160509A. This has been modelled by Vianello et al. (2013), who showed that both attenuation of a non-thermal spectrum by pair-production opacity, as well as a photospheric model with a magnetised outflow, can account for the high-energy cutoff.
Figure 3.2. $E_{\text{peak}}$, $\alpha$ and $\beta$ distributions, in the left, middle and right panel, respectively, of 1494 GRBs. The bursts are observed by different space telescopes and their time integrated spectra have been fitted with the Band function. The fits are taken from Wang et al. (2019). The blue lines show kernel density estimates, providing an unbinned representation of the histograms.

3.3 Observational justification for subphotospheric dissipation

There are several complicating circumstances which make the determination of the origin of the GRB prompt emission hard. The fact that it is not possible to obtain a model-independent measure of the observed spectrum is surely one of the most hindering factors. This will be covered in some detail in Chapter 3. However, the environment in which the emission is created also presents several challenges. The journey of finding the origin of GRB prompt emission has so far also been an exploration in the domains of relativistic outflows, magnetohydrodynamics and particle acceleration. Our understanding of all these areas have increased significantly over the course of the last decades (due not least to the increase in computational power).

The idea of a photospheric origin of GRB prompt emission began as early as 1986, with Goodman (1986) and Paczynski (1986). However, the notion of photospheric emission was later largely disfavoured by observations, which showed that GRB spectra were far from thermal, mainly through the use of the previously described Band function (see Section 3.1). In terms of the Band function parameters a blackbody spectrum yields a steep spectrum, with a hard low-energy slope of $\alpha \sim 1$. However, as mentioned Chapter 3. Abramowicz, Novikov, and Paczynski (1991) soon showed that photospheric emission from a relativistic wind does not yield a pure Planck spectrum. Since then several additional effects yielding non-thermal photospheric spectra have been discovered (see discussion in Chapter 3).

It has also been argued that another contender for the origin of GRB prompt emission, synchrotron radiation, cannot reproduce a spectrum with a low energy slope harder than $\alpha = -2/3$ in the slow-cooling regime, and $\alpha = -3/2$ in the fast-cooling regime. GRBs are often assumed to be in the fast cooling regime, since the cooling time sets the variability time scale, and also since a long cooling
time would make the burst radiate too inefficiently (Rees and Meszaros, 1994; Sari, Narayan, and Piran, 1996; Kobayashi, Piran, and Sari, 1997; Ghisellini, Celotti, and Lazzati, 2000). Observationally, there are many bursts which are inconsistent with these limits on $\alpha$ (Crider et al., 1997; Preece et al., 1998). As a result it has been assumed that synchrotron emission cannot explain a large fraction of observed spectra. Similarly, it has been, erroneously, argued that fits with the Band function ruled out photospheric emission as a source for prompt GRB emission.

However, there is mounting evidence that many inferences about physical scenarios based on fits with the Band function are uncertain (Burgess et al., 2014b; Burgess, 2017; Burgess et al., 2018; Ahlgren et al., 2019). This includes the conclusion that synchrotron models should be considered ruled out for bursts with a Band function $\alpha > -3/2$, as evident from Burgess et al. (2018) and that photospheric models would be ruled out by $\alpha < 1$ (Ahlgren et al., 2015; Ahlgren et al., 2019).

Disregarding arguments made from fits using only the Band function, there is also observational evidence for photospheric emission. For example, there have been some GRBs observed with spectra that could be described by a single Planck function, (Ghirlanda, Celotti, and Ghisellini, 2003; Ryde, 2004). Additionally, there are bursts that are described by a blackbody and an additional component (Ryde et al., 2010; Guiriec et al., 2011; Axelsson et al., 2012; Burgess et al., 2014a). This suggests that even the simplest scenario of photospheric emission is a viable description for at least some bursts. Furthermore, the fact that it is possible to obtain photospheric emission that is non-thermal makes a photospheric origin of prompt emission possible for additional bursts. Particularly the process of dissipating kinetic energy in the outflow near the photosphere can significantly alter the spectrum such that a plethora of non-thermal spectral shapes are recovered from the photosphere (Rees and Mészáros, 2005; Pe’er, Mészáros, and Rees, 2006; Giannios, 2006; Chhotray and Lazzati, 2015). It is this particular scenario which will be explored in more detail in the next chapter.

3.4 Other models and polarisation

There are several other possible physical scenarios, including some that have been evaluated directly against data. This includes a model for synchrotron radiation through external shocks, used to model GRB 141028A, (Burgess et al., 2016a), the ICMART model of Zhang and Yan (2011), which has been used to describe GRB 080916C, and the physical synchrotron model of Burgess et al. (2018) fitted to 19 GRBs. An property of the data which could help discriminate between physical models is polarisation.

Polarisation is a feature of any electromagnetic radiation, including GRB prompt emission. In the wave description of light, polarisation corresponds to the angle of the oscillation of the $E$-field to some reference direction. Different physical processes emit electromagnetic radiation with different polarisation properties (see e.g. Rybicki and Lightman, 1979). Thus, the degree of polarisation, as well as the evolution
of the angle of polarisation, might be used to discriminate between different emission models for GRB prompt emission. Particularly, it is a clear prediction of most photospheric models that the polarisation is low, or even that the emission is unpolarised. This is due to the unordered geometry of radiation from particles in thermal equilibrium and the absence of significant magnetic fields. However, it is still possible to obtain moderately polarised emission (a few tens of percent) in some photospheric models (Lundman, Pe’er, and Ryde, 2014; Ito et al., 2014; Lundman, Vurm, and Beloborodov, 2016). The polarisation then arises the jet structure.

Synchrotron models generally predict higher degrees of polarisation, although it is also possible to achieve low to moderate levels of polarisation (Lyutikov, Pariev, and Blandford, 2003; Götz et al., 2009; Yonetoku et al., 2012). Despite some level of flexibility in many physical models, reliable polarisation measurements would put strong constraints on several models. Unfortunately, only a small number of polarisation measurements have been carried out to date. This is largely due to technical difficulties in reliably measuring polarisation of high-energy emission (McConnell, 2017). There have been a number of report of large degrees of polarisation, up to 90% (McGlynn et al., 2007; Chattopadhyay et al., 2017). However, these measurements have been criticised for suffering from instrumental effects and poor statistics (McConnell, 2017). Recent measurements instead found that GRB emission is moderately polarised, with at least some bursts being consistent with zero polarisation (Burgess et al., 2016; Zhang et al., 2016).
Chapter 4

The DREAM model

“The chances of finding out what’s really going on in the universe are so remote, the only thing to do is hang the sense of it and keep yourself occupied.”


In this chapter I describe the specific model for subphotospheric dissipation used in this work. I outline the the numerical code used to model it and go through the physical scenario within the framework of the code. Finally, I discuss the creation of DREAM (Dissipation with Radiative Emission as A table Model), the resulting table model and some of its features.

4.1 Simulations

I have used the numerical code by Pe’er and Waxman (2005) to simulate the physical scenario. For more details see also Pe’er and Waxman (2004), Pe’er, Mészáros, and Rees (2005), and Pe’er, A. and Mészáros, P. and Rees, M. J. (2006). This code is used to simulate subphotospheric dissipation in an internal shock scenario. The code can in principle handle different dissipation mechanisms, such as magnetic reconnection (Thompson, 1994; Giannios and Spruit, 2003), or hadronic collision shocks (Beloborodov, 2010). The main feature of the code that stems specifically from internal shocks is the relation between the nozzle radius, \( r_0 \), and the dissipation radius, \( r_d \), as presented below and in Chapter 4.

