New connection between central engine weak physics and the dynamics of gamma-ray burst fireballs

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We demonstrate a qualitatively new aspect of the dynamics of gamma-ray burst (GRB) fireballs: the development of a substantial dispersion in the proton component in fireballs in which neutron decoupling occurs and is sufficiently pronounced. This effect depends sensitively on the neutron to proton ratio in the fireball, becoming more dramatic with increasing neutron excess. Simple physical arguments and transport calculations indicate that the dispersion in the Lorentz factor of the protons can be of the order of the final mean Lorentz factor of the fireball. We show how plasma instabilities could play an important role in the evolution of the fireball and how they might ultimately govern the development of such a velocity dispersion in the proton component. The role of these instabilities in setting or diminishing a proton Lorentz factor dispersion represents a new and potentially important venue for the study of plasma instabilities. Significant dispersion in the proton velocities translates into *fewer* protons attaining the highest Lorentz factors. This is tantamount to a reduction in the total energy required to attain a given Lorentz factor for the highest energy protons. As well, a velocity dispersion in the proton component can have consequences for the electromagnetic and neutrino signature of GRB's.

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I. INTRODUCTION

We show that a simple, yet previously overlooked, mechanism may give rise to a substantial velocity dispersion in the proton component of gamma-ray burst (GRB) fireballs. Namely, in GRB fireballs in which neutron decoupling occurs, large center-of-mass energy collisions between decoupled neutrons and protons will induce a velocity dispersion in the proton component. For certain fireball parameters, the time scale for rethermalization of these protons is longer than the dynamical time scale, and so the protons will retain their acquired dispersion.

This has consequences for the dynamics of the fireball. Since the ultrarelativistic proton shell is directly tied to gamma-ray photon production [1,2], the distribution of proton energies can affect the dynamics of photon emission. In the internal shock GRB model the γ-ray photons are produced through internal multiple-shock collisions involving the protons. The efficiency for the conversion of shock kinetic energy to photon energy, increases with increasing relative shock velocities [1,4]. In addition, the energetic proton shock produces particle cascades leading to multi-TeV neutrino emission [5–7]. Therefore, both photon and neutrino radiation may be affected by the process discussed here.

More basically, the process we discuss here represents a new aspect of our understanding of the evolution of homogeneous relativistic fireballs. The standard picture holds that a thermal plasma undergoes an initial acceleration phase, lasting until the energy in relativistic particles is transferred to the kinetic energy of protons, or, in the case of extremely baryon-dilute plasmas, until the plasma becomes optically thin to photons [8]. Following the acceleration phase, a coasting phase ensues. In the coasting phase, the baryons are assumed thermal with typically low temperatures, $T < 10^{-4}$ MeV, in the plasma rest frame.

Recently it has been recognized that in sufficiently baryon dilute (see Sec. II for a precise definition of this) fireballs, heavy neutral particles (neutrons) can dynamically decouple [9–11] from the expanding $e^{\pm}$ photon proton plasma. The reason is that once strong neutron-proton scatterings become ineffective at coupling neutrons to an accelerating, radiation-driven fireball, then ultimately these neutrons will have a smaller average Lorentz factor than the strongly Coulomb-coupled protons in the fireball. There is an interesting connection between this decoupling phenomenon and the net number of electrons per baryon,

$$Y_e = \frac{n_{e^-} - n_{e^+}}{n_b} = \frac{1}{n/p+1}, \tag{1}$$

where Y_e is the electron fraction, n_{e^+} and n_{e^-} are the number densities of positrons and electrons respectively, and n and p are the number densities of neutrons and protons. The connection is that when conditions near the fireball source lead to a low Y_e in the outflow, substantial differences between the final neutron and proton Lorentz factors are possible [11]. We will demonstrate a second connection: when the electron fraction in the fireball is low, high energy collisions between decoupled neutrons and protons induce a velocity dispersion in the protons and that these "hot protons" are not rethermalized. The sensitivity of this effect to Y_e in the fireball is interesting because, in analogy to type II supernovae, the electron fraction may mirror weak physics in the central engine [11,12]. We note that fireballs are not the only proposed mechanism for generating GRB's. Other models involving electromagnetic acceleration of a relatively

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cold plasma (e.g., Ref. [3]) have also been proposed. Implications of neutron decoupling for these possibilities have not been worked out and our work does not apply to them.

