HIGH-ENERGY COSMIC RAYS FROM GAMMA-RAY BURST SOURCES: A STRONGER CASE

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ABSTRACT

The suggested association between the sources of γ-ray bursts (GRBs) and the sources of ultrahigh-energy cosmic rays (UHECRs) is based on two arguments: (1) the constraints that UHECR sources must satisfy in order to allow proton acceleration to greater than $10^{20}$ eV are similar to those inferred for GRB sources from γ-ray observations, and (2) the average energy generation rate of UHECRs is similar to the γ-ray generation rate of GRBs. We show that recent GRB and UHECR observations strengthen both arguments and hence strengthen the suggested association.

Subject headings: cosmic rays — gamma rays: bursts

1. INTRODUCTION

The widely accepted interpretation of the phenomenology of γ-ray bursts (GRBs), bursts of 0.1–1 MeV photons lasting for a few seconds (see Fishman & Meegan 1995 for a review), is that the observable effects are due to the dissipation of the kinetic energy of a cosmologically distant, relativistically expanding wind, a “fireball,” whose primal cause is not yet known (for reviews, see Piran 2000; Mészáros 2002; Waxman 2003a). Waxman (1995b), Milgrom & Usov (1995), and Vietri (1995) have suggested that ultrahigh-energy ($>10^{19}$ eV) cosmic rays (UHECRs) may be produced in GRB sources. The model suggested in Waxman (1995b) was based on two arguments. First, it was shown that the constraints imposed on the relativistic wind by the requirement that it produce observed GRB characteristics were similar to the constraints imposed on such a wind by the requirement that it would allow proton acceleration to greater than $10^{20}$ eV. Second, the energy generation rate of γ-rays by GRBs was shown to be similar to the energy generation rate required to account for the observed UHECR flux (Waxman 1995a, 1995b).

The origin of UHECRs is one of the most exciting open questions of high-energy astrophysics (Bhattacharjee & Sigl 2000; Nagano & Watson 2000). The extreme energy of the highest energy events poses a challenge to models of particle acceleration. Since very few known astrophysical objects have characteristics indicating that they may allow acceleration of particles to the observed high energies (Waxman 2003b), the question of whether GRBs are possible UHECR sources is of great interest. Moreover, since the GRB model for UHECR production makes unique predictions that differ from those of other models (see Waxman 2001 and discussion in § 4), the design and analysis of future large-area UHECR experiments may be affected by the answer to this question.

The detection over the past few years of “afterglows,” delayed low-energy (X-ray to radio) emission of GRBs (for review, see Kulkarni et al. 2000), confirmed the cosmological origin of the GRBs through redshift determination of GRB host galaxies and the standard model predictions of afterglows that result from the collision of an expanding fireball with its surrounding medium (e.g., Piran 2000; Mészáros 2002; Waxman 2003a). In addition to providing strong support to the fireball model, these observations also provided new constraints on fireball model parameters and more accurate information on the redshift distribution of GRB sources. Recently, new data on the spectrum and flux of UHECRs was presented by the HiRes experiment (Abu-Zayyad et al. 2002), providing improved constraints on the generation rate and spectrum of UHECRs (Bahcall & Waxman 2003). Here we discuss the implications of these new GRB and UHECR observations to the GRB model for UHECR production.

In § 2.1 we briefly describe the model proposed in Waxman (1995b) for proton acceleration in GRB fireballs. The main goal of this section is to identify the key constraints that the relativistic wind parameters need to satisfy, equations (1) and (2), in order to allow acceleration of protons to greater than $10^{20}$ eV. (A more detailed and pedagogical description of the model is given in Waxman 2001.) The association of GRB and UHECR sources was motivated mainly by the fact that these constraints were similar to those inferred, based on independent physical arguments, from $\gtrsim 1$ MeV γ-ray observations. Recent lower energy afterglow observations provide new constraints on model parameters, which are independent of the γ-ray constraints. In § 2.2 we show that the afterglow constraints are similar to the γ-ray constraints and in fact imply parameter values that are more favorable for the acceleration of protons to greater than $10^{20}$ eV. In § 2.3 we compare our results to those of other authors. In particular, we show that results derived by several authors, arguing that the maximum proton energy is too low (Gallant & Achterberg 1999; Achterberg et al. 2001) or that the proton spectrum is too steep (Ostrowski & Bednarz 2002) to account for the observed UHECR spectrum, are not applicable to the model proposed in Waxman (1995b).