4.1.1 Numerical code

The code is a radiative transfer code which solves the kinetic equations of energy transportation. All calculations are performed in the comoving frame and assumes both homogeneous and isotropic distributions of particles and photons in this frame. The computations are carried out in time steps of constant size, with an injection
of relativistic electrons in each step, at a constant rate and in a Maxwellian distribution. In addition, the kinetic equations for the Compton and inverse Compton scattering, cyclo-synchrotron emission, synchrotron self-absorption and pair creation and annihilation are solved numerically, using Cranck-Nickolson integration. In each time step, the energy loss times as well as the annihilation times are calculated for the electrons, positions, and photons. When the energy loss times or annihilation times are found to be shorter than the fixed time step, it is assumed that all energy is lost in a single time step. The size of the time steps is set manually and the required step size is dependent on the input parameters. Furthermore, it should be noted that some of the equations in the code differ by a factor of 2 from the theory presented in Chapter 1, e.g. in the expression of the dissipation radius, since these factors are removed for simplification. The code outputs a photon energy grid which spans 13 decades in energy, between $10^{-14}$ and 0.1 erg, containing the spectrum where the simulations stopped, as well as the electron and positron spectra, in energies spanning 6 orders of magnitude, from $\sim 8 \cdot 10^{-7}$ to 1 erg.

The following input parameters are used: the luminosity in terms of $10^{52}$ erg s$^{-1}$, $L_{0.52}$, the optical depth at the site of dissipation, $\tau$, the fraction of dissipated bulk kinetic energy, $\epsilon_d$, the fraction of dissipated energy that goes into the electrons and magnetic fields, $\epsilon_e$ and $\epsilon_b$, respectively, and the coasting bulk Lorentz factor of the outflow, $\Gamma$. Additionally, there is a parameter $\epsilon_{pl}$, which sets the fraction of heated electrons which assume a power-law distribution. The remaining electrons assume a Maxwellian distribution. I have assumed $\epsilon_{pl} = 0$ throughout my work. Not all of the listed parameters are fitted for, see Section 1.2 and the discussion in paper I–III. Additionally, it is assumed, in agreement with the internal shock scenario, that shells of width $\Delta r \sim r_0$ are ejected at some nozzle radius $r_0$, due to central engine activity. It is also assumed that the two shells will start to merge at the dissipation radius, $r_d$, defined through its optical depth as

$$r_d = \frac{L_{0.52}\sigma_T}{4\pi c^2 \Gamma^3 m_p} = \Gamma^2 r_0. \quad (4.1)$$

The time scale over which two shell merger is denoted $\Delta t = r_d/\Gamma^2 c$. The merger time in the comoving frame is thus $t'_{\text{dyn}} = \Gamma \Delta t$, which is here referred to as the comoving dynamical time, and sets the duration of the dissipation in the comoving frame. Hence, the dissipation takes place between $r_d \to 2r_d$, i.e. between $\tau \to \tau/2$, which also corresponds to a distance $\Delta r'$, one shell width in the comoving frame. Thus, the comoving volume of heated electrons as a function of time will be given by $V' = 4\pi r_d^2 c t' = 4\pi r_d^2 \Delta r' t'/t'_{\text{dyn}}$, with $t'$ being the comoving time. The key radii, together with the model parameters, are presented in Fig. 4.1.

The shells contain $N_{\text{shell}} = L_{0.52} \Delta t/\Gamma m_p c^2$ electrons, initially in thermal equilibrium with the photons. With the internal energy density of the electrons being $u_{e-} = \epsilon_e u_{\text{int}} = \epsilon_e \epsilon_d L_{0.52}/4\pi r_d^2 \Gamma^2$ and the internal energy of the photons being $u_{\gamma} = aT(r_d)^4$, it is useful to define the fraction $A = u_{\gamma}/u_{e-}$. Additionally, since the main source of photons are the thermal seed photons, the ratio of power emitted by the electrons in synchrotron and inverse Compton scattering is given by
4.1. Simulations

Figure 4.1. Jet schematics in the framework of the model simulated by the numerical code. The model parameters are presented at the different radii at which they are defined. A luminosity, $L_{0.52}$, is emitted from the compact object at a nozzle radius, $r_0$, and travels outwards in a jet. Initially, the radiation pressure accelerates the outflow such that the Lorentz factor of the outflow increases linearly with radius. At the saturation radius, $r_d$, given by the optical depth at the site, $\tau$, dissipation occurs, converting a fraction $\varepsilon_d L_{0.52}$ of the kinetic energy into internal energy of the outflow, of which a fraction $\varepsilon_e$ and $\varepsilon_b$ goes into the electrons and magnetic fields, respectively. An approximation of the model is that the dissipation does not alter the coasting Lorentz factor of the jet. The dissipation continues for one dynamical time, until the radius has doubled, at $2r_d$. In the early versions of the model the spectrum is instantaneously released at this point. In principle, however, the jet constituents continue to interact until they decouple, which happens in a region centred around the photosphere. In the model presented in paper II and III, the spectrum is instead released at $2.3r_d$, in order to better model the scatterings remaining until the photosphere. Note that the figure is not to scale.
\[ S = P_{\text{sync}}/P_{1C} = u'_B/u'_\gamma, \] with \( u'_B = \varepsilon_b u'_{\text{int}} \) being the comoving energy density of the magnetic fields.

The comoving normalised temperature of the photons is defined as \( \theta = k_B T'/m_e c^2 \). The photons are initially thermally distributed at this temperature. The heated electrons are injected as a Maxwellian distribution and similarly have a normalised temperature \( \theta_{e-} \), defined by the characteristic Lorentz factor of the distribution, \( \gamma'_{\text{char}} \), such that \( \theta_{e-} = \gamma'_{\text{char}}/2 \), where \( \gamma'_{\text{char}} = 2\varepsilon_e \varepsilon_d (m_p/m_e) \) (Pe’er, A. and Mészáros, P. and Rees, M. J., 2006). Using this, we can show that the electrons are expected to lose all their kinetic energy in the comoving frame during one dynamical time. Electrons of a Lorentz factor \( \gamma'_{\text{char}} \) lose their energy by Compton scattering and synchrotron emission over a typical time scale of \( \delta t_{\text{loss}} = E/(dE/dt) = \gamma'_{\text{char}} m_e c^2/(4/3) c \sigma_T \gamma'^2_{\text{char}} u'_\gamma (1 + S) \). Thus, they cool down to \( \gamma \sim 1 \) on the time \( t_{\text{loss}} = \delta t_{\text{loss}} \gamma'_{\text{char}} \). I then obtain the following ratio of the cooling time and the dynamical time, \( t_{\text{loss}}/t_{\text{dyn}} \approx 1/((4/3) A (1 + S) \gamma'^2_{\text{char}} \tau) = (3/4) \Gamma^{2/3} (30\tau)^{-1} (0.44 + 0.48\varepsilon_B - 0.5\varepsilon_d - 1) \). This yields that for \( \varepsilon_B = 10^{-6} \), \( \varepsilon_d = 0.1 \) and \( \tau \leq 1 \), the electron will cool during the dynamical time as long as \( \Gamma \lesssim 10^5 \), and even higher values for higher values of \( \tau \). As long as the electrons cool efficiently in the photon field, the spectrum can be significantly altered by heating of the electrons. The spectrum firstly change in that photons are up-scattered to higher energies, modifying the high-energy part of the spectrum. The low energy part of the spectrum can be modified by synchrotron radiation, which can directly insert photons at low energies, around and below the BB peak. However, even without synchrotron radiation, the low energy part of the spectrum is modified as the BB is destroyed by inverse Compton scattering, which, depending on parameters, can significantly alter the low energy slope and peak position of the spectrum. In Fig. 4.2 I show a few examples of different output spectra from the code. A more extensive overview of the impact of the different model parameters on the spectral shape is given in the appended articles.

### 4.1.2 Approximations and assumptions

The code does not include adiabatic cooling in the sense that the photons are instantaneously released after the dissipation. This is a valid approximation if the dissipation ends at \( \tau \sim 1 \). However, if the dissipation ends below the photosphere, the photons will continue to interact with the plasma, continuously loosing energy to the bulk motion of the outflow. The loss of energy to the bulk expansion will lead to a constant shift in energy of the entire spectrum. Beloborodov (2011) introduces the adiabatic cooling factor, \( a = 2\tau^{-2/3} \), and shows that this factor accounts for the net effect of pure adiabatic cooling for radiation escaping at the photosphere. Thus, it is possible to account for this effect retroactively, without having to run the simulations all the way to the photosphere.

