PARTICLE ACCELERATION IN GAMMA-RAY BURST JETS

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ABSTRACT

The gradual shear acceleration of energetic particles in gamma-ray burst (GRB) jets is considered. Special emphasis is given to the analysis of universal structured jets, and characteristic acceleration timescales are determined for a power-law evolution and a Gaussian evolution of the bulk flow Lorentz factor \( \gamma_b \) with angle \( \phi \) from the jet axis. The results suggest that local power-law particle distributions may be generated and that higher energy particles are generally concentrated closer to the jet axis. Taking several constraints into account, we show that efficient electron acceleration in gradual shear flows, with maximum particle energy successively decreasing with time, may be possible on scales larger than \( r \sim 10^{15} \) cm, provided the jet magnetic field becomes sufficiently weak and/or decreases rapidly enough with distance, while efficient acceleration of protons to ultrahigh energies \( >10^{20} \) eV may be possible under a wide range of conditions.

Subject headings: acceleration of particles — gamma rays: bursts

1. INTRODUCTION

There is mounting evidence today that gamma-ray bursts (GRBs) are associated with collimated relativistic outflows or jets (Rhoads 1999; Kulkarni et al. 1999; Greiner et al., 2003). It is still a matter of ongoing research, however, what types of internal structures are actualized within these jets. Within the fireball framework, for example, two different kinds of jet models seem to be compatible with the observations, i.e., (1) the uniform “top-hat” jet model (Rhoads 1999; Frail et al. 2001; Lamb et al. 2004), in which all the hydrodynamical quantities (e.g., Lorentz factor, energy density) are essentially the same within some well-defined opening angle \( \phi_j \) around the jet axis but sharply drop outside of \( \phi_j \), and (2) the universal structured (“power-law” or “Gaussian”) jet model (Rossi et al. 2002; Zhang & Meszaros 2002; Kumar & Granot 2003; Zhang et al. 2004), in which the hydrodynamic quantities are rather smooth functions of the angle \( \phi \) from the jet axis.

Here we analyze the implications of such jet structures for the acceleration of energetic particles. We focus on shear acceleration as a promising mechanism for converting the kinetic energy of the flow into nonthermal particles and radiation. Such a mechanism has previously been successfully applied to the relativistic jets in active galactic nuclei (Ostrowski 1998, 2000; Rieger & Duffy 2004, 2005a, 2005b). Shear acceleration is based on the simple fact that particles may gain energy by scattering off (small-scale) magnetic field irregularities with different local velocities due to being systematically embedded in a collisionless shear flow (cf. Rieger & Duffy 2005b for a recent review). In the case of nonrelativistic shear acceleration, it is straightforward to show that local power-law particle momentum distributions \( f(p) \propto p^{-(\alpha+1)} \) can be generated, assuming a momentum-dependent mean scattering time of the form \( \tau \propto p^{\alpha+1} \), with \( \alpha > 0 \) (cf. Berezhko & Krymskii 1981; Rieger & Duffy 2005a). Hence, for \( \tau \) scaling with the gyroradius, i.e., \( \tau \propto p \), this results in a power-law particle number density \( n(p) \propto p^2 f(p) \propto p^{-2} \) and thus a synchrotron emissivity \( j_s \propto p^{-1/2} \).

2. SHEAR ACCELERATION IN STRUCTURED GRB-TYPE JETS

Let us consider an idealized radial, relativistic flow profile, which in four-vector notation is given by (see F. M. Rieger & P. Duffy, 2005, in preparation, for the more general case)

\[
u^a = \gamma_b [1, v_r(\phi)/c, 0, 0],
\]

where \( \alpha = 0, 1, 2, \) and 3 and \( \phi \) denotes the polar angle in spherical coordinates, and \( \gamma_b = \gamma_b(\phi) = [1 - v_r(\phi)/c^2]^{-1/2} \) is the bulk Lorentz factor of the flow. In the comoving frame, the related gradual shear acceleration coefficient can be cast into the form (e.g., Webb 1989, eq. [3.27])