The determination of GRB redshifts, made possible by afterglow detection, leads to significant changes in, and to significantly reduced uncertainties of, the estimates of both the GRB rate and average γ-ray energy release (per single GRB). We show in § 3.1 that the local energy production rate in γ-rays by GRBs, inferred using recent redshift measurements, is similar to the pre-afterglow estimate. In § 3.2 we show that the local rate of energy production in UHECRs inferred using recent UHECR observations is consistent with, although more accurate than, earlier estimates (Waxman 1995a) and hence comparable to the energy production rate in γ-rays by GRBs. In § 3.3 we demonstrate that recent claims to the contrary (Stecker 2000; Berezinsky, Gazizov, & Grigorieva...
2. PROTON ACCELERATION IN GRB FIREBALLS

2.1. Brief Description of the Model

General phenomenological considerations, based on γ-ray observations, indicate that regardless of the nature of the underlying sources, GRBs are produced by the dissipation of the kinetic energy of a relativistic expanding fireball. A compact source, \( r_0 \sim 10^7 \) cm, produces a wind characterized by an average luminosity \( L \sim 10^{52} \) ergs s\(^{-1}\) and mass-loss rate \( M \). At small radii, the wind bulk Lorentz factor, \( \Gamma \), grows linearly with the radius, until most of the wind energy is converted to kinetic energy, and \( \Gamma \) saturates at \( \Gamma \approx L/Mc^2 \sim 300 \). Variability of the source on a timescale \( \Delta \tau \sim 10 \) ms, resulting in fluctuations in the wind bulk Lorentz factor \( \Gamma \) on a similar timescale, results in internal shocks in the ejecta at a radius \( r \approx r_d \approx \Gamma^2 \Delta \tau \gg r_0 \). It is assumed that internal shocks reconvert a substantial part of the kinetic energy to internal energy, which is then radiated as γ-rays by synchrotron and inverse-Compton radiation of shock-accelerated electrons. At a later stage, the shock wave driven into the surrounding medium by the expanding fireball ejecta leads to the emission of the lower energy afterglow.

The observed radiation is produced, both during the GRB and the afterglow, by synchrotron emission of shock-accelerated electrons. In the region where electrons are accelerated, protons are also expected to be shock-accelerated. This is similar to what is thought to occur in supernova remnant shocks, where synchrotron radiation of accelerated electrons is the likely source of nonthermal X-rays, and where shock acceleration of protons is believed to produce cosmic rays with energy extending to \( \sim 10^{15} \) eV (e.g., Koyama et al. 1995; Berezhko, Ksenofontov, & Völk 2002; Völk et al. 2002). Thus, it is likely that protons, as well as electrons, are accelerated to high energy within GRB fireballs.

The internal shocks within the expanding wind are expected to be mildly relativistic in the rest frame, due to the fact that the allowed range of Lorentz factor fluctuations within the wind is from a few \( \times 10^2 \) (the lower limit required to avoid large optical depth) to a few \( \times 10^3 \) (the maximum Lorentz factor to which shell acceleration by radiation pressure is possible; e.g., Waxman 2003a). This implies that the Lorentz factors associated with the relative velocities are not very large. Since internal shocks are mildly relativistic, we expect our understanding of non-relativistic shock acceleration to apply to the acceleration of protons in these shocks. In particular, the predicted energy distribution of accelerated protons is expected to be \( dN_p/dE_p \propto E_p^{-2} \) (Axford, Leer, & Skadron 1977; Bell 1978; Blandford & Ostriker 1978), similar to the predicted electron energy spectrum, which is consistent with the observed photon spectrum.