However, the additional scatterings between the end of the dissipation and the photosphere will also affect the shape of the spectrum (i.e. slopes and peak positions). The photons will be increasingly thermalised by each scattering and the
4.1. Simulations

Figure 4.2. Example of output spectra from the numerical code when it is being run to $2r_d$. The black line represents the spectrum given by $[L_{0.52} = 0.1, \tau = 1, \varepsilon_d = 0.05, \varepsilon_b = 0.1, \Gamma = 350]$, the red line by $[L_{0.52} = 10, \tau = 10, \varepsilon_d = 0.1, \varepsilon_b = 10^{-6}, \Gamma = 100]$, the blue line by $[L_{0.52} = 10, \tau = 20, \varepsilon_d = 0.2, \varepsilon_b = 10^{-6}, \Gamma = 350]$, and the magenta line is given by $[L_{0.52} = 0.1, \tau = 20, L_{0.52} = 0.1, \varepsilon_d = 0.2, \varepsilon_b = 0.1, \Gamma = 200]$. The small peaks located at $10^4 - 10^5$ keV are the peaks from pair annihilation. The parameters from which these spectra are produced are not confined to the parameter space I have used when fitting the model to data. Instead, they have been chosen to exemplify the wide range of spectral shapes available from the physical scenario.

The change of energy per scattering for each photon will be dependent on the initial photon energy. This effect cannot be retroactively compensated for when considering the emerging spectrum, and must instead be treated in the code. Unfortunately, the time consuming nature of the simulations makes it practically infeasible to run the code to the photosphere for a large number of simulations. However, the majority of the changes to the spectral shape will occur early, and it turns out that running the simulations for $\sim 30\%$ longer is enough to capture most of the change in spectral shapes. In Fig. 4.3 I provide an example of how the spectral shape changes as we go from $2r_d$ to $2.3r_d$. The most profound change is the high-energy cutoff, which occurs earlier as we treat the remaining scatterings. The low-energy part of the spectrum changes much less. This is because the high-energy photons loose their energy quickly, whereas the low-energy photons thermalise slower due to the smaller energy discrepancy to the electron population, and in general alter their energies less. A more detailed discussion of this can be found in paper II.

Another important approximation is that the code does not include any geometric effects, since it is 0-dimensional. Thus, it does not include any hydrodynamics
or considerations of jet structure. One major effect of this is the lack of high-latitude photons. We would expect photons coming from a larger angle in the outflow to have lower Doppler factors, thus leading to a softening of the spectrum as the high-latitude photons arrive (Lundman, Pe’er, and Ryde, 2013). In the case of pure blackbody emission, this effect leads to a multicolour blackbody spectrum as presented in Fig. 2.

The assumption of internal shocks as dissipation mechanism is probably the most limiting assumption of the physical scenario, and it is mentioned in the appended articles as a condition which should be relaxed in order to achieve better agreement with the data. Releasing this assumption would provide a model which is an effective super-set of the current version and it is obvious that this would lead to additional descriptive power for the model. Doing this requires small changes to the numerical code, reasonably introducing $r_0$ as a new model parameter. However, a significant effort must be expended in simulation time to construct a new grid. Such a model was partially constructed for this thesis, but has not yet been used in any published work.

## 4.2 The Table Model

In this section I outline how the code was used to create a model for xspec which can be fitted to data, and also motivate the specific choice of model parameters. The discussion is brief since these topics are covered in some detail in both paper I and II, and mentioned in paper III. The table model was named DREAM (Dissipation with
4.2. The Table Model

Radiative Emission as A table Model. In order to differentiate between different versions of the model as it was being developed, and since the goal has been to make it publicly available, a naming convention was introduced in paper II. Each iteration of the model is referred to DREAM$\alpha$.b, where $a \in \mathbb{N}$ denotes the version of the physical scenario. This includes assumptions such as internal shocks as a dissipation mechanism. $b \in \mathbb{N}$ indicates smaller changes to the simulation code or changes to the parameter grid. This includes the changes from paper II to III, where the grid is expanded in $L_{0.52}$ and $\Gamma$. Thus, the model presented in paper I is retroactively called DREAM1.1, whereas the model in paper II and III are referred to as DREAM1.2 and DREAM1.3, respectively.

Table models are routinely used in X-ray astronomy, e.g. in the analysis of active galactic nuclei (see models by Ross and Fabian, 2005; García et al., 2014). This thesis introduces the first implementation of a table model for prompt GRB analysis. A table model consists of a table of model spectra, each associated with a set of model parameters. Linear interpolation across one dimension at the time is then employed to find model spectra for any set of parameter values contained in the convex set of grid points. Because the grid has a limited resolution, interpolation in the grid is a potential source of uncertainties in the analysis. This is discussed in paper II.

In order to construct a table model I run the numerical code described above for a large number of input parameters. The goal is to test whether subphotospheric dissipation is a viable origin for prompt emission, and the parameters were chosen with this in mind. Obviously, $\tau > 1$ is required in order for the dissipation to be subphotospheric. Tests showed that at $\tau \gtrsim 35$, there is generally only small incremental changes to the spectrum for higher values of $\tau$, and this was at first chosen as a reasonable cutoff value for this parameter. Additional tests leading up to paper II further showed that it is often motivated to keep $\tau$ as a fix parameter. The luminosity was generally chosen to lie in the range $0.1 - 300 L_{0.52}$, so that bursts are simulated in the range $10^{51} - 3 \cdot 10^{54}$ erg s$^{-1}$, which covers most of the expected GRB isotropic equivalent luminosities (Atteia et al., 2017). In paper III the upper limit was increased to $10^{55}$ erg s$^{-1}$ in order to account for the most luminous spectra, with the caveat that these luminosities are on the limit of what is physically reasonable. Because of the role of dissipation these are not the observed luminosities, which are instead on the order of $\varepsilon_d L_{0.52} a$, where $\varepsilon_d$ and $a$ are the level of dissipation and the adiabatic cooling factor, respectively. The actual luminosities are of course lower due to the collimated jets (see Section 1.3). The Lorentz factor was chosen to lie in the range $50 - 500$, in the first implementation of the model (Paper I). The lower limit of of the Lorentz factor was changed in paper II, since tests showed $\Gamma \geq 100$ to be sufficient to describe the bursts in that sample. However, for paper III, the limit was expanded to again include $\Gamma = 50$, in order to better cover the range of observed values of $\Gamma$ (Ghirlanda et al., 2018). The parameter space was also expanded to higher values to $\Gamma = 1000$. The level of dissipation, $\varepsilon_d$ is set in all articles to be smaller than 0.4. Since the dissipation transfers energy from the kinetic energy of the bulk motion, a high dissipation leads to a situation
where the thermal energy again becomes comparable to the kinetic energy. This would lead to a re-acceleration of the outflow from thermal pressure, like what is happening under the saturation radius. However, this second acceleration scenario is not treated in the numerical code. Hence, this part of the parameter space is avoided completely. Due to computational reasons, and to minimise degeneracies in the model, $\varepsilon_a$ and $\varepsilon_b$ were set to constant values of 0.9 and $10^{-6}$, respectively, thus leaving four free parameters. There have also been experiments with several other values of $\varepsilon_b$ within the work of this thesis, but we here focus on the parameter space employed in the appended articles.

The simulations span a grid in the parameter space, which, due to technical reasons, must be rectangular. The curse of dimensionality, together with the fact that a single run of the code usually takes 1-4 days to complete, sets the limitations on how large and finely spaced parameter grid that can realistically be spanned. Additionally, it is not immediately obvious what step size is required for the simulation to converge, hence a simulation must often be run more than once to ensure that proper convergence has been reached. The table models used in papers I and II use 500 and 891 grid points, respectively. The table model in paper III has 2200 grid points. For the purpose of constructing these grids I have used several super computers to run the simulations; Ferlin and Povel at PDC Center for High Performance Computing at the KTH Royal Institute of Technology, Triolith at the National Supercomputer Centre (NSC) at Linköping University, as well as Abisko at the High Performance Computing Center North (HPC2N) located at Umeå University.
Chapter 5

Telescopes and instruments

“It is a mistake to think you can solve any major problems just with potatoes.”

In this chapter I describe the telescopes and instruments that have been used in the thesis.

