Abstract: Being the most extreme explosions in the universe, gamma-ray bursts (GRBs) provide a unique laboratory to study various plasma physics phenomena. The complex light curve and broad-band, non-thermal spectra indicate a very complicated system on the one hand, but, on the other hand, provide a wealth of information to study it. In this chapter, I focus on recent progress in some of the key unsolved physical problems. These include: (1) particle acceleration and magnetic field generation in shock waves; (2) possible role of strong magnetic fields in accelerating the plasmas, and accelerating particles via the magnetic reconnection process; (3) various radiative processes that shape the observed light curve and spectra, both during the prompt and the afterglow phases, and finally (4) GRB environments and their possible observational signature.

Keywords: jets; radiation mechanism: non-thermal; galaxies: active; gamma-ray bursts; TBD

1. Introduction

Gamma-ray bursts (GRBs) are the most extreme explosions known since the big bang, releasing as much as $10^{55}$ erg (isotropically equivalent) in a few seconds, in the form of gamma rays [1]. Such a huge amount of energy released in such a short time must be accompanied by a relativistic motion of a relativistically expanding plasma. There are two separate arguments for that. First, the existence of photons at energies $\gtrsim \sim \text{MeV}$ as are observed in many GRBs necessitates the production of $e^\pm$ pairs by photon–photon interactions, as long as the optical depth for such interactions is greater than unity. Indeed, the huge luminosity combined with small system size, as is inferred from light-crossing time arguments ensures that this is indeed the case. Second, as has long been suspected and is well established today, small baryon contamination, originating from the progenitor—being either a single, collapsing star or the merger of binary, degenerate stars (e.g., neutron stars or white dwarfs) implies that some baryon contamination is unavoidable. These baryons must be accelerated for the least by the radiative pressure into relativistic velocities.

This general picture was confirmed already 20 years ago by the detection of afterglow—a continuing radiation that is observed at late times, up to weeks, months and even years after the main GRB, at gradually lower frequencies—from X-ray to radio [2–4]. Lasting for many orders of magnitude longer than the prompt phase, this afterglow radiation is much easier to study. Indeed, it had been extensively studied in the past two decades, after the initial detection enabled by the Dutch-Italian Beppo-SAX satellite.

Fitting the observed spectra shows a clear deviation from a black-body spectra. Instead, the afterglow of many bursts is well fitted by synchrotron radiation from a power law distribution of radiative electrons [5–7]; see Figure 1. The late time decay is well explained by the gradual velocity decay of the expanding plasma as it propagates into the surrounding medium. This decay is well-fitted (at late times) by the Blandford–Mckee self-similar solution [8] of a relativistic explosion (I ignore here...
the early afterglow phase which typically lasts a few minutes, as during this phase the decay does not follow a simple self-similar law, and is as of yet not fully understood).

**Figure 1.** X-ray to radio spectrum of GRB970508 taken 12 days after the event is well fitted by a broken power law, as is expected from a power law distribution of electrons that emit synchrotron radiation. Marked are the transition frequencies: the self absorption frequency $\nu_a$, the peak frequency $\nu_m$ and the cooling frequency $\nu_c$. This figure is taken from Galama et al. [9].

At the onset of the afterglow phase, the velocity of the expanding plasma is very close to the speed of light, with initial Lorentz factor of a few hundreds. This is greater than the speed of sound, $c/\sqrt{3}$, and as such necessitates the existence of a highly relativistic shock wave. The combined temporal and spectral analysis thus led to the realization that, at least during the afterglow phase, a relativistic shock wave must exist. This shock wave expands into the circumburst medium, and gradually slows down as it collects and heats material from it.

Interpreting the observed signal during the afterglow phase in the framework of the synchrotron emission model, one finds that the inferred values of the magnetic fields, $\lesssim 1$ G, are about two (and in some cases more) orders of magnitude stronger than the compressed values of the circumburst magnetic field [5,10,11]. This implies that, in order to explain the observed signal, the relativistic shock wave must be able to both (1) accelerate particles to high energies, producing a non-thermal (non-Maxwellian) distribution of particles; and (2) generate a strong magnetic field, which causes the energetic particles to radiate their energy via synchrotron emission.

Studies of the afterglow phase by themselves therefore lead to several very interesting plasma physics phenomena which are not well understood, and are at the forefront of current research. These include (1) the physics of relativistic shock waves, both propagation and stability; (2) particle acceleration to non-thermal distributions; (3) generation of strong magnetic fields; and (4) radiative processes that lead to the observed spectra.

However, the prompt phase of GRB is considered even more challenging. As its name implies, this phenomenon lasts only a short duration of time, typically a few seconds. As opposed to the afterglow phase, this stage is characterized by fluctuative, non-repeating light curve, with no two GRB light curves similar to each other. Furthermore, its spectra does not resemble neither a black body (Planck) spectrum, nor—as has been realized in the past decade—that of a synchrotron emission from
a power law distribution of electrons, as in the afterglow phase. Though the large diversity within the bursts prevented, so far, clear conclusions.

Another very challenging aspect is that the origin of the rapid acceleration that results in the relativistic expansion is not yet fully understood. While it was initially thought to occur as a result of the photon’s strong radiative pressure (the “fireball” model), in recent years, it has been argued that strong magnetic fields—whose origin may be associated with the progenitor(s), hence external to the outflow, may play a key role in the acceleration process. If this is indeed the case, the plasma must be magnetically dominated, namely $u_B \gg \{u_k, u_{th}\}$, where $u_B, u_k$ and $u_{th}$ are the magnetic, kinetic and thermal energies of the plasma, respectively.

Either way, the plasma in GRBs during its prompt emission phase is characterized by strong interactions accompanied by energy and momentum exchange between the particle and photon fields, and/or the particles and the magnetic fields. Combined with the different conditions during the afterglow phase, one can conclude that GRBs provide a unique laboratory to study various fundamental questions in plasma physics. These are related to the creation of magnetic fields, acceleration of particles, emission of radiation and the interaction between all these three fields. Furthermore, the relativistic expansion can lead to the developments of several instabilities in the expanding plasma, which, in turn, can affect the phenomena previously mentioned.

