Magnetically Powered Gamma-Ray Bursts

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Chapter 1

Introduction

1.1 Observations

Approximately once a day satellites detect short flashes of \( \gamma \)-rays, called \( \gamma \)-ray bursts (GRBs), at random positions in the sky which outshine all other sources of \( \gamma \)-rays combined, including the sun. Until today, over 30 years after their discovery (Klebesadel et al. 1973), the origin of GRBs remains unexplained in large parts. Due to progress in observations and theory in the past years the over one hundred models considered as possible in the early 90's (Nemiroff 1994) boiled down to only a few. But no theory is still generally accepted, what makes GRBs to one of the greatest challenges for modern astrophysics.

1.1.1 Prompt emission

From the several thousand bursts which have been observed and localised in the past one can draw some fundamental conclusions. The isotropic spherical distribution of bursts (Fishman & Meegan 1995; Fishman 1999; Paciesas et al. 1999) rule out that GRBs are associated with objects in the Galactic plane or halo. The number distribution function of total received energies tells us something about the distribution in space. Under the simplifying assumption that GRBs are standard candles the flux distribution function hints toward cosmological source distances since the distribution does not resemble that of a homogeneous source distribution in Euclidian space (Meegan et al. 1992).

GRB light curves in \( \gamma \)-rays show a large variety. They can be chaotic with lots of narrow emission peaks or also rather simple as displayed in figure 1.1. No burst is like the other. The shortest observed variability time scale is approximately \( \delta T \approx 1 \text{ ms} \) (Bhat et al. 1992; Walker et al. 2000).

Bursts occur in at least 2 different types, distinguished by their burst duration (shorter or longer than 2s) and spectral hardness (Kouveliotou et al. 1993). Unfortunately, obtaining precise locations has so far been only possible for long bursts. Thus, most information about GRBs, especially those from afterglow observations (see next section), apply only to the class of long bursts.

A typical energy spectrum of a GRB is displayed in figure 1.2. The shape is clearly non-thermal but resembles two smoothly linked power law components (Band et al.
Figure 1.1: Example light curves of GRBs for photon energies > 20 keV. The left panel shows the irregular, chaotic curve of BATSE burst 1676 with peak widths of ~ 1 s. The right panel displays a light curve of simpler shape where the typical variability time scale is of the order of the total burst duration. Both graphs are taken from the BATSE archive (http://f64.nsstc.nasa.gov/batse/grb/lightcurve/).

Figure 1.2: Example of a time integrated spectrum of the bright GRB 910503 obtained by the Compton Gamma Ray Observatory (Schaefer et al. 1994).
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The peak of the $\nu F_\nu$-function, where most of the energy is received, lies typically at a few hundred keV (Mallozzi et al. 1995). Only a small fraction of the total prompt emission energy is detected at low photon energies $E < 10$ keV. The spectra of some bursts extend up to GeV energies (Hurley 1994; Schneid et al. 1995; Fishman 1999).

1.1.2 Afterglows

Besides the ‘prompt’ emission observed mainly in the $\gamma$-ray range radiation can be detected for a much longer time at lower energies ranging from X-rays to the radio band. In 1997 thanks to the Italian-Dutch satellite BeppoSAX it became possible to detect this afterglow of a GRB at optical, soft X-ray and radio wavelengths (van Paradijs et al. 1997; Costa et al. 1997; Frail et al. 1997). The Wide Field hard X-ray Cameras (WFCs) aboard this satellite were able for the first time to locate GRBs precisely enough to allow finding counterparts at other wavelengths. Optical afterglows are associated with distant galaxies which are interpreted to be the host galaxies of the GRBs. Recent observations show that the afterglow, at least in the X-ray band, starts immediately after or even overlaps with the prompt burst (Giblin et al. 1999; Frontera et al. 2000; Tkachenko et al. 2000). For a comprehensive review on afterglows see van Paradijs et al. (2000).

While X-ray afterglows are detected in almost all follow-up observations of long bursts (Costa et al. 1999) only about half of these GRBs show afterglows in the optical range. This may be caused by absorption due to dust (Groot et al. 1998). Optical observations start usually within one day after the $\gamma$-event. As time proceeds the afterglow emission evolves from short to long wavelengths until it reaches the radio band (van Paradijs et al. 2000; Pian 2001).

