ADDENDUM

Certain portions of the text in the section 2.1.1 ‘Gamma ray burst monitor (GBM)’ have been quoted with permission from C. Lundman, 2012, Licentiate Thesis, KTH (urn:nbn:se:kth:diva-101913). The quoted portions in the text are the following:

In paragraph 1: lines 2, 3 and 4; in paragraph 2: lines 2 and 3; in paragraph 3: lines 1, 3, 4, and 5; paragraph 4 and in paragraph 5: lines 1 and 3; in paragraph 6: lines 5, 6, and 8. These constitute the pages 33, 34 and 35 in the thesis.

ERRATA

1. In the cover illustration caption: $r_{\gamma m \rho h}$ should be $r_{\gamma m}$.
2. In Figures 9 and 10 in Paper V, the x-axis labels: $F(\nu)$, (erg$^2$s$^{-1}$cm$^{-2}$keV$^{-1}$) should be $F(\nu)$, (erg$^2$s$^{-1}$cm$^{-2}$keV$^{-1}$).
3. In equation 4.2, instead of lab frame particle density given by $n(r)$ it should be lab frame photon density given by $n_{\gamma}(r)$.
4. In Paper V, Figure 2: panel for burst GRB100707A should be

![Figure 2](image1.png)

5. In Paper V, Figure 7 should be

![Figure 7](image2.png)

4. In Paper V, Figure 8 should be

![Figure 8](image3.png)
Photospheric emission in gamma ray bursts: Analysis and interpretation of observations made by the *Fermi* gamma ray space telescope –

*Shabnam Iyyani Syamsunder*
Photospheric emission in gamma ray bursts: Analysis and interpretation of observations made by the *Fermi* gamma ray space telescope

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Abstract

The large flashes of radiation that are observed in GRBs are generally believed to arise in a relativistic jetted outflow. This thesis addresses the question of how and where in the jet this radiation is produced. It further explores the jet properties that can be inferred from the observations made by the Fermi GST that regularly observes GRBs in the range 8 keV - 300 GeV. In my analysis I focus on the observational effects of the emission from the jet photosphere. I show that the photosphere has an important role in shaping the observed radiation spectrum and that its manifestations can significantly vary between bursts. For bursts in which the photospheric emission component can be identified, the dynamics of the flow can be explored by determining the jet Lorentz factor and the position of the jet nozzle. I also develop the theory of how to derive the properties of the outflow for general cases. The spectral analysis of the strong burst GRB110721A reveals a two-peaked spectrum, with the peaks evolving differently. I conclude that three main flow quantities can describe the observed spectral behaviour in bursts: the luminosity, the Lorentz factor, and the nozzle radius. While the photosphere can appear like a pure blackbody it can also be substantially broadened, due to dissipation of the jet energy below the photosphere. I show that Comptonisation of the blackbody can shape the observed spectra and describe its evolution. In particular this model can very well explain GRB110920A which has two prominent breaks in its spectra. Alternative models including synchrotron emission leads to severe physical constraints, such as the need for very high electron Lorentz factors, which are not expected in internal shocks. Even though different manifestations of the photospheric emission can explain the data, and lead to ambiguous interpretations, I argue that dissipation below the photosphere is the most important process in shaping the observed spectral shapes and evolutions.
This thesis is dedicated to my dearest father and my family...
List of Papers

The following papers, referred to in the text by their Roman numerals, are included in this thesis.

I  GRB110721A: An Extreme Peak Energy and Signatures of the Photosphere
   DOI: 10.1088/2041-8205/757/2/L31

II Variable jet properties in GRB 110721A: time resolved observations of the jet photosphere
   DOI: 10.1093/mnras/stt863

III Transparency Parameters from Relativistically Expanding Outflows
   DOI: 10.1088/0004-637X/792/1/42

IV Extremely narrow spectrum of GRB110920A: further evidence for localised, subphotospheric dissipation.
   DOI: 2015arXiv150305926I

V Synchrotron emission in GRBs observed with Fermi: Its limitations and the role of the photosphere.

The original papers are reproduced in the Appendix, with the permission of the copyright holders.
Author’s contribution

**PAPER I**
I was involved in the spectral analysis of the burst GRB110721A and in the discussions and interpretations of the results, along with our research group here in Stockholm who headed the analysis along with the *Fermi* LAT and GBM collaboration.

**PAPER II**
I headed the project which involved the detailed study of the temporal behaviour of the outflow dynamics of the burst GRB110721A based on the spectral analysis.

**PAPER III**
I was involved in the development of the idea of the project, the spectral analysis of the burst GRB090902B, the calculation of the jet properties and in the discussions and interpretations of the result.

**PAPER IV**
I headed the project which involved the spectral analysis of the burst GRB110920A and the physical interpretation of the results within the subphotospheric dissipation model.

**PAPER V**
I headed the project which involved the analysis and physical interpretations of the results of the spectral analysis of a sample of bursts which was done in Burgess et al. 2014 in which I myself was also a co-author.
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1. The First Pulse of the Extremely Bright GRB 130427A: A Test Lab for Synchrotron Shocks
   DOI: 10.1126/science.1242302

2. Time-resolved Analysis of Fermi Gamma-Ray Bursts with Fast- and Slow-cooled Synchrotron Photon Models
   DOI: 10.1088/0004-637X/784/1/17

3. An Observed Correlation between Thermal and Non-thermal Emission in Gamma-Ray Bursts
   DOI: 10.1088/0004-637X/784/1/17
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1. Introduction

Gamma-ray bursts (GRBs) are the most luminous and mysterious explosions in the universe. They are flashes of gamma-rays typically lasting only for a few seconds, produced as a result of the collapse of massive star forming a black hole or mergers of neutron star - neutron star / neutron star - black hole.

1.1 Discovery and distance scale

GRBs were first detected by the Vela satellites in 1967. However, the discovery was not made public until 1972. Later with the launch of Burst and Transient Source Explorer (BATSE) instrument on the Compton Gamma Ray Observatory (CGRO) in 1991, GRBs were started to be studied more extensively. BATSE was the first large experiment designed for the study of GRBs; along with that it was also an all sky monitoring project [12]. During its 9 + successful years, BATSE recorded 2704 GRBs. The distribution of GRBs were found to be isotropic, not biased towards any direction in the sky which suggested a cosmological origin. But the determination of the distance scale to the origin of GRBs were not possible until 1997, when the afterglows were observed with the Italian-Dutch satellite Beppo-SAX [13]. Afterglows are softer emissions extending from X-rays to radio lasting for a longer period of time. They are believed to be produced by the interaction of the ejecta with the circumburst medium [14]. In 1997, Beppo-SAX [13] detected GRB970228 and its Wide Field Camera detected a fading X-ray emission. An optical counterpart was also detected and deep imaging enabled the identification of a distant host galaxy within the localisation of the GRB. The redshift was determined at $z = 0.835$ which is about 6 billion light years away [15]. This confirmed that the GRBs originate from cosmological distances. Another breakthrough occurred in 1998 with the detection of GRB980425 which was followed by a detection of a bright supernova (SN1998bw) [16]. This showed that some of the GRBs are associated with the death of massive stars.

Further progress in observations were done by HETE-2 satellite which provided quality afterglow positions. It also provided the first unambiguous detection of supernova (SN2003dh) in association with the GRB030329 [17]. International Gamma ray Astrophysics Laboratory (INTEGRAL) is another
multi-wavelength mission which since 2002 has been performing a detailed spectroscopy and imaging of γ-ray emissions in the energy range 15 keV to 10 MeV. GRB031203 was one of the remarkable GRBs detected by INTEGRAL where there was a firm spectroscopical association with Type Ib/c supernovae [18]. Later, the multi-wavelength afterglow (gamma rays, X-ray, ultraviolet and optical) satellite Swift was launched in 2004 which continues to provide accurate localisations of the afterglows [19]. This has enhanced the knowledge about the afterglow behaviours of GRBs. The sample of redshift detected GRBs have considerably enlarged from the pre Swift era. The average redshift detected for the long GRBs (see §1.2) detected by Swift is $z = 2.4$ [20]. Currently, GRBs are observed among others with the Fermi Gamma Ray Space Telescope launched in 2008, providing nearly 7 orders of broad energy range, 8 keV - 300 GeV. This is achieved by two instruments on board: the Gamma ray burst monitor, GBM [4] and the Large Area Telescope, LAT [5], see chapter 2.

1.2 Light curves

BATSE detections of GRBs showed that the light curves of GRBs are very diverse. The GRBs are broadly classified into two groups on the basis of the duration of the burst. They are long GRBs whose burst duration is more than 2 seconds and short GRBs which have duration less than 2 seconds. Long GRBs are generally assumed to be associated with the collapse of a massive star forming a black hole whereas the short GRBs are speculated to be produced as a result of the merger of neutron star (NS) binaries or NS - black hole binaries. However, both the progenitors would result in a black hole of a few solar mass with a torus of debris which can immediately release gravitational energy sufficient for a burst. This thesis is based only on the study of long GRBs.

The observed light curve of the prompt emission of most GRBs show a variability timescale of the order of about milliseconds. This suggests that the gravitational energy released during the formation of the black hole is converted into free energy inside a region of the order of a few kilometres cubed. This means that there is a compact object at the centre. Many bursts show emission above 0.5 MeV, see §1.4 and §2.2. If the outflow of the burst is sub-relativistic then the cross-section of photon-photon pair production would be high, resulting in electron - positron pairs which in turn would result in a cut-off in the observed spectra above 1 MeV. However, in contradiction to this, the GRB spectra are found to extend above 1 MeV and even extending up to several GeVs. In order to avoid the photon-photon interaction, the outflow must be expanding with very high Lorentz factor, $\Gamma = 1/\sqrt{1 - (v/c)^2}$ where $v$ is
the speed of the outflow and $c$ is the speed of light, such that the cross section of photon - photon collisions drops. This is generally referred to as the compactness problem [21, 22]. Thus, by this phenomenological argument we can claim that the GRB outflows are ultra-relativistic.

The amount of energy that we infer from the observations is about $10^{54}$ ergs, assuming the total energy of the explosion to be emitted isotropically. This energy corresponds to a stellar rest mass implying that the entire star is converted into energy, which is not possible. Some part of the energy has to be given to neutrinos and gravitational waves. This problem was resolved by assuming that the GRB flash is a collimated emission of energy, during the explosion [14]. If the outflow is a jet with a jet opening angle, $\theta_j$, then $E_j = \theta_j^2 E_{iso}$ where $\theta_j \ll 1$ which gives a mean value of $E_j \sim 10^{51}$ ergs which is consistent within the energy budget of the core-collapse supernova. The break observed in some afterglow light curves also confirm that the GRB outflow is in the form of a jet [23], however note that most GRBs do not show jet breaks.

1.3 Classical GRB fireball model

The entire GRB emission can be divided into two main phases: prompt phase which occurs immediately to the burst which is generally observed in $\gamma$-rays and afterglow phase.

As the massive star collapses to form a black hole, a fireball of huge energy, $E$ of the order of $10^{52}$ erg, electrons, positrons, photons and baryons (of mass $M$) are produced. This dense medium does not allow the photons to escape from the plasma, thereby remaining optically thick to photons. Assuming the outflow is non-magnetised, due to the high radiation pressure, the fireball expands adiabatically from the nozzle of the jet, $r_0$, thereby accelerating the flow material to very high velocities, close to the speed of light (magnetic acceleration is possible in case of highly magnetised outflows [24]). During the acceleration, by the law of conservation of energy, the internal energy per particle decreases and the bulk kinetic energy per particle (bulk Lorentz factor, $\Gamma$) increases. The $\Gamma$ increases until it reaches its maximum value that is the initial internal energy per particle ($\eta \equiv E_{iso}/Mc^2$). This radius beyond which the outflow coasts with a constant $\Gamma \equiv \eta$ is referred as the saturation radius, $r_s$. As the outflow expands, the volume increases and thereby the density of the plasma decreases. At some point in the outflow, the opacity of the plasma to the photons equals unity. This surface from where the photons escape the plasma is called as the photosphere, $r_{ph}$. Thus, the photosphere is the deepest region in the outflow from where emission can occur. Since the photons undergo a large number of scatterings, the output spectrum from the photosphere is expected to be a blackbody radiation due to thermalisation, however see
Figure 1.1: A schematic diagram depicting the classical GRB fireball model consisting of two main phases: prompt emission and afterglow emission. The main radii are nozzle of the jet, \( r_0 \), saturation radius, \( r_s \), photosphere radius, \( r_{ph} \) and the dissipation radius, \( r_d \).

also chapter 5. The outflow in this phase has a lot of kinetic energy and due to dissipative mechanisms like internal shocks \[25\], magnetic reconnections \[26\] etc, the outflow may dissipate its kinetic energy at a radius, \( r_d \) above the photosphere. This results in heating of the electrons via the shocks produced in the outflow, which then cool off by radiative mechanisms like optically-thin synchrotron emission \[27\] or inverse Compton scattering \[28\], see chapter 3. Thus, within the classical GRB fireball model the observed prompt emission of GRBs is expected from two main regions in the outflow: photosphere (\( r_{ph} \)) and optically thin region (\( r_d > r_{ph} \)). When the relativistic outflow crashes into the interstellar medium, the outflow slows down and the shocks created results in emission in lower energies like soft X-rays, optical, ultraviolet, radio and sometimes even \( \gamma \)-rays, see Figure 1.1.

1.4 Spectra of GRBs

The observed GRB spectra look non-thermal in nature. Most of the observed GRB spectra can be satisfactorily modelled using a Band function \[29\], i.e. two power laws smoothly joined and parametrized by an \( E_{\text{peak}} \). At low energies the spectra are described by a power law with an exponential cut off,

\[
N_E(E) \propto E^\alpha \exp\left(-\frac{E}{E_{\text{peak}}}\right) \quad (1.1)
\]

and at higher energies by a steeper power law,

\[
N_E(E) \propto E^\beta \quad (1.2)
\]

with \( \alpha > \beta \) and \( N_E = \text{photon flux} \[29\], see Figure 1.2.
Figure 1.2: A typical GRB spectrum can be modelled using the Band function which is characterised by parameters: $E_{\text{peak}}$, $\alpha$, $\beta$ and the normalisation. In the above figure, the $\nu F_\nu = \text{Energy}^2 \times \text{photon flux}$, plot of the Band function fit to the GRB spectrum is shown [1].
The Band function is an empirical function with no underlying physical motivation. So, just fitting the data with a Band function does not give us any direct information regarding the radiation mechanism. Such a non-thermal spectrum is generally interpreted as a result of the dissipation of the kinetic energy of the GRB outflow, causing the electrons to accelerate to a power law distribution which can then produce high energy photons via non-thermal processes such as optically thin synchrotron emission \[27\] or inverse Compton scattering \[28\], see chapter 3.

The study of the observed GRB spectra has pointed out some key spectral features as well as some key questions which need to be addressed to understand the radiation mechanism in GRBs \[30\] and they are:

i) **How can the observed spectra have both hard as well as soft sub-peak spectra?** The hardness of the sub peak emission can be quantified by the low energy spectral index, \(\alpha\) of the Band function. It has been found that the distribution of \(\alpha\) peaks at \(-0.8\) \[31; 32\] which is inconsistent with fast cooling synchrotron emission \((\alpha = -1.5)\). However, it is consistent with slow cooling synchrotron emission \((\alpha = -0.6, \) the so-called line of death of synchrotron emission\). At the same time, a considerable number of bursts are found to have harder sub peak spectra with \(\alpha > -0.6\). However, recently, Burgess et al. 2014 \[33\] showed that slow cooling synchrotron function when fitted with a Band function results in an \(\alpha\) that peaks at \(-0.8\) instead of \(-0.6\). Thus, the line of death of synchrotron emission is originally at \(\alpha = -0.8\). This makes a larger sample of bursts inconsistent with synchrotron emission and thereby raises the question underlying the radiation of these bursts.

ii) **What drives the observed evolution of the spectral shapes?** The time resolved spectral analysis of the bursts show a strong evolution in the shape of the spectra with time. The spectral evolution could be strongly related to the dynamics of the outflow which needs to be studied within the proposed emission models for GRBs.

iii) **Why do the \(E_{\text{peak}}\) values cluster in the narrow energy range as they do?** Spectral analysis of the bursts observed by the BATSE and Fermi found that the peak of the spectra is found to be around a few 100s of keV \[34; 35\].

iv) **What underlies the hardness - intensity correlation characteristic of each burst?** The spectral peak and luminosity of the bursts are found to be positively correlated during the decay pulse of the bursts \[36–38\].

v) **Where does the cooling of the heated electrons of the outflow take place, is it in the region of acceleration or in some separated regions?** The non-thermal emission requires the acceleration of the electrons as a result of shocks. The details of the microphysics of shock acceleration is not fully understood till now. This limits our understanding as to where in the outflow does the radiation takes place; and
vi) What accounts for the high radiative efficiency in the gamma ray emission? The observation of the prompt emission and afterglows suggests that the prompt GRB emission is highly efficient [39–41]. For instance, the internal shock model finds it hard to account for this high efficiency [42]. In the internal shock model, the shells with a distribution of Lorentz factors constitute the outflow of the burst. The fast moving shell when collides with the preceding slow moving shell result in shocks which then accelerates the electrons to high energies. The energy dissipated thus is the differential kinetic energy of the consecutive shells which is small and therefore only a small fraction of the burst energy is available for radiation by electrons. This cannot account for the observed high efficiency of the GRB prompt emission.

1.5 Photosphere model

Addressing the difficulties which the purely non-thermal models face, evoked the idea of the presence of a thermal component along with the non-thermal component in the spectra e.g., [43]. The photosphere is inherent in the standard fireball model and so, should the presence of thermal component in the spectra.

Using the above motivation, the GRB spectra recorded by the CGRO BATSE instrument, which explores in the energy range 20−2000 keV, were analysed using a blackbody and a non-thermal component like power law.

These analysis were able to find some recurring behaviours in the properties of the detected thermal component. The temperature, \( T(t) \) and thermal flux, \( F_{\text{BB}}(t) \) shows a repetitive behaviour: broken power law with time [2 3]. It is observed that the temperature almost remains a constant and the flux rises with time before the peak and after the peak, they decay as a power law. The temperature decays as \( T(t) \propto t^{-m} \) where \( m \sim 0.6 - 1.1 \), see Figure 1.3 and thermal flux as \( F_{\text{BB}}(t) \propto t^{-n} \), where \( n \sim 2.0 - 2.5 \). This boosts the idea of the presence of thermal component in the prompt emission of GRBs.

A recurring behaviour is also observed in the normalisation of the thermal component, parametrized by \( \mathcal{R}(t) \equiv \left( \frac{F_{\text{BB}}}{\sigma T^4} \right)^{1/2} \), which is proportional to the effective transverse size of the emitting region, \( r_{\text{ph}}/\Gamma \). \( \mathcal{R} \) is found to increase in size as a power law in time over the entire pulse and sometimes during the entire burst duration [2 3], see Fig 1.4.