II. NEUTRON DECOUPLING IN RELATIVISTIC FIREBALLS

The essential features of the physics of baryon flow in relativistic fireballs are obtained by considering a two component [(i) $e^{\pm}$ photon proton and (ii) neutron] homogeneous fireball with initial radius, temperature, and electron fraction R_0, T_0, and Y_{e0}, respectively. It is useful, in analogy with the discussion of winds from supernovae, to couch our analysis in terms of the entropy per baryon in the fireball. In terms of the above quantities the entropy per baryon in units of $10^5 k_{\mathrm{b}}$ is

$$s_5 \approx 1.250 \times 10^{-2} \eta (1 \quad \mathrm{MeV}/T_0). \tag{2}$$

Here $\eta = E_{\mathrm{tot}}/M$ is the ratio of total energy to baryon rest mass in the fireball. The entropy is also a useful quantity because, apart from small corrections stemming from inelastic nucleon-nucleon scatterings, it is conserved throughout the evolution of the fireball. A central issue for GRB's is the "baryon loading problem," the statement that η must be large in order to get the fireball moving with a high Lorentz factor.

For relativistic fireballs ($\eta >$ a few), numerical and analytic work shows that, to first approximation, the fireball evolves as [13,14]

$$\gamma = (T_0/T) = R/R_0 \quad \text{for} \quad \gamma < \eta, \tag{3}$$

$$\gamma = \eta \quad \text{for} \quad R > \eta R_0. \tag{4}$$

Here γ is the Lorentz factor of the fireball. These relations follow from entropy and energy conservation and are violated at the beginning and end of the fireball's evolution (see below). Equation (3) is derived by writing down the hydrodynamic equations governing the adiabatic expansion of a high entropy gas and taking the limit where the ratio of total energy in baryons to energy in relativistic light particles is small. Equation (4) is obtained by noting that the acceleration of the fireball saturates when the kinetic energy in baryons is equal to the initial (principally thermal) energy in the fireball. In terms of the time t as measured by an observer co-moving with the plasma, the Lorentz factor and temperature evolve as $\gamma = (T_0/T) = e^{t/\tau_{\mathrm{dyn}}}$. Here $\tau_{\mathrm{dyn}} = R_0$ characterizes the fireball source size and is the dynamic time scale for the expansion of the fireball as measured in a frame comoving with the accelerating plasma. (We adopt units where the speed of light is unity.) Observations of time variability in GRB's give the constraint $\tau_{\mathrm{dyn}} < 10^{-3}$ s, while the smallest proposed GRB sources are solar mass scale compact objects with $\tau_{\mathrm{dyn}} \gtrsim 10^{-5}$ s.

Particles in the plasma suffer a four-acceleration with magnitude $d\gamma/dR \approx R_0^{-1}$. Neutrons have such a small magnetic dipole moment that they are essentially only coupled to the accelerating plasma via strong scatterings with protons (near the decoupling point $\sigma_{\mathrm{np}} \sim 0.1 \sigma_{\mathrm{T}} \sim 10^7 \sigma_{ne} \sim 10^{15} \sigma_{n\gamma}$) where σ_{T} is the Thomson cross section. To an excellent approximation, then, the neutron-proton collision timescale (as measured in a frame comoving with the accelerating plasma) in terms of the co-moving proton number density n_{p} in the plasma rest frame, is

$$\tau_{\mathrm{coll}}^{-1} = n_{\mathrm{p}} \sigma_{\mathrm{np}} v_{\mathrm{rel}}, \tag{5}$$

where v_{rel} is the relative neutron proton velocity. Apart from small corrections stemming from inelastic nucleon-nucleon scatterings, entropy is conserved throughout the acceleration of the fireball. This implies

$$\tau_{\mathrm{coll}}^{-1} \propto n_{\mathrm{p}} \propto T^3 \propto \exp(-3t/\tau_{\mathrm{dyn}}) \tag{6}$$

except for the brief period when the electron positron pairs annihilate and transfer their entropy to the photons.

Decoupling occurs if the dynamic and collision time scales become comparable before the end of the acceleration phase of the fireball's evolution. Noting that the proton number density is $n_p \sim 10^{27} T_{\mathrm{MeV}}^3 s_5^{-1} Y_e$ cm^{-3}, with T_{MeV} the temperature in units of MeV, noting also that the temperature at the end of the acceleration phase of the fireball's evolution is given approximately by T_0/η, and substituting into Eq. (5), leads us to the condition for neutron decoupling to occur:

$$\frac{0.02 \; s_5^4}{\tau_5 Y_e (v_{\mathrm{rel}} \sigma_{10})_{\mathrm{dec}}} > 1. \tag{7}$$