Observations of absorption lines in optical afterglows due to absorption by the interstellar medium in the host galaxies reveal the redshift (and distance) of GRBs. The host’s distance is also estimated by investigating the emission features or the colour of the galaxy light. The about 20 redshifts determined up till now lie between $z = 0.4$ and $4.5$ (Greiner 2002) [except for the case of GRB 980425 which likely was associated with SN 1998bw in the spiral galaxy ESO 184-G82 at 45 Mpc distance ($z = 0.008$, e.g. Galama et al. 1998), but was intrinsically about three orders of magnitude weaker than the bursts at cosmological distances] These findings gave the final proof that GRB happen at cosmological distances.

Knowing the distance one can derive the absolute luminosity of bursts. Assuming that the emission is isotropic, the GRBs with known red-shifts indicate that $3 \times 10^{51}$ - $2 \times 10^{54}$ erg (Bloom et al. 2001) are released as prompt emission. Investigations of the the afterglow light curve shapes show that the outflow is jet-like, which lowers the total energy released (Kulkarni et al. 1999; Sari et al. 1999). Recent analysis of a sample of afterglow light curves yields total released energies clustering around $\approx 5 \times 10^{50}$ erg (Frail et al. 2001).
1.2 Implications for γ-ray burst models

1.2.1 Relativistic outflows

From the basic observational properties some stringent conclusions can be drawn. One identifies the shortest observed time scale in GRB light curves $\delta T_{\text{obs}}$ with the extent of the central energy source. A variation time scale $\delta T_{\text{obs}} \approx 1 \text{ ms}$ corresponds to an object size not more than $c \cdot \delta T_{\text{obs}} \approx 300 \text{ km}$. Only compact objects like neutron stars and black holes (BHs) are small enough to allow high energy processes on these short time scales.

From the received radiation energy one can calculate the radiation energy density in the vicinity of the GRB engine, if it were a static object. The inferred high energy density would lead to a very rapid creation of thermalized pairs (Cavallo & Rees 1978; Piran & Shemi 1993). A fireball forms in which the total energy density is extremely large. The optical depth of such a fireball would be huge (Guilbert et al. 1983; Carrigan & Katz 1992; Piran 1999) which would lead to a thermal radiation spectrum. At these optical depths all photons with energies $> m_e c^2$ degrade to create pairs. But because high energy photons and non-thermal spectra are observed, GRB radiation cannot come from optically thick fireballs. This issue, called the compactness problem, was addressed early (Ruderman 1975; Schmidt 1978) and was used initially as an argument against the cosmological origin of GRBs.

The compactness problem is solved if the emitting material is streaming ultra-relativistically towards the observer. Ultra-relativistically moving matter emits radiation within a narrow cone around the direction of motion with opening half-angle $\theta \approx 1/\Gamma$ where $\Gamma$ is the Lorentz factor. The collision angles for photons are reduced which lowers the probability for pair creation and the optical depth. Also, the relativistic Doppler effect lets the emission time interval appear shorter by the factor $2\Gamma^2$ to a stationary observer. Thus the emission time in the restframe of the emitting plasma is longer than the time obtained from the variability time scale. This allows the radiation to originate from a larger spatial region without being contradictory to a central engine's extent of $c \cdot \delta T_{\text{obs}}$.

A large Lorentz factor alleviates the compactness problem by both effects. A detailed analysis of this topic (Fenimore et al. 1993; Woods & Loeb 1995; Lithwick & Sari 2001) reveals that the required Lorentz factor must be of the order $\Gamma \gtrsim 100$. The outflowing material radiates while it travels outward. But the time interval in which this happens is observed highly compressed due to the extreme Doppler effect at these Lorentz factors. It contributes only little to the variability of the source. The variability observed is thus the variability of the central engine itself (up to effects of the cosmological redshift).

1.2.2 Energy transport and conversion into radiation

The GRB central engine injects energy into a small region which produces a ultra-relativistic outflow (Goodman 1986; Paczyński 1986). The energy is carried from
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the engine to larger radii where the flow becomes optically thin and where the non-thermal radiation is produced. The adiabatic expansion of the medium converts part of the energy into kinetic energy. This is especially true if the fireball is contaminated by only few baryons (Shemi & Piran 1990; Paczyński 1990). The opacity is much higher due to the non-annihilating electrons. As a result the thermal energy is almost completely converted into kinetic energy of the baryons. Thus many GRB models assume that the energy is transported outward by kinetic energy flux.