Apart from the fact that thermal emission naturally gives rise to correlations between flux and energy peak, the temperature is expected to lie at about 1 MeV [44]. However, in optically thin synchrotron emission, the peak energy depends on several model parameters (Lorentz factor, \( \Gamma \); electron Lorentz factor, \( \gamma_{\text{min}} \); magnetic field, B) and so, can have a wide range of values, contradicting the observed narrow range of peak energies.
Figure 1.3: The temperature evolution of the photosphere during an emission pulse. Initially the temperature is nearly a constant, afterwards it decreases as a power law in time [2].

Figure 1.4: The parameter, \( R(t) \equiv \left( \frac{F_{BB}}{\sigma T^4} \right)^{1/2} \) increases as a power law over the entire pulse. The inlays show the corresponding light curves [2; 3].
The photosphere model also alleviates the efficiency problem of the internal shock model. In the photosphere model, high efficiencies can be reached if \( r_{\text{ph}} \) is closer to \( r_s \) in which case the thermal energy will be prominent \[30\]. In addition to this, subphotospheric dissipation can further enhance the thermal energy \[44\], see also chapter \[5\]. Thus, by considering that a part of the spectra originates from the photosphere, the total photon energy can be greater than the energy dissipated in internal shocks. Thus, the photosphere model can account for the efficiency of the burst. The combination of thermal and non-thermal components with varying strength also can account for the various spectral shapes observed in GRB spectra recorded in BATSE. The GRB spectral analysis in the BATSE era using the photosphere model (blackbody, BB and power law, PL components) has thus, enabled to address some of the key observational behaviours of the GRBs.

But the major drawback of the BATSE analysis was that it had an insufficient energy window in order to unambiguously determine the overall shape of the GRB spectrum as well as the emission process of GRBs. For instance, as indicated by a few bursts observed by the EGRET instrument on \textit{CGRO}, the power peak in many cases exists at energies > 1 MeV \[3; 45\]. This is consistent with the fact that the fits of BB+PL model in many cases predicts a power peak beyond the analysed energy range of 20 - 2000 keV, since for these cases the power law index, \( s > -2 \). Furthermore, in some cases, a simple extension of this model to lower energies does not fit the data \[46\]. This necessitated the observation over broader energy range to provide better clues to the emission mechanisms of GRBs and this is done by the \textit{Fermi Gamma Ray Space Telescope}.

In my thesis, I present the study of the prompt emission of long GRBs within the framework of the photosphere model. Paper I presents the spectral analysis of the burst GRB110721A, where a blackbody component with a very high significance (5\( \sigma \)) was detected along with a non-thermal Band function. Paper II presents the estimation and the study of the outflow dynamics of the jet of the burst GRB110721A with time, within the two emission zone photosphere model, see chapter \[5\] using the methodology in Pe’er et al. 2007 \[47\]. In Paper III, the estimation of the outflow dynamics of the jet is extended to the scenario where the photosphere forms in the accelerating phase of the jet, see chapter \[4\]. In Paper IV, I present the spectral analysis of the burst GRB110920A, where I identify a very narrow spectrum which is produced within the one emission zone photosphere model, see chapter \[5\]. In Paper V, I analyse the synchrotron emission observed in \textit{Fermi} GRBs and identify its limitations, as the radiation process resulting in the non-thermal part of the observed GRB spectra, as well as the role of the observed photospheric emission.

The thesis is structured in the following manner: in chapter \[2\], I present the
general observations done by *Fermi* gamma ray space telescope and their key implications. In chapter 3, I present the discussion on the physics of the radiation processes: synchrotron emission and inverse Compton scattering, that are relevant to the study done in my papers. In chapter 4, I discuss in detail the basic fireball model and the methodology to calculate the outflow dynamics of the jet when the photosphere forms both in the coasting as well as in the accelerating phase of the jet. In chapter 5, I present the two main photosphere models: two emission and one emission zone model and also present the discussion on the comparison between these two models in relevance to my results in papers IV and V. Finally, in chapter 6, I summarise my work and its key results.
2. GRB observations in the *Fermi* era

The *Fermi Gamma Ray Space Telescope* was launched on June 11, 2008. The *Fermi* mission has a lifetime requirement of 5 years and a goal of 10 years. Currently, *Fermi* has completed 7 years and thus, has entered the extended phase of its mission. The foremost aim of *Fermi* is to open the possibility to study the GRB spectrum over a wide range of energy (8 keV - 300 GeV). This has been made possible by two main science instruments onboard Gamma ray burst monitor (GBM) and Large Area Telescope (LAT). *Swift* and INTEGRAL are also simultaneously making GRB observations during this *Fermi* era.

2.1 *Fermi* Instrument

2.1.1 Gamma ray burst monitor (GBM)

GBM operates in the energy range 8 keV - 40 MeV. GBM includes two sets of detectors, 12 sodium iodide (NaI) scintillators, and two cylindrical bismuth germinate (BGO) scintillators. Each detector consists of a crystal disk (12.7 cm in diameter, 1.27 cm in thickness) attached to a photomultiplier tube (PMT). As photons interact with the scintillation crystals, they are converted into low energy scintillation photons, which are subsequently detected by the PMTs. The low energy threshold of the NaI detectors is set by a thin silicone layer (0.7 mm), attached to the top of the detector for mechanical reasons.

The locations and orientations of the NaI detectors allow for the localisation of sources by inspection of the relative strength of the detected counts in the detectors, similar to the BATSE instrument. Whenever a trigger occurs, on-board flight software computes the location of the event using a pre-calculated table with the relative count rates for 1634 directions (~ 5° accuracy). The location, along with burst data is then sent to the ground for additional processing and eventual follow-up observations.

Two BGO detectors provide coverage in the 200 keV - 40 MeV. It overlaps with the energy range at the lower end with NaI detectors and with LAT at higher energies. The BGO crystals are shaped in thick disks with length and diameter of 12.7 cm. A PMT is attached to each flat side of a BGO crystal.
in order to increase the light collection and to provide redundancy. The BGO detectors are located on opposite sides of the spacecraft to ensure that at least one BGO detector gets illuminated for each possible source location.

The NaI detectors are not collimated. Therefore, the background in lower energies (< 150 keV) includes a significant contribution from the diffuse X-ray background. At higher energies the background is dominated by secondary photon production by cosmic rays. Most of these photons originate from the Earth’s albedo, although a smaller fraction is produced within the satellite. The secondary photon production from cosmic rays is modulated by the Earth’s magnetic field and so the background varies depending on the spacecraft location. The orbit of Fermi passes through the South Atlantic Anomaly (SAA) where the increased flux of charged particles causes the background to rise sharply. Therefore, the PMTs are turned off during each passage through SAA.

Beam tests of both NaI and BGO detectors have shown an energy resolution ($\delta E/E$) of 10% – 20% (depending on the energy of the incoming photon) at normal incidence. The energy resolution of both the NaI and BGO detectors is shown in Figure 2.4. The effective area peaks at $\sim 100 \text{ cm}^2$ for both detector types and is about 70 – 100 cm² within most of the detector energy range. The dependence of the effective area of both detectors on energy at normal incidence is shown in Figures 2.6 and is also compared with the simulated response. The upper panel of the Figure 2.6 shows a good agreement.
with the lab measurements and simulated data. The shaded curves of the on-orbit simulations show the estimated systematic uncertainty in the simulated response. The on-orbit simulations takes into account spacecraft blockage and scatterings.

The two main effects that limits the efficiency of GBM detection at high photon rates are dead time and pile up of pulses in the front-end electronics. This also results in the limited speed in the transfer of data from the GBM to the spacecraft for transmission to the ground. Dead time limits the maximum rate of the digitalised pulses. The dead time between events is $2.6 \mu s$ for all energies except the highest channel in each detector. However, the effective dead time is weakly dependent on the exact spectral shape of the signal but does not exceed $10^{-5}$ s. An estimate of the upper limit to the number of counts per second the detector can handle is therefore $10^5$ counts per second. The pulse pile up occurs when consecutive event pulses transmitted to the front end electronics overlap (pile up) resulting in distortions of the measured spectrum and count rates. The effects of pile up are hard to quantify, however pre-flight simulations were carried out by the GBM team. In GBM, during intense triggers in addition to the above issues if the combined data transfer from all GBM detectors to the spacecraft exceed 1.5 MB s$^{-1}$ would result in TTE events clipped at this maximum rate which causes irrecoverable loss of data. The only GRB that has had high enough count rates for data loss to occur due to the data transfer limit is GRB130427A.
Figure 2.3: The location and orientation of all the GBM detectors: 0-11 marks the position of NaI(Tl) detectors and 12-13 marks the position of the BGO detectors [4].

The three types of science data that are available are CTIME, CSPEC and TTE data. CTIME consists of data collected from each detector with 8-channel pulse height resolution (PHA). CTIME provides data with continuous high time resolution with a temporal resolution at the least of 0.256 s. CSPEC consists of data collected from each detector with 128-channel pulse height resolution. CSPEC provides data with continuous high spectral resolution and has a temporal resolution of 4.096s. Time Tagged Events (TTE) consists of individually digitalised pulse height events from the GBM detector during the event of the burst and are encoded into 32-bit words. TTE events during bursts have an energy resolution of 128 energy channels similar to that of CSPEC.

The GBM data is chiefly analysed using the hypothesis testing where each model is converted into predicted detector models. This model counts for each detector is then statistically checked with the observed detector counts. This conversion process requires a detailed and accurate representation of the com-
posite GBM instrument response function. This is presented in the form of detector response matrices (DRM) for each GBM detector. The DRMs are generated using the General Response Simulation System (GRESS) which is a simulation and modelling code based on GEANT4 Monte Carlo radiation transport simulation package. They have been then validated against data obtained from the radioactive source calibration done for each GBM detector as well as of the integrated Fermi spacecraft. The burst data product that is made available within a day of the burst contains primarily the following: list of counts, binned counts, DRMs and background spectra necessary to analyse the burst data. When performing spectral analysis of data from transient events, the background is separately fitted with a low order polynomial function using data before and after the event of detection. The fitted background is then subtracted from the source data before spectral analysis.

The main function of the GBM detector have been to enable the joint spectral analysis of the GRB spectrum with the observations done by LAT (at energies > 100 MeV). Thereby covering the GRB emission over nearly 7 decades of energy. Also, GBM provides the real time localisation of the burst and thereby enables the repointing of the spacecraft for delayed high energy emission that could be observed by LAT. At the same time, it also provides the burst location details to the ground based detectors enabling the detection of afterglows. GBM detects nearly 250 GRBs per year. While not triggering for GRBs, it gathers the background data which is useful for a wide range of studies such as monitoring of variable X-ray sources using the earth occultation technique.

2.1.2 Large Area Telescope (LAT)

Large Area Telescope (LAT) is a particle detector rather than a conventional telescope [5]. This is because high energy gamma - rays cannot be refracted by lens or focussed by mirrors. Therefore, the detector uses the same method in high energy particle accelerators. It consists of anti coincidence detector, precision converter-tracker and calorimeter, see Figure 2.5. At first, the incoming gamma rays passes through a thin plastic anti coincidence detector (ACD). ACD provides the rejection of charged particle background e.g high energy cosmic rays. Therefore, ACD is required to increase the efficiency in detecting the high energy gamma rays. After that gamma rays continue into the converter- tracker. The converter -tracker contains 16 planes of high Z material (Z is the atomic number; material used here is tungsten). The incoming γ-ray photon interacts with an atom in one of the thin tungsten foils, producing electron and positron pair. The particles then proceed creating ions in thin silicon (Si) strip detector. The Si strips are kept in alternate X and Y
Figure 10: Dependence of the detector energy resolution for a NaI detector (squares) and a BGO detector (triangles) with energy is shown. \[4\]

directions which allows to track the progress of the particles and thereby this information is used to reconstruct the directions of the incident $\gamma$ ray photons. The particles are then stopped by a Cesium iodide (CsI) calorimeter. The two main purposes of the calorimeter are to measure the energy deposition of the electromagnetic shower which is produced by e- -e+ pairs as a result of the incident photons and also to image the shower development profile which in turn is used to discriminate the background and estimate the energy leakage fluctuations. The calorimeter module consist of 96 CsI crystals which are optically isolated from each other and arranged horizontally in 8 layers of 12 crystals each. Each calorimeter module layer is then aligned 90° with respect to its neighbour forming an array.

LAT is designed to measure $\gamma$ rays with energies up to $\sim 300$ GeV. In order to measure such energies require a heavy calorimeter ($\sim 1800$ kg). The heavy calorimeter and then results in a problem called backsplash effect. The secondary particles ($100 – 1000$ keV) produced via electromagnetic shower Compton scatter in the ACD and creates false veto signals from the recoiled electrons. This effect was present in EGRET as a result of which the detection efficiency of photons of energy 10 GeV were less by a factor of 2 or more than at 1 GeV. In LAT, in order to suppress the backsplash effect, ACD is segmented. This means only the ACD segment close to the incident $\gamma$ ray photon is considered and therefore the area of ACD contributing to backsplash
is greatly reduced.

The information from the anti coincidence detector, tracker and calorimeter is combined to get the energy and direction of the detected gamma ray photon. Fermi satellite orbits the earth in 96 minutes. LAT is always kept facing upwards away from the earth. On alternate orbits, LAT is rotated from left to right and vice versa, thereby allowing LAT to cover the entire sky. Thus, the whole sky is scanned in two orbits. In case of a strong GRB, Fermi will repoint itself to the location of the burst given by the GBM for a few hours to get the extra data. LAT detects nearly 10 GRBs per year.

![Schematic diagram of the LAT instrument](image)

**Figure 2.5:** The schematic diagram of the LAT instrument onboard Fermi gamma ray space telescope. The figure depicts that the incoming $\gamma$-ray photons first passes through the ACD on the top and then is converted into electron positron pairs by the converter - tracker and then later are received in the calorimeter. [5]

### 2.2 Key observations of GRBs by Fermi

Much progress have been made with Fermi in understanding as well as in identifying the spectral features and properties of GRBs. Some of the key features of Fermi observations so far are:

i) **The delayed onset of high energy observations for GRBs including both long and short GRBs.**
Figure 2.6: The energy dependence of the effective area at normal incidence, of both the detectors are shown (NaI- red and BGO- blue). The upper panel shows a good agreement between measurements (markers) and lab simulations (lines). The lower panel shows when simulated effects of the spacecraft are also included. The shaded curves include the systematic uncertainty of the simulated responses of the on-orbit simulations. 

This can be clearly seen in the data study of GRB090510 (short) \([48]\) where the delay \(\sim 0.7\) seconds and in GRB080916C (long) \([49]\) where the delay \(\sim 5\) seconds. In case of GRB090510, the LAT emission started nearly 0.65 s after the GBM trigger and was also found to last for 200s. The highest energy photon (31 GeV) was detected at the end of the GBM pulse at 0.83 s. It was also found that most of the photons above 30 MeV arrived much later (i.e nearly 258 s) than those with energy < 1 MeV. Similar observation was also possible in the case of GRB090902B where LAT emission was detected as late as 1000 s after the GBM trigger \([50]\). The highest energy photon (33.4 GeV) was observed 82 s after the GBM trigger. Significant late time emission was also observed for energies > 100 MeV beyond the prompt emission of the burst.

ii) LAT emission lasts longer.

The LAT emission > 100 MeV have a longer duration with respect to the observed GBM emission. It is found to last for a long period of time \(\sim 100\)
for 1000 seconds \cite{ref51}. For e.g. in case of burst GRB080916C, the high energy emission observed by LAT lasted longer than the GBM emission ($\sim 40s$) until 560s after the trigger time \cite{ref51}.

iii) **Very high Lorentz factor is required.**

The detection of high energy GeV photons in many bursts like GRB080916C \cite{ref49}, GRB090510 \cite{ref48}, GRB090902B \cite{ref50}, GRB090926A \cite{ref52}, GRB130427A \cite{ref53}, if assumed to come from the same emission zone as that of the MeV prompt phase suggests that the outflow is highly relativistic. Based on these observations of LAT high energy photons, the inferred minimum Lorentz factor in these cases are found to be very high $\Gamma \sim 1000$ \cite{ref48} and more. These are highest Lorentz factors inferred for GRBs.

iv) **Constraints on Lorentz invariance violation.**

Both general relativity and Quantum Field Theory predict the existence of a natural scale at which the physics of space - time as predicted by relativity theory would break down in order to avoid singularity problems. Quantum gravity theory thus, predicts Lorentz Invariance Violation (LIV) where photon propagation speed depends on its energy and it is expected to significantly deviate from the speed of light, \( c \), when its energy is near the Planck scale $\sim 1.22 \times 10^{19} \text{ GeV}$. The detection of multi - GeV photons on timescales less than 1s from cosmological distances make GRBs suitable candidates for constraining LIV. Thus, LIV induced time delays, $\delta t$, are expected for very high energy GeV photons. Strong limits on $\delta t < t_{h} - t_{l}$ can be obtained by measuring $t_{h}$ is the arrival time of high energy photons and $t_{l}$ is the arrival time of low energy photons whose velocity is $c$. For e.g. in case of burst GRB090510, for the most conservative limit, finds a quantum gravity mass scale significantly larger than Planck mass for a linear energy dependence of the propagation of speed of photons \cite{ref48}, see also \cite{ref54}.

v) **The presence of multiple distinct emission components and spectral cut off in high energy emissions.**

Several bright bursts detected by *Fermi* have shown that a single component like Band function alone does not give a good fit. Multiple component spectral analysis was found to be evident even in the BATSE era where it was found in several bursts by Ryde et al. 2005 \cite{ref55} that instead of Band function alone, blackbody (BB) + power law was a better fit. In that respect, in the *Fermi* analysis we find for e.g GRB100724B, one of the brightest GBM detections, the best fit for the time integrated spectrum was found to be blackbody + Band function \cite{ref8}. The additional component, blackbody, was found at high significance level. Similar detection of a blackbody was possible in GRB110721A where BB could be significantly detected even at very low flux with respect to the total observed flux \cite{ref56}. However, in GRB090902B, it was found that a power law was needed in addition to the Band function extending from low
energies to high energies in LAT. It nearly had 24% of the total fluence observed in the energy range 10 keV - 10 GeV. The photon index was found to remain constant at -1.9 throughout the prompt phase [50]. Similarly in the case of GRB090926A, a power law with an exponential cutoff emerges towards the end of the GBM emission. Also a power law is needed which becomes more significant towards the end of the main emission. LAT data analysis in several GRBs have also suggested the presence of extra PL components [52].

vi) **Band function has a different shape in multi-component fitting.**

With multi component fitting especially in the case of the model BB + Band function, it is found that the Band function has different parameter values when fitted alone to the spectra and when fitted in combination with the blackbody. The striking difference is that the $E_{\text{peak}}$ gets pushed to higher energies when BB finds the low energy peak [57].

vii) **Band crisis**

The GRB spectra in general are described by a Band function alone. For e.g. in the time integrated spectrum of GRB080916C, the Band function, found at low energies, fits the entire spectral data even extending to GeV [49]. The GRB spectral catalog however shows that the majority of the brightest GRBs exhibit the presence of multiple components in their spectra which in turn implies that the GRB spectra are more complex than a single Band function [51].

viii) **Spectral width of the GRB spectrum.**

Augmenting the spectral observations mentioned above, Axelsson & Borgonov 2015 [6] presented a study where the full width half maximum (FWHM) of the $vF_v$ peak of the good fit to the data (i.e Band function), of the full sample of GRBs observed by *Fermi* and BATSE, was measured. The measure is defined as

$$W = \log \left( \frac{E_2}{E_1} \right)$$  \hspace{1cm} (2.1)

where $E_1$ and $E_2$ are the lower and upper energy limits of the FWHM range respectively. In a log $vF_v$ vs log$E$ plot, the area under the curve indicates at what energies most of the power is radiated. Thus, $W$ gives an idea of how much is the spread in the energy range over which this power is radiated. Axelsson & Borgonov 2015 [6] found that for long GRBs $W$ distribution peaks at $W \sim 1$ and for short GRBs the $W$ distribution peaks at $W$ nearly less than 1, see Figure 2.7. Both these measurements were found to be consistent with *Fermi* GBM and BATSE bursts sample. This confirms that this estimation is independent of the instrument. Thus, they find that 78% of the long GRBs and 85% of short GRBs are inconsistent with the width of slow cooling synchrotron emission from a Maxwellian distribution of electrons. A fast cooling case only worsens as it produces a much wider spectrum from a power law distribution of electrons. However, photospheric emission can explain such
spectra if situations like subphotospheric dissipation or geometrical broadening effects such as high latitude emission or viewing effects of a GRB jet, are invoked to broaden the observed photospheric emission from a blackbody.