5.1 The Fermi Gamma-ray Space Telescope: detectors and data products

The Fermi satellite was launched on June 11th, 2008 and orbits Earth in a low-earth orbit, with an orbital period of 90 minutes. The satellite carries two experiments; the Gamma-ray Burst Monitor (GBM; Meegan et al., 2009), and the Large Area Telescope (LAT; Atwood et al., 2009). The analysis of Fermi observations in this thesis primarily relies on data from the GBM, since this operates at energies where the prompt emission from GRBs peak.

5.1.1 GBM

The GBM covers an energy range of 8 – 40 000 keV, and is composed of 12 sodium iodide (NaI) scintillation detectors, operating in the energy range 8 keV – 1000 keV, and two bismuth germinate (BGO) scintillation detectors, operating in the energy range 200 keV – 40 000 keV. Both detector types have an energy resolution of $\sim 10\%$. The GBM has a detection rate of $\sim 240$ bursts year$^{-1}$ (Bhat et al., 2016). Each NaI detector is comprised of a crystal disk, 12.7 cm in diameter and 1.27 cm in thickness attached to a photomultiplier tube (PMT). Fig. 5.1 shows a photograph of an NaI detector flight unit.
The BGOs, similarly, consist of crystal cylinders, 12.7 cm in diameter and connected to PMTs that convert detected photons to electrical signals. Fig. 5.2 shows a photograph of a BGO detector flight unit. Since these units have an energy detection range that overlaps with the NaI detectors and the LAT (described in Section 5.1.2 below), they allow for cross calibration between the detectors.

The NaI detectors are arranged such that the relative counting rates can be used to infer the position of observed GRBs. Atwood et al. (2006) reports an uncertainty of $\sim 10^\circ$ in the onboard localisation for bright bursts. The two BGOs are positioned on each side of the spacecraft in order to ensure that at least one of them detects any given burst occurring above the horizon. In Fig. 5.3 the positions and orientations of the different GBM detectors are shown. This configuration lets GBM observe the whole un-occulted sky.

When an incoming photon interacts with a detector it gets completely or partially absorbed. This gives rise to an electric signal in the detector, inducing a
Figure 5.3. Schematic of detector positions and orientation of the GBM detectors on the *Fermi* satellite. The NaI detectors are indexed 0 – 11 and the BGOs are denoted by 12 and 13 in the figure. The gray box is the LAT. The figure is taken from Meegan et al. [2004].
Figure 5.4. Example of a signal in the PMT of a detector on GBM. The height of the pulse corresponds to the energy of the incident photon and yields the channel in which the photon is observed. The figure also illustrates the down-time before the detector returns to its idle state. The figure is taken from Meegan et al. (2009).

voltage pulse. The height of this pulse depends on the energy of the detected photon, and these data are thus called PHA (Pulse Height Analyser) data. This process is illustrated in Fig. 5.4. Measuring the strength of the induced signal is done in discrete steps, corresponding to detector channels. The units in which the signal is measured is count s⁻¹ PHA channel⁻¹. The implications of this for the spectral analysis are discussed further in Chapter 5.

There are three effects that can cause problems at high photon-rates; detector dead time, pile-up in the electronics, and data loss due to the limited data transfer speed from the GBM to the spacecraft for download to Earth. These effects are not limiting factors for most bursts. There is only one case where the third effect has been an issue. In GRB 130427A (Ackermann et al., 2013) there was ensuing data loss due to limits in the transfer speed of 1.5 MB s⁻¹, as well as pile-up and dead times.

5.1.2 LAT

The LAT is a telescope based on pair-conversion, and detects photons in the energy range 30 MeV to above 300 GeV, (Atwood et al., 2006), spanning 4 orders of magnitude of high-energy gamma-rays, with an on-axis energy resolution of ~ 10%. It has a field of view (FOV) of > 2 sr and a GRB detection rate of ~ 10 – 20 bursts year⁻¹ (Ackermann et al., 2013). The LAT allows for timing and position measurements along with energy measurements of incident photons. Fermi may also slew to to
allow LAT to observe bright bursts located by the GBM. It consists of a calorimeter, precision tracker and anti-coincidence detector for rejecting charged particle background events.

A pair-conversion telescope functions by letting photons of energy twice the rest mass energy of the electron, $E_\gamma \geq 2m_ec^2$, interact with the high Z-material of the detector and create electron-positron pairs. Since energy and momentum are conserved and can be retrieved through detection of the electron and positron, the original photon’s energy and momentum, and hence direction, can be inferred. The energies of the charged particles are measured by the calorimeter, and their directions are obtained by having their path’s registered by the precision tracker.

The calorimeter consists of 16 calorimeter modules, each situated below a tracker module so that both energy and momentum can be retrieved. The calorimeter modules consist of thallium activated caesium iodide (CsI(Tl)) crystals, and each calorimeter module is made up of 96 crystals. When a charged particle enters the calorimeter it will create a shower of secondary particles, which will give rise to energy deposition events in the crystals. Each such event registers the amount of energy deposited and the physical position of the event. Together with leakage corrections, this allows for precise reconstruction of the shower and thus energy of the original particle and finally the photon.

Apart from the regular LAT data, which extends down to $\sim 100$ MeV, there is another type of LAT data available for GRB analysis. The LAT-Low Energy (LLE) data are a type of LAT data designed for the use with bright (since the data in this energy range is generally dominated by background) transients to bridge the energy range of the LAT and GBM (Pelassa et al., 2010). The LAT-LLE data allows fitting in the energy range 30–1000 MeV. This is the only type of LAT data used in this thesis.

### 5.1.3 Data reduction

The resulting data files from the LAT-LLE and GBM are event files for each detector, containing information about each individual photon detected. One such type of file is the time-tagged event file (TTE-file), which provides high-precision timing information on detected photons. There are also CTIME and CSPEC files, with courser time resolutions (256 ms and 8.2 s, respectively). Using e.g. the Fermi tool `gtbin`, I create standardised spectral files from the TTE-files, which can be read by most available spectral analysis software. In order to account for the background when analysing transients, the background is modelled by a low-order polynomial, fitted to the data before and after the GRB. In Fig. 5.5 I present an example of such a fit for GRB 091127. The source of the background can be split into an astrophysical part and a part coming from Earth. The latter mainly consists of gamma-rays scattering on the Earth atmosphere. There is also a small background coming from the satellite itself. The astrophysical part may include sources in the vicinity of the burst, and always include the so-called cosmic gamma-ray background (CGB; also

referred to as e.g. the diffuse gamma-ray background). Below $\sim 300$ keV, most of the emission of the CGB originates from diffuse emission from AGNs and Seyfert galaxies (Madau, Ghisellini, and Fabian, 1994; Ueda et al., 2003). However, in the MeV range, the origin of this background is less well understood (Ruiz-Lapuente et al., 2016). For the GBM detectors, the background is dominated by the CGB at energies $\lesssim 150$ keV, and by the Earth gamma-ray albedo at energies $\gtrsim 150$ keV (Meegan et al., 2009).

Another crucial file type needed when analysing the data is the detector response matrix. This contains information about the instrument response, i.e. the effective area at different energies and how detected counts in the detector are related to incident photon energies. This is presented in greater detail in Chapter 1. Hence, for each detector, the results of the data reduction are source and background spectra. When choosing detectors to use for the analysis, the detectors with the lowest angle towards the source are used, with an upper cut of 60° towards the source also applied. Generally, no more than three NaI detectors are used, and always one BGO detector (Bhat et al., 2016).

5.2 The Neil Gehrels Swift Observatory: detectors and data products

The Neil Gehrels Swift Observatory (Gehrels et al., 2004) was launched on November 20th, 2004, and is like Fermi in a low-Earth orbit with an orbital period of
## 5.2. The Neil Gehrels Swift Observatory: detectors and data products

![Image of Swift satellite](image.png)

**Figure 5.6.** Computer generated image of the *Swift* satellite, from Gehrels et al. [2004].

About 90 minutes. There are three telescopes on board, the Burst Alert Telescope (BAT; Barthelmy et al., [2005b]), the X-ray Telescope (XRT; Burrows et al., [2003]), and the Ultraviolet/Optical Telescope (UVOT; Roming et al., [2005]). An overview of the satellite, with the positions of the different instruments shown, is presented in Fig. 5.6. In this thesis only data from the XRT have been used and it is this instrument on which I will focus in this text.