Since most of the energy of the engine appears to be converted into $\gamma$-radiation, an efficient mechanism is needed to convert kinetic energy into non-thermal radiation. This is a key aspect of a GRB model. One way of achieving such conversion is through shock waves. The GRB outflow might plough into the ambient, external medium creating an external shock (Rees & Mészáros 1992). Based on this model the afterglow was predicted successfully in the radio (Paczynski & Rhoads 1993), optical (Katz 1994; Mészáros & Rees 1997a), and X-ray bands (Vietri 1997) and there is now consensus that external shocks power the afterglow.

The complex GRB pulse profiles are not easily explainable by external shocks. Instead, internal shocks among shells of outflowing matter can explain the light curves (Rees & Mészáros 1994; Sari & Piran 1997a; Daigne & Mochkovitch 1998). But internal shocks are not very efficient in converting the kinetic energy back into radiation. If the Lorentz factor varies by a factor of a few, the efficiency is only of the order of 1% (Kumar 1999; Panaitescu et al. 1999; Lazzati et al. 1999; Spada et al. 2000). To be efficient the Lorentz factors must vary by several orders of magnitude (Beloborodov 2000; Kobayashi & Sari 2001). Otherwise most of the energy stays in kinetic form and powers the afterglow in the external shock. This contradicts the observations that the prompt emission energy is comparable or larger than the energy in the afterglow. Models exist which also explain the variable prompt emission by an external shock (Dermer & Mitman 1999). However, Sari & Piran (1997b) demonstrated that a single release of energy by the central engine can only produce smooth, single peaked light curves. This difficult issue remains unsettled.

The obvious alternative to transport the energy outward is by electromagnetic fields. A plasma-loaded Poynting flux is able to accelerate the flow and transport energy into the optically thin domain. There, the energy can be converted efficiently into radiation by magnetic reconnection processes. The main part of this thesis deals with this scenario.

1.2.3 Energy release by the central engine

The proposed solution of the compactness problem predicts the existence of an ultra-relativistic outflow from a compact central engine. The prompt emission must originate from an optically thin region at a certain distance away from the central engine. The required large Lorentz values forces the total energy density to be much larger than the rest mass energy of the matter involved in the flow. A central question arises: what physical mechanism produces this baryon-poor ultra-relativistic outflow? What is the central engine? These questions are hard to answer since we
found that the radiation does not come from the hidden engine itself. Instead one has to deduce its nature from the outflow it generates.

The collision and coalescence of two neutron stars releases $\approx 5 \cdot 10^{53}$ erg of gravitational binding energy (Clark & Eardley 1977), enough to power a GRB. The existence of such merger events was proven by the observation of the famous binary pulsar PSR 1913+16 (Hulse & Taylor 1975; Taylor & Weisberg 1982). This system loses angular momentum and energy by gravitational waves so that the neutron stars must ultimately merge. The estimated rate of mergers per galaxy is comparable to the rate for GRBs (Piran 1992; Cohen & Piran 1995; van den Heuvel & Lorimer 1996). This makes the coalescence scenario a popular model for the GRB central engine (Paczynski 1990; Eichler et al. 1989; Mészáros & Rees 1992a,b; Narayan et al. 1992). But double neutron star mergers show problems in some other respects. Most of the binding energy escapes as neutrinos (Clark & Eardley 1977) and only a small fraction (Eichler et al. 1989) can annihilate $\nu \bar{\nu} \rightarrow e^+e^-$ to produce a fireball. Numerical calculations validate this statement and also indicate a high baryonic pollution (Ruffert & Janka 1999, 2001). A too high mass loading prohibits the outflow to attain the required large Lorentz factors. Furthermore, the energy release happens in one pulse within 0.1–1 s and is unable to produce a large variability.

