Magnetic Field Amplification in Gamma-Ray Bursts due to Non-Thermal Shocks

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Abstract

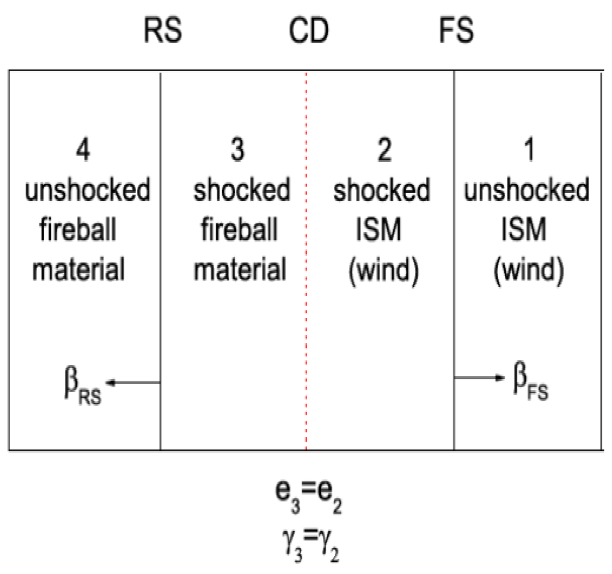
Gamma-ray bursts (GRBs) are one of the most intriguing objects in the universe and **there is growing understanding that magnetic fields play a dominant role in GRBs. Theoretical reasoning, some observations and the analogy with Active galactic nuclei (AGNs) all point to this direction.** In particular the downstream magnetic field, implied by afterglow observations in GRBs, is higher than that of the upstream field (~ μG), by a factor ~ 10^6. Observations indicate that the magnetic field in the downstream region must remain high over distances 10^{10} δ, where δ is the plasma skin depth. Electromagnetic instabilities are believed to create magnetic fields, however only on the order of δ. In this contribution we analyze the effect of the non thermal losses in the shock region and how it affects the amplification of the magnetic field and the coherence scale. This is a work in progress and in this poster we show the results up to now. The next step will be to explore in depth how (Poynting flux) **magnetic dominated relativistic jets can answer the open questions related to the GRBs, including the new puzzles brought by FERMI observations.**

Observations and Models for GRB`s

Strong observational evidence indicates that the observed afterglow arises from synchrotron emission. A relativistic jet with a Lorentz factor Γ~100 punches a hole in the stellar envelope of radius ~10^{10} cm. The kinetic energy of the resultant jet is partially dissipated via internal shocks that take place around ~ 10^{13} – 10^{15} cm. Models in the literature predict that these shocks accelerate electrons to ultra-relativistic energies which emit the prompt gamma-rays. The delayed radiation in the other wavelengths we call afterglow (e.g. Zhang 2011).

Shock Structure in the Standard Fireball Model

The description of the fireball model was given by Piran (2005). In this model we have the formation of two shocks: forward shock (FS) that propagates in the direction of the interstellar medium (ISM) and a reverse shock (RS) that propagates in the direction of the outflow. See figure 1 (Sari, Narayan and Piran 1996).



The set of equations that determines the shock parameters are given by Blandford & Mckee (1976) solutions:

$$\frac{e_2}{n_2 m_p c^2} = \gamma_2 - 1 \cong \gamma_2 \qquad \frac{e_3}{n_3 m_p c^2} = \bar{\gamma}_3 - 1 \qquad \frac{n_3}{n_4} = 4\bar{\gamma}_3 + 3 \qquad \frac{n_2}{n_1} = 4\gamma_2 + 3 \cong 4\gamma_2$$

Where n is the density and gamma the Lorentz factor. The sub-index refers to the different regions in figure 1 (Sari & Piran 1995). The model predicts that the synchroton radiation is emitted by the external forward shock.

Jet Structure and Magnetic Fields

Earlier discoveries by NASA's satellites, Compton-GRB, Swift and the Dutch-Italian satellite Beppo-SAX, as well as theoretical developments have always indicated that the relativistic outflows in GRBs are collimated into narrow jets. Recently, new puzzles have arisen with new observations and in particular, the Fermi satellite has shed new light on this phenomenon. Fermi's observations combined with new theoretical insight indicate that magnetic fields play a much more important role in GRBS than what was previously expected.

Magnetic field generation problem in the afterglow region

As pointed by Waxman (2006), afterglow shocks are highly non-magnetized since the ratio of magnetic field to the kinetic energy is very small ~10^{-10}. On the other hand, the downstream magnetic field implied by the afterglow observations is close to equipartition. Simple shock compression is not enough to explain the observed synchrotron radiation. The challenging point is that in order to account for the synchrotron radiation by the electrons the downstream field must remain close to equipartition deep in the downstream. The point is that the electromagnetic instabilities only generate field on the order of a few skin-depths.