The XRT uses a charge-coupled device (CCD) to detect incident photons and observes in the energy range 0.2 - 10 keV, with an energy resolution of 140 eV at 6 keV. The XRT has a field of view of 23.6 arcmin$^2$, which is significantly smaller than the BAT field of view of 16.5 $\times$ 10$^6$ arcmin$^2$. GRBs are detected by the BAT (about 100 year$^{-1}$) and *Swift* then slews to perform observations with the XRT and UVOT.

In contrast to the GBM, XRT is also capable of taking images. This provides XRT with significantly better localisation properties than GBM, with the localisation error on GRBs for the XRT being on the order of 2 arcseconds compared to $\sim 10^\circ$ for GBM (Barthelmy et al., [2005b]; Berlato, Greiner, and Burgess, [2019]). Once *Swift* has slewed to point towards a detected burst, the UVOT provides yet improved localisation and can perform long-term observation of GRBs in the optical and ultra-violet energy bands. The XRT is mainly used for long-term observations of GRB afterglows in the soft X-ray regime. However, in this thesis I have used early XRT data which overlaps with the late prompt emission. The XRT observes in two modes; window timing (WT) and photon counting (PC). The WT mode is used when the count rate is high (usually at the beginning of the observation) and it has a time resolution of 1.8 ms. The PC mode instead has a time resolution of 2.5 s and the observation is typically automatically shifted to this mode once the count rate is lower.

The XRT data products are available online and include event files keeping track of each detected photon, as well as instrument files. The XRT data reduction

http://www.swift.ac.uk/xrt_live_cat/
can generally be performed online\footnote{See instruction at \url{http://www.swift.ac.uk/analysis/xrt/index.php}}, following Evans et al. (2009). In contrast to GBM, the background spectrum is measured by sampling an off-source region around the burst location. This background is assumed to be Poisson distributed. Additionally, the background level is significantly lower for XRT than for GBM. There are also calibration and pile-up issues which are checked and accounted for automatically when reducing the data online. Due to degradation of the instrument over the years, there is also the possibility of an artificial turn up of the spectrum below 0.6 keV, caused by another redistribution issue. This issue is prevalent mainly for sources with a high degree of absorption and can be remedied either by updating the instrument response used or by removing the affected channels from the fit.
Chapter 6

Data analysis and statistics

"Don't Panic."

In this chapter I describe the principles of the spectral analysis which lays the foundation for this thesis. This includes an overview of the data, as well as the major software used in the work. I also outline a few statistical tools and concepts which are integral to much of the analysis carried out.

6.1 Time binning

There are two major modes by which to perform spectral analysis of GRB prompt emission; by a time-integrated or time-resolved analysis. The time-integrated analysis usually means that all photons from the entirety of the burst are analysed together, with no consideration taken to their individual arrival times. This has the advantage of providing a high count statistics, making it easy to fit a model to the data and yielding tight constraints on model parameters. The obvious downside is that one neglects any temporal evolution of spectral properties, which may significantly change what is inferred from the data. A typical example is that neglecting any evolution of hardness (here meaning the ratio between the flux in a high and low energy band), leads to an observed spectrum which is wider than what is observed in a time-resolved analysis. This will in turn affect the inferences made based on fits to these spectra. Conversely, the goal of a time-resolved analysis is to account for spectral evolution in order to obtain a better representation of the spectrum at any given moment. However, this comes at the cost of fewer photons in each analysed spectrum, which in turn leads to a lower ability to constrain models.

Even in a time-resolved analysis the choice of time bins may affect the results, since there is no guarantee that the spectrum in a given time bin does not contain any spectral evolution (see e.g. Burgess, Ryde, and Yu, 2013). One increasingly popular binning method which tries to accommodate this is the Bayesian blocks
Figure 6.1. Example of Bayesian blocks binning to simulated data. The blue shaded histogram represents a manually selected binning which shows the characteristics of the data. The black border shows the representation determined by the Bayesian blocks algorithm. The data is simulated from a Poisson process using constant rates in the intervals 0-5 s and 5-10 s, and with an exponential decay in the interval 10-20 s. The Bayesian blocks algorithm does a good job of finding the underlying Poisson rates. It is easy to see in this example how a poorly chosen binning could obscure the characteristics of the signal.

Binning (Scargle, 1998; Scargle et al., 2013). Bayesian blocks aims to represent time series data as a series of intervals, each in which the underlying signal is constant (within errors). This corresponds to segments with a constant Poisson rate in the case of a varying Poisson signal. If the GRB spectral evolution stems from e.g. central engine activity, it is reasonable to assume that a constant photon rate in the signal correspond to relatively stable physical conditions at the source, yielding no spectral evolution. If this holds, then the time intervals retrieved by binning with Bayesian blocks corresponds to segments with no spectral evolution. This allows the most reliable spectral analysis to be performed. An example of a Bayesian blocks binning is provided in Fig. 6.1.

6.2 Data and fitting

In this thesis, the main software used is the commonly used software package XSPEC (Arnaud, Dorman, and Gordon, 1999). This software was originally written to analyse X-ray data, but is used today as a flexible tool to analyse data from most wavelengths and instruments. However, when discussing spectral analysis in high-energy astro physics, it is important to first have an understanding of the data. Thus, I start will from the detectors, using the GBM detector as an example.\footnote{Part of this exposition is inspired by the pedagogical introduction to GRB data formats from \url{https://grburgess.github.io/fits_files/}.}
6.2. Data and fitting

6.2.1 Detector response

As mentioned in Chapter 2, GBM outputs data in the form of counts s\(^{-1}\) PHA channel\(^{-1}\). However, photon flux is expressed in units of photon s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\). The reason for this difference is that, for high-energy photons, energy dispersion as well as the fact that the detector effective area is a function of the photon energy become important. This means that an incident photon does not necessarily deposit all its energy into one detector channel. Additionally, because of the effective area, how the energy is distributed in the detector varies probabilistically depending on the energy of the incident photon. This process is described by the detector response matrix, which, for each detector, models the probability that a photon induces a signal for each detector channel, for all possible incident photon energies. In Fig. 6.2, I show an example of a graphical representation of a GBM response matrix.

I denote the incident photon energy \(E\) and the detector PHA channel \(I\). The detector response matrix, \(R(I, E)\), models the transition from the physical flux, \(f(E)\), in units of photon s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\), to the detected counts, \(C(I)\), in units of counts s\(^{-1}\) PHA channel\(^{-1}\). The naïve approach is to obtain the photon spectrum by simply inverting the expression to obtain

\[
f(E) = C(I)R(I, E)^{-1}.
\]

However, due to the non-linearity of the processes involved, \(R(I, E)\) is singular, and inversions yield non-unique, unstable solutions, see e.g. Blissett and Cruise (1979), Kahn and Blissett (1980), and Loredo and Epstein (1989). Thus, some other technique is required in order to fit models to observed photon spectra. The above discussion is generally true for all high-energy photon detectors. However, contrary to GBM, which provides a detector response file describing both energy dispersion and effective area, most instruments separate these effects into different file types, typically called response matrix files (RMFs) and ancillary response files (ARFs), respectively.

6.2.2 Forward folding

The procedure for fitting a model to these kinds of data is to use forward folding (Piron et al., 2001). With this technique, a model is required before a photon spectrum can be produced. The model is convolved with the detector response, yielding the model’s count prediction as

\[
C(I) = \int_0^\infty f(E)R(I, E)dE. \tag{6.1}
\]

\(C(I)\) can then be compared with the detected counts. The model parameters are varied in order to find the best fit. The result is then given as the best-fit parameters for the model which produced the best agreement with the data. I describe how this is usually accomplished further in Section 6.2.3.
Figure 6.2. Example of a GBM response matrix, illustrated as a ridge plot. Incident photon energies are represented going into the figure. Every fourth energy bin is shown here. For clarity the energy bins are also represented by lighter shades at lower energies. Detector channels are indicated on the x-axis. The probability that a photon of a certain energy is detected in a given channel is indicated by the y-axis in each energy bin. It is obvious that the matrix is non-invertible.
6.2. Data and fitting

The use of forward folding introduces some very important caveats to keep in mind: the results are influenced by the initial hypothesis since the fitted model is pre-determined. Due to the noisy nature of the data, this means that some features of the data may be obscured for certain choices of model. Secondly, the data can be equally well fitted by different models predicting different spectral shapes.