Here τ_5 is the dynamic time scale in units of 10^{-5} s, and $(v_{\mathrm{rel}}\sigma_{10})_{\mathrm{dec}}$ is the product of the relative velocity and neutron proton cross section in units of 10 fm^2 at the decoupling point. The precise v_{rel} at which this latter quantity should be evaluated, is unclear from our simple argument. This is not crucial because the product $v_{\mathrm{rel}}\sigma_{10}$ only varies by a factor of 5 from unity as v_{rel} increases from 10^{-3} to near 1. The final Lorentz factor of the neutrons $\gamma_{\mathrm{n,final}}$ can be estimated by using Eq. (6) to find the temperature at the decoupling point, and using the scalings in Eq. (3) to evaluate γ at the decoupling point,

$$\gamma_{\mathrm{n,final}} \approx 220 \left(\frac{(v_{\mathrm{rel}}\sigma_{10})_{\mathrm{dec}} T_{0,\mathrm{MeV}}^3 Y_e \tau_5}{s_5} \right)^{1/3}. \tag{8}$$

Following decoupling, the proton $e^{\pm}$ photon plasma begins to accelerate away from the neutrons. This is because, when Eq. (7) is satisfied, neutron decoupling occurs while photon pressure is still accelerating the fireball. If Eq. (7) is not satisfied, then decoupling occurs after the acceleration phase and the protons and neutrons will coast together until the protons are slowed by interactions with the interstellar medium (Ref. [15]). Energy conservation gives an estimate of the final mean Lorentz factor of the protons,

$$\langle \gamma_{\mathrm{p,final}} \rangle \approx Y_e^{-1} \left[\eta - \gamma_{\mathrm{n,final}} \left(1 - Y_e + \epsilon \frac{E_\nu}{m_n} \frac{\gamma_\pi}{\gamma_{\mathrm{n,final}}} \right) \right]. \tag{9}$$

The term $\epsilon (E_\nu/m_n)(\gamma_\pi/\gamma_{\mathrm{n,final}})$ is present to account for energy lost to neutrinos arising from the decay of pions created in inelastic nucleon-nucleon collisions. Here m_n is the nucleon mass, ϵ is the number of pions created per baryon (at most of order unity), E_ν is the average center of mass energy lost to neutrinos per pion decay, and γ_π is the average Lorentz factor of created pions. For pions created in $n-p$ collisions, the branching ratio for charged pion production below the two pion threshold, is roughly 1/2, and $E_\nu \sim 50$ MeV.

The nuclear physics of pion production is well understood. However, as it is difficult to estimate the Lorentz factor of the protons when the ''average pion'' is created, it is complicated to analytically estimate γ_π. As most inelastic nucleon-nucleon collisions occur near the decoupling point, γ_π is presumably of order $\gamma_{\rm n,final}$. In the numerical examples we present below, neutrino energy loss is estimated and is found to be small enough so as not to alter the qualitative picture presented here.

III. NEUTRON INDUCED PROTON HEATING IN RELATIVISTIC FIREBALLS

Subsequent to neutron decoupling, protons will undergo collisions with decoupled neutrons. The first requirement for the presence of a ''hot'' (velocity-dispersed) proton component is that some of these collisions are high-energy collisions. If in the lab frame a proton and neutron have Lorentz factors $\gamma_{\rm p}$ and $\gamma_{\rm n}$, respectively, then the Lorentz factor $\gamma_{\rm rel}$ of the neutron, as seen by the proton, is

$$\gamma_{\rm rel}=\frac{1}{2}\,\frac{\gamma_{\rm p}}{\gamma_{\rm n}}[1+(\gamma_{\rm n}/\gamma_{\rm p})^2]. \tag{10}$$

A high energy neutron-proton collision implies, therefore, that $\langle\gamma_{\rm p,final}\rangle/\gamma_{\rm n,final} \geqslant$ a few. This condition is intended only as a rough guide for the fireball parameters needed to drive the proton component hot.

For reasonable fireball parameters it is difficult to attain substantial $\langle\gamma_{\rm p,final}\rangle/\gamma_{\rm n,final}$, unless $Y_e<0.5$. It has been argued that a low electron fraction will naturally be obtained in many of the proposed GRB environments [11]. In addition, in calculations of GRB's arising from neutron star mergers, $Y_e \approx 0.1$ has been estimated [15]. It is not clear if such low electron fractions are also obtained, for example, in the collapsar model for GRB central engines [16]. This is because the role of weak processes (in particular, ν_e and $\overline{\nu}_e$ captures) in collapsar dynamics has yet to be worked out in detail.