The present model

Here we plan to analyze the effect of the turbulence acting behind the shock region and also in the jet sides (where Kelvin-Helmholtz (K-H) instability may occur). Because the turbulence develops naturally behind the shock (Giacalone & Jokipii, 2007), a turbulent dynamo action can amplify the magnetic field up to the values needed in order to explain the synchrotron radiation. These values are higher than the predicted by simple shock compression. In addition, in the presence of non-thermal losses, the amplification of the plasma density through the shock can be higher than 4Γ (which is predicted by the relativistic Rankine-Hugoniot conditions), depending on the cooling timescale in comparison with the other dynamical timescales of the system. With the magnetic field frozen into the plasma, the increase in density can lead to a significant increase in the magnetic field.

Preliminary Simulations

Interaction of a jet with the external medium was extensively studied in many different scales, using several numerical methods. Energy and matter that enter this structure are pushed aside due to a high pressure gradient and create a hot cocoon around the jet. The cocoon, in turn, compresses the jet and triggers instabilities like the K-H pinch modes we see in Fig. 1. At his stage, we performed MHD numerical simulations of a non-relativistic jet propagating into a dense environment in order to assess the B-field amplification and structure formation. The jet is lighter than the medium, and the density ratio between medium and the jet is R = 0.1. Below we show two snapshots of the density of the evolving jets:

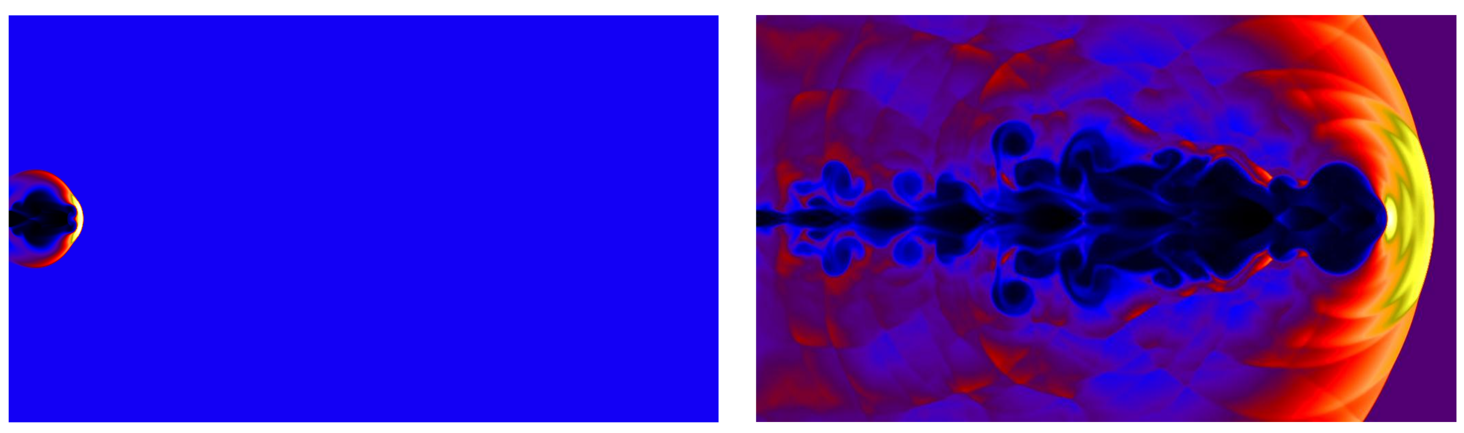


Figure 2 – Two snapshots showing the jet evolution. The color is related to the density. The jet density is lower than the medium density.

The resolution is 1024x512. The velocity field distribution (not shown here) evidences the generation of vorticity in late stages of the jet evolution. The jet has Mach number M =30. We found a magnetic field amplification of 2 orders of magnitude. The magnetic field of the medium is perpendicular the jet.

Conclusions and Perspectives

In the present work we performed preliminary numerical tests of a light jet propagating in a denser and magnetized medium. This is a work in progress and our forthcoming plans are:

- Simulate non-adiabatic jet implementing the cooling effects relevant to the ultrarelatvistic jets associated to GRBs such us as synchrotron, inverse Compton emission, Synchrotron self-compton, and hadronic losses.
- simulate Poynting flux , i.e., magnetically dominated jets.
- implement relativistic effects in order to study in depth the shock structures and the magnetic field effects relevant to understand the physics of the GRBs.

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