6.2.3 Fitting a model to data

The fitting procedure described above is often performed using Maximum Likelihood (ML). This uses the idea that the best-fitting model parameter values maximise the probability of the observed data given the model (i.e. maximising the likelihood). The likelihood is defined as the total probability of observing the data given the model and parameter values, \( \mathcal{L}(\theta) = P(d|\theta) \), for the observed data, \( d \), and the model parameters, \( \theta \). However, for simplicity, one usually instead minimises twice the negative log likelihood, \( -2 \ln(\mathcal{L}) \), obtaining the same result.

The likelihood will look different depending on the nature of the data. The primary concern for GRB spectral analysis is that the data are Poisson distributed. For a pure Poisson process with no background, the likelihood of observing \( N \) counts in a given detector (and detector channel) can be expressed as

\[
P(N|S) = \frac{(ST)^N}{N!} e^{-ST},
\]

where \( S \) is the predicted count rate, given some model for the spectral energy distribution and a set of parameters, \( \theta \), and \( T \) is the time over which which the signal is observed. The total likelihood for all observed counts is then the product of the contributions from all detectors \( (d) \) and channels \( (c) \) and can be written as

\[
P(N_{d,c}|S_{d,c}) = P(N_{d,c}|S_{d,c}) = P(N_{d,c}|S_{d,c}).
\]

The fact that the count rate is rather low makes is unsuitable to apply Gaussian approximations, and Poisson statistics must be employed. Although it is often in principle possible to group energy channels together to achieve a sufficiently high count rate to employ \( \chi^2 \) statistics somewhat reliably, this reduces the spectral resolution and is not advised. Additionally, if the goal is to use \( \chi^2 \) statistics in order to gain access to the reduced chi square as a goodness of fit (GOF) measure, one should be aware of the common pitfalls with this approach (Andrae, Schulze-Hartung, and Melchior, 2010).

There is also a non-negligible background present. Depending on the instrument this is modelled in different ways. In GBM the background is modelled by fitting a low-ordered polynomial to a time interval before and after the signal, as described in Section 5.1.3. This models the background, \( B_{d,c} \), as a normal distribution with mean \( \hat{B}_{d,c} \) and standard deviation \( \sigma_{d,c} \), such that \( B_{d,c} \sim \mathcal{N}(\hat{B}_{d,c}, \sigma_{d,c}) \). The background model is thus created from the off-signal region and is interpolated in time.
to the on-source interval and provides a background estimate and an associated uncertainty for each detector and detector channel.

Combining the likelihood for the observed counts with that of the background yields the total likelihood,

\[
P(N_{d,c}|S_{d,c}(\theta), \tilde{B}_{d,c}, \sigma_{d,c}) =
\prod_{i=1}^{N_d} \prod_{j=1}^{N_c} e^{-\left[\frac{\left(S_{d,c}(\theta)+\tilde{B}_{d,c}\right)T-\frac{\sigma_{d,c}^2 T^2}{2}\right]}{\left(S_{d,c}(\theta)+\tilde{B}_{d,c}\right)T+\frac{1}{2\sigma_{d,c}^2 N}}\right]}, \quad \text{if } N = 0.
\]

\[
\prod_{i=1}^{N_d} \prod_{j=1}^{N_c} (S_{d,c}(\theta)+\tilde{B}_{d,c})^{N_{d,c}} e^{-\left[\frac{\left(S_{d,c}(\theta)+\tilde{B}_{d,c}\right)T+\frac{(\tilde{B}_{d,c}-\hat{B}_{d,c})^2}{2\sigma_{d,c}^2}}{N}\right]}, \quad N > 0.
\]

where the model parameter dependencies have been made explicit, terms which are not dependent on \(S_{d,c}\) have been omitted, and where

\[
\tilde{B} = \frac{1}{2} \left[ B - S(\theta) - \sigma^2 T^2 + \sqrt{(S(\theta) + \sigma^2 T^2 - \tilde{B})^2 - 4(\sigma^2 TS - \sigma^2 N - \hat{B}S(\theta))}\right].
\]

The subscripts \(d\) and \(c\) have been dropped in the expression for \(\tilde{B}_{d,c}\). In order to obtain this expression for the likelihood, some approximations regarding the calculation of the background estimate are made. See e.g. Burgess et al. (2016b) for a thorough description of how to derive the likelihood. In xspec this likelihood is known as the pgstat statistic (Arnaud, Dorman, and Gordon, 1999). This is the likelihood used for all Fermi GRB data in this thesis.

The procedure is slightly different for Swift/XRT data, due to the background estimate being different. As mentioned in Section 5.2, the XRT instrument estimates the background from measurements located away from the source, assuming that the background is Poisson distributed. This is a result of the XRT being an imaging instrument with spatial resolution capabilities. Combining the two Poisson likelihoods instead yields a total likelihood which is known as cstat in xspec.

Parameter errors calculated in xspec are obtained by fixing the parameter of interest and fitting for the other parameters. The value of the fixed parameter is then changed and the model is again fitted for all other parameters. This process is repeated until a change in fit statistic value is obtained which corresponds to the desired level of significance. To find the parameter values at the end of the confidence intervals, xspec employs a bracketing algorithm and then an iterative cubic interpolation. The errors can also be computed, with lower accuracy, using the Fisher information, which can be obtained by inverting the covariance matrix.

### 6.2.4 Goodness of fit

GOF is usually an attempt at quantifying how well a model describes the observed data. Inferences based on model fits are only useful if the model actually describes the data in some meaningful way. There are many tests for quantifying GOF for different scenarios, with some of the most commonly used techniques in the field of astronomy being perhaps the Kolmogorov-Smirnov test or the \(\chi^2\) test. However,
these tests have several drawbacks and limitations (Babu and Feigelson, 2006). A robust but computationally expensive approach for assessing the GOF, which is valid also for the previously discussed pgstat, is by using a bootstrap technique. For an introduction to bootstrap techniques, see e.g. Efron and Tibshirani (1994) and Boos (2003).

Schematically, the principle for this method is as follows. The model is assumed to be the true underlying model which has generated the data. The data is further assumed to be generated with some noise, which is summarised by the fit statistic, \( T \) (e.g. pgstat for GBM data). The value of the observed fit statistic for the best fit, \( T_0 \), is then considered drawn from the distribution of \( T \) under these assumptions. If \( T_0 \) has a value such that it is unlikely to be drawn from the distribution of \( T \), this is evidence against the hypothesis that the data have been generated from the model in question. The difficulty lies in how to obtain the distribution of \( T \). There is no analytical expression for this distribution for statistics such as pgstat. Thus, this is where the bootstrap is employed. From the best fit model, data is generated with statistical noise. ML is applied to find the best fit of the model to the simulated data and the corresponding value of the fit statistic is collected, which is sampled from the distribution of \( T \). The procedure of simulating and re-fitting the model to the simulated data is repeated \( N \) times, such that a sufficient sampling of the \( T \) distribution is achieved. The observed value \( T_0 \) is then compared to the sampled distribution and a \( p \)-value can be calculated as

\[
p = P(T \geq T_0|H_0) \approx \frac{n}{N},
\]

where \( n \) is the number of samples with \( T \geq T_0 \) and where \( H_0 \) is the null hypothesis that the model has generated the observed data.

### 6.3 Bayesian statistics

The fitting procedure outlined in Section 3.2.3 describes the ML approach as implemented in xspec. In this section I instead outline the Bayesian approach. The topic of Bayesian inference and the discussion of a Bayesian versus frequentist perspective is vast and an extended discussion is outside the scope of this text. After a brief introduction, I will here focus mainly on some of the practical aspects of conducting Bayesian inference in the setting of GRB analysis and some of the tools it provides. For a more complete overview of Bayesian statistics, see e.g. Gelman et al. (2004) and Gelman et al. (2013). For an overview of the role of Bayesian statistics in the field of astrostatistics, see also e.g. Loredo (2012).