Several constraints must be satisfied by wind parameters in order to allow proton acceleration to high-energy \( E_p \). We summarize these constraints below. The reader is referred to Waxman (1995b, 2001) for a detailed derivation. The requirement that the acceleration time be smaller than the wind expansion time (which also implies that the proton is confined to the acceleration region over the required time) sets a lower limit to the strength of the wind magnetic field. This may be expressed as a lower limit to the ratio of magnetic field to electron energy density (Waxman 1995b),

\[
\frac{u_B}{u_e} > 0.02\Gamma_{2.5}^2 E_p^{1.5} L_{\gamma,52}^{-1}
\]

where \( E_p = 10^{39} E_{p,20} \) eV, \( \Gamma = 10^{2.5} \Gamma_{2.5} \), and \( L_{\gamma} = 10^{52} L_{\gamma,52} \) ergs s\(^{-1}\) is the wind γ-ray luminosity. A second constraint is imposed by the requirement that the proton acceleration time be smaller than the proton energy loss time, which is dominated by synchrotron emission. This sets an upper limit to the magnetic field strength, which in turn sets a lower limit to \( \Gamma \) (Waxman 1995b; Rachen & Mészáros 1998)

\[
\Gamma > 130 E_p^{3/4} \Delta t_{-2}^{-1/4}
\]

where \( \Delta t = 10^{-2} \Delta t_{-2} \) s. As explained in Waxman (1995b), the constraints equations (1) and (2) hold regardless of whether the fireball is a sphere or a narrow jet (as long as the jet opening angle is greater than 1/7). The luminosity in equation (1) is the “isotropic equivalent luminosity,” i.e., the luminosity under the assumption of isotropic emission.

Internal shocks within the wind take place at a radius \( r_d \approx \Gamma^2 c \Delta \tau \). The constraint of equation (1) is independent of \( \Delta \tau \), i.e., independent of the internal collision radius, while the constraint of equation (2) sets a lower limit to the collision radius for a given \( \Delta \tau \). This implies that protons may be accelerated to greater than \( 10^{20} \) eV regardless of the value of \( \Delta \tau \), which may range from the dynamical time of the source (\( \Delta \tau \sim 1 \) ms) to the wind duration (\( \Delta \tau \sim 1 \) s), provided the magnetization and Lorentz factor are sufficiently large, following equations (1) and (2).

At large radii the external medium affects fireball evolution, and a “reverse shock” is driven backward into the fireball ejecta and decelerates it. For typical GRB fireball parameters this shock is also mildly relativistic (e.g., Waxman 2003a), and its parameters are similar to those of an internal shock with \( \Delta \tau \approx 10 \) s. Protons may therefore be accelerated to greater than \( 10^{20} \) eV not only in the internal wind shocks but also in the reverse shock (Waxman & Bahcall 2000; Waxman 2001). This implies that proton acceleration to greater than \( 10^{20} \) eV is possible, provided the constraints of equations (1) and (2) (with \( \Delta \tau \sim 10 \) s) are satisfied in the (currently less favorable) scenario in which GRB γ-rays are produced in the shock driven by the fireball into the surrounding gas, rather than by internal collisions (as suggested, e.g., in Dermer 1999).

The constraints given by equations (1) and (2) are remarkably similar to those inferred from γ-ray observations, based on independent physical arguments: \( \Gamma > 300 \) is implied by the γ-ray spectrum by the requirement to avoid high pair-production optical depth, and a magnetic field close to equipartition, \( u_B/u_e \sim 0.1 \), is required in order to account for the observed γ-ray emission (Piran 2000; Mészáros 2002; Waxman 2003a). This was the basis for the association of GRBs and UHECRs suggested in Waxman (1995b). In the following subsection we discuss the new constraints on model parameters implied by afterglow observations, and their implications.

2.2. Implications of Afterglow Observations

Afterglow observations lead to the confirmation of the cosmological origin of GRBs and confirmed standard model predictions of afterglow that results from synchrotron emission of electrons accelerated to high energy in the highly relativistic shock driven by the fireball into its surrounding gas. Afterglow observations therefore provide strong support for the underlying
fireball scenario. In addition, afterglow observations provide important information on the values of model parameters that enter the constraints given by equations (1) and (2).