In this chapter, I highlight the current state of knowledge in these areas. I should stress that I limit the discussion here to plasma physics phenomena only; in recent years, there have been many excellent reviews covering various aspects of GRB phenomenology and physics, and I refer the reader to these reviews for a more comprehensive discussion on the various subjects. A partial list includes Atteia and Boër [12], Gehrels and Mészáros [13], Bucciantini [14], Gehrels and Razzaque [15], Daigne [16], Zhang [17], Berger [18], Meszaros and Rees [19], Pe’er [20], Kumar and Zhang [21], Granot et al. [22], Zhang et al. [23], Toma et al. [24], Pe’er and Ryde [25], Beloborodov and Mészáros [26], Dai et al. [27], van Eerten [28], and Nagataki [29].

Of the many plasma physics effects that exist in GRBs—some of them unique to these objects, I discuss here several fundamental phenomena which emerge directly from GRB studies. Due to the wealth of the subject, I can only discuss each topic briefly. In each section, I refer the reader to (some) relevant literature for further discussion. The topics I cover here include the following: acceleration of particles by relativistic shock waves are discussed in Section 2. Section 3 is devoted to magnetic fields. I discuss generation of magnetic fields by shock waves in Section 3.1, and their possible role during the prompt emission phase in Section 3.2. I briefly discuss the acceleration of particles in magnetically dominated outflow via reconnection of magnetic field lines in Section 3.3. I then discuss the radiation field, which plays a key role in GRBs in Section 4. I first introduce the “classical” radiative processes in Section 4.1 and then introduce the photospheric emission in Section 4.2. Finally, I very briefly consider the different environments into which GRBs may explode and their effects in Section 5 before concluding the paper.

2. Acceleration of Particles in Shock Waves

The idea that shock waves can be the acceleration sites of particles dates back to Enrico Fermi himself [30,31], and had been extensively studied over the years since [32–38]. The key motivation was to explain the observed spectrum and flux of cosmic rays. Fermi’s original idea suggests that particles are energized as they bounce back and forth across the shock wave. Its basic details can be found today in many textbooks (e.g., [39]).

In the context of GRBs, it was proposed in the mid 1990s that the relativistic shock waves that exist in GRB plasmas may provide the conditions required for the acceleration of particles to the highest observed energies, $\gtrsim 10^{20}$ eV [40–42]. While this idea is still debatable (e.g., [43]), the observations of $\gtrsim$GeV, and up to $\sim$100 GeV photons [44] during the prompt phase of several GRBs implies that very high energy particles must exist in the emitting region. While these particles can be protons, energetically, it is much less demanding if these are electrons that are accelerated to non-thermal
distribution at high energies. This is due to the lighter mass of the electrons, which implies much more efficient coupling to the magnetic and photon fields, and hence much better radiative efficiency. These energetic particles, in turn, radiate their energy in the strong magnetic fields that are believed to exist, as well as Compton scatter the photons to produce the very high energy photons observed.

Fitting the observed spectra of many GRBs in the framework of the synchrotron model (namely, under the assumption that the leading radiative mechanism is synchrotron emission by energetic electrons) strongly suggests that the radiating particles do not follow a (relativistic) Maxwellian distribution. Rather, they follow a power law distribution at high energies, \( \frac{dN}{dE} \propto E^{-p} \), with power law index \( p \approx 2.0 - 2.4 \) \([5,9,45–47]\). This power law distribution is exactly what is expected from acceleration of particles in shock waves within the framework of the Fermi mechanism (e.g., \([33–35,48]\)). Intuitively, the power law shape of the distribution can be understood as there is no characteristic momentum scale that exists during the acceleration process, implying that the rate of momentum gain is proportional to the particle’s momentum.

The power law index inferred from observations is close to Fermi’s original suggestion of 2.0. This is surprising, given that the shock waves in GRBs both during the prompt (if exist) and afterglow phases must be relativistic, while Fermi’s work dealt with ideal, non-relativistic shocks.

In fact, the situation is far more complicated. Despite many decades of research, the Fermi process is still not fully understood from first principles. This is attributed mainly to the highly nonlinear coupling between the accelerated particles and the turbulent magnetic field at the shock front. The magnetic field is both generated by the energetic particles (via the generated currents) and at the same time affects their acceleration. This makes analytical models to be extremely limited in their ability to simultaneously track particle acceleration and magnetic field generation.

Due to this complexity, most analytical and Monte Carlo methods use the “test particle” approximation. According to this approximation, during the acceleration process, the accelerated particles interact with a fixed background magnetic field. These models therefore neglect the contribution of the high energy particles to the magnetic field, which occurs due to the currents they generate. This assumption can be justified as long as the accelerated particles carry only a small fraction of the available energy that can be deposited to the magnetic field. However, as explained above, this assumption is not supported by current observations.

Furthermore, relativistic shocks, as are expected in GRBs, introduce several challenges which do not exist when considering non-relativistic shocks. These include (1) the fact that the distribution of the accelerated particles cannot be considered isotropic; (2) mixing of the electric and magnetic fields when moving between the upstream and downstream shock regions; and (3) the fact that it is more difficult to test the theory (or parts of it), and one has to rely on very limited data, which can often be interpreted in more than a single way.

Very broadly speaking, theoretical works can be divided into three categories. The first is a semi-analytic approach (e.g., \([49–54]\)), in which particles are described in terms of distribution functions, enabling analytic or numerical solutions of the transport equations. Clearly, while this is the fastest method, reliable solutions exist only over a very limited parameter space region, and several considerable simplifications (e.g., about the turbulence, anisotropy, etc.) are needed. The second method is the Monte Carlo approach \([55–62]\). In this method, the trajectories and properties of representative particles are tracked, assuming some average background magnetic fields. The advantage of this method is that it enables exploring a much larger parameter space region than analytical methods while maintaining fast computational speed. The disadvantages are (a) the simplified treatment of the background magnetic field, which effectively implies that the “test particle” approximation is used; and (b) current Monte Carlo codes use a simplified model to describe the details of the interactions between the particles and magnetic fields. For example, many codes use the “Bohm” diffusion model, which is not well-supported theoretically (see \([63]\)).