**Figure 2.7:** The distribution of spectral width, $W$, for long and short GRBs detected by both *Fermi* and BATSE are shown. Solid line marks the monoenergetic synchrotron emission, $W = 0.93$. Dashed line marks the blackbody, $W = 0.54$. Dotted line marks the synchrotron from Maxwellian electron distribution, $W = 1.4$. Dash-dotted line marks the synchrotron from a power law electron distribution with an index = -2, $W = 1.6$. [6]

### 2.3 Photosphere observations by *Fermi*

The study over this wide range of energy is the needed step to confirm the idea of photosphere model introduced during the pre *Fermi* era. Below, we summarise the results of the spectral analysis of a few long GRB bursts that have exhibited strong signatures of photospheric emission.

#### 2.3.1 Single blackbody spectrum: GRB101219B & GRB100507

Only a handful of bursts have been observed till now, whose prompt emission could be fit with a blackbody alone throughout. BATSE had observed only 4 such bursts [2] [55]. However, it is very interesting to note that such spectrum is also been observed during the *Fermi* era. In a recent analysis of GRB101219B, which was observed by both *Fermi* GBM and *Swift* XRT, by Larsson et al. 2015 [7] found that the prompt emission of the burst is best fitted by a blackbody function alone, see Figure 2.8. This burst was associated
with a supernova and a blackbody component was also detected in its early X-ray afterglow data. However, no possible connection could be established between the BB observed in the prompt phase and that was observed in the early X-ray flare. The time resolved analysis was limited to only two time bins. Since a broken power law was unable to fit the temperature evolution observed in both the phases, the possibility of high latitude emission resulting in late time observed spectra was ruled out [58]. Thus, the late time observance of the blackbody is assumed to be associated with the late time activity of the central engine.

A similar burst, GRB100507, was earlier reported by Ghirlanda et al. 2013 [59] where a blackbody was found to best fit the prompt emission spectra through out. Unlike GRB101219B, this burst could be resolved into several time bins, thereby enabling to study the evolution of such a spectra with time. It was found that the BB temperature showed a flux tracking behaviour and not the typically observed broken power law behaviour that had been observed in case of bursts where a blackbody was detected [2; 3]. Both the bursts, GRB101219B and GRB100507 are relatively weak bursts with a fluence of the order of $10^{-6}$ erg cm$^{-2}$.

The observation of a pure blackbody spectrum in the prompt emission of GRBs is highly constraining for the existing GRB models. Such a spectrum can be produced only from highly thermalised regions such as the photosphere.

![Figure 2.8: The prompt emission spectrum of GRB101219B is well modelled using a blackbody alone.](image-url)
Figure 2.9: Time-resolved spectrum of GRB100724B fit by a Band + BB function. The addition of a BB component gives a significant improvement of the fit compared to a Band only fit. See also [8]

2.3.2 Double humped spectrum: GRB110721A; GRB100724B

GRB110721A is one of the most bright GRBs that had been observed by both Fermi GBM and LAT [Paper I]. The burst detected the highest ever recorded peak energy value of $15 \pm 2$ MeV in the beginning of the burst, which was enabled by the use of LAT Low Energy (LLE) data (30 -130 MeV). In the following time bins of the time resolved analysis of the data, showed a significant $(5\sigma)$ detection of a blackbody component in addition to the Band function. The best fit was found by fitting the data simultaneously with a Band function and a blackbody, which clearly accounts for the spectral bump seen in the low energies. The blackbody temperature, $kT$, followed a broken power law behaviour. However, the Band peak, $E_{\text{peak}}$, showed a smooth power law evolution.

Similarly, the time integrated spectral analysis of GRB100724B [8] showed that the simple Band function does not adequately represent the spectrum of this burst. The best fit was found to be a combination of Band function and a blackbody, which clearly accounts for the spectral bump seen in the time integrated spectra at around $kT= 40$ keV, see Fig 2.9. This burst is one of the most intense bursts seen by Fermi GBM so far and has a peak energy equal to 2500 keV. The probability that the blackbody (BB) component in the spectra, is due to statistical fluctuations, was found to be $< 5 \times 10^{-5}$, thus verifying
that BB is not a statistical fluctuation. The time resolved spectral analysis of GRB100724B affirms the presence of BB component throughout the burst and shows only slight variations with time. In addition to this, the consistency of the mean $kT$ value with the temperature obtained in the time integrated spectral fit further assures that the BB component is not due to a spectral evolution of the Band function during the burst.

![Time-resolved spectrum for the time bin 2.2–2.7 s after the GBM trigger. The spectrum is best modelled using a blackbody (BB) and a power-law (PL).](image)

**Figure 2.10:** Time-resolved spectrum of GRB110721A is best modelled using a combination of BB + Band function giving rise to a double humped spectral shape. [Paper II]

Figure 2.9 and Figure 2.10 show the time-resolved spectrum of GRB100724B and GRB110721A fit by a Band + blackbody function respectively. It is thus evident that the addition of a blackbody component gives a significant improvement of the fit compared to a Band only fit (see [3] and Paper I). The power peak of the spectrum is not given by the blackbody component and lies at a significantly higher energy. In order to examine how this bursts would have appeared if it were detected by BATSE, we deliberately limited the analysed energy range to only cover two orders of magnitude, here chosen to be $8 - 900$ keV (BATSE typically observed in the range $20 - 2000$ keV). The data were then fitted following Ryde et al. (2004) [2], first with a Band function (top panel of Fig. 2.11) and then with a blackbody combined with a power law (bottom panel of Fig. 2.11). Similarly to what was observed in the BATSE studies, the BB+PL model gives a better fit to the data. In contrast to BATSE, *Fermi* now allows us to observe beyond this (limited) energy range and detect the power peak that lies at higher energies. This is consistent with the conclusions drawn from the few bursts in which EGRET data were available, see
A similar spectral shape has also been detected in case of a short burst, GRB120323A, which was the brightest short GRB observed by GBM [57]. It was found that a two component model modelling a thermal emission (BB) and a non-thermal emission (Band function) was found to best fit the data rather than a Band function alone. Band function alone fits, resulted in soft values ($\sim 70$ keV) of $E_{\text{peak}}$ that were not typical of the nature of short bursts. However, on addition of a blackbody component, the fit statistics considerably improved and along with that it was observed that the Band $E_{\text{peak}}$ got pushed to higher values which thereby resulted in the power peak of the spectrum to be of the typical hard values ($\sim 300$ keV) observed in the case of short bursts.

Thus, there has been increasing detections of a thermal component being a significant subdominant part of the GRB spectra [60] which is otherwise dominant by a non-thermal (Band function) component. Such detections have produced a spectral shape which is double humped with a peak or shoulder at low energies below the main power peak of spectrum.

2.3.3 Top-hat spectrum: GRB110920A

The spectral analysis of GRB110920A [Paper V] revealed that the time resolved spectra of the burst are best fit with a Comptonisation model (approximated by BB + BB) and a power law rather than a BB + Band function. The Comptonisation model produced a top hat shape to the spectrum during the earlier time bins, see Figure 2.12, and later with time evolved into a very narrow spectrum where the spectral peak is well modelled by a blackbody. Here the seed thermal emission was found to be very dominant being nearly 50% of the total observed flux. The seed thermal component followed a broken power law behaviour.

The observed narrowness of the spectral peak throughout the burst strongly suggests the spectrum is from the photosphere. Along with that the dominant thermal emission, the observed spectral breaks and a significant deviation from a pure blackbody point towards localised subphotospheric dissipation. The possibility of subphotospheric dissipation leading to a non-thermal like spectrum from the photosphere has been observationally supported in the case of GRB090902B [9]

2.3.4 GRB090902B type

GRB090902B is a fairly intense burst observed by both GBM as well as LAT. It had a redshift of $z = 1.822$. LAT had a significant detection with a photon of energy, $E = 33$ GeV. GRB090902B [61] and see also [Paper III], has been extensively studied.
The emission can be divided into two epochs where the first epoch is the time duration from 0 to 12.5 seconds and the second epoch is from 12.5 to 25 seconds after the GBM trigger. During the first epoch, the Band component is found to be very hard and narrow, \( \alpha = 0.3 \) and \( \beta = -4 \), clearly rejecting any optically thin emission mechanism. The alpha values get harder when the time intervals are made narrower. This feature is interpreted as the spectral component originating from the photosphere. But the data fitting, suggests the peak to be slightly broader than a single Planck function. But such a broadening is expected due to geometrical effects of the photosphere which results in contributions from different regions in space and time [62]: The observed temperature depends on the latitude angle due to the Doppler shift. The observation is thereby expected to be the superposition of spectra with different temperatures as measured in the observer’s frame. Thus, the spectrum would not be a single Planck function but rather a multicolour blackbody [9, 63]. Even then, since the observed spectra in epoch 1 does not differ much from the Planck function, see Figure 2.13, the peak can be attributed to the original, non-processed thermal emission, produced near to the base of the flow at higher optical depths.

Now, epoch 2 has a spectral shape that is more broader with Band function parameters \( \alpha = -0.6 \) and \( \beta = -2.5 \) [61]. A comparison of the two epochs, tells us that the spectral width has increased between the epoch 1 and epoch 2 by a factor of 2, see Figure 2 in [61]. In both the epochs, the power law component remains relatively steady. Comparing the spectra from the two epochs, see Figure 3 in [61], we can clearly see that the MeV component in epoch 2 is a broadened version of the component seen in epoch 1. This indicates that the emission during both these epochs are from a similar origin, i.e., a photosphere and an optically thin component.

Thus, the spectrum has evolved from something close to a Planck function to a broader (Band) function over time. To explain this evolution many ideas have been suggested such as multicolour BB [9, 63], subphotospheric heating [61], relativistic effects and geometric broadening including the effects of viewing angle when observing a GRB jet [62, 64], which when associated with photospheric emission (generally a Planck function) can result in the broadening of the Planck function. It is also interesting to note that within such models, the typically observed GRB spectra that are described by the Band function only, can also be accommodated within the explanation of photospheric emission, see chapter 5.
2.4 Photosphere observations from other missions: Swift and INTEGRAL

Campana et al. 2006 [65] presented the first case wherein the early X-ray afterglow detection of GRB060218 showed the presence of a thermal component. With time, the blackbody cooled and moved into lower energy bands (optical/ultraviolet). It was detected by BAT at a redshift, $z = 0.033$. The blackbody marginally decreased with time and the correspondingly estimated emission radius increased from, $R_{BB} \sim 10^{11}$ cm to $10^{12}$ cm. Blackbody continued to be observed in optical and ultraviolet UV bands, wherein $kT \sim 4$ eV and $R_{BB}^{UV} \sim 10^{14}$ cm. This tells about the expansion speed $\sim 10^9$ cm/s and it is consistent with supernova shock break out. The expansion speed estimated was found to be consistent with the line broadening observed in optical spectra. Here, the large emission radius is associated to the region where the stellar materials ejected by the progenitor is present and this is common for the Wolf-Rayet star. The shock created in the region passes through this shell of material and the thermal component is observed when the wind material becomes optically thin. From the observed variability timescale of $\sim 200$ s, they estimated the stellar radius $\sim 10^{11}$ cm, which is smaller than the typical supernovae like blue supergiants ($\sim 10^{12}$ cm) or red supergiant ($\sim 10^{13}$ cm) which indicates it might be a compact source like Wolf-Rayet star. In addition to this, GRB100316D [66] and GRB090618 [67] are prominent examples of GRBs associated with supernovae (SNe) where they could find a thermal component in the X-ray emission.

Sparre & Starling 2012 [68] presented a sample of 6 bursts where they could find a blackbody component. However, they do not make any conclusion about the blackbody component that is discovered, as they suspect that it could be an artefact due to spectral evolution [69] or due to some absorption effects. They consider that in cases of bursts observed from high redshifts with intermediate environments of high colour densities, the detection of a BB component would be very difficult and therefore, the detections made could be false. This also, provides an explanation as to why only in a small fraction of the bursts BB component is detected.

Fris & Watson 2013 [70] also studied a sample of bursts where the thermal emission could be detected in the early X-ray afterglow. However, here they interpreted the blackbody emission to be associated to the photospheric emission coming from the jet. They find the BB detected to be compatible with the thermal component detected in the prompt phases of many GRBs. They also found that the supernova shock break out interpretation is inconsistent as they found the material to be relativistic and the estimated expansion speed to be superluminal. They conclude that SN shock break out explanation may be
consistent with low luminosity systems rather than high luminosity systems.

Starling et al. 2012 [71] analysed a sample of X-ray spectra in connection with supernova detection, which could be generally described by an absorbed power law. However, they find several of them could be better fit with a blackbody and absorbed power law. The inferred emission radius is found to be larger than the typical size of Wolf-Rayet star ($\sim 10^{11}$ cm) and the inferred expansion velocity is very high nearly 20% of the speed of light. These make it doubtful, whether the observed emission is from the supernova shock breakout. They find an alternative explanation of the cocoon surrounding the jet. Most of the BBs were observed during the steep decay phase of the X-ray light curve. Pe’er et al. 2006 [72] showed that an early X-ray afterglow emission could be from the relativistically expanding cocoon of the jet. They consider a single phase of dissipation that occurs at a radius such that the optical depth of the cocoon $> 1$ and this radius may correspond to the same radius at which the dissipation of the kinetic energy of the jet occurs. However, the photons that are produced at high optical depth in the cocoon are then only observed after a time delay after the diffusion of a few hundred seconds. They find the cocoon emission radius to be $> 10^{12}$ cm; the initial optical depth $\sim 30 – 50$ and the Lorentz factor of the cocoon to be $\sim 4 – 7$. Recently another explanation regarding the emission from the cocoon was presented by, Suzuki & Shigeyama 2013 [73], who studied the hydrodynamical simulations of an ultra-relativistic jet propagating through a massive star and their interaction with the circumstellar medium (CSM). They found that when the highly relativistic jet crashes into the circumstellar medium, even the dense CSM cannot decelerate the jet altogether at once. In such cases, the cocoon associated with the jet gets shocked and the cocoon moving at sub-relativistic speeds can result in the early X-ray afterglow emission which could be the photospheric emission coming the cocoon.

Recently, Peng et al. 2014 [74] studied 32 GRB X-ray flares, that were detected by both BAT and XRT onboard Swift in the energy range $0.3 – 150$ keV. Out of which they found 13 X-ray flares that could be best fitted by a blackbody component and an absorbed single power law. On comparing with other such GRBs observed by Fermi, the temperatures of the detected blackbody component were much lower ($kT \sim 1 – 3$ keV). They have associated this BB component to the photospheric emission from the fireball which could be related to the late time activity of the central engine.

Thus, to summarise, the observed thermal emission in the early X-ray afterglow emission in GRBs detected by Swift have three main possible explanations: a) late time activity of the central engine and so the observed thermal emission is related to that observed in the prompt emission of the GRBs; b) emission coming from the supernova shock break out or c) emission coming
from the cocoon surrounding the jet.

Spectra of majority of GRBs detected by INTEGRAL could be well described by a single power law because of the small energy range that is observed. Only in certain (or a few) cases, there is a curvature in the spectrum such as Band or BB + power law model is required to fit the time averaged burst spectra. INTEGRAL detects a larger number of faint GRBs because of its high sensitivity. To name a few of such bursts where a BB + power law was found to be the best fit were GRB050520; GRB081003A; GRB081016 [75]. In addition to these, there has been detection of a long burst, GRB041219A with a $T_{90} = 186$ s, which is the brightest burst localised by INTEGRAL [76]. Spectra were fit by both Band model and also by BB + power law. An improvement in $\chi^2$ for the BB + power law model over the Band model for the precursor phase of the GRB was observed, where 49% of the total flux was contained in the BB component. The value of $kT$ is the highest in the beginning and declines during the burst.
Figure 2.11: Same spectrum as in Figure 2.9 but analysed over a limited energy range of 2 orders of magnitude. This allows a direct comparison to the analysis made on data observed by BATSE. Top panel: data fitted with a Band function. Bottom panel: data fitted with a BB + PL, giving a better fit.
**Figure 2.12:** The spectrum of the time bin at the peak flux (11.28 -15.2 s) of the burst GRB110920A is shown. The best fit to the spectrum is given by the model: Comptonisation (2 BBs) + power law which gives a top hat shape to the spectrum. [Paper IV]
Figure 2.13: The main spectral component in GRB090902B is close to a Planck function during the initial half of the bursts. The Band function fit shown above is for the time bin $11.60 - 11.88$ s, and is very narrow with $\alpha = 0.55 \pm 0.16$. \cite{9}
3. Radiation processes

3.1 Synchrotron emission

Synchrotron radiation is an emission mechanism that has been widely observed in many astronomical objects like pulsar wind nebulae (e.g. Crab nebulae), blazars etc. The emission is produced when the relativistic electrons gyrate through the magnetic field. The emitted spectrum would be very broad and non-thermal and would be polarised in nature. Since the GRB spectra look non-thermal, the synchrotron emission has been extensively studied to explain the observed GRB spectral properties.

The motion of an electron of mass $m_e$ and charge $q_e$ in a magnetic field, at an angle $\alpha$ (pitch angle) between the field and the velocity, gives

$$\frac{d}{dt}(\gamma_e m_e c^2) = q_e v \cdot E = 0$$

(3.1)

which implies that the electron Lorentz factor $\gamma_e = \text{constant}$ i.e $v = \text{constant}$ and

$$\frac{d}{dt}(\gamma e m_e v^2) = \frac{q_e}{c} v \times B$$

(3.2)

This together with the above equation implies that velocity components $v_\parallel = \text{constant}$ and since total $v = \text{constant}$ implies $v_\perp = \text{constant}$. The combination of this circular motion and the uniform motion along the field is a helical motion of the particle. The frequency of the gyration is given by

$$\omega_B = \frac{q_e B}{\gamma_e m_e c}$$

(3.3)

The acceleration is perpendicular to the velocity with magnitude $a_\perp = \omega_B v_\perp$, which gives the total emitted radiation

$$P_{\text{sync}} = \frac{2}{3} r_0^2 c^7 \beta_\perp^2 \gamma_e^2 B^2$$

(3.4)

In case of isotropic distribution of velocities, by averaging over all angles for a given speed $\beta$ gives $\beta_\perp^2 = 2\beta^2 / 3$. Thus, the isotropic power radiated is

$$P_{\text{sync}} = \frac{4}{3} \sigma_T c \beta^2 \gamma_e^2 U_B$$

(3.5)
where $U_B = B^2 / 8\pi$, magnetic energy density.

