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Constraints on Cold Magnetized Shocks in Gamma-Ray Bursts

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ABSTRACT
We consider a model in which the ultra-relativistic jet in a gamma-ray burst (GRB) is cold and magnetically accelerated. We assume that the energy flux in the outflowing material is partially thermalized via internal shocks or a reverse shock, and we estimate the maximum amount of radiation that could be produced in such magnetized shocks. We compare this estimate with the available observational data on prompt γ-ray emission in GRBs. We find that, even with highly optimistic assumptions, the magnetized jet model is radiatively too inefficient to be consistent with observations. One way out is to assume that much of the magnetic energy in the post-shock, or even pre-shock, jet material is converted to particle thermal energy by some unspecified process, and then radiated. This can increase the radiative efficiency sufficiently to fit observations. Alternatively, jet acceleration may be driven by thermal pressure rather than magnetic fields. In this case, which corresponds to the traditional fireball model, sufficient prompt GRB emission could be produced either from shocks at a large radius or from the jet photosphere closer to the center.

Key words: acceleration of particles – MHD – radiation mechanisms: non-thermal – relativistic processes – shock waves – gamma-ray burst: general

1 INTRODUCTION

A great deal of progress has been made in our understanding of gamma-ray bursts (GRBs), thanks to the launch of a number of dedicated satellites (BeppoSAX, HETE-2, Swift and Integral). These satellites rapidly communicate burst locations to ground-based optical and radio telescopes, which has enabled detailed follow up study of the GRB afterglow emission. It is now known that GRBs produce highly relativistic and beamed jets containing energy $\sim 10^{51}$ erg (see Meszaros 2002; Piran 2005; Zhang 2007; Gehrels, Ramirez-Ruiz & Fox 2009, for extensive reviews of these and other developments). It is also well established that there are two classes of GRBs. One class, called long-GRBs — those lasting for more than a few seconds — is produced when a massive star collapses at the end of its nuclear burning life (see Woosley & Bloom 2006 for a review). For the other class, called short-GRBs – those lasting for less than a few seconds – at least some members are believed to result from mergers of compact stars in binary systems (Gehrels et al. 2009, and references therein).

Despite this impressive progress, several fundamental questions remain unanswered. Foremost among these is the composition of the relativistic jets that power GRBs. We do not know whether GRB jets consist of a normal proton-electron plasma or if they are dominated by electron-positron pairs. Furthermore, it is uncertain whether the jets are dominated by matter or magnetic fields (Poynting outflow). The related question of how the observed γ-ray radiation is produced is also poorly understood.

A popular model for converting jet energy to particle thermal energy and thereby to radiation is the internal shock model (Narayan et al. 1992; Rees, Meszaros 1994; Sari & Piran 1997). According to this model, the relativistic wind from the central engine of a GRB has a variable Lorentz factor, which leads to collisions between faster and slower moving ejecta. A fraction of the kinetic energy of the jet is converted to thermal energy in these "internal" shocks. A fraction of this thermal energy then goes into electrons and is rapidly radiated away as γ-ray photons via synchrotron and inverse-Compton processes. The internal shock model naturally produces the rapid variability observed in the γ-ray emission of GRBs (Sari & Piran 1997). This is one of its principal virtues.

The internal shock model, however, has a problem, viz., the efficiency ϵ_γ (see eq. 12 for the definition) for converting jet energy to radiation is relatively low (Kumar 1999; Lazzati, Ghisellini & Celotti 1999; Panaitescu, Spada & Meszaros 1999). The efficiency depends on the relative Lorentz factor of the colliding blobs, and also, in the case of magnetized ejecta, on the jet magnetization parameter σ (defined in eq. 2). Since the efficiency ϵ_γ of a GRB can be measured directly from observations of the prompt and afterglow emission, we can constrain the parameters of the internal shock model, notably the magnetization σ of the jet material.

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Another location where the jet energy may possibly be converted to γ-rays might be the deceleration radius where the jet starts to slow down as a result of its interaction with an external medium. Two shocks are formed in this interaction, one of which, the "forward" shock, heats up the external medium and produces the afterglow emission, and the other, the "reverse" shock, propagates into the GRB jet. The energy released in the reverse shock could be radiated as γ-rays via synchrotron and/or inverse-Compton processes.[1] The efficiency for converting jet energy to γ-rays depends on various parameters, including the σ of the jet material.