The third approach is the Particle-In-Cell (PIC) simulations \([64–68]\). These codes basically solve simultaneously both particle trajectories and electromagnetic fields in a fully self-consistent way.
They therefore provide the “ultimate answer”, namely the entire spectra of the accelerated particles alongside the generated magnetic field. They further provide the details of the generated magnetic turbulence as well as visualize the formation process of collisionless shocks. However, these codes are prohibitively computationally expensive, and are therefore limited to a very small range both in time and space. Modern simulations can compute processes on a length scale of no more than a few thousands of skin depth \((c/\omega_p)\). This scale is many orders of magnitudes—typically 7–8 orders of magnitude shorter than the physical length scale of the acceleration region, as is inferred from observations. This is an inherent drawback that cannot be overcome in the nearby future.

To conclude this section, GRB observations provide direct evidence—possibly the most detailed observational evidence for the acceleration of particles in relativistic shock waves. This evidence triggered a huge amount of theoretical work aimed at understanding this phenomenon from first physical principles. Due to its huge complexity, and while a huge progress was made in the past two decades or so mainly due to advances in PIC codes, the problem is still far from being solved.

3. Magnetic Fields in GRBs

In addition to the existence of clear evidence that shock waves in GRBs serve as particle acceleration sites, there is a wealth of evidence for the existence of strong magnetic fields in GRBs. When discussing magnetic fields in GRBs, one has to discriminate between two, very different, scenarios.

First, as already discussed above, fitting the data of GRB afterglow strongly suggests that the main radiative mechanism during this phase is synchrotron emission from energetic electrons. This idea therefore implies that strong magnetic fields must exist in the plasma. Fitting the afterglow provides evidence that the magnetic fields are about two orders of magnitude—and in some cases more—than the values expected from compression of the intergalactic field \([5,10,11,69,70]\). This provides indirect evidence that the relativistic shock wave that inevitably exists during this phase must generate a strong magnetic field, in parallel to accelerating particles.

Second, while no direct evidence currently exists, it had been proposed that, during the prompt emission phase, the GRB plasma may in fact be Poynting-flux dominated \([71–78]\). If this idea is correct, then the origin of the magnetic field must be external to the plasma—namely originate at the progenitor. In this scenario, the magnetic field serves as an energy reservoir that is used to both accelerate the plasma and at the same time accelerate particles to high energies.

3.1. Magnetic Field Generation in Shock Waves

As is typical to most (in fact, nearly all) astrophysical plasmas, and certainly in GRBs, the shock waves that exist are collisionless, namely they are not mediated by direct collisions between the particles (as opposed, to, e.g., shock waves that occur while a jet plane exceeds the speed of sound in the earth’s atmosphere). This can easily be verified for the shock wave in the afterglow phase of GRBs by considering the mean free path for particle interaction, \(l = (n\sigma_T)^{-1} \approx 10^{24} \text{ cm}\). Here, \(n \approx 1 \text{ cm}^{-3}\) is the typical interstellar medium (ISM) density, and \(\sigma_T\) is Thompson cross section, which is the typical cross section for particle interaction. This scale is many orders of magnitude longer than the scale of the system, implying that the generated shock waves must be collisionless.

Instead of direct collisions, the shock waves are generated by collective plasma effects, namely the charged particles generate currents. These currents in turn generate magnetic fields that deflect the charged particles trajectories, mixing and randomizing their trajectories, until they isotropize. Thus, the generation of collisionless shock waves must include generation of turbulent magnetic fields. The key questions are therefore related to the details of the process, which are not fully understood. These include: (1) the nature of the instability that generates the turbulent field; (2) the strength—and scale of the generated field; and (3) the interconnection between the particle acceleration process and the magnetic field generation process.

The most widely discussed mechanism by which (weakly magnetized) magnetic fields can be generated is the Weibel instability (e.g., \([79–89]\)). In this model, small fluctuation in the magnetic
fields charge separation have opposite charges in the background plasma. These particles then form “filaments” of alternating polarity, which grow with time, as the currents carried by the charged particles positively feed the magnetic fields. This is illustrated in Figure 2, taken from Medvedev and Loeb [80]. Indeed, this instability is routinely observed in many PIC simulations [64–66,90–94], which enable quantifying it. Furthermore, these simulations prove the ultimate connection between the formation of collisionless shock waves and the generation of magnetic fields.

**Figure 2.** Illustration of the Weibel (also denoted “relativistic two stream”) instability, taken from Medvedev and Loeb [80]. A magnetic field perturbation deflects electron motion along the x-axis, and results in current sheets (j) of opposite signs in regions I and II, which in turn amplify the perturbation. The amplified field lies in the plane perpendicular to the original electron motion.

However, these same simulations show that the generated magnetic fields decay over a relatively very short length scale, of few tens—few hundreds of plasma skin depth, as was suggested earlier [95–98]; see Figure 3. This is in sharp contrast to the observed synchrotron signal, which requires that the magnetic field, necessary for the synchrotron emission, will remain substantial over a much larger scale, comparable to the scale of the system.

This drawback, clearly observed in modern PIC simulations, triggered a few alternative suggestions. First, it was suggested that the prompt emission can possibly be generated over a much shorter scale than previously thought [99]. Other works investigate the effect of energetic particles (resulting from the acceleration process) on the evolution of the magnetic fields. It was argued [97,100,101] that strong magnetic fields can last over a substantial range due to other types of instabilities. It was further suggested that the gradual increase in the population of high energy particles that results from the Fermi acceleration process gradually increases the characteristic length scale of the magnetic field [102]. Other suggestions include macroscopic turbulence that is generated by larger scale instabilities that take place as the shock waves propagate through a non homogeneous media. Indeed, inevitable density fluctuations in the ambient medium will trigger several instabilities (e.g., Richtmyer–Meshkov or kink) that can in principle grow over a large scale [103–107]. Another possibility, which is very realistic in a GRB environment, is generation of magnetic fields by various instabilities (such as kinetic Kelvin–Helmholtz, mushroom or kink instability) that are stimulated if the relativistic jet is propagating into an already magnetized plasma [108,109]. Indeed, helical magnetic fields may be important in jet acceleration and collimation (see the following section), and their existence will stimulate turbulence as the jet propagates through the plasma. This scenario differs
than that presented in Figure 3, as it includes both reverse and forward shocks, as well as contact discontinuity [110], all provide possible sites for enhancement of magnetic turbulence.