Let's consider a relativistic shock through a cold plasma with a particle density, $n$, and a Lorentz factor, $\Gamma$, of the shock fluid. The electrons are assumed to be accelerated in the shock to a power law distribution of electron Lorentz factor, $\gamma_e$, such that $N(\gamma_e)d\gamma_e \propto \gamma_e^{-p}d\gamma_e$ with a minimum Lorentz factor, $\gamma_m$, such that $\gamma_e \geq \gamma_m$. Let a fraction of the shock energy, $\varepsilon_e$, goes into electrons such that

$$\gamma_m = \varepsilon_e \left( \frac{p-2}{p-1} \right) \frac{m_p \Gamma}{m_e}$$

and a fraction, $\varepsilon_B$, of the shock energy goes into the magnetic fields. This gives the magnetic field strength

$$B = (32\pi m_p \varepsilon_B n)^{1/2} \Gamma c$$

Electron does not lose much of its energy via radiation when $\gamma_e < \gamma_c$ which is defined as the electron Lorentz factor at which $\Gamma \gamma c m_e c^2 = P(\gamma_c) t$ which gives

$$\gamma_c = \frac{6\pi m_e c}{\sigma_T \Gamma B^2 t_0}$$

where $t_0$ refers to the time in which an electron with an initial Lorentz factor, $\gamma_e > \gamma_c$, cools down to $\gamma_c$, in the frame of the observer. Maximum emission occurs at $\nu_c$ and is given by $P_{\nu,max}$.

There can be two different cases of cooling: (i) when $\gamma_m > \gamma_c$, all electrons cool to $\gamma_m$ with a time, $t$, less than $t_0$. Such a case is called fast cooling. The spectrum of the radiation consists of three segments: a low energy tail for frequency of radiation, $\nu < \nu_c(\gamma_c)$ where $P_{\nu} \propto \nu^{1/3}$, a power law segment between $\nu_c$ and $\nu_m$ where $P_{\nu} \propto \nu^{-1/2}$ and a power law such that $P_{\nu} \propto \nu^{-p/2}$ for $\nu > \nu(\gamma_m)$ [10], see Figure 3.1a. (ii) When $\gamma_c > \gamma_m$, only electrons that have $\gamma_e > \gamma_c$ can cool. Since bulk of the electron population ($\gamma_e \sim \gamma_m$), do not cool within $t_0$, this case is referred to as slow cooling. The spectrum of such a radiation consists of three segments: a low energy tail for $\nu < \nu_c(\gamma_m)$ where $P_{\nu} \propto \nu^{1/3}$, a power law segment between $\nu_m$ and $\nu_c$ where $P_{\nu} \propto \nu^{-(p-1)/2}$ and a power law such that $P_{\nu} \propto \nu^{-p/2}$ for $\nu > \nu(\gamma_c)$ [10], see Figure 3.1b.

The hydrodynamic evolution of the shock can occur in two ways: radiative and adiabatic. In a radiative regime, all the internal energy produced via shocks is radiated and this requires two conditions (i) the fraction of the shocked energy that goes into electrons, $\varepsilon_e$ is large and (ii) $\gamma_m > \gamma_c$ i.e it is in the fast cooling regime. In adiabatic regime, energy is not radiated, the energy of the shock remains constant. However, in both adiabatic and radiative cases, at early time, $\nu_c < \nu_m$ i.e fast cooling regime and with time $\nu$ keeps decreasing and at later times $\nu_c > \nu_m$ and thereby enters slow cooling regime. This transition occurs at
Figure 3.1: a) The upper panel shows the spectrum of synchrotron emission due to fast cooling. b) The lower panel shows the spectrum of synchrotron emission due to slow cooling. Synchrotron self absorption becomes important below $v_a$. The arrows indicate the scaling of the frequencies $v_m$, $v_c$ and $v_a$ with time. In case of fast cooling the scaling denoted above the arrows represents radiative evolution and the scaling below the arrows represents adiabatic evolution. In case of slow cooling, the shock evolution always remains adiabatic. [10]

$v_m = v_c$ (i.e $t = t_0$). Along with that if $\varepsilon_e = 1$ in the beginning then, the hydrodynamic evolution occurs from radiative to adiabatic at this transition stage. If $\varepsilon_e \ll 1$, the evolution remains adiabatic throughout before and after this stage of transition. In case of fast cooling, the shock evolution can be either radiative or adiabatic and in case of slow cooling, the shock evolution always remains adiabatic.

Shock acceleration processes that have been studied in Baring et al. 1995 [77]; Baring 2011 [78]; Summerlin and Baring 2012 [79] and Ellison and Double 2004 [80], have shown that electrons can be accelerated directly from a thermal distribution to produce a power law distribution such that an electron distribution, which is a combination of Maxwellian and a power law which
is smoothly connected, is achieved. We expect strong dissipation shocks in
the plasma which can result in the thermalisation of many electrons but not
all. Burgess et al. 2014 [60] showed that slow cooling synchrotron emission
resulting from such an electron distribution, in combination with a blackbody
spectral component produces reasonably good fits to the GRB spectra.

In the classical picture of fireball model for GRBs, the synchrotron emis-
sion is expected to be observed from an optically thin region. The dissipation
of the kinetic energy (or Poynting flux) of the outflow, with a bulk Lorentz
factor, $\Gamma$, at a radius, $r_d$ causes the electrons to be accelerated to some random
Lorentz factor, $\gamma_{el}$. The observed peak energy of synchrotron emission from
these electrons is given by

$$E_{\text{sync}} = \frac{3}{2} \frac{\hbar q B}{m_e c} \gamma_{el}^{2} \Gamma \left(1 + \frac{1}{\Gamma^2} \right)$$

(3.9)

where $z$ is the redshift of the burst. The observed synchrotron flux, $F_{\text{sync}}$ is
given by

$$F_{\text{sync}} = \frac{\sigma_T c \Gamma^2 \gamma_{el} B^2 N_e}{24 \pi^2 d_L^2}$$

(3.10)

where $N_e$ is the number of radiating electrons and $d_L$ is the luminosity distance.
As the electrons emit radiation, they cool, and the radiative cooling time is
given by

$$t_{\text{cool}} = \frac{6 \pi m_e c}{\sigma_T B^2 \Gamma \gamma_{el} (1 + \gamma)}$$

(3.11)

where $\gamma$ is the Compton $\gamma$ parameter and the factor $(1 + \gamma)$ takes into account
the cooling due to Compton scattering as well. This cooling time can be com-
pared to the dynamical time,

$$t_{\text{dyn}} \approx \frac{R}{\Gamma^2 c}$$

(3.12)

Within the burst, we assume that the conditions change on a timescale com-
parable to the dynamical time scale of the dissipation event. If $t_{\text{cool}} < t_{\text{dyn}}$
the electron radiate efficiently and loose all their energy within the dynamical
time (fast cooling) and if $t_{\text{cool}} > t_{\text{dyn}}$ the electron does not efficiently radiate and
thereby does not loose its energy during the dynamical time (slow cooling).

From the spectral fits, we can determine the peak of the synchrotron com-
ponent, $E_{\text{sync}}$, and the properties of the flow at the photosphere, e.g., the Lorentz
factor, $\Gamma$ and the photospheric radius, $r_{\text{ph}}$, that can be calculated from the black-
body component observed in the GRB spectrum, see chapter 4. Assuming that
the properties of the flow are the same at the photosphere and the dissipation
site, equation 3.9 then gives a constraint for the product $B\gamma_{el}^2$ for every time bin in our observations:

$$B\gamma_{el}^2 = \frac{E_{sync}(1+z)4\pi m_e c}{\Gamma 3hq}.$$  \hspace{1cm} (3.13)

The maximal spectral flux at the peak frequency is given by

$$\frac{F_{sync}}{E_{sync}} = \frac{\sigma_T \Gamma m_e c^2 B(1+z) N_e}{36\pi qd_L^2}.$$  \hspace{1cm} (3.14)

where $N_e = \frac{8\pi \Gamma^2 r_d c t_{dyn} \tau_e}{\sigma_T}$. Thus, the opacity of the electrons radiating synchrotron emission is given by

$$\tau_e = \frac{F_{sync}}{E_{sync}} \frac{9qd_L^2 \tau_{tot}}{2\Gamma^3 m_e c^3 B r_{ph} t_{dyn} (1+z)}.$$  \hspace{1cm} (3.15)

where $\tau_{tot} = r_{ph}/r_d$ is the opacity due to the electrons associated to the number of baryons in the outflow at $r_d$. $\tau_e$ cannot be larger than $\tau_{tot}$, assuming electron-positron pairs are not created via dissipation, and $t_{dyn}$ at the maximum can only be the observed width of the pulse of the burst, $t_{pulse}$. This gives an upper limit on $\gamma_{el}$ and thereby a corresponding lower limit on $B$ (from equation 3.13).

3.2 Comptonisation

Inverse Compton scattering is an important phenomenon in explaining many observed astrophysical spectra, where highly energetic particles (e.g. relativistic electrons) transfers its energy to photons via scattering, thereby resulting in high energy photons. When a charged particle e.g. electron moves with a velocity, $v$, into a region of isotropic bath of radiation with energy density, $U_{rad}$, the particle undergoes a continuous scattering with the electromagnetic waves constituting the radiation. The photon transfers its momentum to the electron in the direction opposite to that of the motion of the electron. The scattering would be anisotropic as the electron has a nonzero velocity. During the interaction between the photon field and electron, electron loses energy as well as absorbs some energy from the photon field.

We consider a distribution of photons which is isotropic in the lab frame. Let the number density of photons within the range $d^3p$ be $f(p)d^3p$ where $f(p)$ is the photon phase-space density, $p$ represents the 4-momentum vector of photon and $d^3p = p^2 dp\sin \theta d\phi$. The number density of photons within the energy range, $d\epsilon$, be $n(\epsilon)d\epsilon$ where $n(\epsilon)$ is the number of photons per unit volume. In the lab frame, since the photons are isotropic, this gives

$$4\pi p^2 f(p)dp = n(\epsilon)d\epsilon$$  \hspace{1cm} (3.16)
In the rest frame of the electron, the photons are incident at an angle \( \theta' \) to the x-axis which are then scattered into a range of angles given by \( \theta_1' \). The incident flux of the photons on the electron per unit time within the region of \( d^3 p' \) of momentum space is given by \( c \delta n = c f(p')d^3 p' \). Thus, the number of photons scattered per unit time is given by \( \sigma_T c f(p')d^3 p' \).

In the rest frame of the electrons, the scattered photons have same energy as the photons undergo Thompson scattering \( (h \nu' < m_e c^2) \). Hence, the power radiated (energy per unit time) by a single electron is given by

\[
dP' = \varepsilon \sigma_T c f(p')d^3 p'
\]

The total power radiated is given by

\[
P' = c \sigma_T \int \varepsilon' f(p')d^3 p'
\]

\[
P' = c \sigma_T \gamma^2 \left( 1 + \frac{\beta^2}{3} \right) U_{ph}
\]

where \( U_{ph} \) is the energy density in the lab frame. The power radiated is the same in both rest as well as lab frame, \( P' = P \). Therefore, the total power emitted in the lab frame,

\[
P = c \sigma_T \gamma^2 \left( 1 + \frac{\beta^2}{3} \right) U_{ph}
\]

The number of scattering per unit time in the rest frame of the electron,

\[
\frac{dN'}{dt'} = c \sigma_T \int f(p')d^3 p'
\]

Transforming the right hand side of the equation to the lab frame gives,

\[
\frac{dN'}{dt'} = c \sigma_T \gamma n(\varepsilon)d\varepsilon
\]

Thus, we get

\[
\frac{dN'}{dt'} = c \sigma_T \gamma N_{ph}
\]

Since \( dN' \) is a number, it remains invariant under Lorentz transformations and so \( dN' = dN \), whereas \( dt' = dt/\gamma \) (time dilation). Therefore, transforming \( dN'/dt' \) to the lab frame gives \( \frac{dN'}{dt'} = \gamma \frac{dN}{dt} \) which gives

\[
\frac{dN}{dt} = c \sigma_T N_{ph}
\]
The energy removed from the photons (or absorbed by the electrons) within an energy range, \(d\varepsilon\) is \(c\sigma_T \varepsilon n(\varepsilon) d\varepsilon\). Hence, the energy removed from the photon field is given by

\[
\frac{dE_1}{dt} = -c\sigma_T \int \varepsilon n(\varepsilon) d\varepsilon
\]

\[= -c\sigma_T U_{ph} \tag{3.26} \]

\[= -c\sigma_T U_{ph} \tag{3.27} \]

Therefore, the net energy radiated is given by

\[
\frac{dE_{rad}}{dt} = P_{compt} = c\sigma_T U_{ph} \left[\gamma^2 \left(1 + \frac{\beta^2}{3}\right) - 1\right]
\]

\[= \frac{4}{3} c\sigma_T \gamma^2 \beta^2 U_{ph} \tag{3.29} \]

\[= \frac{4}{3} c\sigma_T \gamma^2 \beta^2 U_{ph} \tag{3.30} \]

where we have used \(\gamma^2 \beta^2 = \gamma^2 - 1\).

In general, when photons travel through a region of free electrons, the shape of the specific intensity, \(I_\nu\), of the photon spectrum will be modified depending on whether the photons are scattered to higher or lower energies. The average change in photon’s energy is given by Compton \(\mathcal{Y}\) parameter which is given by the relation

\[
\mathcal{Y} = \frac{\Delta\varepsilon}{\varepsilon} \times N_s \tag{3.32} \]

where \(\Delta\varepsilon/\varepsilon\) is the average fractional change in the photon’s energy, \(\varepsilon\), per scattering and \(N_s\) is the average number of scattering of electrons as the photon passes through the medium of electrons. If \(\mathcal{Y} \ll 1\), the spectrum will only be slightly changed and if \(\mathcal{Y} \gg 1\), the spectrum would be greatly modified.

The mean energy of the scattered photons is given by

\[
\langle\Delta\varepsilon_1\rangle = \frac{4}{3} c\sigma_T \gamma^2 \beta^2 U_{ph} \tag{3.33} \]

\[= \frac{4}{3} \gamma^2 \beta^2 \langle\varepsilon\rangle \tag{3.34} \]

In the ultra-relativistic limit, \(\gamma \gg 1\), the mean scattered energy is \(4/3\gamma^2 \langle\varepsilon\rangle\) and the peak of the scattered energy is \(4\gamma^2 \langle\varepsilon\rangle\).

When the electrons and the photons interact within a region of size, \(L\), repeated number of scatterings occur. The mean free path of the Thompson
scattering is \( l_\gamma = (n_e \sigma_T)^{-1} \). The ratio of \( L/l_\gamma \) is defined as the optical depth, \( \tau \). If the \( \tau \ll 1 \) (size of the region, \( L \leq l_\gamma \)), the photons will undergo few scatterings whereas when \( \tau \gg 1 \) (\( L \gg l_\gamma \)), photons undergo several collisions in this region.

When \( \tau \gg 1 \), from standard random walking arguments we have \( N_s^{1/2} l_\gamma \sim L \) which gives the number of scatterings, \( N_s = \tau^2 \). However, in the relativistic case, the number of scattering, \( N_s \sim \tau \) \([58, 64]\). Thus, the Compton \( \gamma \) parameter, in a relativistic case,

\[
\gamma = \frac{4}{3} \gamma^2 \tau \quad (3.36)
\]

The energy gain by the photons continue till the mean energy of the photons reaches \( 4\gamma^2 \langle \epsilon \rangle \), wherein the photons and electrons come to equilibrium. Therefore, after this limit there is no further transfer of energy. The critical optical depth needed for this is obtained from the equation

\[
\frac{\epsilon_1}{\epsilon} = \exp(4\gamma^2 \tau_{\text{crit}}) \quad (3.37)
\]

which gives, \( \tau_{\text{crit}} = \frac{1}{4\gamma^2} \ln\left(\frac{\epsilon_1}{\epsilon}\right) \). When the optical depth becomes comparable with \( \tau_{\text{crit}} \), the spectrum of the photons will evolve because of repeated scattering. Such an evolution is described by Kompaneets equation.

Let the photon phase space density be given by \( n(\omega) \) and the electron phase density by \( f_e(p_e) \) where \( p_e \) is the momentum of the electron. For an interaction
of photon and electron such that
\[ p_e + \omega \iff p_{e1} + \omega_1 \] (3.38)
the Boltzmann equation is given by
\[
\frac{\partial n(\omega)}{\partial t} = c \int d^3 p_e \int d\sigma d\omega \left[ f_e(p_{e1})n(\omega_1)(1 + n(\omega)) - f_e(p_e)n(\omega)(1 + n(\omega_1)) \right].
\] (3.39)
Here the first term represents the scattering of the frequency \( \omega_1 \) to \( \omega \) and the second term represents the scattering of the frequency \( \omega \) to \( \omega_1 \). The term \( (1 + n(\omega)) \) takes into account the stimulated scattering effects which means the probability of the scattering from \( \omega_1 \) to \( \omega \) increase by the factor \( (1 + n(\omega)) \) because photons obey Bose -Einstein statistics.

This equation if have to be solved for relativistic electrons where the fraction of energy transferred per scattering is large requires a numerical solution of the full integrodifferential equation. However, for non-relativistic electrons, the fraction change in energy is small and in such a case the Boltzmann equation can be expanded to the second-order yielding an approximation called as the Fokker-Planck equation. This Fokker-Planck equation was first derived by A.S. Kompaneet (1957) for the photons scattering off non-relativistic, thermal distribution of electrons and this is known as Kompaneet’s equation.

The Kompaneets equation describing the evolution of the photon distribution, \( n(\omega) \), due to repeated scattering off non-relativistic electrons by inverse Compton scattering process is:
\[
\frac{\partial n}{\partial t_c} = \left( \frac{kT}{m_e c^2} \right) \frac{1}{x^2} \frac{\partial}{\partial x} \left[ x^4 (n' + n + n^2) \right]
\] (3.40)
where \( x \equiv \frac{h\omega}{kT} \) which is proportional to the momentum of the photon and \( t_c = n_e \sigma_T c t \) is the time measured in units of mean time scattering. To get the actual solution, the above equation requires to be numerically solved. However, several limiting cases can be discussed.

When the photons are up scattered to very high energies such that the spectrum reaches equilibrium forming Bose-Einstein distribution. The steady state (or saturated spectrum) is approximated by Wien law. For energies where the Compton \( Y \) parameter, \( Y \ll 1 \), it results in modified blackbody and for energies where \( Y \gg 1 \) results in saturated Comptonization, see Figure 3.2.