Prior to the detection of afterglows, it was commonly assumed that the farthest observed GRBs lie at redshift \( z \sim 1 \) (Mao & Paczynski 1992; Piran 1992). Based on afterglow redshift determinations, we now know that detected GRBs typically lie at farther distances (e.g., Bloom, Frail, & Kulkarni 2003). This implies that the characteristic GRB luminosity is higher by an order of magnitude compared to pre-afterglow estimates, \( L_\gamma \approx 10^{52} \text{ erg s}^{-1} \) instead of \( L_\gamma \approx 10^{51} \text{ erg s}^{-1} \). This relaxes the constraint on magnetic field energy fraction given by equation (1). The implications of the revised GRB redshift distribution to the inferred GRB energy production rate are discussed in detail in \( \S \) 3.

In several cases, fast follow-up afterglow observations allowed the detection of radio and optical emission from the reverse shock (Zhang, Kobayashi, & Mészáros 2003; Soderberg & Ramirez-Ruiz 2003 and references therein). These observations provide direct information on the plasma conditions in the reverse shock, where acceleration of protons to high energy may take place (see \( \S \) 2.1). Two major conclusions were drawn from the analysis of the early optical and radio reverse shock emission. First, lower limits to the initial fireball Lorentz factors were inferred, in the range of \( \Gamma > 100 \) to \( \Gamma > 1000 \) (Zhang et al. 2003; Soderberg & Ramirez-Ruiz 2003). Second, the magnetic field in the reverse shock was inferred to be close to equipartition, that is, \( u_B/u_e \) was inferred to be of order unity (Waxman & Draine 2000; Zhang et al. 2003). Early afterglow observations therefore provide constraints on \( \Gamma \) and on \( u_B/u_e \) that are (1) independent of the constraints derived from \( \gamma \)-ray observations, (2) consistent with the \( \gamma \)-ray constraints, and (3) remarkably similar to the constraints of equations (1) and (2), which need to be satisfied in order to allow proton acceleration to greater than \( 10^{20} \text{ eV} \).

2.3. Comparison with Other Authors

Gallant & Achterberg (1999) and, more recently, Achterberg et al. (2001) have considered particle acceleration by the ultrarelativistic \( \Gamma \sim 300 \) shock driven by the fireball into its surrounding medium. They argue that protons cannot be accelerated in this \emph{external ultrarelativistic} shock to ultrahigh energy. Regardless of whether or not this claim is valid, it is irrelevant for the model proposed in Waxman (1995b) and discussed in \( \S \) 2.1, where proton acceleration takes place in \emph{internal (reverse) mildly relativistic} shocks. Similarly, the claims in Ostrowski & Bednarz (2002) that the spectrum of protons accelerated in \emph{ultrarelativistic} shocks is much steeper than \( dn_p/dE_p \propto E_p^{-2} \), the spectrum expected for subrelativistic shocks, and required to account for the observed UHECR spectrum (see \( \S \) 3.2), are not applicable to the model proposed in Waxman (1995b).

It should be emphasized here that nonrelativistic collisionless shocks are observed in many types of astrophysical systems and that the theoretical understanding of particle acceleration in such shocks (Drury 1983; Blandford & Eichler 1987) is more developed than in the case of relativistic collisionless shocks. The GRB model for particle acceleration, described in \( \S \) 2.1, relies on our understanding of acceleration in nonrelativistic collisionless shocks and therefore is not subject to the uncertainties described in the preceding paragraph, which are related to acceleration in ultrarelativistic shocks.

