Models of gamma-ray bursts

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Abstract.

We present a very short overview of two popular models of gamma-ray bursts, the fireball model, the cannonball model and we introduce a recent model involving electromagnetic reconnection in strong magnetic fields. We show that a study of gamma-ray burst light curves supports the new idea. We describe the framework used in numerical simulations of three-dimensional model of magnetic reconnections. We reveal our further plans to build up a relativistic resistive magnetohydrodynamical code.

Introduction

Although it has already been more than 30 years since their discovery, gamma-ray bursts (GRBs) are still an astrophysical enigma. Thus the best description seems to be a summary of observational facts. Because the nature of GRBs is unclear we can only guess which of their properties we know are important and valuable and which are not.

For our purpose a gamma-ray burst is a transient event, a high energetic flash that appears randomly at the sky with a peak flux in the gamma-ray energy band. GRBs show non-thermal spectra and complex chaotic light curves which are believed to be consisted of many pulses.

There are at least two different classes of GRBs: the long ones with duration greater than 2 s and the rest called short ones shorter than 2 s. Since the BeppoSAX mission we know that at least the long GRBs are usually followed by an afterglow in the lower energy band, from the X-ray to radio wavelength. Nowadays some GRBs have their redshift identified and thus an isotropic equivalent of radiated energy in a range of $10^{51} - 10^{54}$ ergs was inferred. At this time we have detected about 3000 bursts.

A progenitor of these mysterious sources is probably a compact object, the mechanism of the emission remains unknown. There exist several pieces of evidence that GRBs could have a connection to supernovae. An energy reservoir is usually assumed to be a combination of gravitational, rotational and electro-magnetic energy as a most natural source.

Due to the absence of any sign of a $\gamma\gamma \rightarrow e^{\pm}$ reaction in the spectrum we deduce that a) the emitting region is optically thick up to a distance of $10^{14} - 10^{16}$ cm from the source b) the region is moving at a relativistic speed toward us c) there is a small baryonic loading within the emitting region.

A revolution came in after a discovery of 80% linear polarization of the prompt gamma-ray emission from RHESSI data (Coburn & Boggs, 2003).

For a more detailed review see e.g. (Topinka, 2002) and references therein.

Models

In this paper we concentrate only on the long GRBs. The key questions are a) what is the progenitor of the explosion to supply such an extremal energy release, b) what is the mechanism of a transport of this energy up to a distance where the medium is optically thin for gamma-rays, c) how to convert the energy into gamma-rays we observe as a gamma-ray burst and d) how to produce a late-time afterglow.

There were 271 theories of GRBs proposed at the conference in Huntsville in 1974, all of them maybe but one have something in common, they were not real models of GRBs. Generally accepted scenarios are a coalescence of merging neutron stars or a core-collapse of a very massive star. There are three leading scenarios for creating a GRB: a baryonic relativistic fireball model, a cannonball model and an electromagnetically dominated wind dissipation. In this talk we concentrate on the last one. We discuss only the prompt gamma emission, not the afterglow.

Fireball model

Overview. A basic scenario of the model of the baryonic relativistic fireball model of a GRB (Rees & Meszaros, 2000), (Piran, 1999) is the following: a rotating massive star collapses and the energy is converted into the form of a kinetic energy of bulk motion of shells relativistically expanding from the engine at a speed of a Lorentz factor $\Gamma \sim 100-1000$. The shells are assumed to consist of plasma mixture of photons, electrons and positrons or a simple electron and ion plasma. These shells either collide with an external dense interstellar medium, decelerate – external shock version, or collide with each other and decelerate – internal shocks. As the shells decelerate a shock front arises and the magnetic field behind the front is amplified. As the particles accelerate while crossing the shock front e.g. via relativistic 2nd order Fermi process they interact with the magnetic field and radiate through the synchrotron emission, blue-shifted into the observational frame we see a gamma-ray burst. Later when Γ of the shock velocity decreases enough and the energy-mass of the swept up material becomes comparable to the energy of the initial explosion we observe an afterglow.