\[
\langle p' \rangle = \frac{1}{(p')^2} \frac{\partial}{\partial p} [(p')^4 \Gamma],
\]

where \( p' \) denotes the comoving particle momentum, \( \tau' = \chi' c \) is the mean scattering time, and \( \Gamma \) is the relativistic shear coefficient. We are interested in the strong scattering limit (corresponding to \( \omega_s \tau' \ll 1 \), with \( \omega_s \) being the relativistic gyrofrequency measured in the comoving jet frame, i.e., assuming a sufficiently weak longitudinal mean magnetic field and the presence of strong turbulence, so that collisions are efficient enough to restore isotropy), where the shear coefficient is given by \( \Gamma = (c^2/30) \sigma_{\alpha \beta} \sigma^{\alpha \beta} \) (see Webb 1989, eq. [3.34]) and \( \sigma_{\alpha \beta} \) with \( \alpha, \beta = 0, 1, 2, \) and 3, is the usual covariant fluid shear tensor (cf. Webb 1989, Rieger & Duffy 2004, and F. M. Rieger & P. Duffy, 2005, in preparation, for more details). Using spherical coordinates and the velocity profile above, it can be shown that the relativistic shear coefficient becomes (cf. F. M. Rieger & P. Duffy, 2005, in preparation)

\[
\Gamma = \frac{4}{45} \gamma_b^2 \left[ \frac{v_r^2}{v^2} + \frac{3}{4 \gamma_b^2} \frac{\partial v_r}{\partial \phi} \right] \left( \frac{\partial v_r}{\partial \phi} \right)^2,
\]

which in the nonrelativistic limit (\( \gamma_b \rightarrow 1 \)) reduces to the (non-relativistic) viscous transfer coefficient derived by Earl et al. (1988; their eq. [7]) when the latter is expressed in spherical coordinates and the corresponding velocity profile \( v = \ldots \)
$v_c(\phi)e$, is applied. The (comoving) timescale $t_{\text{acc}} \approx \left\langle p' \right\rangle / \left\langle p'' \right\rangle$ for the shear flow acceleration of particles then becomes

$$t_{\text{acc}}(r, \phi) \approx \frac{45}{4(4 + \alpha)} \frac{c^2}{\gamma_0^2} \left[ v_r^2 + 0.75 \gamma_0^2 (\partial v/\partial \phi)^2 \right],$$

where $r$ is the radial coordinate measured in the cosmological rest frame (i.e., the supernova, collapsar, or merger rest frame) and where a power-law dependence $\gamma' = \lambda/c \propto p^\alpha$ has been assumed. As the jet flow is diverging, $t_{\text{acc}}$ obviously increases with $r$ to the square. In order to investigate the acceleration potential of structured GRB jets, two applications appear particularly interesting (e.g., Zhang & Mészáros 2002; Kumar & Granot 2003; Zhang et al. 2004): a power-law model, in which $\gamma_0$ is a power-law function of $\phi$ outside a core of opening angle $\phi_c$, i.e.,

$$\gamma_0(\phi) = 1 + (\gamma_{00} - 1)[1 + (\phi/\phi_c)^2]^{-\beta/2},$$

with $1.5 < \beta \leq 2$ (cf. Zhang & Mészáros 2002), and a Gaussian model with $\gamma_0(\phi) = 1 + (\gamma_{00} - 1) \exp(-\phi^2/2\phi_c^2)$, where $\gamma_{00}$ denotes the Lorentz factor at the jet axis and typically $\phi_c = 0.1$ rad (Zhang et al. 2004). The shear acceleration timescale (with the time and space coordinates measured in the cosmological rest frame and the particle Lorentz factor measured in the comoving jet frame) then becomes