There are several key concepts in Bayesian statistics worth noting even in a brief exposition such as this. Firstly, the Bayesian interpretation of probability is that probability of an event corresponds to a degree of belief in that said event occurs. This is different from the frequentist interpretation that a probability of an event is the relative frequency of its outcome in the limit of an infinite number of trials. This leads to significantly different interpretations of several concepts in statistics when considering a Bayesian or a frequentist interpretation.
Another key concept in Bayesian statistics is Bayes’ theorem, which, in a notation similar to that used in Section 6.2, states that

$$P(\theta|d) = \frac{P(\theta)P(d|\theta)}{\int P(\theta)P(d|\theta)d\theta}, \quad (6.2)$$

where $P(\theta|d)$ is the posterior probability of $\theta$ conditioned on some observed data $d$. Additionally, $P(\theta)$ is the prior, $P(d|\theta)$ is the likelihood of the observed data given $\theta$, and $\int P(\theta)P(d|\theta)d\theta$ is the marginalised likelihood which is also known as the evidence, also called $Z$. This theorem is at its core just a result of probability theory. However, because of how it relates the above quantities, it plays a central role in Bayesian statistics and when performing Bayesian inference. When making parameter estimations the posterior holds all the relevant information. Constraints can be obtained simultaneously on any number of parameters using the joint posterior and marginalising over (i.e. integrating out) the other parameters. The evidence is not dependent on any of the model parameters and is often left out if parameter estimation is the only goal. However, it plays an important role in model selection and hypothesis testing.

Bayesian statistics is also characterised by the usage of prior information, incorporated in Bayes’ theorem through the aforementioned prior, $P(\theta)$. This can be viewed either as a process of updating a pre-existing state of knowledge by considering new data, or as incorporating previous knowledge when being confronted with new data. Due to the subjective nature of incorporating and quantifying existing beliefs, and the fact that, in principle, different people using the same analysis but with different prior beliefs, may end up with different results, the usage of Bayesian inference can be controversial (Gelman, 2008). However, the choice between sensible priors often has only a small impact on the resulting inferences and the importance of priors tends to be exaggerated when criticising Bayesian statistics. From a practical perspective, for a model with parameters, $\theta$, choosing priors comes down to deciding on a probability density function for each parameter (or a joint multivariate probability densities), that matches ones prior beliefs. A prior is called proper if it integrates to unity. In the case of model selection it is important to use proper priors, whereas in the case of parameter estimation it is less important.

Finally, I want to stress a slightly more subtle but crucial difference between Bayesian and frequentist statistics. Bayesian statistics deals with probability mass, i.e. integrated intervals of probability distributions. Conversely, frequentist statistics is more concerned with point estimates (c.f. ML which provides a single set of parameter values as the best fit). An analogy to thermodynamics is that the Bayesian statistician is interested in heat, whereas the frequentist is concerned with temperature. This is of course a simplification, but is reflected in what results are presented and how they are used to make inferences in the respective disciplines.
6.3. Bayesian statistics

6.3.1 Sampling

One of the major reasons why Bayesian statistics has seen a rise in popularity in later years is because of the general increase in computational power. The reason why the popularity of Bayesian statistics has been tied to the availability of computational power is because of the difficulties in evaluating posterior probabilities. A posterior is usually a multidimensional surface, and where the frequentist approach of finding the maximum of this surface is easy, it can be notoriously hard to map the entirety of the posterior sufficiently well.

The common solution is to sample the posterior in such a way that the density of samples is proportional to the posterior. There are several well-known Markov chain Monte Carlo (MCMC) based algorithms which can be used to sample posteriors, such as the now classical Metropolis-Hastings algorithm (Hastings, 1970), or the newer parallel tempering technique (Ronquist et al., 2004). Another method is nested sampling (Skilling, 2004), with implementations such as MultiNest (Feroz, Hobson, and Bridges, 2009; Feroz et al., 2013). Nested sampling was devised with the purpose of accurately calculating the Bayesian evidence, $\mathcal{Z}$ (which is usually hard for MCMC based algorithms), but provides posterior samples as a by-product.

6.3.2 Predictive posterior check

Predictive posterior checks (PPCs) are a way of simulating replicated data under the fitted model and comparing it with the observed data in order to infer how well the model can describe the original data (Gelman and Hill, 2007). This is essentially the Bayesian equivalence to a goodness of fit. However, there are several important distinctions. Here I will provide a short overview of the kind of PPC used and discussed in my work.

The basic idea is that you start with the posterior predictive distribution (PPD)

$$P(d^{\text{rep}}|d) = \int P(d^{\text{rep}}|\theta)P(\theta|d)d\theta;$$

This corresponds to the probability of observing some replicated data, $d^{\text{rep}}$, conditioned on having observed the data $d$. As previously, $\theta$ represents our model parameters. The next step is to obtain a measure of a goodness of fit, or how typical the observed data is in the distribution of replicated data.

A convenient way of constructing a PPC is the posterior predictive $p$-value ($ppp$-value),

$$p_b = P(T(d^{\text{rep}}) > T(d)|d).$$

This is a generalisation of the frequentist approach described in Section 6.2.4, with the only difference being that we here average our $p$-value over the posterior, $P(\theta|d)$, and that $T$ can be a more general test statistic (Rubin, 1984). Note that if $T$ is the fit statistic and the posterior is a delta function, we would recover the classical $p$-value.
Chapter 6. Data analysis and statistics

There are many other possible PPCs available. The advantage of the \textit{ppp}-value is that it can be summarised as a single number. Many other methods yield graphical representations of how well the model agree with the observed data, e.g. by comparing the observed data directly to sets of replicated data (Gelman et al., 2004; Buchner et al., 2014). These methods can provide better diagnostics than a \textit{ppp}-value, but are often cumbersome in large samples. Additionally, it may be less clear what condition to use as a discriminator for when a fit is sufficiently good and when it should be rejected.

6.3.3 Visualisation

One of the advantages of using a Bayesian approach is the additional information given by the posterior, compared to frequentist point estimate and some estimate of the uncertainty at a given significance. However, presenting this additional information is not always trivial (it’s not possible to summarise an arbitrary distribution by a single number) and visualising the results of a Bayesian analysis is a science in itself. In this section I exemplify some of the tools used to visualise the result of a Bayesian analysis. For consistency I show examples from the joint analysis of GRB 161117A at 72 – 144 s, using simultaneous GBM and XRT data from paper III.

A multidimensional posterior is usually represented by a corner plot, see Fig. 6.3. This plot shows the marginalised posterior distributions for all parameters, as well as all pairs of parameters. This allows for an easy overview of the characteristics of the posterior distribution, including the mean and variance of all parameters, and any model degeneracies.

In the context of spectral analysis, there is an important distinction to be made with how a frequentist or a Bayesian prefer to plot the model and data together. The frequentist approach is often to plot the model only for the best-fit parameters, whereas a common Bayesian method is to instead show point-wise credible bands. These bands represent a credible region of the model at each energy in the spectrum (meaning that the true model lies within this interval with the given probability). An example of this is presented in Fig. 6.4. It is also worth noting that this figure shows the model and data in detector count space. This is because any representation of the data in unfolded model space yields a biased representation of the data (see Section 6.2). This would be particularly problematic when constructing credible bands, since a large number of model spectra are used to construct the bands, and each model spectrum would yield slightly different positions of the data points. Thus, in order to plot model credible bands together with the data it is required that the plot is in detector count space. For similar reasons, this method of representing the posterior and data cannot be summarised using traditional residuals.

It is often desired to consider the temporal evolution of parameters. In a frequentist scheme this is conveniently represented graphically by plotting the parameter point estimates as a function of time. In a Bayesian analysis, if one wants to conserve the information of the full posterior, a possibility is so-called ridge plots (also
6.3. **Bayesian statistics**

![Figure 6.3](image)

**Figure 6.3.** Example of a corner plot. The histograms show the marginalised posterior for each free parameter in the fit. The contour plots show the joint posteriors of each pair of parameters. This particular corner plot shows the posterior of the DREAM model from paper III conditioned on the joint GBM and XRT data of GRB 161117A in the interval 92.7 – 100.2 s. The levels in the contour plots denote the 68.3, 95 and 99.7 % HDP regions.
Figure 6.4. Example of a fit in count space, resulting from Bayesian inference. The credible bands denote the 95% credible regions of the model. The different colours represent the different detectors used in the analysis. The fit is taken form the analysis in paper III of joint GBM and XRT data from GRB 161117A in the interval 92.7 – 100.2 s.

known as joy plots), see Fig. 6.5. These plots have the advantage of showing the full posterior, but are clearly not as comprehensible. Additionally, when dealing with unevenly distributed time-bins, the vertical offset of the posteriors become a possible issue.