There are a couple of other models based on the release of gravitational binding energy. Some involve the core collapse of a massive and rotating star to a BH around which a torus of accreting material forms. Such a scenario is called 
failed supernova
(Woosley 1993), hypernova (Paczyński 1998) or collapsar (MacFadyen & Woosley 1999). Fryer et al. (1999) describe some stellar evolution paths which lead to possible progenitors for this scenario. The term supranova Vietri & Stella (1998) describes the implosion of a supra-massive neutron star which has lost its centrifugal support and collapses to a BH with remnant torus. All these models involve an accreting massive torus around a BH. The GRB energy is gravitational and rotational energy of the torus and might also contain rotational energy of the BH extracted by the Blandford & Znajek (1977) mechanism. If the accretion happens within the stellar envelope the energy might be funnelled into a jet along the rotation axis and collimated by the surrounding matter.

A gravitational collapse primarily leads to the conversion of gravitational binding energy into thermal energy. If the rotation of an object is around its maximal breakup value, as it is the case in the BH-torus models above, the rotational energy is comparable to the gravitational binding energy. The rotational energy is also fed by gravitational energy if the objects contracts. This rotational energy reservoir can be tapped by an electromagnetic field. A magnetic field at the surface exerts magnetic stresses which extract rotational energy and drive an outflow of Poynting flux. The physics of this mechanism constitutes a large part of this thesis and is further discussed below in section 1.3. A large magnetic field in an accreting torus is naturally generated by the differential rotation. The magnetic field is wound up and amplified to a field strength at which it becomes buoyant. Emergence of the field at the surface creates a magnetic rotator, leading to the extraction of the rotational and binding energy and the generation of a Poynting flux (Narayan et al. 1992; Thompson
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1994; Mészáros & Rees 1997b; Katz 1997; Wheeler et al. 2000). Since the energy does not get converted into neutrinos such rotationally driven engines are potentially more efficient.

The Poynting flux luminosity is proportional to the square of the magnetic field strength at the source surface and the third power of rotation rate. In order to qualify for a GRB central engine and the production of a required luminosity, models have to supply a high enough rotation energy in addition to the large magnetic field and the fast rotation rate. Besides the BH-torus models there exist alternatives explaining how other objects can evolve to fulfil all three of the conditions listed. A collapsed white dwarf possesses a sufficiently high rotational energy to power a GRB. If the star accretes matter in a binary system until it exceeds the Chandrasekhar limit, it might collapse to a neutron star, which amplifies the magnetic field and the rotation rate significantly (Usov 1992, 1994; Ruderman et al. 2000). This would produce a source with a powerful Poynting flux. Another proposed scenario is a spun-up neutron star in a X-ray binary system (Spruit 1999). In this scenario differential rotation winds up an internal magnetic field to a critical field strength so that it becomes buoyant and emerges abruptly from its surface.

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A rotating non-axisymmetric magnetic field emits energy and angular momentum through an electromagnetic field in vacuum. For stellar objects the electromagnetic field is plasma loaded and magnetohydrodynamic (MHD) effects allow even axisymmetric rotators to lose angular momentum by MHD winds. The rate of angular momentum loss is similar in both cases. The magnetic field is usually modelled to consist of open field lines running from the stellar surface to infinity and a region of closed field lines. The field slings the plasma along its open field lines. The matter must be initially lifted a bit from the stellar surface by thermal pressure or centrifugal forces but is then accelerated by MHD forces in the direction of rotation so that it tends to corotate. Though this corotation is not strict and gets weaker at larger distances from the star, the matter flow is accelerated in azimuthal direction and thus gains energy and angular momentum. This angular momentum is extracted from the central object by magnetic stress.

This model of a centrifugally driven stellar wind is quite old in astronomy. It was first applied to the solar wind by Weber & Davis (1967) and Mestel (1968). The Sun is a slowly rotating star with a rather small magnetic field on its surface so that the outflow is mainly driven by the thermal energy. It is therefore not the best example for magnetically driven wind. But for rapidly rotating stars with a stronger magnetic field the picture changes (Belcher & MacGregor 1976). In this case the sling-shot mechanism supplies most of the energy to the outflow. Near the surface, where velocities are low, the Poynting flux carries almost all the wind energy, while the kinetic energy flux of the matter constitutes only a small fraction. In this case the outflow is called Poynting flux dominated. Pulsars are the best example for the
electromagnetic extraction of rotational energy. Due to the precise period timing one can observe the slowing down of the neutron star and can thus infer the energy extracted.