Note, that the model does not describe the central engine. It predicts a synchrotron power-law spectrum, possibly altered by inverse Compton scattering of the photon seed in the shell, or self-Compton scattering. There are also several reasons to believe that the explosion is not spherical but collimated into a narrow jet. The collimation is achieved e.g. by Blandford-Znajek process or through a magnetic field present during the collapse of the core. The chaotic light curve is explained by inhomogeneous clumpy interstellar medium or by the interaction of a high number of shells between each other and considering the light-travel effect. This model predicts a power-law spectrum of the afterglow as well as its power-law flux decrease in time, both is observed.

Problems. Unfortunately there are several weak points in this model. The external shocks cannot explain a variability of light curves, on the other hand the internal shocks are very inefficient because the energy release is proportional to the ratio of Lorentz factors of the colliding shells.

Another problem comes from the baryon density assumption. If the baryon loading is too high the shells will decelerate at much shorter radius and no gamma-rays will be visible. If it is too low it will not be enough to carry the initial energy in the bulk motion.

It is not natural to produce an ordered plane magnetic field as a seed for observed synchrotron radiation. It is known that when a spherically emitting source moves at a relativistic speed we can see only the radiation coming from a narrow jet of an angular size $\theta \leq 1/\Gamma$. To see the highly polarized light all emitting regions and thus all colliding shells must be parallel and have a similar Lorentz factor which make the efficiency worse.

As well as there is only a negligible chance to observe the ejecta in the jet on-axis, even a small viewing angle would be affected by high Doppler factor and amplitudes of the pulses in the light curve would have a decreasing trend.

If the GRB and afterglow explosion is jetted and the jet is assumed to be expanding, cooling and decelerating then the jet is wider in the time of the afterglow emission than in the prompt gamma emission. Thus we shall observe a $\sim \theta^{-2}$ more of "orphan" afterglows, the afterglows without a gamma phase seen, than GRBs.

Resume. Despite of all these short-comings the fireball model is a generally accepted paradigm for the GRBs.

Cannonball model

Overview. The cannonball model (de Rujula & Dar, 2003) was inspired by quasar and micro-quasar jets. A star explodes as a supernova leaving a rotating compact central engine which accelerates remnants of an accretion disk along the rotational axes and fires them out at a relativistic speed of $\Gamma \sim 100-1000$. As these bulbs hit the previously ejected supernova shell, they scatter the radiation from the shell through inverse Compton scattering. Viewing it from aside and computing Doppler factor we see a pulse in the gamma-ray light curve for each bulb crossing the shell. As the bulb cools we see an afterglow as well as the contribution of the light from the supernova.

Problems. The calculation have been made only for the radiation coming from the surface of the blob and do not take into account a shock which is believed to be created while the blob hits the supernova shell.

Resume. The cannonball model is in the contrary to numerical simulations and for this reason it is not popular within the majority of GRB community. To be honest we have to remark that many ideas used in the cannonball scenario was used later for polishing and patching the fireball model, e.g. off-axis viewed jet, an underlying supernova, inverse Compton scattering.

Reconnection of magnetic field in electromagnetically dominated wind model

Overview. While in the fireball scenario the energy is extracted from the gravitational and rotating energy through the electromagnetic interaction into the kinetic energy of particles in the bulk motion