Association of GRBs and UHECRs has also been suggested by Vietri (1995) and by Milgrom & Usov (1995), who noted that GRBs may accelerate protons to greater than \( 10^{20} \text{ eV} \) energy. While Milgrom & Usov did not suggest an acceleration mechanism, the criticism of Gallant & Achterberg (1999) may be relevant to the mechanism proposed by Vietri. Their main point is that the fractional energy gain per shock crossing is of order unity for highly relativistic shocks, rather than of order \( \Gamma^2 \) as suggested in Vietri (1995). This implies that the acceleration time in ultrarelativistic shocks is much longer than estimated by Vietri (1995). However, this conclusion does not necessarily imply that the acceleration process is ineffective. In their estimate of the acceleration time, Gallant & Achterberg (1999) and Achterberg et al. (2001) used an upstream magnetic field amplitude of \( 1 \mu \text{G} \), typical of the interstellar medium. GRB observations imply that this preshock magnetic field must be amplified by many orders of magnitude in the GRB shock (Gruzinov & Waxman 1999), and it is therefore far from clear that the magnetic field value relevant for particle deflection upstream is the unperturbed preshock field. The upstream magnetic field may be amplified ahead of the shock by, e.g., the streaming of high-energy particles (Bell & Lucek 2001; Dermer 2002), in which case acceleration to ultrahigh energy is possible.

3. UHECR ENERGY GENERATION RATE AND SPECTRUM

3.1. The GRB Energy Generation Rate

The GRB model for UHECR production was suggested prior to the detection of afterglows. Estimates of the rate of GRBs were based at that time on the \( \gamma \)-ray flux distribution and ranged from \( \sim 3 \text{ Gpc}^{-3} \text{ yr}^{-1} \) (Piran 1992) to \( \sim 30 \text{ Gpc}^{-3} \text{ yr}^{-1} \) (Mao & Paczynski 1992). The estimated average \( \gamma \)-ray energy release in a single GRB, based on a characteristic peak flux of \( \sim 10^{51} \text{ ergs s}^{-1} \) (e.g., Fishman & Meegan 1995), was \( \sim 10^{52} \text{ ergs} \). These estimates were subject to large uncertainties, since the \( \gamma \)-ray luminosity function as well as the evolution of GRB rate with redshift were poorly constrained. Based on the rate and energy estimates, the rate of \( \gamma \)-ray energy generation by GRBs was estimated to be \( \sim 10^{44} \text{ ergs Mpc}^{-3} \text{ yr} \). The determination of GRB redshifts, which was made possible by the detection of afterglows, allows a more reliable estimate.

Most of the GRBs are observed from \( z > 1 \), since they can be detected out to large redshift. This implies that the GRB rate density at \( z > 1 \) is better constrained by the observations than the local, \( z = 0 \), rate. The inferred local rate depends on the assumed redshift evolution. It is now commonly believed that the GRB rate evolves with redshift following the star formation rate, based on the association of GRBs with Type Ib/c supernovae. This association, which was originally motivated by the temporal and angular coincidence of GRB 980425 and SN 1998bw (Galama et al. 1998), has gained significant support from the identification of an SN 1998bw-like spectrum in the optical afterglow of GRB 030329 (Stanek et al. 2003; Hjorth et al. 2003). It is also supported by evidence for optical supernova emission in several GRB afterglows (Bloom 2003). Adopting the assumption that the GRB rate follows the redshift evolution of the star formation rate, the local \( (z = 0) \) GRB rate density was inferred by Schmidt (2001) to be \( \dot{N}_{\text{GRB}}(z = 0) \approx 0.5 \times 10^{-6} \text{ Mpc}^{-3} \text{ yr}^{-1} \). A similar result was later obtained, under similar assumptions, by Perna, Sari, & Frail (2003).

The main uncertainty in the local rate density determined by Schmidt (2001) and by Perna et al. (2003) is related to uncertainties in the determination of the evolution of the star
formation rate: a faster evolution (rate increase) with redshift implies a lower local, $z = 0$, GRB rate. However, in their analysis, neither Schmidt (2001) nor Perna et al. (2003) have used the detailed information provided by BATSE on the observed distribution of GRB peak fluxes or the detailed shape of the observed GRB redshift distribution (Schmidt 2001 has used only the value of $(V/V_{\text{max}})$). In a more detailed analysis, taking into account these constraints, Guetta, Piran, & Waxman (2003) have shown that observations allow one to discriminate between different assumptions regarding the evolution with redshift of the GRB rate density. Redshift evolution following the Rowan-Robinson (1999) star formation rate evolution ($R_{\text{GRB}} \propto 10^{0.72z}$ up to $z = 1$) was found consistent with observations, while a more rapid evolution (as assumed in, e.g., Porciani & Madau, 2001), was found inconsistent. For the Rowan-Robinson evolution, Guetta et al. (2003) find $R_{\text{GRB}}(z = 0) \approx 0.5 \times 10^{-9}$ Mpc$^{-3}$ yr$^{-1}$. Given the current (systematic uncertainties in the redshift) data, this rate is accurate to within a factor of a few (Guetta et al. 2003).

