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$e^{\pm}$ PAIR LOADING AND THE ORIGIN OF THE UPSTREAM MAGNETIC FIELD IN GRB SHOCKS

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ABSTRACT

We investigate here the effects of plasma instabilities driven by rapid $e^{\pm}$ pair cascades, which arise in the environment of GRB sources as a result of back-scattering of a seed fraction of their original spectrum. The injection of $e^{\pm}$ pairs induces strong streaming motions in the ambient medium. One therefore expects the pair-enriched medium ahead of the forward shock to be strongly sheared on length scales comparable to the radiation front thickness. Using three-dimensional particle-in-cell simulations, we show that plasma instabilities driven by these streaming $e^{\pm}$ pairs are responsible for the excitation of near-equipartition, turbulent magnetic fields. Our results reveal the importance of the electromagnetic filamentation instability in ensuring an effective coupling between $e^{\pm}$ pairs and ions, and may help explain the origin of large upstream fields in GRB shocks.

Subject headings: gamma rays: bursts – instabilities – magnetic fields – plasmas – shock waves

1. INTRODUCTION

More than three decades ago, it was pointed out that γ-rays produced in sufficiently luminous and compact astrophysical sources would create $e^{\pm}$ pairs by collisions with lower energy photons: $\gamma\gamma \rightarrow e^+e^-$ (Jelley 1966). This mechanism both depletes the escaping radiation at high energies and also changes the composition and properties of the radiating gas through the injection of new particles. An approximate condition for such pair creation to become significant is that a sizable fraction of the radiation from the object be emitted above the electron mass energy, $m_ec^2 = 511$ keV, and that the compactness of the source,

$$l = \frac{L\sigma_T}{4\pi r_l m_e c^3}, \tag{1}$$

exceeds 1, where L is the total luminosity, and r_l is the characteristic source dimension. When $l \sim 1$, a photon of energy $\epsilon = h\nu/m_ec^2 \sim 1$ has an optical depth of unity for creating an $e^{\pm}$ pair.

As an illustration consider a spherical source with a spectrum emitting a power L in each decade of frequencies. l would be > 1 for γ-rays of energy ϵ if the radius of the source satisfies

$$r_l \leq 10^{17}\epsilon\left(\frac{L}{10^{49}\mathrm{erg\ s^{-1}}}\right)\mathrm{cm}. \tag{2}$$

The relevant values of L range from $10^{50} - 10^{52}$ erg s^{-1} for GRBs. In addition, the short spikes observed in the high energy light curves suggest that GRBs dissipate a significant fraction of their energy at $r \ll r_l$, so that the source is indeed so small that equation (2) is easily satisfied. This argument is, however, only applicable to γ-ray photons emitted isotropically and is alleviated when the radiating source itself expand at a relativistic speed (Piran 1999). In this case, the photons are beamed into a narrow angle $\theta \sim 1/\Gamma$ along the direction of motion, and, as a result, the threshold energy for pair production within the beamed is increased to $\epsilon \sim \Gamma$.

The non-thermal spectrum of GRB sources is therefore thought to arise in shocks which develop beyond the radius at which the relativistic fireball has become optically thin to $\gamma\gamma$ collisions (Piran 1999). However, the observed spectra are hard, with a significant fraction of the energy above the $\gamma\gamma \rightarrow e^+e^-$ formation energy threshold, and a high compactness parameter can result in new pairs being formed outside the originally optically thin shocks responsible for the primary radiation (Thompson & Madau 2000). Radiation scattered by the external medium, as the collimated γ-ray front propagates through the ambient medium, would be decollimated, and, as long as $l \gtrsim 1$, absorbed by the primary beam. An $e^{\pm}$ pair cascade can then be produced as photons are back-scattered by the newly formed $e^{\pm}$ pairs and interact with other incoming seed photons (Thompson & Madau 2000; Beloborodov 2002, 2005; Mészáros et al. 2001; Ramirez-Ruiz et al. 2002; Li et al. 2003; Kumar & Panaitescu 2004).

In this *Letter*, we consider the plasma instabilities generated by rapid $e^{\pm}$ pair creation in GRBs. The injection of $e^{\pm}$ pairs induces strong streaming motions in the ambient medium ahead of the forward shock. This sheared flow will be Weibel unstable (Medvedev & Loeb 1999), and if there is time before the shock hits, the resulting plasma instabilities will generate sub equipartition quasi-static long-lived magnetic fields on the collisionless temporal and spatial scales across the $e^{\pm}$ pair-enriched region. This is studied in §3 using three-dimensional kinetic simulations of monoenergetic and broadband pair plasma shells interpenetrating an unmagnetized medium. The importance of the electromagnetic filamentation instability in providing an effective coupling between $e^{\pm}$ pairs and ions is investigated in §2. The implications for the origin of the upstream magnetic field, in particular in the context of constraints imposed by observations of GRB afterglows, are discussed in §4.