### 3.3 Processes below the photosphere

Photospheric emission is generally expected to be thermal in nature. Thermalisation is required for the blackbody emission to be produced. For this
to occur the zone of thermalisation should be deep below the photosphere at high optical depths. In the optically thick region, the radiation produced moves only a small distance in relative to the region size before being absorbed again. Thus, the shape of the spectrum is based on the emission and absorption processes. This amounts to constraining the spectrum to be a blackbody. Any dissipation of the kinetic energy (or Poynting flux) occurring below the photosphere results in accelerating/heating the electron population of the outflow. In such a scenario of subphotospheric dissipation, it becomes relevant to look at processes that can produce photons which in turn can effect the interpretations of the observed thermal emission in GRB spectra, see §4.6. In a non-magnetised outflow, the accelerated electrons then radiate their energy via various emission processes such as bremsstrahlung, double Compton, cyclotron and if the shocks produced via dissipation results in significant magnetic field, synchrotron emission would also play an important role as the source of radiation (or photons) below the photosphere \[82\].

**Bremsstrahlung** is an electromagnetic radiation when a charge particle is decelerated by the field of another charged particle. If the density is large, this process can serve as a key source of photons. In a GRB outflow, when dissipation occurs deep in the outflow where a large population of electron-positron pairs are formed, bremsstrahlung radiation becomes important. The thermalisation of the bremsstrahlung radiation is possible only if the bulk Lorentz factor of the outflow $\Gamma \leq 2$ at radii, $r \sim 10^{9.7} - 10^{10.2}$ cm.

**Double Compton** is a process in which a photon when scatters off a charge particle, produces two photons. It is similar to the ordinary Compton scattering with an extra photon that is emitted. Again, double Compton can also act as a source of photons deep in the outflow. The thermalisation of the radiation achieved in such conditions require the dissipation to occur in a mildly relativistic outflow, such that $\Gamma \leq 4.8$ at radii, $r \sim 10^{10.2} - 10^{10.6}$ cm.

**Cyclotron** is an electromagnetic radiation emitted when charged particles move in circular orbits around the lines of the magnetic field. When the electrons are relativistic in nature, the cyclotron radiation is known as synchrotron radiation. The thermalisation of the cyclotron radiation occurs in mildly relativistic outflow when $\Gamma \leq 5.4$ at radii, $r \sim 10^{10.2} - 10^{10.8}$ cm.

These values are obtained assuming a burst luminosity, $L = 10^{52}$ ergs/s \[82\].

Along with these emission processes, it is also possible that the dissipated energy is much above the threshold for pair production, $m_e c^2$ and in such a scenario electron-positron pairs are produced. But the pair production would be significant only if the optical depth of these high energy photons is high or in other words the compactness of the region should be high enough such that high energy photons can annihilate with the low energy photons to result
Figure 3.3: Schematic figure of the zoomed part of the outflow till the photosphere radius, $r_{ph}$ is shown. The figure shows the various radii at which different photon production processes are relevant. The blue region denotes the region relevant for bremsstrahlung radiation; grey shaded region represents the region relevant for double Compton process and the barred region denotes the region relevant for cyclotron emission.

in pairs. If the condition of optical depth (compactness) is satisfied, there can be a significant amount of pairs and if the time taken by these pairs to cool is less than the dynamical time then these pairs have a chance to thermalise and thus a second photosphere (a pair photosphere) in addition to the baryonic photosphere can be formed in the outflow. The pairs remain in the outflow for the time, till there is a balance between the injection of energy and pair annihilation. Once the injection of energy stops, the balance is lost and the pairs start to annihilate and pair opacity reaches unity. Thus, if the event of dissipation is localised, and occurs deep in the outflow below the baryonic photosphere, then the chances of formation of pair photosphere is minimal. In case of localised dissipation, the formation of pair photosphere becomes relevant when it takes place close (above/below) to the baryonic photosphere or otherwise requires continuous dissipation until the photosphere. In addition to this, it also requires that $\varepsilon_d > m_e/m_p$ where $\varepsilon_d$ denotes the efficiency of dissipation producing photons with energy $> m_e c^2$ [44].
4. Fireball Model of GRBs

4.1 Fireball dynamics

The most popular model of GRBs is the relativistic fireball model [14]. Towards the end of its life, the massive star collapses to form a black hole. Accretion of debris around the black hole formed, as well as energy extracted from its rotation, produces a huge amount of energy whose major part is imparted to neutrinos and gravitational waves. The remaining portion of the energy forms a high temperature fireball (of radius $r_0$, energy $E_0$ and mass $M_0$) of electrons-positrons, gamma ray photons and baryons. Fireball is approximated as a steady wind which means there is no time evolution of the system. However, as each fluid element moves radially outwards, the outflow experiences changes with time. Thus, the properties of the wind change as a function of radius from the central object.

The fireball luminosity is typically about $10^{51}$ ergs/sec which is much larger than the Eddington luminosity. Assuming a non-magnetised jet, in such a case, the radiation pressure becomes dominant and causes the fireball to expand adiabatically. The photons thereby accelerate the gas to relativistic speeds and thus, the internal energy gets converted into the kinetic energy of the plasma. Therefore, the total energy density of the plasma at any radius is given by

$$U(r) = U_\gamma(r) + U_k(r)$$

(4.1)

where $U_\gamma$ and $U_k$ are the energy densities of the photon and kinetic energy of the outflow material in the lab frame respectively. However, in case of a magnetised jet, most of the burst energy would be in the magnetic field and in such a scenario the outflow would be accelerated by the magnetic energy [24], see §4.5.

Photon energy density, $U_\gamma = En_\gamma$ where $E$ is the average photon energy and $n_\gamma$ is the photon number density in the lab frame. Similarly, the kinetic energy density can be written as $U_k = \Gamma nm_ec^2$ where $\Gamma = \Gamma(r)$ is the local Lorentz factor, $n$ is the number density of electrons (which is equal to the number of protons given by $\dot{M}/m_p$ where $\dot{M}$ is the mass ejecta rate and $m_p$ is mass of the proton) and $c$ is the speed of light. Consider a sphere of radius, $r$, after a time $dt$, the particles produced at the radius $r$ (provided no new particles are
produced) now occupies a volume bounded by radius, \( r \) and \( r + dr \). Due to spherical expansion, the volume occupied by the particles is given by \( dV = 4\pi r^2 dr \), where \( dr = \beta c dt \). The lab frame particle density is thus given by

\[
n(r) = \frac{dN}{dV} = \frac{\dot{N}}{4\pi r^2 \beta c} \tag{4.2}
\]

where \( \dot{N} = L/kT_0 \) where \( L = dE/dt \) is the luminosity of the burst, \( k \) is the Boltzmann constant and \( T_0 \) is the plasma temperature at \( r_0 \) which denotes the radius from where the plasma starts to expand adiabatically.

Similarly, the radiation energy density is given by

\[
U_{\gamma}(r) = \frac{dE}{dV} = \frac{L}{4\pi r^2 \beta c} \tag{4.3}
\]

At large optical depths, the outflow is in local thermal equilibrium and therefore, the comoving radiation energy density is given by \( U_{\gamma}(r) = aT'^4(r) \), where \( a \) is the radiation density constant and \( T'(r) \) is the comoving temperature of the plasma. The comoving density, \( U'_{\gamma} = E'n'_{\gamma} \) where \( E' \sim kT' \) is the average photon energy. Due to length contraction, the comoving volume is given by \( dV' = \Gamma dV \) and the corresponding number densities is given by \( n'_{\gamma} = n_{\gamma}/\Gamma \).

Using the above relations, we get

\[
T'^3 = \frac{L/T_0}{a4\pi r^2 \beta c} \propto \Gamma^{-1} r^{-2} \tag{4.4}
\]

Deep inside the outflow, at lower radii, the total energy density is dominated by the photon energy density, \( U = U_{\gamma}(r) \). The average photon energy

\[
E = \frac{U_{\gamma}}{n_{\gamma}} \tag{4.5}
\]

As long as the radiation is dominant, \( E = constant \) as \( U_{\gamma} \) and \( n_{\gamma} \) scales as \( r^{-2} \). The average lab frame photon energy, \( E = \Gamma kT' \). From the above equation, we thus find that

\[
T' \propto \Gamma^{-1} \tag{4.6}
\]

and inputting this in equation 4.4 we get

\[
T' \propto r^{-1} \tag{4.7}
\]

which in turn gives that

\[
\Gamma \propto r \tag{4.8}
\]
Thus, we conclude that when the outflow is radiation dominated, the plasma is accelerated such that $\Gamma \propto r$ at the expense of the internal energy of the outflow, $kT' \propto r^{-1}$.

At some point of the flow, the internal energy becomes equal to the kinetic energy of the plasma, $\mathcal{U}_\gamma = \mathcal{U}_k$ i.e.

$$\frac{\Gamma kT'(L/kT_0)}{4\pi r^2 \beta c} = \frac{\Gamma m_p c^2 (\dot{M}/m_p)}{4\pi r^2 \beta c} \quad (4.9)$$

which gives

$$\frac{T'}{T_0} = \frac{\dot{M} c^2}{L} \quad (4.10)$$

We know that $T' \propto r^{-1}$, so $T' / T_0 = r_0 / r$. This results in

$$r = r_0 \frac{L}{\dot{M} c^2} \quad (4.11)$$

$L/\dot{M} c^2$ is parameterised as $\eta$ and is referred to as the free energy per particle at the base of the outflow. The bulk Lorentz factor per particle cannot increase beyond this initial value, $\eta$. The radius at which this condition is attained $r = \eta r_0$ is called as the saturation radius, $r_s$. After this radius, the flow coasts with a constant Lorentz factor, given by equation 4.8

$$\Gamma = \frac{r_s}{r_0} = \eta \quad (4.12)$$

The comoving temperature, $T'$ at the $r_s$ is given by equation 4.4

$$T'(r_s) = T_0 \frac{r_0}{r_s} = \frac{T_0}{\eta} \quad (4.13)$$

Above the saturation radius, $r_s$, the kinetic energy of the outflow dominates and the average energy per particle remains constant as $\mathcal{U}_k(r)$ and $n(r)$ scales as $r^{-2}$. The outflow thus gets saturated at the Lorentz factor, $\eta$. Thus, from equation 4.4, we find that above the saturation radius, the co-moving temperature evolves as $T' \propto r^{-2/3}$. The co-moving temperature at any radius above $r_s$ is then given as

$$T'(r) = T'(r_s) \left( \frac{r}{r_s} \right)^{-2/3} = \frac{T_0}{\eta} \left( \frac{r}{r_s} \right)^{-2/3} \quad (4.14)$$

The factor $(r/r_s)^{-2/3}$ corresponds to the amount of adiabatic cooling the photons undergone in the coasting phase of the outflow (region above $r_s$) till the radius $r$. 69
As the fireball expands, at some point, the optical depth falls below unity and the photons get decoupled from the plasma. The surface from where the photons get decoupled from the plasma is called as the photosphere, which is defined by the radius, \( r_{\text{ph}} \). For non-relativistic bulk motion, the optical depth, \( \tau \), for a photon propagating a distance \( ds \) is given by \( d\tau = n\sigma_T ds \), where \( n \) is the electron number density and \( \sigma_T \) is the Thomson cross-section. However, when we consider the outflow is relativistic, we need to take into consideration the relative distance, \( \beta \cos \theta ds \) travelled by the electron in the direction of photon motion while the photon travels the distance \( ds \) where \( \theta \) is the angle between the photon and electron’s direction of motion. Therefore, the effective electron number density that photon encounters is \((1 - \beta \cos \theta)n\) and thereby the optical depth, \( \tau \), is given by

\[
d\tau = (1 - \beta \cos \theta)n\sigma_T ds \tag{4.15}\]

For electron motion in the direction of photon has \( \theta = 0 \), gives \( d\tau = (n\sigma_T ds)/2\Gamma^2 \). Thus, the \( \tau \) decreases in comparison to that of static electrons. When \( \theta = \pi \) i.e electrons move opposite to the direction of photons gives, \( d\tau = 2n\sigma_T ds \). The \( \tau \) increases by a factor 2 than in the case of static electrons. For the perpendicular motion of electrons, the optical depth, \( \tau \), remains the same as that of the static electrons.

In a relativistic outflow, due to aberration of light most of the photons propagate almost radially. Therefore, the optical depth for a photon to escape from a position \( r \) in the outflow towards infinity along the radial direction is given by

\[
\tau(r) = \int_r^{\infty} \frac{n\sigma_T}{2\Gamma^2} dr \tag{4.16}
\]

Assuming the Lorentz factor is constant for the integration (i.e \( r > r_s \) and so, \( \Gamma = \eta \)), the optical depth is given as

\[
\tau = \frac{L\sigma_T}{8\pi m_pc^3 \Gamma^2 \eta} \frac{1}{r} \tag{4.17}
\]

As this \( \tau \) decreases to unity, photons escape the plasma and the radial distance along the line of sight of the observer from the centre of the outflow where \( \tau \) equals unity is known as the photospheric radius and is given by

\[
r_{\text{ph}} = \frac{L\sigma_T}{8\pi m_pc^3 \Gamma^3} \tag{4.18}
\]

Thus, the key parameters of the GRB outflow in the fireball model are \( r_0 \), \( \eta \), \( r_s \) and \( r_{\text{ph}} \), see Figure 4.1.
4.2 Outflow dynamics

As discussed in the basic fireball model, photosphere represents the innermost region of the outflow from where the emission reaches the observer. As the properties of the flow vary the observed properties of the photosphere also vary. Using the properties which depend on the initial condition at the central engine such as burst luminosity, \( L_0(t) \), dimensionless entropy, \( \eta(t) = L_0/\dot{M}c^2 \) and nozzle radius, \( r_0(t) \), the dynamics of the outflow can be calculated.

In the fireball scenario, the dissipation mechanisms giving rise to non-thermal component is not clear, but in contrast to this, it is certain that the thermal component originates at the photosphere. Thus, once identifying a blackbody component in the GRB spectrum and associating it to the photospheric emission with no subphotospheric dissipation (i.e the blackbody is the remnant of the thermalised fireball), we can calculate the outflow parameters using the method presented in Pe’er et al. 2007 [47] which is also described in detail in later part of the text. The blackbody has two free parameters: temperature, \( T = T(t) \) and the normalisation, \( A(t) \) giving the photon flux:

\[
N_E = A(t) \frac{E^2}{\exp(E/kT(t)) - 1}
\]  

(4.19)

where \( E \) is the photon energy and \( k \) is the Boltzmann constant. The observed blackbody normalisation can be related to a physical quantity, \( \mathcal{R} \) which parameterises the quantity, \( (F_{BB}/\sigma T^4)^{1/2} \).

The observed blackbody flux, \( F_{BB} \), is obtained by integrating the intensity
over the emitting surface,

\[ F_{\text{BB}} = \frac{2\pi}{d_L^2} d\mu \mu^2 \mathcal{D}^4 \left( \frac{\sigma T^4}{\pi} \right) \]  

(4.20)

where \( T' \) is the co-moving plasma temperature, \( \mathcal{D} \) is the Doppler factor and \( \mu = \cos \theta \). The observed blackbody temperature, \( T = \mathcal{D} T' = (\Gamma(1 - \beta \cos \theta))^{-1} T' \) where \( \theta \) is the angle to the line of sight and \( \beta = (1 - \Gamma^2)^{-1/2} \) is the expansion velocity of the plasma. The equation 4.20 when integrated and expressed such that \( (F_{\text{BB}}/\sigma T^4)^{1/2} \) gives

\[ R \equiv \left( \frac{F_{\text{BB}}}{\sigma T^4} \right)^{1/2} = \frac{\zeta (1+z)^2 r_{\text{ph}}}{d_L \Gamma} \]  

(4.21)

where \( \zeta \) is a numerical factor of the order of unity resulting from angular integration, \( z \) is the redshift and \( d_L \) is the luminosity distance. \( R \) represents the transverse size of the emitting region when \( \Gamma \gg 1/\theta_j \) where \( \theta_j \) is the jet opening angle.

The observed normalisation, \( A(t) \), is related to \( R \) such that

\[ R = 2\pi c \bar{h}^{3/2} A(t)^{1/2} \]  

(4.22)

where \( \bar{h} \) is the reduced Planck constant. \( R \) is found to increase with time in many CGRO BATSE bursts that have been successfully analysed with a black-body. The rise in \( R \) given by the power law index, \( \rho \), was found in Ryde & Pe'er 2009 \[3\] to have a very large spread, centred around an average value of 0.51 and has a standard deviation of 0.25.

The outflow properties can be determined depending on where the photosphere forms in the outflow: coasting phase or accelerating phase of the flow. In other words, we need to first discriminate between two possibilities: \( r_{\text{ph}} < r_s \) or \( r_{\text{ph}} > r_s \).

In above equation 4.21, substituting the condition \( r_{\text{ph}} = r_s \) and the corresponding Lorentz factor, \( \eta_\ast \), which can be called as the critical Lorentz factor, is obtained,

\[ \eta_\ast = \frac{r_s \zeta (1+z)^2}{R d_L}. \]  

(4.23)

If \( \eta \) (obtained from equation 4.25) is such that, \( \eta < \eta_\ast \), then \( r_{\text{ph}} \) will be larger than \( r_s \), and the photosphere forms in the coasting phase.

### 4.2.1 Photosphere in the coasting phase

In a classical fireball scenario, assuming no subphotospheric dissipation of the kinetic energy of the outflow, the initial emission is observed mainly due to the
thermal radiation coming from the photosphere along the radial axis towards the observer. The radius of the photosphere can thus be determined. The opacity is typically assumed to be due to electrons associated with the baryons in the outflow and since the optical depth of the flow is unity at \( r_{\text{ph}} \), we get

\[
r_{\text{ph}} = \frac{L_0}{8\pi m_p c^3 \Gamma^3}
\]

where \( \sigma_T \) is the Thompson crosssection, \( L_0 \) is the luminosity of the burst, \( L_0 = 4\pi d_L^2 Y F_{\text{tot}} \) where \( F \) is the total observed flux and \( Y = \text{ratio of total fireball energy and the energy emitted in gamma rays} \). Generally \( Y \) is unknown unless there is an afterglow detection for the burst [40], see §4.4. Starting with the early measurements of temperature, \( T \), thermal flux, \( F_{\text{BB}} \) and total flux, \( F_{\text{tot}} \), we can deduce the parameter \( R \) which is proportional to the radius of the surface emitting thermal radiation i.e., the radius of the photosphere, \( r_{\text{ph}} \). Substituting the equation 4.24 in the equation 4.21 gives the estimate of the Lorentz factor, \( \Gamma = \eta \)

\[
\Gamma = \left( \zeta (1+z)^2 dL \frac{YF}{2m_p c^3 R} \right)^{1/4}
\]

Using this value of \( \Gamma \) in equation 4.24 gives an estimate of the photospheric radius, \( r_{\text{ph}} \).