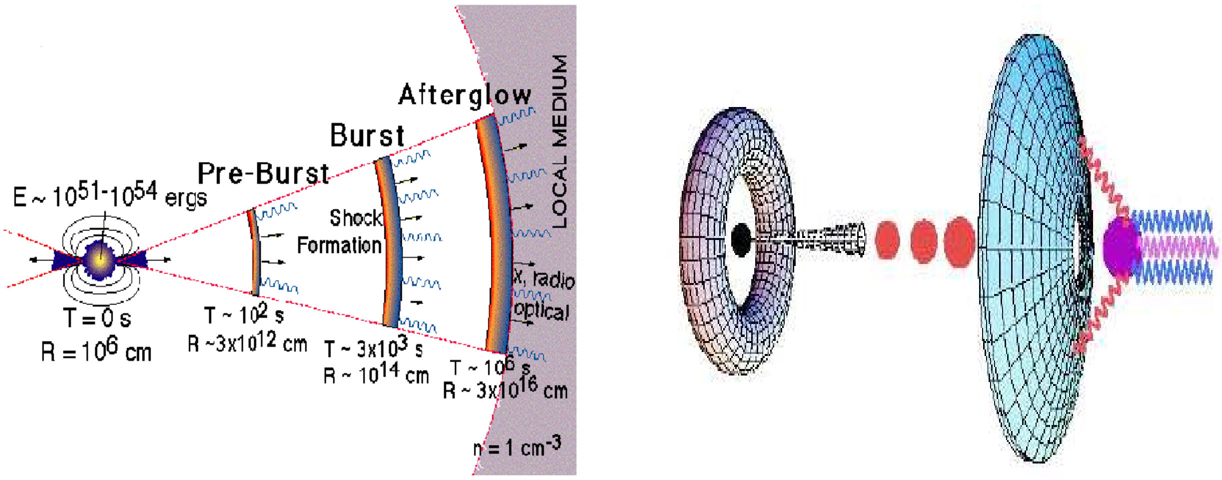


Figure 1. Sketches of the fireball (left) (Piran, 1999) and the cannonball (de Rujula & Dar, 2003) (right) model of GRBs

of the plasma, then reconverted back into the internal magnetic field energy in the shocks and finally transformed into the radiation through the synchrotron emission, the newest proposed scenario of an electromagnetically (EM) dominated plasma is much more economical. It assumes that the energy is extracted by EM field, then it propagates in the form of the EM dominated plasma where the ratio between the magnetic field B and the proper density ρ is

$$\sigma = \frac{U_B}{U_P} = \frac{B^2}{8\pi\rho c^2} \gg 1 \tag{1}$$

and dissipates through fast magnetic reconnections (MRs) (Lyutikov & Blandford, 2004). When the EM bulb hits a dense interstellar medium it produces a shock and an afterglow shines.

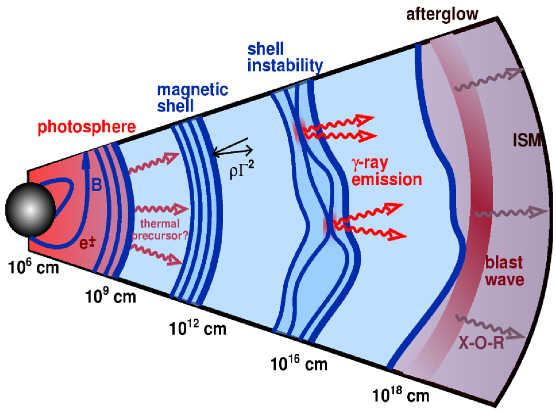


Figure 2. Reconnection of magnetic field in electromagnetically dominated wind model of GRBs (Lyutikov & Blandford, 2004)

Gamma-ray burst light curves statistical analysis

How to decide which of these models is more favorite for the long GRBs? We computed Fourier spectra of GRB light curves in cases of long multi-peaked light curves, namely CGRO BATSE triggers 1440, 1676, 2156, 2856, 6472, 7906, 7994, 8001, 8026 and 8036 (BATSE web page). We expected that the GRBs are affected by Poisson noise, which resembles white noise characterized by the flat spectrum $\sim f^0$ for a large number of photons. Thus we subtracted the white noise level power density spectrum

(PDS) from a normalized GRB PDS. We show that the PDS follows a power-law with a slope very close to $\alpha \sim -5/3$ in a log-log graph.