### 6.4 Correlations

A common objective in data analysis is to ascertain the existence of correlations, well as to quantify the correlations. As mentioned in Section 6.1, there are several observed correlations related to GRBs. The topic of correlation analysis is extensive and I will here limit myself to describing some of the common methods and measures used to quantify linear correlations. For an introduction to correlation analysis and linear regression, see e.g. Cowan (1998).

There are several measures of correlation, of which the Pearson correlation coefficient is probably the most common and well known. The Pearson correlation coefficient for two variables, $X$ and $Y$, is defined as the covariance of $X$ and $Y$, divided by the product of their standard deviations. For a population this can be expressed as

$$
\rho_{X,Y} = \frac{E[(X - \mu_X)(Y - \mu_Y)]}{\sigma_X \sigma_Y},
$$
6.4. Correlations

![Plot](image)

**Figure 6.5.** Example of a ridge plot representation of the temporal evolution of the posteriors for the model luminosity parameter resulting from Bayesian inference using the DREAM model, of GRB 161117A at 72 – 144 s, using simultaneous GBM and XRT data. Each posterior is shown with a constant offset on the y-axis. A greater offset and a darker shading here indicates a later time.

where $E[X]$, $\mu_X$, and $\sigma_X$ is the expectation value, the mean, and the standard deviation of $X$, respectively (and similarly for $Y$). However, the data will usually consist of a sample drawn from the full population, in which case the appropriate quantity becomes the sample Pearson correlation coefficient, which is typically expressed as

$$r_{xy} = \frac{\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{n}(x_i - \bar{x})^2} \sqrt{\sum_{i=1}^{n}(y_i - \bar{y})^2}},$$

with $x_i$ denoting the $i^{th}$ out of $n$ observations from the population variable $X$ and $\bar{x}$ the sample mean (and similarly for $y$). It should be noted that the Pearson correlation coefficient does not uniquely determine the relation between two parameters.

It also turns out that the sample correlation coefficient is proportional to the slope one obtains with simple linear regression of $y(x)$, using e.g. the method of least squares. However, this method assumes that there are no uncertainties in the data. Conversely, when the data are the result of spectral analysis, e.g. parameter values or observed luminosities, there will be associated uncertainties. These arise both from measurement errors and intrinsic scatter (i.e. physical variations not captured by the variables in the regression). A common approach is to assume that there are only uncertainties in the dependent variable, since this is computationally simple. However, this approach biases the results (Brown, 1990; Akritas and Bershady, 1996). A relatively recent method, using a Bayesian hierarchical model, was developed by Kelly (2007). This method incorporates heteroscedastic measurement errors in both variables when fitting a straight line to data (the method also includes a generalisation to the multidimensional case). Further, it allows the errors
to be correlated and accounts for intrinsic scatter in the linear relationship, as well as selection effects.
Summary of publications

Paper I
Ahlgren et al. (2015), Confronting GRB prompt emission with a model for subphotospheric dissipation

In this paper we fit Fermi GRB data with a photospheric emission model which includes dissipation of the jet kinetic energy below the photosphere. We create DREAM (Dissipation with Radiative Emission as A table Model), a table model for xspec, and fit it to GRB 090618 and GRB 100724B, and compare the fits to the corresponding Band function fits. We conclude that our model can fit both single and double peaked spectra.

Paper II
Ahlgren et al. (2019a), Testing a model for subphotospheric dissipation in GRBs: fits to Fermi data constrain the dissipation scenario

We consider a specific model for subphotospheric dissipation which produces non-thermal spectra from the photosphere. Building on the work of Ahlgren et al., we consider an improved version of the DREAM model which we fit to 36 bursts using a time-resolved analysis. We show that the model can describe about a third of the fitted spectra and that the main reason for the non-successful fits is that the model typically under-predicts the observed flux, which makes the model unable to reproduce the brightest bursts. We attribute this mainly to the internal shocks assumption. Additionally, we note that our sample is strongly biased towards bright GRBs and we argue that the fraction of accepted bursts will be significantly lowered when considering the full population. From the successful fits we show that all spectral slopes present in our sample can be fitted, affirming that inferences based on fits with the Band function should not be used to constrain physical models.
We also find a correlation between the fireball luminosity and the Lorentz factor. We conclude that if GRB spectra are due to photospheric emission, the dissipation cannot only be the specific scenario we consider here.

**Paper III (Draft)**

**Ahlgren et al. (2019b), Searching for subphotospheric dissipation in prompt GRB emission using joint Fermi-Swift observations**

We build further on Ahlgren et al., 2019, by considering the same model, including a small expansion of the parameter space, in the light of joint observations from the *Fermi* GBM and *Swift* XRT instruments. Our sample consists of all 8 bursts with known redshift and a significant overlap between the two instruments. We perform a Bayesian analysis by implementing the nested sampling tool *MultiNest* in the X-ray fitting software *XSPEC*. The extended energy range allow us to investigate the model where critical predictions of the model spectra occur. We find that the available XRT data in the energy range 0.3 – 10 keV significantly change the parameter estimates. However, a closer inspection of the posteriors show that the data are largely consistent with our model predictions, with a few notable exceptions. In GRB 151027A there are strong indications of additional emission components in the XRT data, which causes our one-zone model to fail. We conclude that although the model can describe most of the analysed spectra, the model assumptions from internal shocks should be removed to allow for a more flexible model scenario. We also note that XRT data should be used whenever possible since it can provide crucial tests of a model.
Chapter 7

Outlook

“ Aristotle said a bunch of stuff that was wrong. Galileo and Newton fixed things up. Then Einstein broke everything again. Now we’ve basically got it all worked out, except for small stuff, big stuff, hot stuff, cold stuff, fast stuff, heavy stuff, dark stuff, turbulence, and the concept of time.”

— Zach Weinersmith, Science: Abridged Beyond the Point of Usefulness

The future of the field of GRBs looks bright (pun fully intended). There has been significant progress in the last few years, particularly in analysis techniques and in moving towards testing of physical models. Although the Band function and other empirical functions can be used to find correlations and to characterise GRB spectra to a certain degree, it is clear that they cannot get us all the way to the origin of GRB prompt emission. As some of the conclusions drawn from Band based inferences are shown to be erroneous it is becoming increasingly clear that the way forward is through more physically motivated models. However, more work is required on the physical models before we can have a unified picture of GRB prompt emission.

For DREAM, this future work includes further expansion of the parameter space. Particularly the joint analysis of Fermi/GBM and Swift/XRT suggests that better fits to the data is possible for an expanded parameter space. However, to accommodate the normalisation issue identified in paper II the dissipation scenario must be revised. Even further down the road awaits physics that is not at all included in DREAM, such as hydrodynamics. As the model and analysis (and hopefully eventually also data) improve, effects from e.g. hydrodynamics or jet geometries are likely to become increasingly important. It seems likely that the table model format is going to be the relevant in the future as the physical models will remain computationally expensive, particularly in the case of hydrodynamic models.
There is a general increase of Bayesian techniques which has been going on for well over a decade, bringing new possibilities to the field. These techniques allow for better treatment of some of the significant uncertainties stemming from the difficult process of observing sparse high-energy photons.

On the topic of detecting these photons, the *Fermi Gamma-ray Space Telescope* has been providing us with spectra over a wide energy range from a large number of GRBs for over a decade. Unfortunately, there seems to be no replacement ready once it is decommissioned. However, the launch of POLAR and its successful polarisation measurements have helped shed new light over a previously only sparsely explored part of GRB prompt emission. Hopefully the plethora of results brought by the current instruments will help the realisation of new detectors in the near future. One such proposed mission is SPHiNX (Pearce et al., 2013), a small dedicated GRB instrument which includes polarimetry capabilities.
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