$$t_{\text{acc}}(r, \phi) = \frac{45}{4(4 + \alpha)} \frac{c^2}{\gamma_0^2} \left[ v_r^2 + \frac{3}{4} \left[ \gamma_0(\phi) - 1 \right] \left( \gamma_0(\phi) + 1 \right) \phi_r^2 \phi_c^2 \right],$$

where

$$\begin{cases} \left( \frac{v_r^2}{c^2} + \frac{3}{4} \left[ \gamma_0(\phi) - 1 \right] \phi_r^2 \phi_c^2 \right)^{-1} \text{power-law model,} \\ \left( \frac{v_r^2}{c^2} + \frac{3}{4} \left[ \gamma_0(\phi) - 1 \right] \phi_r^2 \phi_c^2 \right)^{-1} \text{Gaussian model.} \end{cases}$$

Note that in contrast to nonrelativistic parallel shock acceleration, $t_{\text{acc}} \propto 1/\lambda$ as the probability of a particle sampling a higher shear, and thus a more energetic scattering event increases with $\lambda$. The general evolution of $t_{\text{acc}}/t_0$ as a function of $\phi$, with $t_0 = 45r^2/[4(4 + \alpha)\lambda c]$, is illustrated in Figure 1, indicating that a power-law model becomes somewhat more favorable than a Gaussian model. Obviously, the shear acceleration timescale in structured jets generally increases with $\phi$ due to the decrease in $\gamma_{00}$ suggesting different maximum attainable energies in the local comoving frame. Hence, at constant $r$, the higher energy particles and thus the higher energy emission are expected to be naturally concentrated closer to the jet axis, i.e., toward smaller $\phi$ (provided the magnetic field is not very inhomogeneous across the jet), enforcing the effect that observers looking at the same GRB from different directions will see different gamma-ray light curves.

In general, several constraints need to be satisfied in order to allow for efficient particle acceleration in GRB jets; e.g., the particle acceleration process may be limited by (1) radiative synchrotron losses, (2) the transversal confinement size, (3) particle escape via cross-field diffusion, or (4) the duration of the jet expansion. The first constraint implies that the acceleration timescale has to be smaller than the comoving synchrotron cooling timescale, which, for particles with Lorentz factors $\gamma'$ and isotropic pitch angle distribution, is given by

$$t_{\text{cool}} = \frac{9m_e^2c^5}{4e^4} \frac{1}{\gamma' B^2} = 4.8 \times 10^{12} \left( \frac{1}{\gamma'} \right) \left( \frac{m_p}{m_e} \right)^{2/3} \left( \frac{10^1 G}{B'} \right)^2 \text{[s]},$$

with $m_p$ being the proton mass. According to equation (5), the minimum shear acceleration timescale is

$$t_{\text{acc}} \sim \frac{5}{2} \frac{r^2}{c\lambda \gamma_{00}^2},$$

so that for a gyro-dependent particle mean free path $\lambda' = \xi r_c$, with $\xi < 1$ (as motivated by the observationally implied particle spectra with momentum index $\sim -2$), the ratio of shear to cooling timescale becomes independent of the particle Lorentz factor. Note that equation (7) is also the timescale for a uniform flow with $v$, independent of $\phi$ (cf. eq. [4])! For a given magnetic field strength, the acceleration process may thus work effi-
ciently as long as the velocity shear remains sufficiently high, i.e., as long as the radial coordinate satisfies

\[ r < 4 \times 10^3 \xi^{1/2} \left( \frac{m_p}{m} \right)^2 \left( \frac{10^4 \, G}{B^2} \right) \left( \frac{\gamma_i}{300} \right) \text{[cm]}, \]