The total energy being extracted from a rotating object depends on the rotation rate and the magnetic field strength on the surface. For application to GRBs it is essential to explain both the acceleration to large Lorentz factors of $\Gamma \gtrsim 100$ and the radiation. The processes must be efficient, such that the total energy needed does not exceed the total energy supplied by standard models as discussed in section 1.2.3.

Synchrotron radiation is commonly assumed to play an important role for the non-thermal radiation. In the context of the internal shock model the magnetic field needed is assumed to be generated locally by microscopic processes in the shock (Mészáros & Rees 1993; Wijers et al. 1997; Thompson & Madau 2000). The energy density of the magnetic field must be on the order of the thermal energy density of the plasma for the radiation process to be sufficiently fast. These assumptions are not well founded and the physics of magnetic field generation by shocks is not clear. Other studies show that the field generated is weak and limited to a small region behind the shock (Gruzinov 2001). A large scale magnetic field carried along in the outflow would alleviate these problems and ensure short synchrotron cooling times (Rees & Mészáros 1994). All models involving a Poynting flux dominated outflow, including the one presented in this thesis, supply the magnetic field needed for the synchrotron radiation in a natural way.

1.3.1 Magnetocentrifugal acceleration of outflows

One of the things a magnetic field has to achieve in a successful GRB model is acceleration to a high Lorentz factor. There turn out to be two magnetic processes that help accelerate the flow. The first is centrifugal acceleration by the rotating magnetic field, the process invoked with great success for protostellar and AGN jets. The second is acceleration by an outward magnetic pressure gradient. This happens especially when there is internal dissipation of magnetic energy in the flow. It turns out that the second is by far the most important in the GRB context, but for historical reasons we start with the discussion of the centrifugal process.

Let us first regard the acceleration potential of a magnetocentrifugally driven outflow using ideal MHD. The general magnetic field structure is three-dimensional and time-variable, and the MHD interaction with the matter is extremely complicated. In the simplest approach a configuration with high symmetry is considered. For an axisymmetric configuration with aligned magnetic and rotation axes, called an aligned rotator, the outflow in the equatorial plane is stationary and axisymmetric in an idealised case. The field lines are assumed to be anchored at the stellar surface and extend to infinity. In addition, the streamlines are assumed to be straight in the poloidal plane which makes the problem one dimensional in space. This model is the classical one used for magnetic stellar winds. For an outflow which is non-relativistic everywhere, one finds rather simple limits. If the flow is Poynting flux dominated near the source, 1/3 of the Poynting flux is converted into kinetic energy flux (Belcher
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& MacGregor 1976). This may be regarded as ‘efficient’ since the kinetic energy flux is of the same order as the remaining fraction of Poynting flux.

Sadly, this promising result cannot be transferred to the case where the flow is relativistic from the beginning. In this case the flow’s Lorentz factor increases only weakly and the ratio of initial Poynting to kinetic energy flux remains almost constant. The energy simply stays in the form of an electromagnetic wave.

One has to note that the radial flow geometry in the poloidal plane is a very special case. In a real environment the flow shape is determined by the pressure exerted perpendicular to the flow direction. A flow in which the lateral pressure is balanced everywhere is not radial in the poloidal plane. Calculating a magnetised outflow self consistently in two dimensions is a great computational challenge. But one can investigate as a first step an outflow for a pre-given poloidal geometry.

Begelman & Li (1994) found that the poloidal flow geometry, that is the the shape of the flow lines in the meridional plane, determines the Poynting flux conversion for magnetically driven relativistic cold outflows. The flow geometry is not decisive at all radii but only at source distances where the flow is faster than the fast magnetosonic speed. The radius where the flow becomes faster than the fast magnetosonic speed is called fast point radius $r_{fp}$. From this radius on the Poynting flux is converted into kinetic energy if the flow lines diverge faster than in the radial case. To put it more precisely, if the crossection of a magnetic flux tube has the area $A$ at radius $r > r_{fp}$, the Poynting flux scales as $r^2/A$. Efficient conversion would happen if the flow passes through a kind of nozzle, and then were to expand beyond the fast point radius. In the relativistic case, only this rather special geometry allows for good Poynting flux conversion.