The local energy generation rate in $\gamma$-rays by GRBs, $\dot{\varepsilon}_\gamma$, is given by the product of $R_{\text{GRB}}(z = 0)$ and the average $\gamma$-ray energy release in a single GRB, $\varepsilon_\gamma$. Bloom et al. (2003) provide $\varepsilon_\gamma$ for 27 bursts with known redshifts, in a standard rest-frame bandpass, 0.02–2 MeV. The average is $\varepsilon_\gamma = 2.9 \times 10^{53}$ ergs, with estimated uncertainty, due to the correction to a fixed rest-frame bandpass, of $\sim 20\%$ for individual bursts (and much smaller for the average). In calculating $\dot{\varepsilon}_\gamma$ from this value of $\varepsilon_\gamma$, the following point should be taken into account: $\varepsilon_\gamma$ is the average energy for bursts with known redshift, most of which were localized by the BeppoSAX satellite. Since BeppoSAX has a higher detection flux threshold than BATSE (see Band 2003; Guetta et al. 2003), it is sensitive to $\sim 70\%$ of the bursts detectable by BATSE, for which the GRB rate $R_{\text{GRB}}(z = 0)$ was inferred. Thus, the energy generation rate by bursts detectable by BeppoSAX is

$$\dot{\varepsilon}_{\gamma}[0.02\text{ MeV}, 2\text{ MeV}] \approx 0.7R_{\text{GRB}}(z = 0)\varepsilon_\gamma = 10^{44} \text{ ergs Mpc}^{-3} \text{ yr}^{-1}.$$  

(3)

As mentioned above, the main uncertainty in determining $\dot{\varepsilon}_\gamma$ is related to the uncertainty in the local GRB rate, because of which the value given in equation (3) is accurate to within a factor of a few.

The energy generation rate given by equation (3) does not reflect the total energy emitted by GRBs in $\gamma$-rays, rather the energy emitted in the [0.02 MeV, 2 MeV] band. Emission at higher energy has been detected in many GRBs (see, e.g., González et al. 2003), implying that the total $\gamma$-ray energy emission is higher than that limited to the [0.02 MeV, 2 MeV] band. A bandpass-independent result may be obtained as follows. GRB $\gamma$-ray spectra are well described by broken power laws, $d\dot{\varepsilon}_\gamma/dE_\gamma \propto E_\gamma^{-\alpha}$ for $E_\gamma < E_0$ and $E_\gamma^{-\beta}$ for $E_\gamma > E_0$ (Band et al. 1993; Preece et al. 1998). The observed (redshifted) break energy $E_0$ is typically a few hundred keV, $\beta \approx 2$ and $\alpha \approx 1$. The observed $\gamma$-rays are produced in the fireball model by synchrotron and inverse-Compton emission of electrons accelerated to high energy by collisionless shocks in the expanding fireball wind (see § 2 for more detail). The high-energy part of the GRB spectrum is produced by energy loss of relativistic electrons, accelerated to a power-law distribution, $d\dot{\varepsilon}_\gamma/dE_\gamma \propto E_\gamma^{-2}$. Taking into account the fact that the photon energy is proportional to the square of the electron energy [and hence that $\log (E_\gamma)$ spans twice the range spanned by $\log (E_0)$], and that the rest-frame break energy is higher than that observed by a factor $1 + z$, the rate of energy generation in relativistic electrons is

$$E_\gamma^2 \frac{d\dot{\varepsilon}_{\gamma}}{dE_\gamma} \approx \varepsilon_{\gamma0}[0.02\text{ MeV}, 2\text{ MeV}] \approx 10^{44} \text{ ergs Mpc}^{-3} \text{ yr}^{-1}.$$  