suggesting that, in contrast to the acceleration of protons, efficient electron acceleration is suppressed in the presence of high magnetic fields. It seems very likely, however, that due to the expansion of the wind, the comoving magnetic field \( B' \) will depend inversely on \( r \); i.e., \( B' \propto 1/r^\beta \) with \( \beta > 0 \). In order to study possible implications in more details, we may thus consider the following simple parameterization for the comoving jet magnetic field strength, \( B' = 1000 b_0 (10^{13} \text{ cm}/r)^\beta \) G. For \( \beta = 1 \) and \( b_0 = 30 \), this expression corresponds to the lower limit required by Waxman (1995) in order to allow for efficient (second-order) Fermi-type acceleration of protons to ultrahigh energies during expansion of the wind (cf. his eq. [4a]). While it can be shown then that proton acceleration is nearly unconstrained by radiative synchrotron losses, electron acceleration can only work efficiently if the field decays rapidly enough and becomes comparatively weak; e.g., for \( \beta = 2 \), efficient electron acceleration may occur for \( r > 10^2 \xi^{-1/2} \left( 300/\gamma_i \right)^{3/2} \text{ cm} \).

The second constraint requires the particle mean free path \( \lambda' \) to be smaller than the transversal width \( R \sim \phi_r \) of the jet (with \( \phi > \phi_r \) being the jet opening angle in the cosmological rest frame). For \( \lambda' = \xi r_{\gamma'} \), \( \xi < 1 \), and \( r_{\gamma'} = \gamma' m c \sqrt{\varepsilon (b')} \), this implies an upper limit for the maximum possible (comoving) particle Lorentz factor given by

\[ \gamma'_{\text{max}} \sim 10^9 \left( \frac{1}{\xi} \right) \left( \frac{m_p}{m} \right) \left( \frac{B'}{10^4 \, G} \right) \left( \frac{r}{10^{13} \text{ cm}} \right) \left( \frac{\phi_r}{0.3 \text{ rad}} \right). \]

Note, again, that for \( B' = 1000 b_0 (10^{13} \text{ cm}/r)^\beta \) G, this translates into maximum particle energies of \( E \sim 2.8 \times 10^{20} \xi^{-4} b_0 (10^{13} \text{ cm}/r)^{\beta-1} (\phi_r/0.3 \text{ rad}) (\gamma_i/300) \) eV in the observer frame. For a similar linear scaling, i.e., \( \beta = 1 \), the maximum energy would become independent of \( r \), while for \( \beta > 1 \), the higher energy particles would originate on smaller scales.

The third constraint requires that the timescale for (cross-field) diffusion in the comoving frame \( t_{\delta c} \sim \Delta^2 \delta' \), where \( \delta' \sim c \delta/3 \), is larger than \( t_{\text{acc}}' \); i.e., \( t_{\text{acc}}' \leq 3 (r^{3/2} \delta')/(\xi \lambda') \). Comparison with equation (5) reveals that \( t_{\text{acc}}' \) scales with \( r \) and \( \lambda' \) in the same way as \( t_{\delta c} \), indicating that the third constraint may be easily satisfied as long as \( \gamma'_{\text{min}}(\phi_r) \) is larger than a few (cf. Fig. 1).

Finally, the fourth constraint requires \( t_{\text{acc}}' \) to be smaller than the time \( t'_{\gamma} = \Delta c/\delta' \) needed to transverse the overall radial (comoving) width \( \Delta' \) of the flow, which translates into a lower limit for the required particle Lorentz factors. This width is essentially determined by the activity of the inner engine driving the GRB and, when specified in the observer frame, should be at least of order of the observed GRB duration \( t_{\gamma} \) (cf. Piran 2005); i.e., \( \Delta = t_{\gamma} c = \Delta' r_{\gamma} \). Allowing for expansion effects on larger scales with \( \Delta' \geq r_{\gamma} \) (cf. Meszáros & Rees 1993), we have \( t_{\gamma}'' = \max \left[ \gamma_i t_{\gamma}, r_{\gamma}(\gamma_i) \right] \). Using equation (7), one thus finds