Thus, in either the internal shock model or the reverse shock model, the γ-ray efficiency ϵ_γ depends on the magnetization σ of the jet. The present work is motivated by the fact that, under some circumstances, we can independently estimate σ for a GRB jet. This follows from the recent work of Tchekhovskoy, Narayan & McKinney (2010b) who studied the properties of a magnetically accelerated GRB jet. If the jet material is cold, i.e., there is no thermal pressure, and all the acceleration is from electromagnetic forces (Poynting-dominated jet), these authors show that σ can be estimated from the terminal Lorentz factor γ_j and the opening angle θ_j of the jet. Both of the latter quantities can be measured from afterglow data. We thus have an opportunity to check if the values of σ obtained from observations of GRB afterglows are consistent with the γ-ray efficiencies ϵ_γ measured for the same GRBs. Carrying out this test is our goal.

In §2 we write down the standard jump conditions for a magnetized relativistic "perpendicular" shock in which the magnetic field is perpendicular to the flow velocity (or parallel to the shock front). By solving the jump conditions, we calculate the efficiency with which the kinetic energy of a cold relativistic magnetized fluid is converted by the shock to thermal energy. In §3, we calculate the efficiency of the internal shock model and compare it against observations, and in §4, we carry out a similar exercise for the reverse shock model. In both cases, we show that there is an inconsistency between the predictions of the model and measured values of ϵ_γ and σ. We discuss the implications of this result in §5 and suggest possible solutions.

2 RELATIVISTIC PERPENDICULAR SHOCK

2.1 Preliminaries

The problem of interest was discussed in detail by Kennel & Coroniti (1984, hereafter KC84). We follow their methods with a few minor changes. We consider a cold magnetized fluid with a magnetic field strength B_0 in its rest frame. We assume ideal magnetohydrodynamics (MHD) and set the electric field in the rest frame to zero. Transforming to a frame in which the magnetized fluid moves with dimensionless velocity $\beta = v/c$, Lorentz factor $\gamma = 1/\sqrt{1-\beta^2}$, in a direction perpendicular to the magnetic field, the magnetic and electric fields become

$$B = \gamma B_0, \qquad E = uB_0 = \frac{u}{\gamma}B, \qquad u = \beta\gamma = (\gamma^2-1)^{1/2}, \tag{1}$$

where u is the relativistic 4-velocity. The fields B and E in the new frame are parallel and perpendicular, respectively, to B_0, and each is also perpendicular to the velocity.

[1] It would be very difficult to produce the observed γ-ray variability in the reverse shock model unless there is relativistic turbulence in the shocked fluid (Narayan & Kumar 2009; Lazar, Nakar & Piran 2009).

We define the magnetization parameter σ of the moving fluid as the ratio of the Poynting energy flux to the particle rest energy flux. Thus

$$\sigma = \frac{cEB/4\pi}{n\gamma umc^3} = \frac{B^2/4\pi}{n\gamma^2mc^2} = \frac{B_0^2/4\pi}{nmc^2}, \tag{2}$$

where n is the particle number density in the fluid rest frame and m is the mass of each particle. In the final expression, the numerator is the rest frame "enthalpy" of the magnetic field, which is equal to $[\Gamma_B/(\Gamma_B-1)](B_0^2/8\pi)$ (taking the adiabatic index of the magnetic field $\Gamma_B = 2$ for compression transverse to the field), and the denominator is the rest energy density. Since we see that σ depends only on rest frame quantities, it is a relativistic invariant and is frame-independent. KC84 use a slightly different definition of σ where they replace γ^2 in the denominator of the third quantity in equation (2) by γu. As a result, their σ is not truly frame-independent. However, the difference between the two definitions is negligibly small for highly relativistic flows.

2.2 Jump Conditions

We follow KC84, except that we use the definition of σ given in equation (2) and avoid certain approximations. We use subscript u for the gas upstream of the shock and subscript d for the downstream gas. The upstream gas is cold ($P_u = 0$), has a magnetization parameter σ, rest number density n_u, and moves with Lorentz factor γ_u in the frame of the shock. The downstream gas is hot ($P_d \neq 0$) with adiabatic index Γ, has number density n_d, and Lorentz factor γ_d. In the shock frame, the magnetic fields in the two regions, B_u and B_d, are related by

$$B_d = \frac{\gamma_d}{u_d}E_d = \frac{\gamma_d}{u_d}E_u = \frac{\gamma_d u_u}{\gamma_u u_d}B_u, \tag{3}$$

where we have used the fact that the electric field is continuous across the shock.