Protons undergoing collisions with neutrons will lose energy to the background photons and electrons. Whether or not these protons rethermalize with the plasma depends on their thermalization time scale $\tau_{\rm therm}$. The protons will remain ''cool'' (i.e., well coupled and thermal) if $\tau_{\rm therm}<\tau_{\rm dyn}(\leqslant\tau_{\rm coll})$, where the last inequality holds near and after decoupling. If the opposite case holds, $\tau_{\rm therm}>\tau_{\rm dyn}$, the protons could keep the velocity dispersion they acquire through collisions with neutrons (i.e., become hot).

A. Collisional rethermalization mechanisms

There are two energy loss mechanisms for protons with a velocity *relative* to the background plasma. The first is proton-electron scattering. Bethe's formula [17] gives this rate as

$$\left(\frac{dE}{dt}\right)_{pe}\approx(7.6\times10^{-18}\ \ {\rm GeV\,s^{-1}})\frac{n_e}{v}\left[\ln\left(\frac{2\gamma^2v^4}{n_e}\right)+74.1\right]. \tag{11}$$

Here n_e is the electron number density in units of cm^{-3}, and v and γ refer to the velocity and Lorentz factors, respectively, of the proton relative to the plasma.

The relations derived above [Eq. (7)] imply that neutron decoupling occurs at a temperature $T_{\rm decouple} \approx T_{\rm D}[s_5/(v_{\rm rel}\sigma_{10})_{\rm dec}Y_e\tau_5]^{1/3}$, with $T_{\rm D}=0.005$ MeV. This clearly implies that neutron decoupling occurs after $e^\pm$ annihilation. Noting that the ionization electron number density is $n_e \sim 10^{27}T_{\rm MeV}^3 s_5^{-1}Y_e$ cm^{-3}, and noting that typical kinetic energies of protons relative to the plasma are of the order of a few GeV, we see from Eq. (11) that the thermalization time scale via proton electron scattering is $\tau_{\rm therm,pe}\approx 8\times10^{-5}$ s$(T_{\rm D}/T)^3 s_5/Y_e$.

Reference [10] made the observation that a pion-induced electromagnetic cascade may lead to an increase in the number density of electrons and positrons in the fireball. The greatest this increase could be occurs when all of the pion mass (minus neutrino losses) goes into e^+/e^- pairs and when, in addition, the processes creating e^+/e^- pairs are sufficiently rapid that they come into equilibrium with electron or positron pair annihilation.

By considering this limiting case, one finds that a pion-induced electromagnetic cascade can delay the onset of a dispersion in the proton component [i.e., make $\tau_{\rm therm,pe}(T=T_{\rm decouple}/4)<\tau_{\rm dyn}$] only for extremely small electron fractions, $Y_e<0.01$. (The number 4 appearing in parentheses here arises from requiring that a large center of mass energy collision is needed to drive a proton dispersion and is explained in more detail below.) Therefore, a pion induced electromagnetic cascade has little or no leverage in delaying the development of a dispersion in the protons for the moderately low electron fractions that we expect in condensed object environments.

The second energy loss mechanism for protons arises because, when the protons acquire a dispersion, the electrons must rearrange themselves in order to preserve charge neutrality. This rearrangement, on its own, has a negligible effect on the proton dispersion because of the smallness of the ratio of the electron to proton mass. However, Compton scattering following this rearrangement can be a source of energy loss for the protons. In other words, runaway protons may be viewed as being tightly paired with electrons via the Coulomb force, and the proton loses energy not only at the rate given in Eq. (11), but in addition, at the rate at which the electron to which it is coupled loses energy to the background photons via Thomson or Compton drag

$$\left(\frac{dE}{dt}\right)_{\mathrm{pe}\gamma}\approx\sigma_{\mathrm{T}}U_{\gamma}\approx(10^{6}\ \ \mathrm{GeV\,s^{-1}})\left(\frac{T}{T_{\mathrm{D}}}\right)^{4}, \tag{12}$$

with U_γ the photon energy density, giving the time scale for thermalization via this process as $\tau_{\mathrm{therm,pe}\gamma}\approx 10^{-6}\ \mathrm{s}(T_{\mathrm{D}}/T)^4$. Note that the inverse Compton scattering of protons is not important because at the temperatures near the neutron decoupling point the photon-proton scattering cross section is smaller than the electron photon scattering cross section by a factor of $(m_e/m_p)^2\sim 10^{-7}$, with m_e and m_p the neutron and proton mass, respectively.