Figure 3. Snapshot of a region from a large 2D relativistic PIC shock simulation, taken from Chang et al. [98]. (a) density structure in the simulation plane showing the plasma density enhancements in the foreshock region that steadily grow up to the shock transition region, where the density becomes homogeneous; (b) magnetic energy, normalized in terms of upstream energy of the incoming flow. The upstream magnetic filaments, which can be visualized as sheets coming out of the page, that are formed by the Weibel instability reach a peak just before the shock; (c) plasma density averaged in the transverse direction as a function of the distance along the flow; (d) magnetic energy density averaged in the transverse direction, as a function of distance along the flow. Clearly, strong magnetic fields are generated but quickly decay.

Thus, overall, the origin of the magnetic field as is required to produce the observed (synchrotron) radiation is still an open question. This field remains one of the very active research fields.

3.2. Highly Magnetized Plasma during GRB Prompt Emission?

3.2.1. Motivation

Very early on, it was realized that the extreme luminosity, rapid variability and >MeV photon energies imply that GRB plasma must be moving relativistically during the prompt emission phase; otherwise, the huge optical depth to pair production, $\tau \gtrsim 10^{15}$ would prevent observation of any signal (see, e.g., [20,111,112], for reviews). This idea was confirmed by the late 1990s with the discovery of the afterglow, which proved that the plasma indeed propagates at relativistic speeds.

Thus, two major episodes of energy conversion exist: first, the conversion of the gravitational energy to kinetic energy—namely, the acceleration of plasma that results in the generation of relativistic jet. Second, the huge luminosity suggests that a substantial part of the kinetic energy is dissipated, and used to heat the particles and generate the observed signal.

Originally, it was argued that instabilities within the expanding plasma would generate shock waves, which are internal to the flow (“internal shocks”; see [113–115]). By analogy with the afterglow phase, it was then suggested that a very similar mechanism operates during the prompt phase. Shock waves generated by internal instabilities both generate strong magnetic fields and accelerate...
particles, which in turn emit the observed prompt radiation [113,116]. In the framework of this model, the internal shocks are therefore the main mechanism of kinetic energy dissipation, and magnetic fields “only” provide the necessary conditions needed for synchrotron radiation.

While this scenario gained popularity by the late 1990s, it was soon realized that it suffers several notable drawbacks. First, the very low efficiency in kinetic energy dissipation, of typically a few % [117–122]. This can be understood, as only the differential kinetic energy between the propagating shells can be dissipated by internal collisions. The only way to overcome this problem is by assuming a very high contrast in the Lorentz factors of the colliding shells [123].

Second, once enough data became available, it became clear that as opposed to the afterglow phase, the simplified version of the synchrotron model does not provide acceptable fits to the vast majority of GRB prompt emission spectra [46,124–127]. Thus, one has to consider alternative emission mechanisms, or, at least, consider ways to modify the synchrotron emission model (see further discussion in Section 4 below).

Third, the details of the initial explosion that triggered the GRB and the mechanism that produce relativistic motion (jet) in the first place remain uncertain. One leading model is the “Collapsar” model [128,129], according to which the core collapse of a massive star triggers the GRB event. In this scenario, the main energy mediators are neutrinos that are copiously produced during the collapse, and transfer the gravitational energy to the outer stellar regions, which are accelerated to relativistic velocities.

An alternative model for the formation of relativistic jets is the mechanism first proposed by Blandford and Znajek [130]. According to this idea, rotational energy and angular momentum are extracted from the created rapidly spinning (Kerr) black hole by strong currents. In this scenario, strong magnetic fields play a key role in the energy extraction process. Thus, the emerging plasma must be Poynting-flux dominated, and the kinetic energy is sub-dominant.

This idea has two great advantages. First, the rotation of a rapidly spinning black hole provides a huge energy reservoir that can in principle be extracted. Second, this mechanism is fairly well understood, and is believed to exist in nature. Furthermore, it does not suffer from the low efficiency problem of the “internal shock” scenario. Indeed, this mechanism gained popularity over the years, and is in wide use for explaining energy extraction in other astronomical objects, such as active galactic nuclei (AGNs; see [131,132]) or X-ray binaries (XRBs; [133]).

I should stress that, as of today, there is no clear evidence that points to which of the two scenarios act in nature to produce the relativistic GRB jets—or possibly a third, as of yet unknown, scenario. However, the possibility that strong magnetic fields may exist motivated studies of the dynamics of highly magnetized plasmas. Under this hypothesis of Poynting-dominated flow, one needs to address two independent questions. The first is the creation of the relativistic jet (namely, the acceleration of the bulk outflow to highly relativistic velocities). The second is the acceleration of (individual) particles to high energies needed to explain the observed radiative signal.

3.2.2. Detailed Models

As opposed to the “internal shock” model, the basic idea in the “Poynting-flux dominated models” is that the strong magnetic fields serve as “energy reservoir”. The magnetic energy is converted to kinetic energy and heat (or particle acceleration) by reconnection of the magnetic field lines. In the past few years, many authors considered this possibility. Very crudely speaking, one can divide the models into two categories. The first assumes continuous magnetic energy dissipation (e.g., [72–74,134–141]). These models vary by the different assumptions about the unknown rate of reconnection, outflow parameters, etc. The second type assumes that the magnetic dissipation—hence the acceleration occurs over a finite, short duration [142–149]. The basic idea is that variability in the central engine leads to the ejection of magnetized plasma shells, which expand due to the internal magnetic pressure gradient once they lose causal contact with the source.
A relatively well understood scenario is the “striped wind” model, first proposed in the context of pulsars [150,151]. According to this model, the gravitational collapse that triggers the GRB event leads to a rapidly rotating, highly magnetized neutron star (which can later collapse into a black hole). The rotational axis is misaligned with its dipolar moment, which naturally produces a striped wind above the light-cylinder (see Figure 4). This striped wind consists of cold regions with alternating magnetic fields, separated by hot current sheets. Reconnection of magnetic field lines with opposite polarity is therefore a natural consequence; such reconnection leads to the acceleration of the wind.