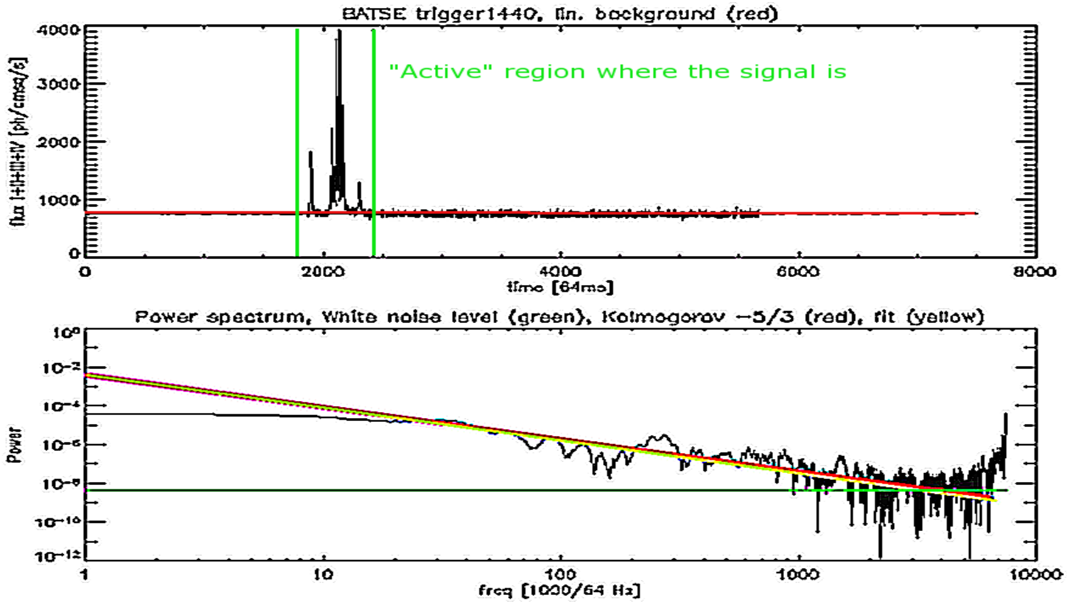


Figure 3. Analysis of CGRO BATSE trigger #1440. Fourier spectrum shows a power-law with a $-5/3$ slope

Note, that it is not important that we do not know the distance from these bursts, because the redshift does not change the slope of the PDS.

The value of $-5/3$ is a Kolmogorov slope of a turbulence and an avalanche effect may play a plausible role in the pulse generation. Thus different pulses within a burst or bursts are produced by one physical mechanism of stochastic nature, an individual burst is a random realization of the same standard process. Magnetohydrodynamics (MHD) turbulence involving MRs of field lines is a suitable solution based on a turbulent and stochastic process. However it does not strictly reject the other models where the similar slope can be achieved by a different process and by setting special initial conditions.

Magnetohydrodynamics and magnetic reconnections

Magnetic fields in astrophysics

The are no doubts that magnetic field is very popular in many astrophysical phenomena. There are several examples of astrophysical objects where the magnetic fields play a crucial role, e.g. quasars and their jets launched and maintained by the magnetic field, MRs in accretion disks around black holes, cataclysmic variables, pulsars or extremely magnetized neutron stars – magnetars. The best studied case are MRs in solar flares.

Resistive MHD equations

The description of plasma flows is usually treated in the framework of ideal MHD. But ideal MHD approach has several restrictions: a) two particles on a given magnetic field line belong to this line forever b) magnetic field line cannot be teared, thus the magnetic flux through the closed surface is constant and the topology of the magnetic field which is usually represented in terms of the helicity H is constant too

$$\frac{dH}{dt} \equiv \frac{\mathrm{d}}{\mathrm{d}t} \int_V A \cdot B dV \tag{2}$$

where $B \equiv \nabla \times A$. Its consequence is that two magnetic fields cannot interact with each other and the magnetic energy gained by the kinetic motion of the field lines frozen into the plasma cannot dissipate and cannot be released. It means that one could achieve an infinitely strong magnetic field in the MHD dynamo process, the MHD dynamo has no inverse process. For these reasons we have to introduce a resistive MHD (RMHD).