If magnetic fields are present, either because they were present in the central engine and advected out with the fireball, or because they are generated via plasma instabilities (see Sec. III), then electrons may also lose energy to synchrotron emission. As with Compton scattering, the proton synchrotron losses are smaller than electron synchrotron losses by a factor of $(m_e/m_p)^2\sim 10^{-7}$ and are unimportant. The expression for the synchrotron loss rate is similar to the expression for the loss rate due to Thomson drag [Eq. (12)], but with the magnetic field energy density U_B replacing the photon energy density U_γ. Therefore, unless the magnetic field energy density is comparable to the photon energy density, synchrotron losses are unimportant. Note that the photon energy density dominates over the proton rest mass energy density until the Lorentz factor of the fireball has nearly attained its asymptotic value. Equipartition of the magnetic field with the plasma implies that magnetic field pressure is as important in driving the fireball expansion as photon pressure. For such large magnetic field strengths the standard analysis for the fireball evolution, which is based on the assumption that photons and electrons positrons dominate the pressure, does not hold. We therefore neglect synchrotron losses in what follows.

The total thermalization time scale is given by

$$\tau_{\mathrm{therm}}^{-1}\approx\tau_{\mathrm{therm,pe}\gamma}^{-1}+\tau_{\mathrm{therm,pe}}^{-1}. \tag{13}$$

A velocity dispersed proton component arises, then, if neutron decoupling occurs, and at the end of the fireball's acceleration phase $\tau_{\mathrm{therm}}>\tau_{\mathrm{dyn}}$. Applying the simple picture given above for the evolution of the fireball, gives the second condition for a hot proton component:

$$s_5^4>(400+Y_e)\tau_5. \tag{14}$$

In fact, the fireball is still accelerating for fireball radius values greater than ηR_0 (Ref. [13], and see below). This implies that the temperature during the acceleration phase becomes lower than T_0/η and, hence, that the condition for the development of a hot proton component is somewhat weaker than that given above.

In Fig. 1 we illustrate the decrease in degree of thermalization with increasing initial $\tau_{\mathrm{therm}}/\tau_{\mathrm{dyn}}$ for a proton moving relative to a background plasma and losing energy via the processes described in Eqs. (11) and (12).

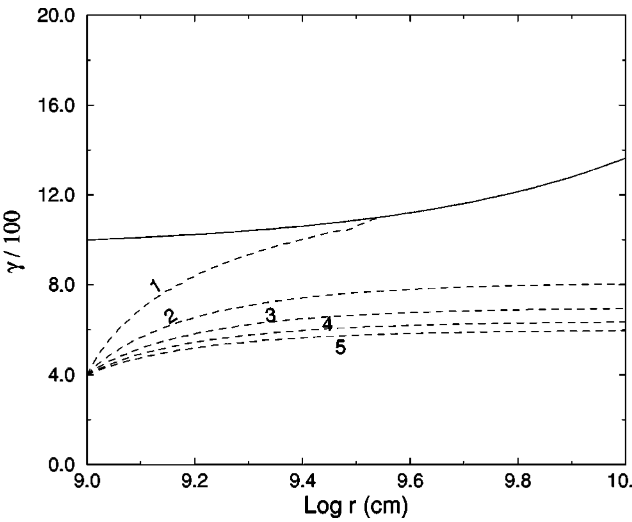

FIG. 1. Illustration of the evolution of a Lorentz factor of a test proton in a background plasma. The solid line is for the Lorentz factor of the background plasma and the dashed lines are for the Lorentz factors of the test protons. Different dashed lines correspond to different values of $\tau_{\mathrm{therm}}/\tau_{\mathrm{dyn}}$ (i.e., to different plasma temperatures) at 10^9 cm. The appropriate values of $\tau_{\mathrm{therm}}/\tau_{\mathrm{dyn}}$ are given next to the curves.

B. Collisionless considerations

In addition to the requirement of charge neutrality leading to proton energy loss via electron Compton scattering, there are other collisionless processes that may affect the dynamics of the protons. Indeed, the proton and electron plasma frequencies, which generically govern the time scale for the development of plasma instabilities, are comparable to or larger than the collision frequencies after decoupling. This is seen by noting that the proton and electron plasma frequencies (ω_{pi} and ω_{pe}, respectively) are given by $\omega_{\mathrm{pi}}=\sqrt{4\pi n_p e^2/m_p}=\sqrt{m_e/m_p}\,\omega_{\mathrm{pe}}$, with e the charge of the electron. In terms of the entropy and temperature, these plasma frequencies can be written as

$$\omega_{\mathrm{pi}}\sim 10^{11}s^{-1}[Y_e s_5^{-1}(T/T_{\mathrm{D}})^3]^{1/2}\sim(1/43)\,\omega_{\mathrm{pe}}. \tag{15}$$

Because the plasma frequencies can be large compared to the collision frequency, the post decoupling proton-velocity-dispersed fireball may provide a fertile and novel ground for the study of plasma instabilities.