Figure 4. Upper panel: poloidal structure of the striped pulsar wind, according to the solution of Bogovalov [152]. The arrows denote the pulsar rotational axis (along $\Omega$, vertical) and magnetic axis (along $\mu$, inclined). Within the equatorial wedge bounded by the dashed lines, the wind consists of toroidal stripes of alternating polarity, separated by current sheets (dotted lines). Lower panel: 2D PIC simulation setup geometry. The figure is taken from Sironi and Spitkovsky [153].

Evolution of the hydrodynamic quantities in these Poynting-flux dominated outflows within the “striped wind” model was considered by several authors [71–78,154–156]. The scaling laws of the acceleration can be derived under the ideal MHD limit approximation, which is a good approximation due to the high baryon load [71]. Furthermore, in this model, throughout most of the jet evolution the dominated component of the magnetic field is the toroidal component, and so the magnetic field is perpendicular to the outflow direction, $\vec{B} \perp \vec{\beta}$. Under these assumptions, it can be shown that the standard equations of mass, energy and momentum flux conservations combined with the assumption of constant reconnection rate (which is not specified in this model) leads to a well defined scaling law of the Lorentz factor, $\Gamma(r) \propto r^{1/3}$. This is different than the scaling law expected when the acceleration is mediated by photon field, as originally proposed in the classical “fireball” model, $\Gamma(r) \propto r$. Furthermore, these scaling laws lead to testable predictions about the total luminosity that can be achieved in each of the different phases [157]. However, so far, these were not confronted with observations.

The main uncertainty of these models remains the unknown rate in which the reconnection process takes place. This rate is model dependent, and in general depends on the rate of
magneto-hydrodynamic (MHD) instabilities that destroy the regular structure of the flow [158–162]. Furthermore, the presence of strong radiative field can affect this rate [156]. It should be noted that several PIC simulations predict a nearly universal reconnection rate, of ~ 0.1c for highly magnetized flows [163–165]. This rate is dictated by the dynamics of the plasmoid instability. However, due to the limitations of existing PIC codes, I think it is fair to claim that this is still an open problem.

3.3. Acceleration of Particles in Highly Magnetized Plasma: Magnetic Reconnection Process

While it is natural to envision a highly magnetized progenitor that results in Poynting-flux dominated outflow in the early stages of GRB evolution, this possibility leads to two basic questions. The first is the details of the reconnection process that dissipates the magnetic energy. The second is the mechanism by which particles are accelerated. Observations of non-thermal emission during the prompt phase necessitates some mechanism that accelerates the particles (for the least, the electrons) to high energies. However, in Poynting-dominated flow, this mechanism needs to be different than the celebrated Fermi process. In this environment of highly magnetized plasmas, both shock formation is limited [166] and particle acceleration by shock waves is suppressed [167].

First, it was shown that the properties of shock waves (if form) and in particular their ability to accelerate particles to high energies are different if these shock waves reside in highly magnetized regions. In this case, the ability of a shock wave to accelerate particles strongly depends on the inclination angle $\theta$ between the upstream magnetic field and the shock propagation direction [168–170]. Only if this angle is smaller than a critical angle $\theta_{\text{crit}}$ can the shock accelerate particle efficiently. At higher angles, charged particles would need to move along the field faster than the speed of light in order to outrun the shock, and therefore cannot be accelerated. I point out, though, that these simulations assumed a simple configuration of the initial magnetic field, and thus the results in GRB jets may differ.

On the other hand, particles can be accelerated to high energies by the reconnection process itself [171–184]; (see [185] for a recent review). The basic idea is that whenever regions of opposite magnetic polarity are present, Maxwell’s equations imply that there must be a current sheet in between. In this current layer, magnetic field lines can diffuse across the plasma to reconnect at one or more “x”-lines. When particles cross the current sheet, they are forced back by the reversing magnetic field. This is seen in Figure 5, taken from [186]. The particles can then be accelerated in the direction perpendicular to the plane of reconnection by the generated inductive electric fields [187]. Their energy gain per unit time is therefore $dW/dt = qE \cdot v \sim qEc$ in the relativistic case.

![Figure 5](image)

Figure 5. Structure of the particle density in the reconnection layer at $\omega pt = 3000$, from a 2D simulation of magnetized plasma having magnetization parameter $\sigma = 10$. The figure is taken from [186].

This general idea had been extensively studied over the years by PIC simulations, both 2D [180,181,186–195] and 3D [153,165,169,177,196–199]. These show the generation of hard, non-thermal distribution of energetic particles that are accelerated at (relativistic) reconnection sites. These particles follow a power law distribution, with power law index $p \gtrsim 2$, for strongly magnetized plasma, having magnetization parameter $\sigma \equiv u_B/u_{th} \approx 10$ [186]. Here, $u_B$, $u_{th}$ are the magnetic field and thermal particle energy densities, respectively. While this index is fairly similar to the one obtained by the Fermi process, it was shown to be sensitive to the exact value of $\sigma$ [192,194]. Early works suggested that, in a strongly magnetized plasma, the power law index is $p < 2$, implying that most of
the energy is carried by the energetic particles. However, recent simulations that were run for longer times and using larger box sizes, showed convergence towards $p \sim 2$ at late times [200].

A heuristic argument for the power law nature of the particle distribution was first suggested by Zenitani and Hoshino [187], and was demonstrated by Sironi and Spitkovsky [186]. More energetic particles have larger Larmor radii, and therefore spend more time near the “x” point of the reconnection layer than particles of lower energies. They suffer less interaction with the reconnected field (in the perpendicular direction), and therefore spend longer time in the accelerated region, where strong electric fields exist. Thus, overall, the gained energy in the acceleration process is proportional to the incoming particle energy, which results in a power law distribution.