(4)

Finally, the following point should be mentioned. The numbers quoted above for the GRB rate density and $\gamma$-ray energy release are based on the assumption that GRB $\gamma$-ray emission is isotropic. If, as now commonly believed (see Frail et al. 2001, and references therein), the emission is confined to a solid angle $\Delta \Omega < 4\pi$, then the GRB rate is increased by a factor $(\Delta \Omega/4\pi)^{-1}$ and the GRB energy is decreased by the same factor. However, their product, the energy generation rate, is independent of the solid angle of emission.

### 3.2. Comparison with UHECR Observations

The cosmic-ray spectrum flattens at $\sim 10^{19}$ eV (Bird et al. 1994; Takeda et al. 1998). There are indications that the spectral change is correlated with a change in composition, from heavy to light nuclei (Bird et al. 1994; Dawson, Meyhandan, & Simpson 1998; Abu-Zayyad et al. 2001). These characteristics, which are supported by analysis of Fly’s Eye, AGASA, and HiRes-MIA data, and for which some evidence existed in previous experiments (Watson 1991), suggest that the cosmic-ray flux is dominated at energies less than $10^{19}$ eV by a Galactic component of heavy nuclei, and at ultrahigh energy by an extra-Galactic source of protons. Also, both the AGASA and Fly’s Eye experiments report an enhancement of the cosmic-ray flux near the Galactic disk at energies $\leq 10^{18.5}$ eV, but not at higher energies (Bird et al. 1999; Hayashida et al. 1999; Takeda et al. 1999). Fly’s Eye stereo spectrum is well fitted in the energy range $10^{17.6}$–$10^{19.6}$ eV by a sum of two power laws: a steeper component, with differential number spectrum $J \propto E^{-3.50}$, dominating at lower energy, and a shallower component, $J \propto E^{-2.61}$, dominating at higher energy, $E > 10^{19}$ eV. The data are consistent with the steeper component being composed of heavy nuclei primaries and the lighter one being composed of proton primaries.

Bahcall & Waxman (2003) have shown that the observed UHECR flux and spectrum may be accounted for by a two component, Galactic+extragalactic model. For the Galactic component, this model adopts the Fly’s Eye fit,

$$\frac{dn}{dE} \propto E^{-3.50}.$$  

(5)

The spectrum and energy generation rate of extragalactic protons are given in this model by

$$E_p^2 \frac{d\dot{\varepsilon}_p}{dE_p} = 0.65 \times 10^{44} \text{ ergs Mpc}^{-3} \text{ yr}^{-1}.$$  

(6)

The spectral index, 2, is that expected for acceleration in subrelativistic collisionless shocks in general, and in particular for the GRB model discussed in § 2.1. The energy generation rate integrated over the energy range of $10^{19}$–$10^{21}$ eV is

$$\varepsilon_{\text{CR}}^{\gamma}[10^{19}, 10^{21}]_{\text{eV}} = 3 \times 10^{44} \text{ ergs Mpc}^{-3} \text{ yr}^{-1}.$$  

(7)
Uncertainties in the absolute energy calibration of the experiments lead to uncertainty of \(\approx 20\%\) in this rate (Bahcall & Waxman 2003).

The model used in Bahcall & Waxman (2003) is similar to that proposed in Waxman (1995a). The improved constraints on UHECR spectrum and flux provided by the recent observations of HiRes do not change the estimates given in (Waxman 1995a) for the energy generation rate and spectrum, equation (6), but reduce the uncertainties. Comparing equations (6) or (7), and (4) (which, as explained in § 3.1, is accurate to within a factor of a few), we find that the rate at which GRBs produce energy in accelerated high-energy electrons is comparable to the rate at which energy should be produced in high-energy protons in order to account for the observed UHECR flux.