In particular, the protons may be subject to an analog of the two-stream instability because of collisionally produced "bumps" in the proton distribution function at the bulk plasma and near the mean neutron component velocities (see Fig. 2). This instability arises in part because free energy can be liberated by smoothing out the bumps in the distribution function [22].

The plasma may also be subject to velocity space anisotropy-driven electromagnetic instabilities as the transverse velocity freezes out during the expansion of the fireball. These instabilities arise because, when a particle distribution function is anisotropic in velocity space (an extreme example is when all the particles have momenta in only a single direction) free energy can be liberated by isotropizing

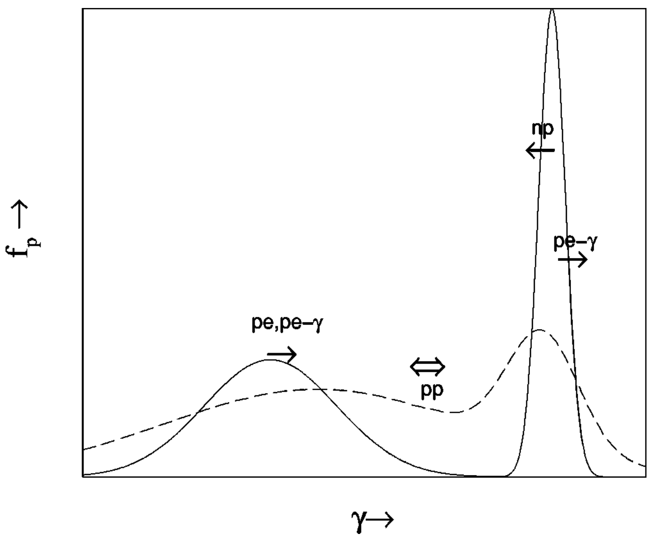

FIG. 2. A schematic picture of the various influences on the proton Lorentz factor distribution function during the acceleration of the fireball. The solid line represents a collisionally produced proton distribution function, while the dashed line represents the tendency of instabilities to smooth the distribution as collisionless processes liberate free energy. In this figure, pp and np represent proton-proton and neutron-proton collisions, while pe and pe γ represent the processes in Eqs. (11) and (12), respectively.

the distribution function. These instabilities are called "electromagnetic" because they proceed via an electromagnetic (rather than an electrostatic) wave. Relevant for the present work, it has been shown that magnetic trapping can saturate these instabilities at substantial ion anisotropies [18], and that they are moderately stabilized by relativistic effects [19,20]. A detailed study of the saturation level of the proton anisotropy in this system would be interesting because lower saturation levels imply less dispersion reduction due to adiabatic cooling of the tranverse momenta. In the presence of a magnetic field, either generated by the central engine or created through the instabilities discussed here, other instabilities, involving, for example, ion-cyclotron waves, may operate.

Instabilities may play an important role in the setting of the proton distribution function. They are not expected to alter our result of a dispersion in the proton component, because for the closely related system of counterstreaming ion beams, they are well studied and a substantial reduction in an initial dispersion is not seen [18,21,22]. These instabilities have also been studied in the regime where collisions are important, and in this case counterstreaming ion beams take, as expected, a few collision time scales to slow [23]. However, studies of the coupling between plasma instabilities and the hydrodynamic evolution of the protons in the peculiar high photon entropy small dynamic time scale environment, characteristic of GRB fireballs, have apparently not been done, and may give interesting and unexpected results. The fact that plasma instabilities play a role during the acceleration phase of some relativistic fireballs is quite interesting, because the previous picture was that collisional processes are sufficient to describe the early evolution in the absence of central engine-generated magnetic fields.

A diagram illustrating the various influences on the proton distribution function, including the trend toward a smoother distribution function resulting from plasma instabilities, is shown in Fig. 2.