Finally, as discussed in the previous section, jet propagation into an already magnetized plasma triggers and enhances several instabilities, such as kinetic Kelvin–Helmholtz or mushroom instabilities. As was recently shown [107,109], these instabilities, which have geometries that are different in nature than the “slab” geometry presented in Figures 4 and 5 above, also serve as acceleration sites of particles [170].

4. Photon Field in GRB Plasmas

Our entire knowledge (or lack thereof) of GRB physics originates from the observed electromagnetic signal. As GRBs are the brightest sources of radiation in the sky, a strong radiation field must exist within the relativistically expanding plasma. This photon field adds to the strong non-thermal particle field and the possible strong magnetic fields that exist.

Similar to the questions outlined above about the sources and role played by magnetic fields (being dominant or sub-dominant), one can divide the basic open questions associated with the photon fields into two categories. The first is understanding the radiative processes that lead to the observed signal. The second is to understand the possible role of the photon field in shaping the dynamics of the GRB outflow.

4.1. Radiative Processes: The Classical Ideas

The most widely discussed model for explaining GRB emission both during the prompt and the afterglow phases is synchrotron emission. This model has several advantages. First, it has been extensively studied since the 1960s [201,202] and its theory is well understood. It is the leading model for interpreting non-thermal emission in many astronomical objects, such as AGNs and XRBs. Second, it is very simple: it requires only two basic ingredients, namely energetic particles and a strong magnetic field. Both are believed to be produced in shock waves or magnetic reconnection process. Third, it is broadband in nature (as opposed, e.g., to the “Planck” spectrum), with a distinctive spectral peak, that could be associated with the observed peak energy. Fourth, it provides a very efficient way of energy transfer, as for the typical parameters, energetic electrons radiate nearly 100% of their energy (during the prompt and parts of the afterglow phases). These properties made synchrotron emission the most widely discussed radiative model in the context of GRB emission (e.g., [5,7,45,203–215], for a very partial list).

Synchrotron emission requires a population of energetic electrons. These electrons, in addition to synchrotron radiation, will inevitably Compton scatter the emitted photons, producing synchrotron-self Compton emission (SSC). This phenomenon is expected to produce high energy photons, that can extend up and beyond the GeV range. Its relative importance depends on the Compton Y parameter, namely the optical depth multiplied by the fractional energy change of each photon. This phenomenon was extensively studied both in the context of the prompt phase [216–219] and the afterglow phase in GRBs [220–225]. Note that the results of the scattering does not only affect the photon field directly, but also indirectly, as the scattering cools the electrons, hence modified the synchrotron emission. Naturally, the importance of this nonlinear effect depends on the Compton Y parameter, and is significantly more pronounced during the prompt phase, where the plasma is much denser and significantly more scattering is expected than during the afterglow phase.
Observations of high energy photons, above the threshold for pair creation, implies that both pair production and pair annihilation can in principle take place. If this happens, then a high energy electromagnetic cascade will occur, namely energetic photons produce $e^\pm$ pairs, which lose their energy by synchrotron and SSC, thereby producing another population of energetic photons, etc. These phenomena further modifies the observed spectra in a nonlinear way [216,226,227].

A different suggestion is that the main source of emission is not leptonic, but rather hadronic. This idea lies on the assumptions that the acceleration process, whose details are of yet uncertain, may be more efficient in accelerating protons, rather than electrons to high energies. In this scenario, the main emission mechanism is synchrotron radiation from the accelerated protons [218,221,228–233]. The main drawback of this suggestion is that protons are much less efficient radiators than electrons (as the ratio of proton to electron cross section for synchrotron emission $\sim (m_e/m_p)^2$). Thus, in order to produce the observed luminosity in $\gamma$-rays, the energy content of the protons must be very high, with proton luminosity of $\sim 10^{55}–10^{56}$ erg s$^{-1}$. This is at least three orders of magnitude higher than the requirement from leptonic models.

4.2. Photospheric Emission and GRB Dynamics

The idea that photospheric (thermal) emission may play a key role as part of GRB plasma is not new. Already in the very early models of cosmological GRBs, it was realized that the huge energy release, rapid variability that necessitates small emission radii (due to light crossing time argument), and the high $\gamma > 1$ MeV photon energy observed, imply the existence of photon-dominated plasma, namely a “fireball” [135,234–236].

Initially, therefore, it was expected that the observed GRB spectra would be thermal. Only with the accumulation of data that showed non-thermal spectra—both during the prompt and afterglow phases—did the synchrotron model gain popularity.

While the synchrotron emission model remains the leading radiative model that can explain the observed signal during the afterglow phase, it was realized by the late 1990s that it fails to explain the low energy part of the prompt emission spectra of many GRBs [46,124–126]. Being well understood, the synchrotron theory provides a robust limit on the maximum low energy spectral slope that can be achieved. As the observed slope in many GRBs was found to be harder than the limiting value, Preece et al. [124] coined the term “synchrotron line of death”. Despite two decades of research, this result is still debatable [127,237]. This is due to the different analysis methods chosen. Nonetheless, this observational fact, combined with the fact that the photospheric emission is inherent to GRB fireballs, motivated the study of photospheric emission as a possibly key ingredient in the observed prompt spectra.

Due to the weakness of the observed signal, most of the analysis is done on time integrated signal, as simply not enough photons are observed. However, when analyzing the data of bright GRBs where a time-resolved analysis could be and indeed was done, it was proven that indeed some part (but not all) of the observed prompt spectra can be well fitted with a thermal (Planck) spectrum [238–242]. This was confirmed by several recent observations done with the Fermi satellite [243–249].