\[ \gamma''_{\text{min}} \approx 10^2 \xi^{-1} \left( \frac{m_p}{m} \right) \left( \frac{B'}{10^4 \, G} \right) \left( \frac{300}{\gamma_i} \right)^{1/2} \left( \frac{r}{10^{13} \text{ cm}} \right)^2 \times \min \left[ \frac{10 \, s}{t_{\gamma}}, \chi(r) \right], \]

where \( \chi(r) = 2.7 \times 10^3 (\gamma_i/300)^4 (10^{13} \text{ cm}/r) \). For the chosen magnetic field parameterization \( B' = 1000 b_0 (10^{13} \text{ cm}/r)^\beta \) G, this results in \( \gamma''_{\text{min}} \approx 10^2 (\xi^{-1} b_0 r_{\gamma}(10^{13} \text{ cm})^{\beta-3} \times (300/\gamma_i)\min [10 \, s/t_{\gamma}, \chi(r)] \), indicating that for \( \beta = 2 \), the leading term becomes independent of \( r \), which may be favorable for efficient electron acceleration. A more restrictive condition, roughly corresponding to \( \gamma_{\text{min}}' \) as implied by \( \chi(r) \) in equation (10), is usually associated with the requirement to overcome adiabatic losses. Accordingly, shear acceleration can only act efficiently on particles that were sufficiently accelerated through other processes. In the GRB context, it is possible that such particles can be provided, for example, by the mechanism responsible for the prompt burst of emission (e.g., shock acceleration).

In summary, if the jet magnetic field is sufficiently weak (e.g., \( b_0 \sim 1 \)) and/or decays rapidly enough (say, e.g., with \( \beta = 2 \)), both the first and the fourth constraint may be satisfied even for electrons, so that the maximum energy is essentially determined by the third constraint. Particles may then, for example, be accelerated efficiently at distances larger than \( r > 10^{12} (b_0/\gamma_i) \) cm (cf. the first constraint), with possible maximum energies, measured in the observer frame, of less than \( \sim 10^{19} \) eV for electrons and \( \sim 10^{23} \) eV for protons, and successively (i.e., linearly for \( \beta = 2 \)) decreasing with time. For a high (e.g., \( b_0 \sim 10 \)) and slowly decaying (say, e.g., \( \beta \leq 1 \)) jet magnetic field, on the other hand, efficient shear acceleration of electrons is virtually excluded, while protons again may well be accelerated up to energies \( \sim 10^{20} \) eV.

3. COMPARISON WITH SHOCK ACCELERATION

It is widely believed that shock-accelerated electrons are responsible for the observed prompt GRB and afterglow emission via synchrotron radiation processes (e.g., Piran 2005). In particular, diffusive electron acceleration at mildly relativistic internal shocks (with Lorentz factor \( \Gamma' \sim 2 \) for Lorentz factor \( \Gamma' \sim 2 \)) is usually thought to be behind the powerful burst of \( \gamma \)-rays (Rees & Mészáros 1994). In the case of nonrelativistic shocks, Fermi acceleration leads to power-law particle spectra \( N(\gamma) \propto \gamma^{-\gamma'} \), which are only dependent on the shock compression ratio \( \rho = u_s/u \) (where \( 1 < \rho \leq 4 \)), i.e., \( s = (\rho + 2)/(\rho - 1) \), so that for strong shocks \( \rho = 4 \) the famous \( s = 2 \) result is obtained (e.g., Drury 1983; Kirk & Duffy 1999). In general, the acceleration timescale for diffusive shock acceleration depends on both the upstream and downstream residence times. For an unmodified nonrelativistic shock, one thus obtains (e.g., Drury 1983; Jokipii 1987)

\[ t_{\text{acc}} = \frac{3}{u_1 - u_2} \frac{\kappa_1}{u_1} + \frac{\kappa_2}{u_2} = \frac{3 \beta}{(\rho - 1)} \left( \frac{k_1 + \kappa_2}{\rho \kappa_2} \right) \frac{c}{u_s'}, \]

