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Simulation of magnetic field dissipation in gamma-ray bursts(*)

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Summary. — We report on the first steps in 3D simulation of magnetic field dissipation in gamma-ray burst (GRB) prompt emission. Our model is based on magnetically driven Poynting flux outflow. We study the evolution of multi-layered anti-parallel magnetic field in expanding self-accelerated systems.

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1. – Introduction

While the *internal shock* model has had some success in reproducing GRB characteristics [1], it suffers from an *efficiency problem* (the relatively low efficiency with which the central engine's energy is converted to prompt gamma-rays), and a *field strength problem* (generating the field strength needed to produce efficient synchrotron emission).

In several of the more promising models of the central engine, a rotating relativistic object powers the outflow. These objects naturally have strong magnetic fields, and the transmission of rotational energy to the outflow via the field (Poynting flux) is also the the most effective ways of satisfying the *baryon loading constraint* (the large energy-to-rest-mass ratio needed to explain GRBs).

Such magnetically powered outflows come in two basic varieties: the DC model (axisymmetric, *e.g.* [2]), and the AC model (flow generated by a central engine with a non-axisymmetric magnetic field, *e.g.* [3]). Their advantage over the internal shock model is that they can produce prompt emission with high (50%) efficiency, naturally provide the strong magnetic field needed for synchrotron emission, and are very effective at accelerating the flow.

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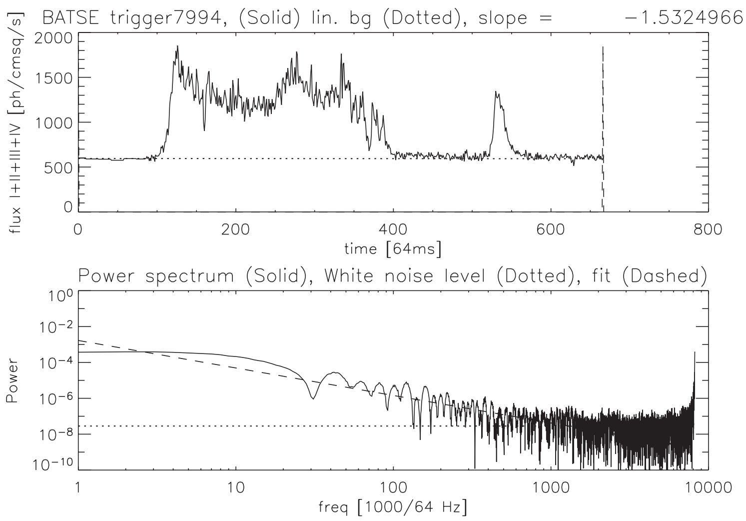

Fig. 1. – Example of the PDS analysis for BATSE trigger 1676. The fitted slope gives the value of $-5/3$.

2. – Power density spectrum

We have done an analysis of 12 long multi-peak GRBs: the BATSE triggers 0108, 1288, 1440, 1676, 2156, 2856, 6472, 7906, 7994, 8001, 8026 and 8036 [4]. We subtracted white noise and we show that the slope of Fourier power density spectrum (PDS) of these GRBs is close to Kolmogorov turbulent spectrum $-5/3$, typical for MHD turbulence and/or magnetic reconnection. The example of the output is shown in fig. 1. High diversity of peaks in the lightcurve yields that the stochastic process we encounter works near the critical regime. This result is in good agreement with the overall analysis made by [5].

3. – Magnetic reconnection

Magnetic reconnection is a consequence of non-ideal MHD. It is associated with a change of the topology of the field lines. Thus the energy trapped in magnetic field can be released and transform to kinetic energy of the particles. The velocity of the outflow is controlled by the reconnection rate $\mathcal{M}$ that represents the efficiency of the process as well.

A natural question arises, can we achieve a feasible configuration in the case of GRBs? There could be an extreme magnetic field $\sim 10^{14}$ G induced, *e.g.* by the α-Ω dynamo process [6]. Also the striped magnetic wind could produce anti-parallel magnetic field behind the the light cylinder of a non-axisymmetric pulsar or a magnetar [7].

4. – Model

We try to run a simulation of the resistive MHD processes in the magnetically driven fireball. We assume a relativistic Poynting flux outflow in the form of a jet where the magnetic reconnections happen.

The interesting part of our model (first suggested in [3]) is that magnetic field dissipation can solve both the acceleration of the jet and the radiation mechanism at once. The law of the energy conservation yields

$$\frac{\mathrm{d}w}{\mathrm{d}t} + \nabla \cdot S = -j \cdot E, \tag{1}$$

where $w = (E^2/8\pi + B^2/8\pi)$ is the electromagnetic energy density and S is the Poynting flux. It can be seen that the energy trapped in the magnetic field and available to dissipate is not only the magnetic energy density $B^2/8\pi$ but the energy driven by $S = B^2/4\pi$. It is useful to think about it in the term of magnetic enthalpy

$$w_m = u_m + p_m. \tag{2}$$

The dissipated magnetic energy is converted into internal energy u_m. This can be radiated away through synchrotron radiation mechanism, if it happens in the optically thin region above the photosphere, or it heats the plasma and let it expand, if it occurs within the photosphere. The dissipation of magnetic field leads to the pressure losses and the pressure gradient accelerates the flow, its Lorentz factor Γ.