The basic fluid description of a plasma is given by classical RMHD Maxwell equations for the mass density ρ, the velocity field v, the isotropic pressure p and the magnetic field B which is coupled to the current density $j = (c/4\pi)\nabla \times B$ (Chiuderi & Einaudi, 1994)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0 \tag{3}$$

$$\rho \frac{\partial v}{\partial t} + \rho (v \cdot \nabla) v = -\nabla p + j \times B + F_\pi \tag{4}$$

$$\nabla \times E = -\frac{1}{c}\frac{\partial B}{\partial t} \tag{5}$$

where the electric field E is determined from Ohm's law (equation of motion) as

$$E + \frac{1}{c} v \times B = R \tag{6}$$

$F_\pi = \rho\nu\nabla^2 v$ is the diffusion term and $R = \eta j$ represents non-ideal effects. The pressure is given by the equation of state $p = p(\rho)$. In the adiabatic case

$$\frac{\mathrm{d}p}{\mathrm{d}t} + v \cdot \nabla p = -\gamma p \nabla \cdot v \tag{7}$$

In case of an incompressible fluid ($\nabla \cdot v = 0$) and a constant density ρ the equations reduce to

$$\frac{\mathrm{d}\omega}{\mathrm{d}t} - \nabla \times (v \times \omega) - \nabla \times (j \times B) = \nu \nabla^2 \omega \tag{8}$$

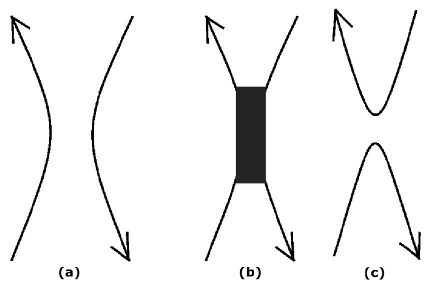
$$\frac{\mathrm{d}B}{\mathrm{d}t} - \nabla \times (v \times B) = \eta \nabla^2 B \tag{9}$$

$$\nabla \cdot v = \nabla \cdot B = 0 \qquad \omega = \nabla \times v \qquad j = \nabla \times B \tag{10}$$

for the vorticity ω and B field. We use dimensionless units $x \to \frac{x}{L}$, $v \to \frac{v}{v_A}$, $\rho \to \frac{\rho}{\rho_0} = 1$ and $B = \frac{B}{B_0}$ where L is the typical length scale, B_0 the typical field intensity, $\rho_0 = nm_i$ the typical mass density and $v_A = B_0/\sqrt{4\pi\rho_0}$ the Alfven velocity. We introduced normalized resistivity $\eta \to \eta c^2/4\pi v_A L$ and normalized kinematic viscosity $\nu \to \nu/v_A L$. The quantity $S \equiv \eta^{-1}$ is called the Lundquist number, $R_m = vL/(c^2\eta/4\pi)$ the magnetic Reynolds number, $R_m = Sv/v_A$, where v is the typical fluid velocity.

Magnetic reconnection

Due to a non-zero resistivity RMHD allows the magnetic field lines to change the topology, break and reconnect and the accumulated energy can be released. This process is called a magnetic reconnection (MR), see Fig. 4.



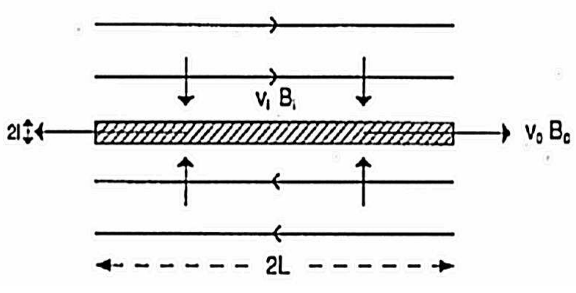


Figure 4. Left: Magnetic reconnection basic scheme a) initial configuration b) magnetic field lines enter the diffuse region c) result. Right: 2D Sweet-Parker model of magnetic reconnection (Priest & Forbes, 2000)

The simplest model of the magnetic reconnection is a two-dimensional Sweet-Parker reconnection (SP). The basic scheme is sketched on the Fig. 4. Due to the "freezing in plasma" effect the anti-parallel magnetic field lines enter a diffusion region of a size $l \times L$ where they reconnect. From Maxwell equations there exists a current sheet between the anti-parallel magnetic field lines. This current can effectively accelerate charged particles from the central stagnation null magnetic X-point along the length of the diffuse region L (Priest & Forbes, 2000), (Karlický, 2004).