2. PAIR LOADING AND MAGNETIC FIELD GENERATION

Given a certain external baryon density n_p at a radius r outside the shocks producing the GRB primordial spectrum, the initial Thomson scattering optical depth is $\tau \sim n_p\sigma_T r$ and a fraction τ of the primordial photons will be scattered back, initiating a pair $e^{\pm}$ cascade. Since the photon flux drops as r^{-2}, for a uniform (or decreasing) external ion density most of the scattering occurs between r and $r/2$, and the scattering and pair formation may be approximated as a local phenomenon.

Consider an initial input GRB radiation spectrum of the form $F(\epsilon) = F_b(\epsilon/\epsilon_b)^{-\alpha}$ for $\epsilon > \epsilon_b$, where $\epsilon_b \sim 0.2 - 1.0$ is the

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break energy above which the spectral index $\alpha \sim 1-2$ (for the present purposes the exact low energy slope is unimportant). Radiation scattered by the external medium is therefore decollimated, and then absorbed by the primary beam.The impact of such process strongly depends on how many photons each electron is able to scatter (Beloborodov 2002)

$$\lambda_T \sim 4\times 10^8 \left(\frac{r_l}{10^{15}\,\mathrm{cm}}\right)^2 \left(\frac{L}{10^{51}\,\mathrm{erg\,s^{-1}}}\right)\,\mathrm{cm} < \Delta, \quad (3)$$

where $\lambda_T = 1/(n_\gamma \sigma_T) \approx c/(F_b \sigma_T)$ is the electron mean free path and n_γ is the photon density. The photons forced out from the beam by the electrons can then produce $e^\pm$ pairs as they interact with incoming photons, so that a large number of scatterings implies a large number of pairs created per ambient electron.

At some distance $\varpi \leq \Delta$ from the leading edge of the radiation front, the number of photons scattered by one ambient electron is $\sim \varpi/\lambda_T$ and a fraction $\sim \varpi/\lambda_{\gamma\gamma}$ of these photons are absorbed Beloborodov (2002). One $e^\pm$ pair per ambient electron is injected when $\varpi = (\lambda_T \lambda_{\gamma\gamma})^{1/2} \approx \lambda_T \epsilon_{\rm th}^{\alpha/2}/[\Pi(\alpha)]^{1/2} \geq \lambda_T$, where $\Pi(\alpha) = 2^{-\alpha}(7/12)(1+\alpha)^{-5/3}$ (Svensson 1987) and $\epsilon_{\rm th}$ is the photon threshold energy for $e^\pm$ formation. For $1.5 \lesssim \alpha \lesssim 2$, one has $15\lambda_T \lesssim \varpi_l \lesssim 25\lambda_T$, so that pair creation substantially lags behind electron scattering (Beloborodov 2002).

Most of the momentum deposited through this process involves the side-scattering of very soft photons, which collide with hard γ-rays to produce energetic (and almost radially moving) pairs. A photon of energy $\epsilon_r \ll 1$ that is side-scattered through an angle $\sim \theta_r$ creates a pair if it collides with another photon with energy exceeding $\epsilon_{\rm th} \sim 4(\theta_r^2 \epsilon_r)^{-1}$. The injected pair will be relativistic with $\gamma_\pm \sim \epsilon_{\rm th} \geq 1$. The distribution of injected pairs is therefore directly determined by the high energy spectral index α. This motivates our study in §3 of radially streaming, relativistic pair plasma shells with a broadband kinetic energy distribution interpenetrating an unmagnetized medium.

This pair-dominated plasma, as long as its density $n_\pm \lesssim n_p(m_p/2m_e)$, is initially held back by the inertia of its constituent ions, provided that the pairs remain coupled to the baryons (Thompson & Madau 2000; Beloborodov 2002). The latter is likely to be the case in the presence of weak magnetic fields (Thompson & Madau 2000). In the absence of coupling, the pair density would not exponentiate, mainly due to the $(1-\beta)$ term in the scattering cross section, where $\beta = v/c$. Instabilities caused by pair streaming relative to the medium at rest, as we argued in §3, are able to generate long-lived magnetic fields on the collisionless temporal and spatial scales, which are modest multiples of the electron plasma frequency, $\omega_e = (4\pi e^2 n_e/m_e)^{1/2}$, and the collisionless skin depth,

$$\lambda_e = \frac{c}{\omega_e} \sim 5\times 10^5 \left(\frac{n_e}{1\,\mathrm{cm}^{-3}}\right)^{-1/2} \ll \lambda_T < \lambda_{\gamma\gamma}. \quad (4)$$