The upstream and downstream gas enthalpy per particle are, respectively,

$$\mu_u = mc^2, \qquad \mu_d = mc^2\left[1 + \frac{\Gamma}{(\Gamma-1)}\,\frac{P_d}{n_d mc^2}\right]. \tag{4}$$

The second term inside the square brackets is a dimensionless number which describes the thermal enthalpy per particle of the shocked gas. It can be written as

$$\frac{\Gamma}{(\Gamma-1)}\,\frac{P_d}{n_d mc^2} = h(\theta_d)\theta_d, \quad \theta_d = \frac{P_d}{n_d mc^2} = \frac{kT_d}{mc^2}, \quad h(\theta_d) = \frac{\Gamma}{\Gamma-1}, \tag{5}$$

where θ_d is the relativistic temperature of the downstream gas. When $\theta_d \ll 1$, the gas is non-relativistic, and we have $\Gamma = 5/3$, $h(\theta_d) = 5/2$, whereas when $\theta_d \gg 1$, the gas is ultra-relativistic, and we have $\Gamma = 4/3$, $h(\theta_d) = 4$. At intermediate temperatures ($\theta_d \sim 1$), $h(\theta_d)$ can be written in terms of modified Bessel functions (see Chandrasekhar 1960). For simplicity, we use the following approximation (Service 1986),

$$h(\theta) = \frac{10+20\,\theta}{4+5\,\theta}, \tag{6}$$

which is sufficiently accurate for our purposes. In principle, if the jet material consists of a normal electron-proton plasma, we should allow for two species of particles in the shocked gas, each with a different temperature. We ignore this complication for simplicity.

A5 Weak Non-Relativistic Shock with Weak Magnetization: $1 \gg \beta_u^2 \to \sigma$

Finally, we consider the case when the shock is non-relativistic and $\beta_u = \sqrt{\sigma}(1+\Delta)$ with $\sqrt{\sigma} \ll \Delta \ll 1$. In this limit, we find

$$\beta_d \approx \left(1 - \frac{1}{3}\Delta + \frac{46}{81}\Delta^2\right)\sqrt{\sigma} + o\left(\Delta^2\sqrt{\sigma}\right), \tag{A16}$$

$$\frac{B_d}{B_u} \approx 1 + \frac{4}{3}\Delta - \frac{10}{81}\Delta^2 + o\left(\Delta^2\right), \tag{A17}$$

$$\theta_d \approx \left(\frac{32}{81}\Delta^3 - \frac{112}{243}\Delta^4\right)\sigma + o\left(\Delta^4\sigma\right). \tag{A18}$$

APPENDIX B: THE RELATIVITY PARAMETER ξ

We generalize the discussion of the parameter ξ given in SP95, following the analysis of Giannios et al. (2008). We consider a spherically expanding shell of cold magnetized jet material of radius R, shell thickness Δ, and Lorentz factor γ_j, all measured in the lab frame. The "spreading radius" of the shell is given by

$$R_s = \gamma_j^2\Delta. \tag{B1}$$

The total (isotropic equivalent) energy of the shell is

$$E = 4\pi R^2\Delta n_4 mc^2\gamma_j^2(1+\sigma) \equiv M_{\rm ej}\gamma_j c^2(1+\sigma), \tag{B2}$$

where n_4 is the rest frame particle number density of the jet material, σ is the magnetization of the material, and $M_{\rm ej}$ is the total rest mass of the shell. From E, we obtain the "Sedov length" ℓ and the "deceleration radius" $R_{\rm dec}$,

$$\ell = \left(\frac{3E}{4\pi n_1 mc^2}\right)^{1/3} = \left[\frac{3M_{\rm ej}\gamma_j(1+\sigma)}{4\pi n_1 m}\right]^{1/3}, \tag{B3}$$

$$R_{\rm dec} = \frac{\ell}{\gamma_j^{2/3}} = \left[\frac{3M_{\rm ej}(1+\sigma)}{4\pi n_1 m\gamma_j}\right]^{1/3}, \tag{B4}$$

where n_1 is the number density of the external ambient medium. Substituting for $M_{\rm ej}$ (with $R = R_{\rm dec}$) in the equation for $R_{\rm dec}$, we find that

$$R_{\rm dec} = 3\Delta\,\frac{n_4}{n_1}\,(1+\sigma), \tag{B5}$$

from which we obtain

$$\xi = \left(\frac{R_{\rm dec}}{R_s}\right)^{1/2} = \left[\frac{3}{\gamma_j^2}\,\frac{n_4}{n_1}\,(1+\sigma)\right]^{1/2}. \tag{B6}$$

Note that n_4 is the number density of the jet ejecta at the moment when the shell radius R is equal to $R_{\rm dec}$.

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