The reconnection rate is given by $M = 1/R_m^{1/2}$ where the Reynolds number is based on the Alfven speed $R_m = \frac{Lv_A}{\eta}$. One can show that the inflow produces the electrical energy $(E \cdot j)$ (or the Poynting flux $E \times B$) which appears partly as Ohmic heat and partly as the work done by accelerating plasma

$$-\nabla \cdot (E \times B) = \mu E \cdot j + \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{B^2}{2}\right) \tag{11}$$

$$E \cdot j = \frac{j^2}{\sigma} + v \cdot j \times B \tag{12}$$

where $\sigma = 1/\mu\eta$ is the resistivity. Another relation yields

$$\frac{l}{L} = \frac{1}{R_{me}} \frac{1}{M_e^{1/2}} \frac{1}{M_i^{1/2}} \tag{13}$$

where M_i and M_e are reconnection rates of the inflow and the outflow accelerated over the distance L and R_{me} is the global Reynolds number. It is obvious that less the thickness of the diffusion region l is the higher outflow speed one can reach. The rates are in terms of magnetic Mach numbers $M = v/v_A$ so the stronger incoming field, the higher rate we obtain.

Magnetic reconnection and GRBs

Magnetic field in GRBs

It is seen that we need a strong and anti-parallel magnetic field to create a GRB. A natural question arises, could it happen in the case of GRBs? There exists e.g. a α-ω dynamo process seen in magnetars, which can build a magnetic field of up to 10^{14} Gauss (Usov, 1994), which gives about 10^{50} ergs, the desired amount of energy is a combination of high number of reconnections. Considering the collimating angle of the factor of $10 - 100$ and a typical number of pulses in a GRB light curve about 1000 we have a desired energy budget.

The topology of the magnetic field has to be more complicated than in a pulsar-like dipole. There exists the anti-parallel magnetic field e.g. outside the light cylinder of a rotating non-spherical pulsar (Coroniti, 1990).

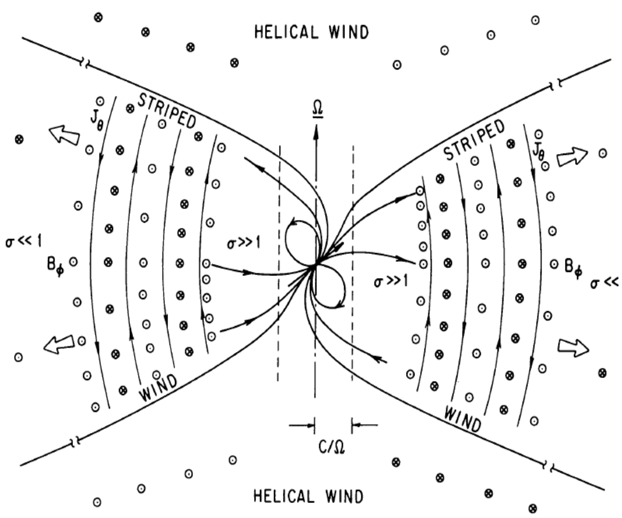


Figure 5. Helical wind with anti-parallel magnetic field lines theoretically out of the light cylinder of an oblate pulsar (Coroniti, 1990)