The magnetic field in the outflow is spiral-like. While at smaller radii the radial field component $B_r$ is important, the azimuthal component $B_\phi$ dominates at larger radii. This is due to the scaling $B_r \propto r^{-2}$, $B_\phi \propto r^{-1}$ at large radii. To understand why the geometry has such a large influence on the flow acceleration one can regard the field configuration neglecting $B_r$. Without thermal pressure of the matter, only the magnetic tension and the magnetic pressure gradient act on the flow along the radial unit vector $e_r$. For the outflow geometry considered the magnetic pressure acts outwards $-\nabla B^2/(8\pi) = e_r B^2/(4\pi r)$ while the tension force points into the opposite direction $(B \cdot \nabla)B/(4\pi) = -e_r B^2/(4\pi r)$, causing these force components to cancel exactly for $B \propto r^{-1}$. This is also true for other latitudes besides the equatorial plane. At smaller distances to the polar axis the tension force is greater due to the larger field curvature, but the projection on the radius vector compensates for that. Only a scaling which is different from $B \propto r^{-1}$ produces an unbalanced force component. This treatment at larger radii where the flow is super-fast-magnetosonic is intuitive and simple. At smaller distances the radial field component comes into play. This complicates the task to determine the flow and field geometry there and a purely intuitive treatment is hardly possible.

Since the geometry is the critical element in magnetocentrifugally driven outflows it is important to investigate the effects of general relativity. For GRBs, the central engines are assumed to be compact objects and the strong gravitational field near the
source might influence the outflow and the Poynting flux conversion. Frédéric Daigne and I investigated these effects by extending Sakurai’s (1985) elegant treatment of stellar winds to the general relativistic case. In chapter 3 it is shown that change in space time geometry due to general relativity is not relevant for the conversion of Poynting flux to kinetic energy flux. Still, the flow geometry at larger radii controls the Poynting flux conversion completely. We show there that the results of Begelman & Li (1994) also apply for relativistic outflows including thermal and gravitational effects.

Chapter 4 arose in an attempt to model equatorial outflows more self consistently. I investigate there how the flow geometry, and therefore the Poynting flux conversion, of non-relativistic stellar winds is influenced by an external static magnetosphere. This approach does not specify the flow divergence a priori but one needs some knowledge about the strength of the magnetosphere.

1.3.2 Dissipation by reconnection of magnetic fields: powering γ-ray burst outflows and radiation

In the previous discussion we assumed that ideal MHD applies. The assumption is quite reasonable if there are enough free electric charges in the plasma to sustain the needed currents. Then, resistivity and magnetic diffusivity can be neglected. On the other hand, if the density of charges cannot account for the needed currents, an electric field forms in the comoving frame and the magnetic field dissipates by plasma-physical processes, e.g. large amplitude electromagnetic waves (LAEMW). In the context of GRBs this situation might occur for a pure $e^\pm$-fireball since almost all particles annihilate (Usov 1994; Blackman & Yi 1998; Lyutikov 2001). For GRB parameters, however, one finds that even a very small baryon content suffices to provide enough charge carriers in the outflow to maintain the MHD condition throughout the relevant parts of the flow. This statement is substantiated and discussed in chapter 2 and 5.

Even if enough charges are present for the ideal MHD approximation in large parts of the outflow, magnetic fields can still dissipate by means of rapid reconnection (Petschek 1964; Parker 1979; Biskamp 2000; Priest & Forbes 2000). This happens if flow elements drag oppositely aligned magnetic fields towards each other. Even ‘harmless’ looking flows (smooth and relatively large scale) can mix up the field so fast that large field gradients develop and diffusion becomes important. This is especially the case in the collisionless plasmas occurring here, where so-called ‘anomalous resistivity’ is usually important. In the fractal reconnection volume where this happens the magnetic energy is released as thermal energy. The topological change of the field looks as if the field lines are cut and reconnected at different ends. For such a process to happen it is necessary that there are variations in the magnetic field direction on small length scales. Since these variations are produced naturally by a rotating non-axisymmetric magnetic field, dissipation of magnetic energy by reconnection is a viable idea for magnetised GRB outflows.