By including the relation between \( T \) and the comoving temperature, \( T'(r_{\text{ph}}) \) from equation 4.14 in the above relation between \( R \) and \( r_{\text{ph}} \), one can deduce the value of the nozzle radius of the jet, \( r_0 \), which is given by

\[
\frac{r_0}{\Gamma_0} = \psi \frac{dL}{(1+z)^2} \left( \frac{F_{\text{BB}}}{\epsilon_{\text{BB}} Y F_{\text{tot}}} \right)^{3/2} \mathcal{R}
\]

where \( \psi \) is a numerical coefficient of the order of unity, \( \Gamma_0 \) is the Lorentz factor at the radius, \( r_0 \) and \( \epsilon_{\text{BB}} \) is the fraction of the total burst energy that is thermalised at the radius, \( r_0 \). Once knowing \( r_0 \), we get an estimate of the saturation radius, \( r_s \) which is given by

\[
r_s = \Gamma r_0.
\]

The outflow parameters were estimated for the burst GRB110721A in Paper II, for a redshift, \( z = 2 \) (an average value for long GRBs) since the redshift was unknown as no afterglow detection was made for this burst. The average values of parameters are: \( r_{\text{ph}} = 3 \times 10^{12} Y^{1/4} \text{cm} ; \eta = 400 Y^{1/4} \), \( r_0 = (1 \pm 1.7) \times 10^8 (Y \epsilon_{\text{BB}})^{-3/2} \text{cm} \) and \( r_0 = 6.3 \times 10^{10} Y^{-5/4} \epsilon_{\text{BB}}^{-3/2} \). The values obtained are in agreement with the predictions of the fireball model [14], which further reinforces the idea of photospheric emission. Similar analysis was also done in e.g., Larsson et al. (2011) [83], Guiriec et al. (2011) [8].
4.2.2 Photosphere in the accelerating phase

If the photosphere forms in the accelerating phase of the outflow, i.e. \( \eta > \eta^* \), then in such a case the Lorentz factor at the photosphere is given by

\[
\Gamma_{\text{ph}} = \frac{r_{\text{ph}}}{r_0} \quad (4.28)
\]

Using the equation 4.21 of \( R \), we get an estimate of \( r_0 \) which is given by

\[
r_0 = \frac{\mathcal{R}d_L}{\zeta(1+z)^2} \quad (4.29)
\]

If we assume, the outflow dynamics is dominated by the thermal pressure, then the energy conservation is given by \( L_0 = L_{\text{BB}} + L_{\text{kin}} \), where \( L_{\text{BB}} \) is the thermal luminosity and \( L_{\text{kin}} = \Gamma(r) M c^2 \) is the kinetic energy of the outflow per second. Using the definition of \( \eta = L_0/Mc^2 \) and \( \Gamma_{\text{ph}} \) in the equation of energy conservation, we get

\[
\frac{r_{\text{ph}}}{r_0 \eta} = 1 - \frac{L_{\text{BB}}}{L_0} \quad (4.30)
\]

Knowing \( L_{\text{BB}}, L_0 \) from the observations and \( r_0 \) from the equation 4.29, we get the expressions for \( \eta, \Gamma_{\text{ph}} \) and \( r_{\text{ph}} \), which are derived in Paper III and they are

\[
\eta = \left( \frac{\phi \sigma T}{6m_p c^3 \mathcal{R}} \right)^{1/4} \frac{d_L^{1/4}(1+z)^{1/2} YF_{\text{tot}}}{(YF_{\text{tot}} - F_{\text{BB}})^{3/4}} \quad (4.31)
\]

\[
r_{\text{ph}} = \left( \frac{\sigma T \mathcal{R}^3}{6m_p c^3 \phi^3} \right)^{1/4} \frac{d_L^{5/4}(YF_{\text{tot}} - F_{\text{BB}})^{1/4}}{(1+z)^{3/2}} \quad (4.32)
\]

\[
\Gamma_{\text{ph}} = \left( \frac{\phi \sigma T}{6m_p c^3 \mathcal{R}} \right)^{1/4} \frac{d_L^{1/4}(1+z)^{1/2}(YF_{\text{tot}} - F_{\text{BB}})^{1/4}}{YF_{\text{tot}} - F_{\text{BB}}} \quad (4.33)
\]

where \( \phi \) is a numerical factor of the order of unity.

When the photosphere forms in the accelerating phase of the outflow, most of the burst energy is in the thermal radiation and there is less kinetic energy. In such a scenario, the dominant emission in the observed spectrum would be the blackbody emission (thermalised radiation) from the photosphere. GRB090902B is one of the most luminous bursts observed by \textit{Fermi} [50]. Observationally, the whole emission can be divided into two epochs: 0 -12.54 s and 12.54 - 24.58 s. During the first epoch, the burst spectrum is very narrow and is therefore, interpreted to come from the photosphere of the outflow. In Ryde et al. 2010 [9], the first epoch is fitted using a multicolor blackbody and a power law. However, the second epoch of the burst shows a broader spectral component.
The broadening observed in later times could be either due to subphotospheric dissipation [9, 84] or geometrical broadening [62, 64]. Thus, GRB090902B was considered as a good candidate to study the outflow parameters in the case when the photosphere forms in the accelerating phase.

During the first epoch, $\eta$ (maximum Lorentz factor that can be attained) was found to be on an average two times larger than $\Gamma$ at the photosphere, which clearly shows that the photosphere is indeed formed in the accelerating phase. It is also seen that the saturation radius $r_s$, is well above the photospheric radius, $r_{ph}$, see Figure 4.2. However, during the second epoch, $\Gamma$ and $\eta$ lies closer to each other which suggests that the photosphere is now moving into the coasting phase of the outflow, see Figure 4.2.

![Figure 4.2](image)

**Figure 4.2:** Top panel: time evolution of the Lorentz factor, $\Gamma$ (green), along with the dimensionless entropy $\eta$ (blue) assuming that the photosphere is formed in the accelerating phase is shown. For comparison, the values of $\Gamma = \eta$ (red) when the photosphere is formed in the coasting phase is also shown. The time, $t = 12.8$ s marks the beginning of the second epoch. Bottom panel: time evolution of the photospheric radius $r_{ph}$ (continuous line) and the nozzle radius $r_0$ (dashed line) in units of $10^{11}$ cm for the both cases of accelerating and coasting phase are shown. The blue line shows the saturation radius when assuming that the photosphere forms in the accelerating phase. [Paper III]

On average, the parameter values are the following: $\Gamma \sim 500$, $\eta = 1000$, $r_{ph} = 10^{11}$ cm, $r_0 = 10^9$ cm and $r_s = 10^{12}$ cm for $Y = 1$. 

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4.3 Variable jet properties

In Paper II as well as in Paper V, we study the evolution of the outflow parameters of the single pulsed GRBs with time and find the following results:

4.3.1 Decreasing Lorentz factor

Lorentz factor, $\Gamma$, is found to decrease monotonously with time, see Figure 4.3a. The Lorentz factor, $\Gamma$, depends on the observables, such as: $\Gamma \propto (F_{\text{tot}}/R)^{1/2}Y^{1/4}$. Thus, it mainly follows the flux behaviour of the bursts. The Figure 4.3b shows that all the bursts in the sample studied in Paper V have their lowest calculated Lorentz factor to lie above 100. Only one burst in the sample has a $\Gamma$ larger than 1000 in the beginning. The average value of $\Gamma$ for this sample of bursts, considering their temporal evolution, is of the order of hundreds.

In each burst, we find that during the rising phase of the pulse, $\Gamma$ is high and remains nearly steady with a very gradual decrease with the rise time of the pulse. However, during the decay phase of the pulse, $\Gamma$, decreases along with the decay of the pulse of the burst. During the rise phase of the burst, the total flux, $F_{\text{tot}}$, increases with time and the parameter $R$, which represents the transverse size of the observed photosphere of the jet ($r_{\text{ph}}/\Gamma$), also increases with time. As a result, we find $\Gamma$ to be steady during the rising phase of the burst.

Figure 4.3: a) Lorentz factor, $\Gamma$, of the burst decreases monotonously with time over a single pulse of the burst, for e.g. the case of GRB110721A is shown [Paper II]. b) The range of $\Gamma$ values obtained for the different bursts studied in Paper V is shown. The values are estimated for a redshift, $z = 2$ as redshift is unknown for all the bursts. However, to illustrate the dependence on $z$, in figure (a) where the values of $\Gamma$ for $z = 0.38$ (blue/star) and $z = 3.5$ (red/circle) are shown.
4.3.2 Photospheric radius

Photospheric radius is found to increase moderately with time, see Figure 4.4. During the rising phase of the pulse when $\Gamma$ remains steady, an increasing $\mathcal{R}$ suggests that the photospheric radius of the jet is increasing with time. This increase in $r_{\text{ph}}$ is due to the increase in the luminosity of the burst which in turn implies that the baryon load ($L_0/\eta m_p c^2$) of the outflow increases. As a result of which the opacity of the outflow due to the electrons associated with the baryons also increases. This in turn results in pushing the last scattering position of the photons (photosphere) to a larger radius with time.

However, during the decay phase, $\Gamma$ decreases along with the luminosity of the burst. As a result, the increase observed in $r_{\text{ph}}$ is mainly due to the decrease in $\Gamma$ even though the number of baryons decreases. As $\Gamma$ decreases, the relative distance travelled by the electrons with respect to the photons along the radial motion of the photon, decreases. As a result, the size of the region where the photons and electrons interact increases, thereby resulting in larger optical depth, see §4.1. In other words, the effective electron number density ($n/2\Gamma^2$) increases, where $n$ is the electron number density. Thus, the increase in optical depth results in a farther position of the photosphere with time.

Figure 4.4: a) The photosphere radius, $r_{\text{ph}}$, increases moderately with time, for e.g the case of GRB110721A is shown [Paper II]. b) The range of $r_{\text{ph}}$ values obtained for the different bursts studied in Paper V is shown. The values are estimated for a redshift, $z = 2$. The dependence on $z$, is illustrated in figure (a) where the values of $r_{\text{ph}}$ for $z = 0.38$ (blue/star) and $z = 3.5$ (red/circle) are shown.
4.3.3 Nozzle radius

The nozzle radius of the jet, $r_0$, signifies the radius from where the jet starts to expand ballistically. $r_0$ evolves within the range of $10^6$ to $10^9$ cm. It initially increases and reaches a peak after which $r_0$ decreases or becomes steady. This evolution can be interpreted as the increase of $r_0$ from the black hole event horizon radius to that of the surface core of the Wolf - Rayet progenitor star.

Increasing $r_0$ suggests that there are photons being produced in the region above the central engine (which has a typical size of the order of $10^6 - 10^7$ cm). This means that there is efficient photon production and increased dissipation with time within the limits of the thermalisation radius \cite{82}. This dissipation can be due to the collimation of the jet \cite{85,86} by the cocoon of the star resulting in oblique shocks \cite{87}. Beyond the core radius of the star, the oblique shocks due to the confinement of the jet by the cocoon of the progenitor becomes weak and less efficient. As a result, $r_0$ does not increase any further instead decreases or remains nearly steady. Another possibility has been suggested by Ghisellini et al. 2007 \cite{88}, where shocks are produced in the outflow when it encounters the progenitor or cocoon material which is in the way of the jet. As a result of which the fireball is reborn at a larger radius. However, in such a scenario with the accretion of the stellar matter with time, the $r_0$ would decrease with time, which is not observed during the major part of the burst duration.

Most of the bursts in the sample exhibited a pulse like nature. During the rising phase of $r_0$, the evolution of $r_0$ is inversely proportional to $\Gamma$. Small velocity of the outflow can result in shear turbulence and oblique shocks within the stellar core and this can result in large values of $r_0$. A large velocity instead can prevent the formation of shocks which can then result in small values of $r_0$. Thus, it may be speculated that during the period where $r_0$ increases with time between the limits of the size of the event horizon of the black hole formed and the size of the progenitor star, the position of $r_0$ may be determined by the collimation or oblique shocks created within the outflow when the jet is propagating through the progenitor envelope. Once reaching the peak value, $r_0$ decreases with time showing a weak positive correlation with $\Gamma$. Thus, after reaching the stellar core one can speculate that due to the accretion of the stellar material $r_0$ starts decreasing with time. But these ideas are mere speculations and till now there have been no direct simulation studies done to investigate how $r_0$ evolves with time. However, there are several hydrodynamical simulations which have shown that there is significant collimation shocks produced within the outflow as the jet traverses through and emerges out of the stellar cocoon \cite{87}.
Figure 4.5: a) The nozzle radius, $r_0$ evolves like pulse from $10^6$ to $10^8$ cm and then decreases for e.g in case of GRB110721A is shown. [PaperII] b) The range of $r_0$ values obtained for the different bursts studied in Paper V is shown. The values are estimated for a redshift, $z = 2$. The dependence on $z$, is illustrated in figure (a) where the values of $r_0$ for $z = 0.38$ (blue/star) and $z = 3.5$ (red/circle) are shown.

4.3.4 Saturation radius

The pulse like nature in $r_0$ gets reflected in the behaviour of $r_s$ in case of a non-dissipative outflow until the flow saturates. We observe that $r_s$ becomes close to the photosphere at some point in time and then moves away from the photosphere. The thermal component would be quite significant in the spectrum, at this point than at any other time in the outflow [89].

4.4 Parameter $Y$

The decreasing $\Gamma$ is a challenge to the dissipation mechanisms like internal shocks [10] or ICMART [90] which require the central engine to vary with time such that the faster moving shells are produced with time so that faster shells can crash into the preceding slow moving shell to result in shocks. In addition to this, generally in literature the Lorentz factor of the outflow is assumed to remain a constant through out the burst. However, there is no physical reason as to why it should be so. We find that all the observed spectral features of the burst evolves with time such as photon flux, luminosity, spectral peak $E_{\text{peak}}$, $kT$ etc, so it is more intuitive to expect the outflow parameters also to evolve with time. However, the current estimation of the $\Gamma$ has a dependence on the unknown parameter, $Y$ which is given by the ratio of total burst energy
Figure 4.6: a) The saturation radius, $r_s$ shows a pulse like nature, mainly reflects the behaviour of $r_0$, for e.g in case of GRB110721A is shown. [Paper II] b)The range of $r_s$ values obtained for the different bursts studied in Paper V is shown. The values are estimated for a redshift, $z = 2$. The dependence on $z$, is illustrated in figure (a) where the values of $r_s$ for $z = 0.38$ (blue/star) and $z = 3.5$ (red/circle) are shown.

to the observed $\gamma$-ray energy. Assuming the burst is non-magnetised and is a baryonic outflow, the estimate of $Y$ can be done if afterglow of the burst is observed [40]. However, for none of the bursts in the sample [Paper V], afterglows have been observed thereby not enabling us to estimate $Y$.

Since the estimation of $\Gamma$ has a dependence on $Y$, we study if the observed decreasing behaviour of $\Gamma$ is nothing but an evolution in $Y$ such that $\Gamma$ remains a constant. For this we need to assume a constant value of $\Gamma$ to study how $Y$ evolves with time. We find that this assumed value of $\Gamma$ has to be either the highest value of the currently estimated $\Gamma$ or any value larger than this. We now choose a value of $\Gamma$ equal to the highest value currently estimated and find that the corresponding estimated values of $Y$ to increase with time from nearly 1 to 1000. Using this estimated evolution of $Y$, we also estimate the value of the nozzle radius of the jet, $r_0$ and find that in all bursts $r_0$ decreases with time from nearly $10^8$ to $10^3$ cm, see Figure [4.7]. For black holes that are typically formed after the collapse of highly massive stars are estimated to have a Schwarzschild radius of the order of $10^6$ to $10^7$ cm. Thus, the value of $r_0$ estimated towards the end in all the bursts are less physical and are too low values. Thereby, it is not possible to have such an evolution of $Y$ with time. This in turn means that the evolution of parameter $Y$ cannot account for the observed decrease in $\Gamma$. In addition to this, recently Wygoda et al. 2015 [41] have found that there is less spread in the estimation of the efficiency of bursts.
whose afterglows could be detected and finds an average value of $Y \sim 2$. This suggests that large variations in $Y$ are unlikely.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{GRB_100707A.png}
\caption{Figure 4.7: If $\Gamma$ remains a constant throughout the burst, we find $Y$ (black/squares) to increase with time. Along with that, we estimate the value of $r_0$ (blue/squares with line), for such an outflow and find that the $r_0$ decreases with time and reaches very low values which are not feasible. [Paper V]}
\end{figure}

4.5 Magnetisation parameter, $\sigma_0$

In a hybrid model for the GRB outflow \cite{89, 91} with the dimensionless entropy, $\eta$ (hot component), and magnetisation, $\sigma_0$ of the central engine (cold component), the total burst luminosity, $L_0 = L_b + L_c$ where $L_b$ is the hot component (fireball) and $L_c$ is the cold component (Poynting flux) of the burst. The magnetisation parameter, $\sigma_0$ is defined as

$$\sigma_0 = \frac{L_c}{L_b}$$  \hspace{1cm} (4.35)

For conditions such as $\sigma_0 \ll 1$ and $\eta \gg 1$ results in a pure fireball and when $\sigma_0 \gg 1$ results in a highly magnetised outflow.
In a hybrid system there are three main regimes in the outflow. Initial phase where the thermal acceleration occurs thereby marking the rapid acceleration regime till the radius, \( r_{ra} \). The second phase beyond \( r_{ra} \) where the outflow is slowly accelerated till the saturation radius, \( r_s \) and finally the phase where the outflow coasts with the constant Lorentz factor, \( \Gamma_c \). If \( \sigma_0 \) is very large then the second phase of acceleration may continue such that the outflow does not reach the coasting phase, instead, may start to decelerate after crashing into the ambient interstellar medium.

In a scenario where there is no magnetic dissipation taking place below the photosphere which is formed in the coasting phase, the outflow parameters are obtained as follows:

The coasting Lorentz factor, \( \Gamma_c \) is given as \( \Gamma_c = \Gamma_{ph} = \eta (1 + \sigma_0) \). The photospheric radius, \( r_{ph} \), is given by

\[
r_{ph} = \frac{L_0 \sigma_T}{8 \pi m_p c^3 \Gamma_{ph}^2 \eta (1 + \sigma_0)}
\]

Substituting equation 4.36 in the equation of \( R \) (see equation 4.21), gives an estimate of \( \eta \) of the burst which is given by

\[
\eta = \left[ \frac{L_0 \sigma_T 1.06(1+z)^2}{8 \pi m_p c^3 d_L (1+\sigma_0)^4 R} \right]^{1/4}
\]

assuming a value of \( \sigma_0 \). Once knowing \( \eta \), gives an estimate of \( \Gamma_{ph} \). Thus, the estimates of \( \Gamma_{ph} \) and \( r_{ph} \) have no dependence on the magnetisation parameter, \( \sigma_0 \) and the expressions obtained are equivalent to the one obtained in Pe’er et al. 2007 [47]. The difference to be noted is that in this scenario \( \Gamma_{ph} \neq \eta \) which was otherwise the case in Pe’er et al. 2007 [47].

From the equation of observed blackbody temperature, \( T \), see §4.2, we are able to estimate the nozzle radius of the jet, \( r_0 \), which is given by

\[
r_0 = \psi \frac{R d_L}{(1+z)^2} \left( \frac{F_{BB}}{F_{tot}} \right)^{3/2} \left( \frac{1+\sigma_0}{\epsilon_{BB} Y} \right)^{3/2}.
\]

In summary, if we assume a value for \( \sigma_0 \), we can estimate the outflow parameters \( r_{ph}, r_0, \Gamma_{ph} \) and \( \eta \). However, in this scenario we cannot estimate \( r_s \) as \( r_s \) is given by

\[
r_s = r_{ra} \left( \frac{\Gamma_c}{\Gamma_{ra}} \right)^{1/3}
\]

where we assume \( \delta = 1/3 \) [24], and \( r_{ra} \) is unknown.