Relativistic resistive magnetohydrodynamics

Unfortunately, although the equations are in the non-dimensional form it is obvious that for the relativistic velocities of the inflow, the outflow and for the super strong fields (which, we believe, are present in GRBs) we have to use special relativistic RMHD. Maxwell equations are already naturally special relativistic, the only correction appears in Ohm's law and in rewriting the equations into the tensor form:

$$T^{\mu\nu}{}_{,\nu} = 0 \qquad (\rho u^{\mu})_{,\mu} = 0 \qquad F_{[\alpha\beta,\gamma]} = 0 \qquad F^{\mu\nu}u_{\nu} = \eta j^{\mu} \tag{14}$$

$$T^{\mu\nu} = (w + b^2 + e^2)u^{\mu}u^{\nu} + (p + \frac{b^2 + e^2}{2})g^{\mu\nu} - b^{\mu}b^{\nu} - e^{\mu}e^{\nu} \tag{15}$$

$$b_{\mu} = \frac{1}{2}\epsilon_{\mu\nu\kappa\lambda}u^{nu}F^{\kappa\lambda} \qquad e_{\mu} = u^{\nu}F_{\mu\nu} \tag{16}$$

They yield the conservation of momentum, energy of a single plasma component, mass, Maxwell equations and the frozen-in condition. $b^2 = b^{\mu}b_{\mu}$ and $e^2 = e^{\mu}_{\mu}$ are magnetic and electric field densities, w is the enthalpy, $g^{\mu\nu}$ Minkowski metric tensor and $F^{\mu\nu}$ and $T^{\mu\nu}$ are electromagnetic and stress-energy tensors (Weinberg, 1972), (Blackman, 1994). When the EM dominated wind is assumed the steady-state solution of 2D Sweet-Parker reconnection is known (Lyutikov & Uzdensky, 2002). Due to the lack of space we cannot describe it here. Generally, the relativistic RMHD MRs are at least γ (Lorentz factor) times more effective than the non-relativistic ones and another dimensionless parameter σ defined in Eq. 1 enters the scene. The density and the resistivity are transformed into their relativistic counterparts $\rho \to \gamma\rho$ and $\eta \to \frac{\eta}{\gamma}$.

Simulations

Although there exists a lot of powerful codes for numerical solving ideal MHD equations computing the simulations of MRs in the non-relativistic regime, only (Zenitani & Hoshini, 2003) has done one for the relativistic case. However it is not a true MHD fluid code but a simulator of a huge number of particles.

Due to Maxwell equations the B and j are coupled quantities, we can freely choose B to describe the system. The basic scheme for the numerical approach in the MHD point of view is the following: 1) set up the initial conditions 2) compute the time step 3) compute the velocity fields (move the particles in the magnetic field) 3) compute new magnetic fields from the new positions of the particles 4) scan for reconnections 5) go to the phase 2.

There are several difficulties in the relativistic regime. The equations are non-linear again. But the main problem is the absence of a privilege reference frame and the relativity of the time step. Accelerating of the particles costs much more energy than in the non-relativistic regime. This heavy non-linearity makes solving of these equations very complicated even through the numerical methods.

We plan to develop a 3D true RMHD code (not a particle simulator) with a grid $512 \times 512 \times 512$ which gives more than 3 GB of the used memory in the simplest second order Lax-Wendroff integration scheme, in the Newtonian regime first. The lack of memory and CPU resources is a serious limitation but the reconnection in 3D would allow much more complex structures of the field lines and more types of reconnection.

We plan to transform the equations into the comoving coordinates governed by the transformation rule $x \to L(t)x'$ and let the system expand during the evolution and see how it will affect the reconnection rate. We will set the initial conditions to be the multi anti-parallel layers and we will use the periodical boundary conditions to express the stochastic nature of the reconnection process.

We will construct a chromo-stereoscopic projection to display the result stored in the form of a 3D data cube.

Conclusions and future plans

We showed that there are some serious doubts about the validity of the mainstream fireball and cannonball models of GRBs and we explained reasons for introducing a new model based on the dissipation of the Poynting flux in the EM dominated plasma wind. We showed that the Fourier analysis of GRB light curves supports the idea that the prompt gamma phase in GRBs could originate in MRs.

We presented our plans to make a 3D simulation of the reconnection model in the framework of special relativity as a possible way of the explanation of the chaotic multi-pulsed GRB light curve.

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