Here n_e is the electron number density. Plasma instabilities therefore evolve faster than the time between successive scatterings and much before the scattered photons are absorbed by the primary radiation (Beloborodov 2002). In the presence of transverse magnetic field B the pairs gyrate around the field lines frozen into the medium on the Larmor time, $\omega_B^{-1} = m_e c/(Be)$. The net momentum of the $e^\pm$ pairs is thus efficiently communicated to the medium. Magnetic coupling may dominate if $\omega_B > \omega_e$, which requires $B^2/4\pi > n_e m_e c^2$ (Beloborodov 2002). In what follows we assume the scattering medium to be composed purely of $e^\pm$ pairs since it greatly simplifies the calculations.

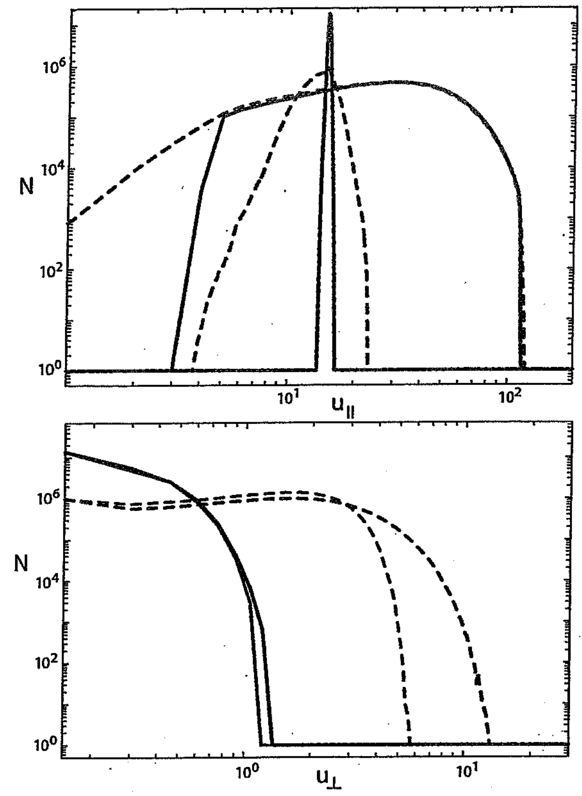

FIG. 1.— $e^\pm$ pair momentum distribution functions at $t = 20.8\omega_e^{-1}$ (*solid* curves) and $t = 59.8\omega_e^{-1}$ (*dotted* curves). The *blue* (*red*) curves are for a monoenergetic (broadband) initial momentum distribution function. The *top* (*bottom*) panel show the distribution functions for particles moving parallel (perpendicular) to the injected $e^\pm$ pair plasma.

3. THE WEIBEL INSTABILITY IN $e^\pm$ PAIR CASCADES

3.1. *Simulation Model*

Here we illustrate the main features of the collision of an $e^\pm$ pair plasma shell into an unmagnetized medium, initially at rest, using a modified version of the PIC code TRISTAN – first developed by (Buneman 1993) and most recently updated by (Nishikawa et al. 2005, 2006). The simulations were performed on a 85 × 85 × 640 grid (the axes are labeled as x, y, z) with a total of 3.8×10^8 particles for 4600 time steps, with periodic ([x,y] plane) and radiative (z direction) boundary conditions. In physical units, the box size is $8.9 \times 8.9 \times 66.7\,(c/\omega_e)^3$, and the simulations ran for $60(\omega_e)^{-1}$.

In the simulations, a charge-neutral plasma shell, consisting of $e^\pm$ pairs and moving with a bulk momentum $u_z = \gamma_0 v_z/c$ along the z direction, penetrates an ambient plasma initially at rest. Here γ_0 is the initial Lorentz factor of the pairs and v_z is the bulk velocity of the shell along z. Pairs are continuously injected at $z = 2.6\lambda_e = 25\Lambda$, where $\Lambda = \lambda_e/9.6$ is the grid size. The $e^\pm$ pairs in the ambient medium (i.e., a mass ratio m_e/m_p of 1) have a thermal spread with an rms velocity $v_{\rm th}/c = 0.1$. The shell and the ambient plasma have a pair density ratio of 0.75. Two different bulk Lorentz factor configurations for the injected (cold) pairs are considered: a monoenergetic ($u_z = 15.0$, $v_{\rm th}/c = 0.01$) and a broadband distribution ($4.0 \leq u_z \leq 100.0, v_{\rm th}/c = 0.01$). Both distributions have similar kinetic energy contents and plasma temperatures (Fig 1).