From a theoretical perspective, photospheric emission that is combined with other radiative processes was considered as of the early 2000s [250,251]. The key issue is that the thermal photons, similar to the synchrotron photons, can be up-scattered by the energetic electrons. In fact, by definition of the photosphere, they have to be upscattered as the optical depth below the photosphere is $>1$. This implies both modification of the electron distribution from their initial (accelerated) power law distribution, and modification of the thermal component itself, in a nonlinear way [252,253]. This naturally leads to a broadening of the “Planck” spectrum, which, for a large parameter space region, resembles the observed one [253]. This is demonstrated in Figure 6.
Figure 6. Time averaged broad band spectra expected following kinetic energy dissipation at various optical depths. For low optical depth, the two low energy bumps are due to synchrotron emission and the original thermal component, and the high energy bumps are due to inverse Compton phenomenon. At high optical depth, $\tau \geq 100$, a Wien peak is formed at $\sim 10$ keV, and is blue-shifted to the MeV range by the bulk Lorentz factor $\Gamma \simeq 100$ expected in GRBs. In the intermediate regime, $0.1 < \tau < 100$, a flat energy spectrum above the thermal peak is obtained by multiple Compton scattering. The figure is taken from Pe'er et al. [253].

This idea of modified Planck spectra gained popularity in recent years, as it is capable of capturing the key observational GRB properties in the framework of both photon-dominated and magnetic-dominated flows [254–271].

An underlying assumption here is that a population of energetic particles can exist below the photosphere (or close to it). This is not obvious, as recent works showed that the structure of shock waves, if existing below the photosphere (“sub-photospheric shocks”), does not enable the Fermi acceleration process, at least in its classical form [263,272–274]. Nonetheless, particle heating can still take place below the photosphere via other mechanisms—for example, due to turbulence cascade which passes kinetic fluid energy to photons through scattering [275]. Thus, overall, the question of particle heating below the photosphere and sub-photospheric dissipation is still an open one.

A second, independent way of broadening the “Planck” spectra that enables it to resemble the observed prompt emission spectra of many GRBs is the relativistic “limb darkening” effect, which is geometric in nature. By definition, the photosphere is a region in space in which the optical depth to scattering is $>1$. In a relativistically expanding plasmas, this surface has a non-trivial shape [276]. Furthermore, as photon scattering is probabilistic in nature, the photospheric region is in a very basic sense “vague”—photons have a finite probability of being scattered anywhere in space in which particles exist [258,276–283]; see Figure 7. The exact shape of this “vague” photosphere depends on the jet geometry, and in particular on the jet velocity profile, namely $\Gamma = \Gamma(r, \theta)$. Under plausible assumptions, this relativistic limb darkening effect can lead to an observed spectra that does not resemble at all a “Planck” spectra, and, in addition, can be very highly polarized—up to 40%, if viewed off the jet axis [279,284,285]. This is demonstrated in Figure 8, taken from Lundman et al. [279].
Figure 7. The green line represent the (normalized) photospheric radius $r_{ph}$ as a function of the angle to the line of sight, $\theta$, for spherical explosion. The purple dots represent the last scattering locations of photons emitted in the center of a relativistic expanding “fireball” (using a Monte Carlo simulation). The black lines show contours. Clearly, photons can undergo their last scattering at a range of radii and angles, leading to the concept of “vague photosphere”. The observed photospheric signal is therefore smeared both in time and energy. This figure is taken from [276].

Figure 8. Left: the observed spectrum that emerges from the optically thick regions of an expanding, relativistic jet having a spatial profile, $\Gamma = \Gamma(\theta)$ does not resemble the naively expected “Planck” spectrum. Separate integration of the contributions from the inner jet (where $\Gamma \approx \Gamma_0$), outer jet (where $\Gamma$ drops with angle) and envelope is shown with dashed, dot dashed and dotted lines, respectively. Right: the assumed jet profile. The figure is taken from Lundman et al. [279].

Identification of this thermal emission component has several important implications in understanding the conditions inside the plasma. First, it can be used to directly probe the velocity at the photospheric radius—the innermost region where any electromagnetic signal can reach the observer [286–289]. Second, identification of a photospheric component can be used to constrain the magnetization of the outflow [290–294]. In a highly magnetized outflow, the photospheric component is suppressed, and therefore identifying it can be used to set upper limits on the magnetization. Furthermore, within the context of the “striped wind” model, the existence of strong photon field modifies the rate of reconnection [156]. These identifications led to the suggestion that possibly the GRB outflow is initially strongly magnetized (as is suggested within the Blandford and Znajek [130] mechanism), but that the magnetic field quickly dissipates below the photosphere [293,295].
5. GRB Environments and GRB170817a

One of the key open questions that had been the subject of extensive research over the years is the nature of the GRB progenitors. There are two leading models. The first is the “collapsar” model mentioned above, which involves a core collapse of a massive star, accompanied by accretion into a black hole ([128,129,296–302], and references therein). The second scenario is the merger of two neutron stars (NS–NS), or a black hole and a neutron star (BH–NS). The occurrence rate, as well as the expected energy released, $\sim GM^2/R \sim 10^{53}$ erg (using $M \sim M_\odot$ and $R \sim R_{sch}$, the Schwarzschild radius of stellar-size black hole), are sufficient for extra-galactic GRBs [303–307].

The association of long GRBs with core collapse supernova, of type Ib/c [6,308–313] serves as a “smoking gun” to confirm that indeed, the long GRB population originates from the “collapsar” scenario. Indeed, in all cases but two (GRB060505 and GRB060614) whenever the GRBs were close enough that evidence for supernovae could be detected, they were indeed observed [314].

While long being suspected, until last year there was only indirect evidence that short GRBs may be associated with the merger scenario. These were mainly based on morphologies of the host galaxies (short GRBs are associated with elliptical galaxies, while long GRBs reside in younger, star-forming galaxies), as well as their position in the sky relative to their host galaxy [315,316]; (For reviews, see, e.g., [18,317,318]). This situation changed with the discovery of the gravitational wave associated with the short GRB170817 [319–321]. This discovery proved that neutron star–neutron star (NS–NS) merger does indeed produce a short GRB, thereby providing the missing “smoking gun”. This event, though, was unique in many ways—e.g., the large viewing angle [322], and thus it is not clear whether it is representative of the entire short GRB population. Indeed, a detailed analysis show that the environments of short GRBs do not easily fit this “merger” scenario model [323].