In chapter 2 the possible structure of the magnetic fields is studied. Time and
length scales for the physical processes in the outflow are estimated. Chapter 5 consists of a dynamic model of outflow driven by the release of dissipated magnetic energy. The description of the magnetic dissipation rate makes use of the fact that the rate of reconnection scales with the local Alfvén speed in the comoving medium. Since the typical scale of the small scale field variability is known (from the rotation rate of the central object and the outflow speed) one can model the mean time on which the magnetic field decays. From this an evolution equation for the magnetic field is derived. Together with the conservation of mass, energy and momentum for stationary relativistic MHD the system of equations is solved. In chapter 5 analytic approximations to these solutions are derived, using additional simplifying assumptions. These results already show the main qualitative behaviour of some physical properties at the photosphere and asymptotically at large distance, and identify the photosphere as a potentially interesting source of thermal radiation.

Finally, in chapter 6 the full stationary outflow solutions are computed numerically. The mass, energy, momentum and field evolution equations are rewritten as set of coupled ordinary differential equations. These are integrated numerically starting from small radii. The flow shows two distinct regions. In the optically thick regime the fluid is radiation dominated but still rather cold (cooled by adiabatic expansion in spite of the magnetic dissipation that is already setting in) and without pairs. At the photosphere the flow becomes transparent and thermal radiation escapes. There, fast cooling keeps the medium cool while the dissipating magnetic energy gets converted rapidly into non-thermal radiation. The magnetic pressure gradient leads to acceleration even in the optically thin domain until the dissipation ceases. This model predicts robustly a thermal component in GRB radiation. Also, X-ray flashes (Heise et al. 2001; Heise & in ’t Zand 2002), the probable soft counterparts to GRBs, are explained to be just the same kind of magnetised winds, but with a larger mass loading.

The magnetic energy released in the optically thin regime produces non-thermal radiation. The production of this radiation is efficient: asymptotically (at low baryon loading) half of the magnetic energy is transformed into non-thermal radiation (the remainder into kinetic energy). The reconnection process thus produces, at the same time, a very effective acceleration and efficient non-thermal radiation. Two major questions of the GRB mystery are thus answered by the model.

1.4 Summary of main results

In this section I summarise the highlights presented in this thesis:

- An elegant formulation for magnetocentrifugally accelerated outflows in general relativity was found in collaboration with Frédéric Daigne. The investigation showed that neither the influence of curved spacetime near the compact source nor the thermal pressure of the matter are important for the conversion of Poynting flux to kinetic energy flux. Instead, if the flow is relativistic from the
beginning only the shape of the flow lines at larger distances are crucial. This extends and verifies the findings of Begelman & Li (1992) which were found for cold flows without gravity influence.

- Non-axisymmetric rotating magnetic fields produce MHD outflows with wave-like spatial structure in which a considerable amount of magnetic energy is stored. This energy can be released by reconnection processes in the outflow. The magnetic field carried along with the matter enables the synchrotron process while its dissipation powers the acceleration of fast particles. This scenario evades the problem of generating magnetic fields locally in shocks as faced in standard internal shock models.

- The dissipation of the magnetic field proceeds as matter travels outward from the source. This produces a radial gradient in the magnetic pressure resulting in an acceleration of the flow. This acceleration is much more efficient than magnetocentrifugal acceleration.

- Dissipation in the optically thin domain of the flow converts half of the Poynting flux into non-thermal radiation. The other half accelerates the flow. For low baryon loading the dissipation takes place in the optically thin part of the flow. A Poynting flux-dominated flow from a non-axisymmetric rotator is thus at the same time an effective accelerator and an effective $\gamma$-radiator.

- The model yields robust flux estimates for the non-thermal and thermal radiation components as well as the apparent temperature of the latter. These quantities are in principle observable and can be determined by analysing GRB spectra. The model thus presents a diagnostic tool for the physical properties of the outflow near the source.

- The amount of baryon loading is the central parameter which determines the nature of the outflow. For a large loading all the dissipation takes place in the optically thick domain, leading to kinetic energy and little radiation. At intermediate values the thermal emission becomes energetically important (up to 15% of the total energy), and the expected radiation energy falls into the observed regime of X-ray flashes. The model shows that the same kind of outflow, but with different baryon loading, may be responsible for X-ray flashes, X-ray rich GRBs and regular GRBs.