Generally in literature the \( r_0 \) is associated to the size of the central engine and is assumed to be a constant through out the burst duration. If we assume
Figure 4.8: If $r_0$ is assumed to be a constant throughout the burst duration at $r_0 \sim 2 \times 10^7\text{ cm}$ (upper panel) or $r_0 \sim 10^9\text{ cm}$ (lower panel), we find $\chi$ (measure of magnetisation of the outflow) to evolve as shown (blue circles with line). The deduced evolution of $r_0$ is also shown in shade (grey squares with line). [Paper V]
r_0 to be a constant, we explore the variation that is possible in the unknown quantity \((1 + \sigma_0)/\varepsilon_{BB}Y\) which is parameterised as \(\chi\). Figure 4.8a shows that when \(r_0 = 2 \times 10^7\) cm throughout the burst, the \(\chi\) varies between values 0.35 and 0.1. This clearly rules out any possibility of having \(\sigma_0\) larger than 1 (assuming \(Y = 1\)) which means the burst is very weakly magnetised. Figure 4.8b shows that when we assume \(r_0 = 10^9\) cm (size of the core of the progenitor star), we find the \(\chi\) to vary between 4 and 1.2. This implies that the \(\sigma_0 > 1\); however since it is not \(\sigma_0 \gg 1\) the burst is only moderately magnetised.

Thus, we understand that even when considering a scenario where the central engine is magnetised, if there is no subphotospheric dissipation, the outflow parameters obtained by the methodology in Pe’er et al. 2007 [47] are very robust.

In such a hybrid model, the \(Y = (L_b + L_p)/L_{\text{obs}}\) where \(L_{\text{obs}}\) is the observed luminosity of the burst, which gives

\[
Y = \frac{L_b}{L_{\text{obs}}} (1 + \sigma_0)
\]

(4.40)

If we assume all of the fireball energy \((L_b)\) is fully dissipated and thereby observed i.e \(L_b \sim L_{\text{obs}}\), then we find \(Y \sim (1 + \sigma_0)\). In such cases, the estimate of \(Y\) gives a direct estimate of the magnetisation of the central engine. If we assume, in such cases, \(\Gamma\) remains constant or increasing with time, requires \(Y\) to increase dramatically with time. This means the magnetisation of the burst is increasing with time. Otherwise, the estimate of \(Y\) relates to the amount of energy that has not been dissipated and thereby not observed (fraction of \(L_0\)), neglecting any loss of energy from the system.

### 4.6 Outflow parameters in case of subphotospheric dissipation

When the observed spectrum is interpreted such that the whole emission, is from the dissipative photosphere, then the Lorentz factor, \(\Gamma\) and photospheric radius, \(r_{\text{ph}}\) would correspond to the values after the event of dissipation. Let \(\varepsilon_d\) be the fraction of the kinetic energy \((L_0\) when the flow is in the coasting phase) of the outflow that is dissipated and \(\varepsilon_e\) be the fraction of the dissipated energy, \(\varepsilon_dL_0\), that goes into the electrons of the plasma which then in turn goes into the internal energy of the outflow, \(\gamma U_k^{\text{pre}}\). If \(\gamma U_k^{\text{post}}\) is much larger than the kinetic energy density of the plasma, \(\gamma U_k^{\text{post}}\), then the outflow will reaccelerate.

\(^1\)Superscript 'pre' denotes values of the parameters before the event of dissipation.

\(^2\)Superscript 'post' denotes the values of the parameters after the event of dissipation.
till it reaches the new coasting Lorentz factor, $\eta_{\text{post}}$. In such a scenario, it is
difficult to estimate where the photosphere occurs as it depends on the details
of the outflow dynamics.

However, if the dissipation occurs such that

$$U_{\gamma}^{\text{post}} \ll U_k^{\text{post}}$$

(4.41)

then the outflow would nearly coast with the $\Gamma_{\text{post}}$ till the new photosphere,
$r_{\text{ph}}^{\text{post}}$, with nearly no acceleration [Paper III]. Then, in such a scenario, if the
localised dissipation takes place at a radius, $r_d$, in the coasting phase, then the
Lorentz factor at $r_d$ is given by

$$\Gamma_{\text{post}} = (1 - \varepsilon_d)\eta$$

(4.42)

and the photosphere radius is given by

$$r_{\text{ph}}^{\text{post}} = \frac{L_0\sigma_T}{8\pi m_p c^3 (1 - \varepsilon_d)^2 \eta^3}$$

(4.43)

where $\eta = \Gamma_{\text{pre}} = L_0 / \dot{M}c^2$, since before the dissipation took place, the outflow
was already in the coasting phase. The equation [4.21] now becomes

$$\mathcal{R} \equiv \left( \frac{F_{\text{BB}}}{\sigma T^4} \right)^{1/2} = 1.06 \frac{(1 + z)^2}{d_L} \frac{r_{\text{ph}}^{\text{post}}}{\Gamma_{\text{post}}}$$

(4.44)

substituting equation [4.43] in the above equation [4.44] gives

$$\eta = \left( \frac{1.06 \sigma_T d_L Y F_{\text{tot}} (1 + z)^2}{2 m_p c^3 (1 - \varepsilon_d)^3 \mathcal{R}} \right)^{1/4}$$

(4.45)

which can also be rewritten as $\eta = \Gamma_{\text{pre}} / (1 - \varepsilon_d)^{3/4}$ where $\Gamma_{\text{pre}}$ is equivalent to
the Lorentz factor of the outflow when there is no subphotospheric dissipation.

In Paper III, it is shown that for the condition given in equation [4.41] to
hold, $\varepsilon_d \ll 2/(2 + \varepsilon_e)$ assuming that $r_d \gg r_s$ so that
$U_{\gamma}^{\text{post}} \propto \varepsilon_e \varepsilon_d L_0 / 2$ and
$U_k^{\text{post}} \propto \Gamma_{\text{post}} \dot{M} c^2$. $\varepsilon_e$ can vary between 0 and 1. When $\varepsilon_e = 0$, it means that for
any value of $\varepsilon_d$, none of the dissipated energy goes into the internal energy
of the outflow. In such a case, the outflow would not undergo any re-acceleration.
When $\varepsilon_e = 1$, it means all the dissipated energy goes into the internal energy
of the outflow. In such a case, for the above condition (equation [4.41]) to hold
not more than 67% of the kinetic energy can be dissipated. Thus, for a given
value of $\varepsilon_e$, there is an upper limit value of $\varepsilon_d$ above which the equation [4.41]
can never hold. However, when $\varepsilon_e = 1$, if the outflow reaccelerates, then the
Lorentz factor grows back to its initial coasting value of $\eta$. 

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If there is efficient photon production as a result of dissipation (see §3.3), the calculation of the nozzle radius of the outflow jet, \( r_0 \), using the adiabatic expansion formulae [47] would not be valid unless we are able to identify the fireball blackbody component. If anything of the dissipated energy has thermalised then we lose the information of the original fireball photospheric thermal component and thus, cannot estimate the value of \( r_0 \). This is more likely when the \( \tau_{\text{post}} \) is large. But if \( \tau_{\text{post}} \leq 1 \) or close to one, then in such a scenario, it is possible to retrieve the fireball thermal component as there is no chance for thermalisation to occur and so the dissipated energy would appear as the non-thermalised flux of the spectrum. This enables us to calculate \( r_0 \) by either assuming adiabatic expansion of the fireball [47] or by the conservation of photon number given by original fireball thermal photons, \( N_0 = N_{BB} \), number of observed photons in the observed fireball blackbody component. This allows us to calculate the nozzle radius, \( r_0 \), independent of the assumption of adiabatic expansion of the outflow in the accelerating phase and is given by

\[
\frac{r_0}{\Gamma_0} = \left( \frac{1.48 N_0}{(1+z)} \right)^2 \left( \frac{(\varepsilon_{BB} L_0)^{-3/2}}{7 \sigma_{SB}^{1/2}} \right)
\]  

(4.46)

where \( \sigma_{SB} \) is the Stefan-Boltzmann constant, \( \varepsilon_{BB} \) is the fraction of the burst energy that has thermalised at the base of the nozzle radius of the jet.

### 4.6.1 Photon starvation scenario

When we consider a dissipative photosphere scenario, it is relevant to note that Vurm et al. 2013 [82] and Beloborodov 2013 [85] have shown that there cannot be efficient photon production mechanisms close to the photosphere except synchrotron emission. However, for synchrotron emission to be the source of photons, requires an efficient transfer of the kinetic energy to the electrons accelerating them to relativistic Lorentz factors, as well as a strong magnetic field. Vurm et al. 2013 [82] showed that all the other photon producing mechanisms like bremsstrahlung, double-Compton scattering and cyclotron (see chapter 3), are only effective when the optical depth is very large.

In addition to this, the thermalisation requirements put an upper limit on the radius of thermalisation to be of the order of \( 10^{10} \) to \( 10^{11} \) cm where the \( \Gamma \leq 10 \). In other words, there cannot be efficient photon production and thermalisation above this radius along with a high \( \Gamma \).

Thus, dissipation taking place below the photosphere at some Compton \( y \)-parameter \( \gg 1 \), does not produce new photons instead the dissipated energy gets distributed between the existing photons and thereby increase the mean energy of the photons resulting in a Wien spectrum. Thus, the information regarding the fireball blackbody component is lost as the Wien flux, \( F_w = b \sigma T^4 \)
where \( b \) is the photon starvation factor and \( b < 1 \). Thus, the Wien flux does not change proportionally to \( T^4 \). However, by assuming the Wien spectrum to come from the photosphere where the kinetic equilibrium is maintained, we can still estimate the Lorentz factor, \( \Gamma^w \) and photospheric radius, \( r^w_{ph} \) provided \( \Gamma \sim \eta \) remains valid after the event of dissipation (see the above discussion). Then, the equation 4.21 can be rewritten as

\[
\mathcal{R}_w \equiv \left( \frac{F_w}{b \sigma T^4} \right)^{1/2} \sim b^{-1} \mathcal{R}_{BB} \tag{4.47}
\]

\[
\mathcal{R}_w = 1.06 \frac{(1+z)^2}{d_L} \frac{r^w_{ph}}{\Gamma^w} \tag{4.48}
\]

where \( \mathcal{R}_{BB} \equiv \left( \frac{F_{BB}}{\sigma T^4} \right)^{1/2} \) where \( F_{BB} \) is the blackbody flux. The last approximation of equation 4.47 holds because in the spectral fits, the normalisation of the blackbody and the Wien spectrum for the same temperature is nearly the same and therefore, gives nearly the same flux. The Lorentz factor and the photospheric radius thus calculated would have the following dependences on the photon starvation factor, \( \Gamma^w = b^{1/4} \Gamma; \ r^w_{ph} = b^{-3/4} r_{ph} \) and \( b < 1 \). When \( b = 1 \), we recover the expressions obtained for the case of blackbody spectrum.

The calculation of \( r_0 \) using the photon number conservation would still remain valid. If we assume the spectrum to be Wien for the same observed temperature, we find that the corresponding radius, \( r^w_0 \), from where the Wien spectrum is formed to be

\[
\frac{r^w_0}{\Gamma^w_0} = \left( \frac{1.48 N_0}{1+z} \right)^4 \frac{\left( \varepsilon_{BB} L_0 \right)^{-3} b^3}{4 \pi \sigma_{SB}} \right)^{1/2} \tag{4.49}
\]

\[
\frac{r^w_0}{r_0} = 2 \frac{\Gamma^w_0}{\Gamma_0} b^{3/2} \tag{4.50}
\]

where \( \Gamma^w_0 \) is the Lorentz factor at the Wien radius. Since \( b < 1 \), this implies that \( r^w_0 < r_0 \), the nozzle radius of the outflow calculated assuming the spectral component to be a Planck function. \( r_0 \) lies between \( 10^9 - 10^{10} \) cm which is similar to the estimate for the radius of the core of a Wolf - Rayet star with mass of \( 20M_{\text{sun}} \). However, in Beloborodov 2013 [85], the Wien radius is expected to be outside the core of the star.
5. Varying faces of photospheric emission

5.1 Two types of photosphere models

In the section §2.3, we have presented the different spectral shapes that have been observed by Fermi in relevance to the photospheric emission. The two main perspectives of photospheric emission models are the following:

(a) **Two emission zone model** where the blackbody represents the emission from the non-dissipative photosphere and the non-thermal component (i.e. Band function) represents the emission from the optically thin region due to non-thermal processes like synchrotron emission. For e.g. in Burgess et al. 2014 [60] a sample of 8 single pulse GRBs were analysed within this model where instead of the empirical Band function, a synchrotron function was used. It was found that in those bursts, the spectra are equally consistent with this model in comparison to the BB + Band function fits.

In such a scenario, there is no dissipation taking place below the photosphere. Thus, the spectrum from the photosphere is thermal in nature but the Planck spectrum is modified at low energies due to geometrical and radial effects of the photosphere in the relativistic outflow. The observed photosphere thus would be a superposition of blackbodies of different observed temperatures, $T_{\text{ob}} = \left(\frac{\Gamma(1 - \beta \cos \theta)}{1 - \beta \cos \theta}\right)^{-1} T'$ where $\theta$ is the angle of emission from the line of sight of the observer, and $T'$ is the comoving temperature at the photosphere. Thus, high latitude emission result in varying observed temperatures even when the photosphere has a constant $T'$ along the surface of the photosphere. This emission broadens the observed thermal spectra from a Planck function resulting in a multicolour blackbody or modified Planck spectrum [62]. In addition to this, if we consider the viewing angle effects while observing a GRB jet, can also result in photospheric emission that is broadened from a blackbody, see [64]. However, in case of BB + Band function fits, a pure blackbody is used because in case of dominant non-thermal emission, these relativistic effects are masked and the prior is to find the peak (or hump) at low energies below the main peak of the spectrum.

The Band function (or synchrotron function) in such a scenario is associated to the non-thermal emission occurring in the optically thin region. In a
non-magnetised outflow, the dominant energy is in the form of kinetic energy of the outflow, above the saturation radius. At regions above the photosphere, the kinetic energy of the outflow is dissipated via internal shocks such that the electrons are accelerated to high energies which then cool either by synchrotron emission \[10\] \[92\] or by inverse Compton scattering of the thermal photons from the photosphere \[93\].

In a highly magnetised outflow, most of the burst energy is in magnetic fields. The photospheric emission is expected to be weak \[94\] and in the optically thin region the magnetic energy is dissipated as a result of the reconstructions of magnetic field lines resulting in non-thermal emission but the physics of reconnection of magnetic fields is yet to be fully understood \[95\]. Dissipation due to internal shocks in such cases would be possible only if there is an efficient transfer of energy from the magnetic fields to the kinetic energy of the outflow during the acceleration phase. This would eventually result in weak magnetic fields at optically thin radius. However, if conversion of magnetic energy to kinetic energy is less efficient then, the outflow remains strongly magnetised even at larger radii. In such cases, the amount of internal energy is less and therefore strong photospheric emission is not expected \[90\]. This scenario do fit with the observations where the blackbody emission is only 1 to 10% of the total observed flux \[56\]. In such a scenario, the main radiative process would be synchrotron emission.

Thus, the two emission zone model predicts multiple components in the spectrum of GRB: blackbody from the photosphere; and non-thermal component like the Band function (or synchrotron) from the optically thin region. This is in agreement with quite a number of bright bursts that have been observed by Fermi like GRB100724B \[8\], GRB110721A \[56\], GRB130427A \[96\] etc and recently the sample analysed by Burgess et al. 2014 \[60\]. Another important point to note is that the bright bursts observed by Fermi are found to be incompatible with fits with Band function alone \[51\]. This increases the significance of multiple component spectral analysis. Also, it is found that the addition of a blackbody component considerably improves the fit statistic of the spectra of most of the bright bursts.

The various spectral shapes of the observed GRB spectra in this scenario, can be attributed to the relative strength of these two spectral components \[30\]. The ratio of non-thermal luminosity to thermal luminosity is given by

\[
\frac{L_{\text{ob}}^{\text{NT}}}{L_{\text{ob}}^{\text{Th}}} \leq \epsilon_d \epsilon_e \left(\frac{r_{\text{ph}}}{r_s}\right)^{2/3}
\]

(5.1)

where \(\epsilon_d\) is the fraction of kinetic energy that is dissipated and \(\epsilon_e\) is the fraction of dissipated energy that is converted into energetic electrons \[97\]. The ratio will give the relative strength of thermal component to the non-thermal com-
ponent, which can vary from burst to burst. Emission from the photosphere thus, may be manifested in various ways: i) If $r_{ph}$ is closer to $r_s$, it can result in a prominent Planck function. ii) If $r_{ph}$ is much above $r_s$, the thermal emission component will be relatively weaker and can result in a subdominant blackbody component (less dominant Planck function) in the GRB spectrum.

Thus, different combinations of the various manifestations of the thermal component coming from the photosphere with the non-thermal components originating from the optically thin region, can produce a large variety of spectral shapes, see also [98].

Figure 5.1: A schematic diagram of a two emission zone photosphere model depicting $r_{ph}$ (photosphere) and $r_d$ (dissipation region), the two zones of emission.

(b) **Single emission zone model** where the entire spectrum (including the multi-components) represents the emission coming from the photosphere. In such a case, the broadening observed from that of a Planck function may be due to subphotospheric dissipation [9] [61] or geometrical broadening effects [64]. If this broadening is produced due to subphotospheric heating, the evolution of the spectra has to be attributed to the dissipation of the kinetic energy of the plasma in the subphotospheric regime. The mechanism of dissipation is still a matter of debate. The leading options are i) internal shocks (where the shells with different Lorentz factors collide with each other) [99]; ii) oblique shocks [63; 100]; iii) collisional dissipation in the flow [101; 102] and iv) Poynting flux dominated flows (where the dissipation can be caused due to magnetic reconnection) [103; 104]. In such a case, the observed shape of the spectra indicates the kind of subphotospheric dissipation profile. The presence of spectral breaks other than the main power peak suggests that the dissipation is localised at some region below the photosphere [Paper IV]. If the dissipation of the kinetic energy of the outflow occurs continuously radially until the photosphere, then the spectral breaks would be smeared out and the observed spectrum would be smooth like a single Band function [101; 105].

Dissipative photospheric emission model considers the entire prompt emission extending from keV to MeV to come from the photosphere of a relativistic outflow. The subphotospheric dissipation taking place at moderate optical
depths, $\tau$, can result in a spectrum that is much broader than a Planck function. The comptonisation of the seed thermal photons entrained in the outflow, by the high energy electrons will give rise to the high energy tail of the spectrum. With strong magnetic fields, there would be strong synchrotron emission and this would result in significant low energy emission which broadens the subpeak spectrum. Thus, the overall spectrum would look more broader than a Planck function and thereby non-thermal in nature. The resultant spectral shapes of photospheric emission with subphotospheric dissipation can be complicated depending on various factors like burst luminosity, optical depths, fraction of the kinetic energy that is dissipated, $\epsilon_d$, and the fraction of dissipated energy that goes into electrons, $\epsilon_e$ and into the magnetic fields, $\epsilon_B$.