Despite these uncertainties, it is widely believed that these two types of progenitors may end up with very different environments. The merger of binary stars is expected to occur very far from their birthplace, in an environment whose density is roughly constant, and equals the interstellar medium (ISM) density. On the other hand, a massive star (e.g., a Wolf–Rayet type) is likely to emit strong wind prior to its collapse [324], resulting in a “wind” like environment, whose density (for a constant mass ejection rate and constant wind velocity) may vary as $\rho \propto r^{-2}$. I should stress though that this is a very heuristic picture, as the properties of the wind emitted by stars in the last episode before they collapse is highly speculative. Furthermore, even if this is the case, one can predict the existence of a small “bump” in the light curve, resulting from interaction of the GRB blast wave with the wind termination shock [325]. This, though, could be very weak [326], and indeed, no clear evidence for such a jump (whose properties are very uncertain) currently exists.

Nonetheless, as early as a few years after the detection of the first long GRB optical afterglow [3], a split between ISM-like and wind-like environments was observed, with up to 50% of bursts found to be consistent with a homogeneous medium (e.g., [327–329]). In later studies, (e.g., [330,331]), ISM-like environments continued to be found in long GRB afterglows. Further measurements of the spectral and temporal indices for optical [332] and X-ray [70,333–335] afterglows of long GRBs all point to a split in environment types between wind and ISM.

The theoretical analyses that lead to this conclusion are relatively simple, as these are based on measurements of the properties of the late time afterglow. During this stage, the outflow is expected to evolve in a self-similar way. Despite the uncertainty in the detailed of the processes, it is expected that the velocity profile, the particle acceleration and the magnetic field generation all follow well defined scaling laws. These enable the the relatively well sampled afterglow data to infer the properties of the environment at late times. From this knowledge, one can hope to constrain the nature of the progenitor, hence the properties of the GRB plasma. The inconsistencies frequently found between the afterglow data of both the long and short GRBs and the simplified environmental models implies that we still have a way to go before understanding the nature of the progenitors, hence the conditions inside the GRB plasmas.
6. Conclusions

GRBs serve as unique laboratories to many plasma physics effects. In fact, GRB observations triggered many basic studies in plasma physics, whose consequences reach far beyond the field of GRBs, and even extend beyond the realm of astrophysics.

GRBs are the only objects known to produce ultra-relativistic shock waves, whose Lorentz factors exceed $\Gamma \gtrsim 100$. As such, they are the only objects that serve as laboratories to study the properties of ultra-relativistic shocks. In Section 2, I highlight a key property that directly follows GRB afterglow observations, that of particle acceleration to high energies in relativistic shock waves. While the existence of cosmic rays implies that such mechanism exists, and although the mechanism by which (non-relativistic) shock waves accelerate particles was discussed in the 1950s by Fermi, the details of the process in two important limits: (1) the relativistic limit, and (2) the “back reaction” of the accelerated particles on the shock structure (i.e., the opposite of the “test particle” limit) are not known. However, from observations in GRB afterglows, it is clear that these two limits are the ones that exist in nature.

Section 3 was devoted to discussing magnetic fields in GRBs. This section was divided into three parts. First, I discussed the current state of knowledge about the generation of strong magnetic fields in shock waves. This again is directly motivated from GRB afterglow observations, which show the existence of strong magnetic fields during this phase. As these fields are several orders of magnitude stronger than the compressed magnetic fields in the ISM, they must be generated by the shock wave itself. It is clear today that the process of magnetic field generation is intimately connected to the process of particle acceleration.

I then discussed energy transfer from magnetic fields by the magnetic reconnection process. This is important in one class of models—the “Poynting flux” dominated models, which assume that early on the main source of energy is magnetic energy. This thus motivates a detailed study of the reconnection process, as a way of transferring this energy to the plasma—both as a way of generating the relativistic jets (accelerating the bulk of the plasma), and as a way of accelerating individual particles to high energies, giving them a non-thermal distribution. This last subject was treated separately in Section 3.3.

In Section 4, I discussed the last ingredient of GRB plasmas, which is the photon field and its interaction with the particle and magnetic fields. The discussion in this section was divided into two parts. I first highlighted the “traditional” radiative processes such as synchrotron emission and Compton scattering that are expected when a population of high energy particles resides in a strongly magnetized region. As far as we know, these are the conditions that exist during the (late time) GRB “afterglow” phase. I then discussed the role of the photosphere in Section 4.2. The photosphere exists in the early stages of GRB evolution, and may be an important ingredient that shapes the prompt emission signal.

However, in addition to shaping the observed prompt emission spectra, the photosphere affects other aspects of the problem as well. As, by definition, the optical depth to scattering below the photosphere is $\gtrsim 1$, there is a strong coupling between the photon and particle fields. This leads to various effects that modify the structure of sub-photospheric shock waves, affect the dynamics, and can affect the magnetic field–particle interactions, via modification of the magnetic reconnection process. Most importantly, there are several observational consequences that can be tested.

Finally, I briefly discussed in Section 5 our knowledge about the different environments in GRBs. The current picture is very puzzling, and there is no simple way to characterize the environment. The importance of this study lies in the fact that understanding the environment can provide very important clues about the nature of the progenitors, hence on the physical conditions inside the GRB plasmas. Such clues are very difficult to be obtained in any other way.

Thus, overall, GRBs, being the most extreme objects known, provide a unique laboratory to study plasma physics in a unique, relativistic astrophysical environment. While GRB studies triggered and stimulated many plasma physics studies in the laboratory, clearly, unfortunately we cannot mimic the conditions that exist within the GRB environment in the lab. Thus, in the future, by large, we
foresaw that we will have to continue to rely on GRB observations to provide the necessary input to test the theories.

As I demonstrated here, as of today, there is no consensus on many basic phenomena which are at the forefront of research. However, as the study of GRBs is a very active field—both observationally and theoretically—one can clearly expect a continuous stream of data and ideas that will continue to change this field.

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