C. Dispersion in the proton component: Analytic and numerical estimates

When neutron decoupling occurs, and is pronounced, a rough estimate gives the dispersion in the proton Lorentz factor as $\langle \gamma_{\rm p,final}\rangle - \gamma_{\rm n,final}$. (A somewhat more precise measure of dispersion will be given below.) For example, consider a fireball described by $Y_e = 0.2$ and $\tau_5 = 2.7$ and suppose that $T_0 = 3$ and $s_5 = 4$ (implying $\eta \sim 1000$). We find $\gamma_{\rm n,final} \sim 340$ and $\overline{\gamma}_{\rm p,final} \sim 3.4\times 10^3$, implying a dispersion in the proton component of 10^3, which is comparable to η.

We have defined the dispersion in terms of the central engine rest frame. For some purposes it is more useful to express the dispersion in terms of the mean proton rest frame. A simple approximate measure of the dispersion in this frame is

$$\frac{1}{2}\left(\frac{\langle \gamma_{\rm p,final}\rangle}{\gamma_{\rm n,final}}\right)^{1/2}(\gamma_{\rm n,final}/\langle \gamma_{\rm p,final}\rangle + 1), \tag{16}$$

which is at most on the order of a few.

A more precise determination of the dispersion in the protons requires a transport calculation describing the evolution of the fireball. A simple single angular zone, hydrodynamically consistent, steady state relativistic wind transport calculation has been performed. Neutrino energy loss is estimated by assuming that, following an inelastic collision, the available kinetic energy is shared equally between two baryons and a pion. The pion energy is then assumed lost from the system via neutrino emission. In the calculation, protons suffering large energy ($\gamma_{\rm rel} > 2$) collisions with neutrons, are assumed to decouple from the plasma if $\tau_{\rm therm} > \alpha \tau_{\rm dyn}$, where α is taken as a free parameter. In the limit where neutrons and protons are coupled to the photon $e^{\pm}$ plasma, our calculation reduces to that done in the pioneering study by Paczyński [24] on ultrarelativistic winds from compact sources.

In Fig. 3 we present the results of these calculations for the parameters listed above: $\tau_5 = 2.7$, $T_0 = 3$, and $s_5 = 4$ and for the cases where $Y_e = 0.1, 0.2, 0.3$, and 0.5. Results for different values of Y_e have been presented to illustrate that the lower the electron fraction, the more pronounced the effects of collisions between neutrons and protons.

To illustrate the effects discussed here, we present results for the case where (i) protons and neutrons are assumed coupled to and thermalized with the plasma, (ii) a velocity distribution function is used to describe the neutrons but the protons are assumed coupled to and thermalized with the $e^{\pm}$ photon plasma [the agreement between the final proton Lorentz factors in this case and the simple estimate given by Eq. (9) is good], and (iii) a velocity distribution function is used to describe the neutron velocities, and protons are assumed to decouple from the plasma once they have undergone a collision with a neutron where $\gamma_{\rm rel} > 2$. For part (iii) of the calculation, the parameter α was taken to be 5. For the ex-

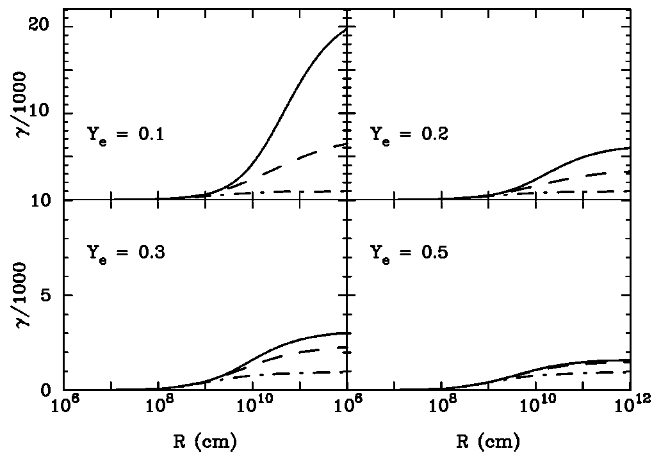

FIG. 3. Evolution of proton Lorentz factor in a steady state relativistic wind characterized by the parameters given in the text, for different cases of electron fraction, Y_e. The dot dashed line is for case (i), where baryons are assumed coupled to the plasma; the dashed line is for case (ii), where neutron velocities are described by a velocity distribution function and where neutrons are allowed to decouple while protons are assumed frozen into the plasma; and the solid line is for case (iii), where neutrons and protons are both allowed to decouple. Note the change in scale between the upper and lower figures.