Recently, Axelsson & Borogonov 2015 [6] found that 78% of the observed GRB spectra are narrower than the synchrotron emission from the most narrow electron distribution. A possible explanation for such observed spectra could be the emission from the photosphere, that is broadened via subphotospheric dissipation, since it is difficult to invoke situations in the optically thin region where the spectrum produced via non-thermal processes like optically thin synchrotron emission, whose spectrum has a large curvature, be narrowed such as to fit the observed narrow GRB spectra, however see also §5.2.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{diagram.png}
\caption{A schematic diagram of single emission zone of photosphere model depicting subphotospheric dissipation occurring at $r_d$ below the photosphere, $r_{ph}$, the zone of emission.}
\end{figure}

In contrast to all the different observed spectral shapes mentioned in §2.3, the GRB spectra in general are described by a Band function alone. For e.g. in the time integrated spectrum of GRB080916C, the Band function, found at low energies, fit the entire spectral data even extending to GeV [49]. A characteristic signature of the emission from the photosphere is a cut off at energies $> 100$ MeV due to pair production. Therefore, the observation of photons with energies above several GeV coming from the same component as at lower energies poses a challenge for photospheric emission to explain the spectra [106]. On the other hand, we note that the data analysis in certain
time bins of the spectra by initial studies had indicated the presence of extra power law (PL) component [49], however, recently Fermi LAT collaboration [51] have confirmed that an additional PL is indeed required at a significance of $4 - 5\sigma$. This suggests that an emission site accounting for optically thin emission may be present, which produces such a power law in the high energy emission. It is therefore suggestive that the spectra of GRB080916C can be modelled with multiple components [98; 107], in which case the photospheric interpretation of the emission $< 100$ MeV is not contradicted. Beloborodov 2010, 2011 [101; 105] have showed that continuous dissipation of the kinetic energy of the outflow till the photosphere radius would result in a smooth single Band function like spectrum and spectral features such as breaks would not be observed as they would get smeared out with the effect of continuous dissipation radially.

In addition to the Band function and BB defining the main part of the spectrum within the photosphere model, it is found that a third component power law is also required in certain bursts (e.g. GRB080916C [51]; GRB090902B [50]; GRB110920A [Paper IV]). It is found that power law extends over a very wide energy range, sometimes extending from very low energies (even before the Band function or BB) to very high energies. The need of a power law component in these energy ranges clearly suggest that spectrum is complicated. It is difficult to ascertain if it is the same component that is observed in the lower energies as well as at higher energies, as the component gets masked in between. From a theoretical point of view, to describe a physical process giving rise to a radiation that extends over a wide energy range (nearly 5 decades) is quite difficult. At the same time, it is important to note that power law is only the most simplest way to model the spectra at those energies due to the limited window of observation as well as data. In reality, the spectra might be of more complicated shapes. The power law extending into the high energies clearly signify that it does not originate from the photosphere and that it might be related to an external origin. This then raises the question what gives rise to the power law emission that is observed at lower energies ($< 10$ keV) [97]. Thus, spectral analysis with the proposed GRB models should be carried out in order to understand the physical origin of the power law component observed in lower and higher energies within the window of observation.

5.2 Model comparison and complications in interpretation

In order to have a clear comparison between the two photosphere models, from an observational point of view, I studied the burst GRB110920A within both the scenarios.

In Paper IV, I presented the spectral analysis of the data of the burst with the
model Comptonisation + power law which represents the photospheric emission including subphotospheric dissipation (one emission zone model). The key results and some of the key issues that need to be addressed are the following:

i) The $\nu F_\nu$ peak of the spectrum is very narrow and is found to become narrower with time and reaches a narrowness as that of a blackbody, which makes this burst an extreme case of narrowness, see Figure 5.3. This observed narrowness is in contradiction to the expected broadness due to high latitude emission.

ii) The subphotospheric dissipation is localised and occurs close to the saturation radius through out the burst duration, see Figure 5.4.

iii) The dissipation occurs at a moderate optical depth, $\tau \sim 20$.

iv) A power law component is required in addition to the Comptonisation component which extends from low to high energies. It is unclear if that emission is a part of the photosphere emission or it comes from the optically thin region. If it corresponds to the optically thin emission, as discussed in the previous section it raises the question as to what could be such an emission process that can result in emission extending over a large energy range. Also, within the physical picture, it raises the question as to what accounts for this discretised dissipation events, one occurring close to the saturation radius and one occurring above the photosphere. Interestingly, we find this power law component to disappear after 100 s.

![Figure 5.3: The spectral width of the $\nu F_\nu$ peak decreases with time from $\sim 7$ to 3.6, approaching the width of a blackbody. [Paper IV]](image-url)
In Paper V, along with 7 other bursts, GRB110920A was analysed within a two emission zone model where the optically thin emission was represented by the synchrotron emission model. The key results are the following:

i) GRB110920A was one of the 5 bursts in the sample that was found to be consistent with the model: blackbody + synchrotron emission.

ii) Blackbody was found to be dominant, describing the $\nu F_\nu$ peak of the spectrum. Thus, the fact that $\nu F_\nu$ peak of the spectrum is very narrow is true.

iii) The synchrotron emission was found to be the emission from an uncooled electron distribution.

iv) This requires that the heated electrons as a result of dissipation need to either cool very slowly with respect to the dynamical time or the electrons can be fast cooling but with continuous reacceleration of the electrons such that the electron distribution looks uncooled.

v) The constraints are obtained on the magnetic field strength, $B$ and electron Lorentz factor, $\gamma_{el}$, see Figure 5.5 using the observational fit parameters such as the peak synchrotron energy, $E_{\text{sync}}$ and the Lorentz factor $\Gamma$ deduced using the blackbody fit values. If the electrons have to be undergoing slow
cooling requires large $\gamma_{el}$ ($10^4 - 10^7$). This means that only a small fraction of the electrons are accelerated if assuming internal shock scenario [108, 109].

vi) If the electrons are fast cooling, the $\gamma_{el}$ can be small however, then very large magnetic fields, $B$ are required. For fast cooling of electrons to be consistent with the attained uncooled electron distribution requires that the fast cooled electrons to be reaccelerated on a timescale equal to or less than the cooling timescale of the electrons. The detection of strong blackbody component suggests that the outflow is baryonic [106, 110] and baryonic shocks cannot maintain such reacceleration process of the same electrons as the shocked particles immediately leave the shocked zone and cool undisturbed [111, 112]. However, in a scenario of extended shocks where the shock is spread over a larger volume due to Rayleigh - Taylor instability, there can attain a balance between heating and cooling of electrons [113–115]. In such a case, the resultant $\gamma_{el}$ is a result of this balance and would be less than $m_p/m_e$ [93]. This in turn suggests that the magnetic field, $B > 10^4$ G, see Figure 5.5. These proposed possibilities of scenarios that can explain the observations need to be confirmed by, for instance, numerical simulations.

Thus, I find that both the photosphere models have their own share of problems in explaining the constraints obtained from observations. In addition to these, sometimes both the models are equally consistent with the data. I thus, illustrate the ambiguity in the interpretation of the data in such situations for e.g. in case of GRB081110A and GRB110920A. GRB081110A is one of the bursts in the sample analysed in Paper V where the data was found to be consistent with a synchrotron emission alone. However, the data also could be modelled using the Band function. Figure 5.6 shows the spectral fit to the time bin at the peak flux of the burst. The Band function fit is shown in orange and a synchrotron emission fit obtained from an uncooled electron distribution is shown in green. The shaded region depicts the uncertainty in the spectral shape related to both the models respectively. It is interesting to note that the Band function fit gives a spectral shape that is narrower at the full width half maximum (FWHM) of the $\nu F_{\nu}$ peak of the spectrum than the synchrotron function. Such a spectrum with narrow peak can be interpreted within a subphotospheric emission model which is not restricted by the fundamental curvature required by synchrotron emission. Thus, from a statistical point of view, it is difficult to ascertain which is the best model for the spectrum. In such cases, it is necessary to explore the physical scenario of each model and validate its constraints obtained from observations. Figure 5.6 also cautions the interpretation that a narrow spectrum (spectral width at FWHM) is inconsistent with synchrotron emission.

Elaborating this fact further, in Figure 5.7 I show the comparison between the spectral fits done to the spectrum of GRB110920A with the models: Comp-
Figure 5.5: The constraints obtained for $B\gamma_{el}^2$ from the equation 3.9 in three time bins: one before, at and after the peak photon flux are shown in black lines. The dependence of $t_{cool}$ on $\gamma_{el}$ is shown in blue lines. The dynamical time for different characteristic radii ($r_{ph}$, $10^{14}$ cm) and $t_{pulse}$ are shown with pink triangles. The red section of the lines shows the values of $B$ and $\gamma_{el}$ that result in $t_{cool} < t_{dyn}(r_d)$ for all allowed values of $r_d > r_{ph}$ i.e. the electrons always undergo fast cooling. The orange section of the lines shows the values of $B$ and $\gamma_{el}$ that will always result in $t_{cool} > t_{pulse}$ i.e electrons always undergo slow cooling. The black part of the lines represents the condition where the cooling of the electrons can be either fast or slow depending at which radius the dissipation occurs. $\tau_e \leq \tau_{tot}$ gives an upper limit on the $\gamma_{el}$ and thereby a corresponding lower limit on $B$, which is marked in green squares. The dash dot lines shown in grey on both the curves represent the forbidden parameter space of $B$, $\gamma_{el}$ and $t_{cool}$. [Paper V]

tonsionation + power law which represents subphotospheric dissipation including localised dissipation, shown in pink (Paper IV) and blackbody + synchrotron emission representing the two emission zone model (Paper V), shown in green. This figure clearly shows that two different models give two different spectral shapes of the model. This is because of the forward folding method of spectral analysis. From a statistical point of view we find the one emission zone model to be a better model. However, since the models are not nested and have different physical motivations, the statistical comparison is highly indecisive. This again points out the requirement that both observed behaviour of the models and their constraints need to be validated within their respective physical scenarios. This in turn requires the existing GRB theories to have precise predictions regarding the temporal behaviour of their models which can then
Figure 5.6: The spectral fit to the time bin at the peak flux of the burst GRB081110A, modelled using the Band function (orange solid line) and the synchrotron function (green solid line) alone are shown. The related shaded regions, shown in orange and green, depict the uncertainty in the spectral shape when modelled using the Band function and the synchrotron function respectively. The Band function results in a spectral shape that is narrower at the $\nu F_\nu$ peak than the synchrotron function. [Paper V]

be validated by observations and numerical simulations.
Figure 5.7: The spectral fits of the models: two blackbodies + power law (pink solid line) and blackbody +synchrotron emission (green solid line), to the time bin at the peak flux of GRB110920A is shown. The spectral shapes resulting from the two models are clearly different. The shaded regions depict the uncertainty in the spectral shapes of the respective models. [Paper V]
6. Summary

The analysis of GRB spectra in the pre Fermi era using non-thermal models experienced difficulties to explain some of its key features such as hard low energy slopes, efficiency of burst. This lead to a natural alternative, the photosphere model which is inherent in the fireball scenario. The analysis of BATSE observed GRB spectra with thermal emission gave satisfactory explanations for the low energy spectral slopes, efficiency of the burst and clustering of energy peaks. But the observations done by BATSE in a narrow energy range could not lead us to firm conclusions on this model as well as the overall shape of the GRB spectrum. With the launch of Fermi, this drawback has been overcome by introducing observations over a broader energy range (8 keV - 300 GeV).

In the recent Fermi observations, there have been bursts whose spectra could be well modelled using a blackbody alone. This is in addition to other observations where blackbody component has been identified as a part of the observed GRB spectrum. Thus, to summarise the problem: over 0.3% of the observed GRB spectra are consistent with blackbody alone and recently, it was also shown that 78% of the observed GRB spectra are narrower than a synchrotron function produced from the most narrow electron distribution. This raises the question as to how can we explain the observed GRB data? This can be made possible within the photosphere model, with two kinds of scenarios: a) one emission zone model where the dominant emission of the observed GRB spectrum comes from the photosphere alone and b) two emission zone model where the photospheric emission forms only a part or a dominant part of the observed GRB spectrum and the non-thermal emission comes from the optically thin region.

In this thesis, Paper I presents the spectral analysis of the burst GRB110721A. The highest ever peak energy of 15 MeV was recorded for this burst which was made possible by the usage of LAT Low Energy (LLE) data. In the spectral analysis, we find a significant detection (5σ) of a blackbody component in the spectra and the time resolved spectrum has a double humped shape. The blackbody and non-thermal component of the spectrum show two distinct behaviours. In Paper II, within the two emission zone model, associating the detected blackbody to the non-dissipative photospheric emission, the outflow parameters of the burst GRB110721A: Lorentz factor, photospheric radius, sat-
uration radius and the nozzle radius of the jet are estimated and their temporal behaviour is studied. The parameters were found to exhibit a distinct evolution with time over a single pulse of GRB emission. Moreover, I conclude that three main flow quantities can describe the observed spectral behaviour in the burst: (i) the burst luminosity (ii) the Lorentz factor of the flow (or baryon load of the jet) and (iii) the nozzle radius of the flow. In Paper V, this study was extended to 5 single pulsed GRBs and the temporal behaviours of the parameters were indeed found to be common in nature. The results are the following: Lorentz factor of the outflow decreases monotonously with time and its value lies between 1000 and 100. The photospheric radius instead either remains nearly steady or shows a gradual increase with time and is generally of the order of $10^{12}$ cm. The nozzle radius of the jet increases with time from close to the black hole event horizon radius ($10^6 - 10^7$ cm) to a radius of the order of $10^8 - 10^9$ cm which can be associated to the stellar core of the Wolf-Rayet progenitor star. In Paper III, the theory for how to derive the outflow parameters for finite winds including the scenario where the photosphere forms in the accelerating regime of the outflow is developed. As a case study, the method was applied to the burst GRB090902B. During the first epoch of the burst (0 - 12.5 s), we found that the photosphere is indeed formed in the accelerating phase however during the second epoch (12.5 - 25 s) the photosphere moves into the coasting phase of the outflow.

Analysing some of the key bursts wherein significant photospheric emission was detected showed that the GRB spectral shape can be very narrow (e.g. GRB090902B or blackbody alone) or double humped shape wherein the blackbody forms a shoulder to the main spectral peak. In Paper IV, we identify a top-hat shape spectrum in case of the burst GRB110920A which could be interpreted within the photospheric emission including localised subphotospheric dissipation at moderate optical depths, $\tau \sim 20$. Such a shape is presented as a missing link between the observed very narrow and double humped spectral shapes. Thus, the scenario of localised subphotospheric dissipation brings to the conclusion that these different observed spectral shapes can be produced depending on two main factors: a) how much of the kinetic energy of the outflow is dissipated and b) with respect to the saturation radius, where in the outflow the dissipation occurs.

In Paper V, a sample of 8 single pulse GRBs whose spectra are fit with two emission zone photosphere model: blackbody + optically thin synchrotron emission is studied. For majority of the spectra, synchrotron emission is consistent only if the jet photospheric emission forms a significant part of the spectrum. The synchrotron emission that is found to fit the spectrum comes from an uncooled electron distribution and the data clearly rejects the typical fast cooled synchrotron emission from impulsive heating, due to its broad
curvature. Using the photospheric component, we estimate the outflow parameters which in turn enables us to constrain the plausible parameter space of the magnetic field strength and the electron Lorentz factor. If the electrons cool infinitely slowly with respect to the dynamical time of the event of the dissipation, then the electron Lorentz factor should be $10^4 - 10^7$. This is much higher than what is typically considered for e.g in case of internal shocks $\sim m_p/m_e$. This suggests that only a small fraction of the electrons are accelerated. If the electrons cool fast with respect to the dynamical time, it then requires that the electrons are continuously reaccelerated on a timescale faster than the cooling timescale such that the electron distribution appears uncooled.

Thus, within one emission zone model, in order to explain the observed spectrum with several breaks requires localised dissipation at moderate optical depths and along with that sometimes needs to have an extra power law component which can be associated to the non-thermal emission coming from the optically thin region. On the other hand, within a two emission zone model, the synchrotron emission coming from the optically thin region requires large electron Lorentz factors which are not naturally expected. Thus, finally, comparing both the photosphere models, we come to the conclusion that both the models have their own share of problems in justifying the constraints obtained from observations. In addition to this, there also exists the ambiguity in finding which is the best model to the GRB spectrum. Spectral fitting using physical models is indeed the step forward in analysis and further understanding of GRB spectra. However, from a statistical point of view, it is possible that the determination of the best model to the spectrum becomes indecisive. This therefore requires the spectrum to be analysed and explored within each physical model and thereafter, the constraints obtained from observations to be validated, for instance, by numerical simulations. This in turn also requires clear temporal predictions from GRB theories regarding the behaviour of the physical models.

Thus, while presenting the pros and cons of both the photosphere models, based on the analysis in the thesis, I consider the one emission zone photosphere model i.e the subphotospheric dissipation model, to be the most likely dominant underlying radiation mechanism giving rise to the observed variety of GRB spectra. This is mainly because the subphotospheric dissipation model can incorporate all different types of GRB spectral shapes, varying between very narrow, top-hat, double humped and even very broad smooth Band function like shapes. At the same time, it is more tenable to have dissipations of the jet energy below the photosphere due to oblique shocks such as ones produced while the jet pierces through the star as observed in recent numerical simulations like López-Cámara et al. 2013 [116], Zhang et al. 2003 [117] and also see Lazzati et al. 2015 [118]. Moreover, the problems with the needed particle
acceleration in the two emission zone model are theoretically very challenging. However, the subphotospheric dissipation model needs to be confirmed firmly by future spectral fittings using the physical model of subphotospheric dissipation when applied to a larger sample of GRBs as well as by the numerical simulations investigating the cause of subphotospheric dissipation.
Sammanfattning

För cirka 40 år sedan upptäcktes enorma kosmiska utbrott av gammastrålning, gamma-ray bursts (GRBs). Sannolikt rör det sig om processer i samband med att svarta hål bildas vid gravitationell kollaps av ovanligt tunga stjärnor. I dessa processer formas relativistiska plasmautflöden som ger upphov till de observe- rade gamma-strålarna.

Denna avhandling behandlar frågan om hur strålningen som observeras från GRBs uppkommer och hur man med hjälp kan den kan förstå mer om plasmautflödets egenskaper. Arbetet baseras sig på observationer gjorda med rymdteleskopet Fermi gamma-ray space telescope.

Det relativistiska utflödet har en fotosfär från vilken strålning emitteras. Jag har visat att fotosfären spelar en viktig roll för hur energispektrumet av de observerade fotonerna kommer att se ut.

Med hjälp av den fotosfäriska strålningen har jag bl.a. beräknat utflödets egenskaper och jag har utvecklat metoden för hur dessa beräkningar skall göras i det generella fallet.

Hur fotosfären påverkar det observerade spektrumet skiljer sig åt mellan olika GRBs. En viktig faktor är hur mycket energi som dissiperas i områden under fotosfären. Komplexa spektrala former kan då uppkomma och jag har visat hur en sådan analys kan förklara hela händelse förloppet hos GRB110920A.
Openness means no conclusions - simply looking at everything the way it is.

Sadhguru Jaggi Vasudev
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