with \( u_1 \) and \( u_2 \) the upstream and downstream flow velocities measured in the shock frame, respectively, \( \kappa_1 \) and \( \kappa_2 \) the upstream and downstream (spatial) diffusion coefficients, respectively, and \( u_s \) the shock speed as measured in the upstream frame. If the acceleration process operates at nearly the Bohm limit [i.e., \( \kappa_1 = \lambda c/3 = \eta r c/3 \), with \( \eta = (\Gamma - 1)/(\Gamma + 1) \)], one finds

\[ t_{\text{acc}} \approx 6 \eta r_c \frac{c}{u_s'}, \]

assuming \( k_1 = \kappa_2 \). When \( u_s \sim c \), this is comparable to the Larmor time, which is a result also predicted by the simulations of Lemoine & Pelletier (2003). It has been often suggested that
the nonrelativistic limit can also be approximately applied to mildly relativistic shocks in GRBs, proposing, for example, that efficient proton acceleration to ultrahigh energies might be possible (e.g., Waxman 2004). Equating the acceleration timescale (eq. [12]), replacing \( r \) by \( r' \), and \( u_r \) by \( u_r' \) as the (comoving) internal shock speed, with the cooling timescale (eq. [6]), using \( B' = 1000b_0(10^{15} \text{ cm/}r)^2 \) G and \( u_r' = \beta c \), with \( \beta < 1 \), gives

\[
\gamma_{\max}' = 2.5 \times 10^8 \eta^{-1/2} b_0^{1/2} \left( \frac{\beta_c}{0.9} \right) \left( \frac{m_p}{m} \right) \left( \frac{r}{10^{13} \text{ cm}} \right)^{8/2} .
\]

Note that magnetic field amplification in the vicinity of a shock may yield a field value \( b_0 \) well above the usual (background) flow magnetic field, thus leading to a somewhat more restrictive condition. In addition, the acceleration timescale also has to be smaller than the comoving time \( r/c \gamma_b \) needed to transverse the width of a shell, which gives

\[
\gamma_{\max}' \leq 1.5 \times 10^8 \eta^{-1} b_0 \left( \frac{\beta_c}{0.9} \right)^2 \left( \frac{m_p}{m} \right) \left( \frac{300}{\gamma_b} \right) \left( \frac{10^{13} \text{ cm}}{r} \right)^{\beta - 1} .
\]

A more detailed comparison of shear with shock acceleration may perhaps be reached by analyzing a critical particle Lorentz factor \( \gamma_{\text{cr}} \), defined by equating equation (7) with equation (12), above which shear acceleration may become more efficient than shock acceleration. Several applications with respect to the acceleration of protons are illustrated in Figure 2, suggesting the possibility that under a reasonable range of conditions, shear acceleration in GRB jets may become more relevant for the production of ultra–high-energy (UHE) cosmic rays than shock-type acceleration processes. Concerning electron acceleration in weak magnetic fields (e.g., \( b_0 \leq 1 \), \( \beta = 2 \), \( r \approx 10^{15} \) cm), on the other hand, shock-type processes would allow for a much quicker particle energization (but would also be more severely limited by eqs. [13] and [14]), and shear effects would only become dominant above \( \gamma' \sim 10^8 \times 10^{15} \text{ cm/}r \).

4. CONCLUSIONS

Using an idealized model, we have analyzed the possible role of shear acceleration for the energization of particles in relativistic GRB-type jets. Our results suggest that efficient electron acceleration on scales \( r \approx 10^{15} \) cm, with maximum energy decreasing with distance, may be possible in the presence of weak magnetic fields, assuming that high-energy seed particles are provided by the mechanism responsible for the prompt burst of emission. This may result in a weak and long-duration component in the GRB emission. Protons, on the other hand, may reach UHE energies \( >10^{20} \) eV under a broad range of conditions.

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