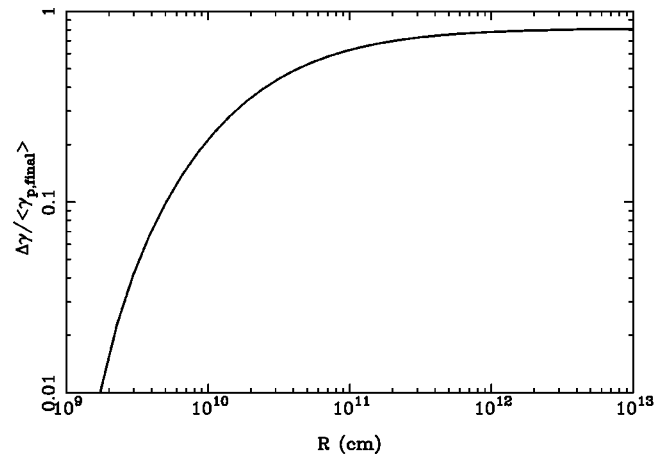

FIG. 4. Evolution of $\Delta\gamma/\langle\gamma_{\mathrm{p,final}}\rangle$ with radius for the case $Y_e=0.2$ and the parameters given in the text.

ample parameters we have chosen, the condition $\tau_{\mathrm{therm}}>5\tau_{\mathrm{dyn}}$ is always satisfied at the stage in the fireball's evolution when $\gamma_{\mathrm{rel}}>2$ collisions occur, and so the first condition is somewhat superfluous here.

Perhaps the most striking feature of this calculation is the increase in Lorentz factor of the highest energy protons as the protons acquire a dispersion. Because energy conservation implies that the mean Lorentz factor of the protons is unchanged between cases (ii) and (iii) (modulo changes in the net energy carried by the neutrons and pions due to the protons acquiring a velocity dispersion) the difference in final Lorentz factors between cases (ii) and (iii) provides a measure of the proton dispersion. Note that because our calculation does not allow for a proton to interact with the expanding plasma once it has undergone a high-energy collision with a neutron, and once $\tau_{\mathrm{therm}}>5\tau_{\mathrm{dyn}}$, our calculation may somewhat overestimate the proton dispersion. In our calculation we have attempted to err on the side of underestimating the proton dispersion by assuming a stringent criterion for neglecting the interaction of the scattered proton with the plasma, and by assuming that, for $\tau_{\mathrm{therm}}<5\tau_{\mathrm{dyn}}$, the proton is instantly rethermalized. By contrast, our approximation would have been unreasonable if we had chosen to neglect the interaction of the protons with the plasma when the dynamic and expansion time scales were equal. Figure 1 shows that our approximation is reasonable: for $\tau_{\mathrm{therm}}/\tau_{\mathrm{dyn}}\geqslant 3$, the increase in the Lorentz factor of a scattered proton is small ($\sim 20\%$). A precise determination of the proton distribution function would require a calculation coupling the evolution of plasma instabilities to the hydrodynamic outflow.

In Fig. 4 we display the evolution of a measure of dispersion in the proton component of the fireball ($\Delta\gamma/\gamma_{\mathrm{p,final}}$). In this figure, $\Delta\gamma$ is defined to be the difference in proton Lorentz factors between models (ii) and (iii) for the case $Y_e=0.2$ shown in Fig. 3.

IV. CONCLUSIONS

We have pointed out and made estimates of an overlooked (and possibly generic) feature of the baryon (neutron proton) flow in GRB fireballs: the acquisition of a large dispersion in the Lorentz factor of the proton component subsequent to neutron decoupling. This represents a qualitatively new feature of GRB fireballs because the previous picture of the evolution of the proton component held that the protons were thermal, even when neutron decoupling occurs. A dispersion in the proton component also implies that plasma instabilities may play an important role and suggests new studies of the role of collisionless processes during the acceleration and later shocking phase of the fireball's evolution. Because the effect we have described is principally sensitive to the neutron to proton ratio in the fireball, this work represents a new connection between the central engine weak physics that sets Y_e and GRB fireball dynamics. Because shocks involving protons are thought to give rise to the photon signal characteristic of GRB's, a proton dispersion also has implications for the details and efficiency of photon production. A direct consequence for the charged particle dynamics of neutron decoupling is interesting because the signal from the decay of pions, created in inelastic collisions during neutron decoupling, is expected to be weak. Detector event rates for the neutrinos from pion decay are estimated at a few per year [25]. Direct evidence of neutron decoupling in a GRB event would provide information about the progenitor fireball parameters and perhaps give a clue about the properties of the central engine.

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