5. – Simulation

Because the three dimensions allow much more complex topological structures we decided to build up a pure MHD (not PIC) 3D simulator. The general resistive compressible MHD equations

$$\begin{gathered} \partial_t \rho = -\nabla \cdot (\rho \mathbf{v}), \qquad p\partial_t \mathbf{v} = -\rho(\mathbf{v}\cdot\nabla)\mathbf{v} - \nabla p + \mathbf{j}\times\mathbf{B}, \\ \partial_t U = -\nabla \cdot \mathbf{S}, \qquad \partial_t \mathbf{B} = \nabla \times (\mathbf{v}\times\mathbf{B}) - \nabla \times (\eta \mathbf{j}), \\ \mathbf{E} = -\mathbf{v}\times\mathbf{B} + \eta\mathbf{j}\,, \end{gathered} \tag{3}$$

where the electric current $\mathbf{j}$, internal energy U and Poynting flux defined as follows:

$$\begin{gathered} \mathbf{j} = \frac{1}{\mu_0}\nabla\times\mathbf{B}, \qquad U = \rho w + \frac{\rho}{2}v^2 + \frac{B^2}{2\mu_0}, \\ \mathbf{S} = (U + p + \frac{B^2}{2\mu_0})\mathbf{v} - (\mathbf{v}\cdot\mathbf{B})\frac{\mathbf{B}}{\mu_0} + \eta\mathbf{j}\times\frac{\mathbf{B}}{\mu_0}, \end{gathered} \tag{4}$$

with the pressure defined as $p = (\gamma - 1)\rho w$ and $\gamma = 5/3$. All the quantities are rewritten into dimensionless form. We use one-liquid model, but with locally artificially raised anomal resistivity wherever the virtual drift velocity $|v_D \equiv (m_i/e)\mathbf{j}/\rho| \geq v_{\mathrm{cr}}$, where v_{cr} is parameter of the model.

To describe the expanding nature of the explosion and to keep the ratio between the size of the system and the details constant we introduce spatially symmetrically linearly expanding co-moving frame. We rewrite the equations (3) and (4) according to the transformation rule

$$\mathbf{x}' \to \mathbf{x} + \mathbf{x}v(t)t = \mathbf{x}(1 + v(t)) \equiv L(t)\mathbf{x}\,. \tag{5}$$

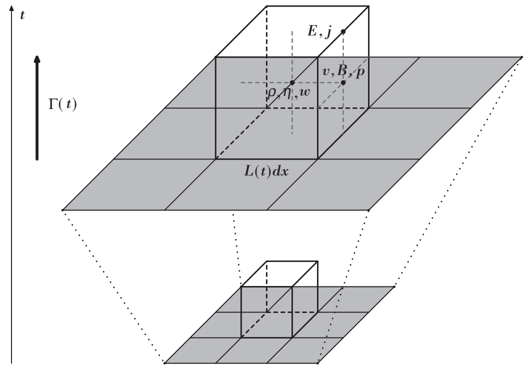

Fig. 2. – Description of the simulation and an elementary cell in the model.

This resembles Hubble expansion. We assume that the reconnection rate $\mathcal{M}$ (we scan for it each step of the simulation) is proportional to the velocity of the bulk motion $\Gamma \sim (1-\alpha)\Delta p_m$ where α represents the fraction of radiated losses. We calculate the reconnections in Newtonian framework using Lax-Wendroff 2nd-order integration scheme, then at the end recalculating (blue-shifting) it from the outflowing jet of $\Gamma(t)$ into the observer frame.

We plan to implement in several pseudo-relativistic tricks into the equations to simulate the special relativistic effects (*e.g.* $\eta \to \eta/\Gamma$, $\rho \to \Gamma\rho$). The sketch of an elementary cell in the simulation is shown in fig. 2.

As initial conditions we have chosen anti-parallel magnetic field multi-layers. The separation between the layers is assumed to be $\lambda = \Gamma 2\pi c/\Omega$, where Ω is the rotational velocity of the magnetic field progenitor, *e.g.* a magnetar. To simulate the stochastic nature of the magnetic reconnection process we use spatially periodic boundary conditions. Due to the technical limits we are restricted to maximally $512 \times 512 \times 512$ cells in the grid/matrix. Each cell contains ρ, $\mathbf{v}$, $\mathbf{E}$, $\mathbf{B}$, η, w, p the particle density, the velocity, the electric and magnetic field, the resistivity, the internal energy and the pressure located in the cell as can be seen from fig. 2. First results are coming soon...

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