It is important to emphasize the following point. As explained in § 3.1, the \(\gamma\)-ray energy production rate reflects the rate at which energy is produced by GRBs in relativistic electrons. The ratio between the energy carried by relativistic electrons and protons is not known from basic principles (observations suggest that in subrelativistic shocks protons carry \(\approx 10\) times more energy than electrons; see, e.g., Blandford & Eichler 1987; Berezhko et al. 2002). Thus, an exact match between the \(\gamma\)-ray and UHECR generation rates should not in general be expected. Rather, the two rates are expected to be similar to within an order of magnitude.

### 3.3. Comparison with Other Authors

Recent claims that the GRB energy generation rate is too small to account for the observed UHECR flux, (Stecker 2000; Berezhinsky et al. 2002) are not valid.

In Stecker (2000, p. 207) it is argued that at most “10% of the cosmic rays observed above 10^{20} eV can be accounted for by GRBs.” The UHECR energy generation rate estimated in Stecker (2000) is similar to the rate given by equation (6), as derived in Waxman (1995a) and Bahcall & Waxman (2003), but the GRB \(\gamma\)-ray energy generation rate estimated in Stecker (2000) is smaller by approximately an order of magnitude compared to the rate derived here, equation (3). The \(\gamma\)-ray energy generation rate by GRBs is underestimated in Stecker (2000) by an order of magnitude, since it is based on an earlier, less accurate estimate of the GRB rate per unit volume (cf. Schmidt 1999 and 2001; Frail et al. 2001; Guetta et al. 2003) and neglects GRB \(\gamma\)-rays in the 1–2 MeV band.

Berezinsky et al. (2002) claim that the required UHECR generation rate is 3 orders of magnitude larger than the GRB \(\gamma\)-ray energy generation rate. They argue that the energy generation rate of UHECRs implied by observations is \(\approx 3 \times 10^{46} \text{ ergs Mpc}^{-3} \text{ yr}^{-1}\). The discrepancy with our derived rate, equation (7), arises because Berezhinsky et al. assume that extragalactic protons dominate the observed flux in the range of \(10^{17} - 10^{18} \text{ eV}\). However, most observers attribute the flux in this energy range to Galactic cosmic rays. Thus, in our model, equations (5)–(6), extra-Galactic sources dominate the flux only above \(10^{19} \text{ eV}\), and the fraction of the observed cosmic-ray flux that is contributed by the extra-Galactic component at the energy range of \(10^{17} - 10^{18} \text{ eV}\) is

\[
\frac{J_{\text{exgal}}}{J_{\text{gal}}} \sim 10^{-2} \left( \frac{E}{10^{17} \text{ eV}} \right).
\]

Observations strongly suggest that cosmic rays above and below \(10^{19} \text{ eV}\) originate from different sources: Galactic sources of heavy nuclei are likely to dominate below \(10^{19} \text{ eV}\), while extragalactic proton sources are likely to dominate at higher energy. Thus, by assuming that extragalactic particles dominate the flux down to \(10^{17} \text{ eV}\), Berezinsky et al. greatly overestimate the required energy for extragalactic sources. In addition, the GRB energy generation rate is underestimated in Berezhinsky et al. (2002) in the same way as in Stecker (2000).

### 4. DISCUSSION

The main constraints that a relativistic wind (fireball) need to satisfy to allow proton acceleration to greater than \(10^{20} \text{ eV}\) are given by equations (1) and (2): the magnetic field energy density \(u_B\) should exceed a few percent of the relativistic electron energy density \(u_e\), and the wind Lorentz factor \(\Gamma\) should exceed \(\approx 10^5\). The similarity of these constraints and the constraints imposed on wind parameters, based on independent physical considerations, by \(\gamma\)-ray observations were the basis for the association of GRB and UHECR sources suggested in Waxman (1995b). Afterglow observations have shown that the characteristic GRB luminosity is higher than estimated based on \(\gamma\)-ray observations alone, \(10^{42}\) instead of \(10^{44} \text{ ergs s}^{-1}\), relaxing the constraint of equation (1) on \(u_B/u_e\).

In addition, early optical and radio afterglow observations provide new constraints on wind parameters: they imply large Lorentz factors, \(\Gamma > 10^3\) to \(\Gamma > 10^4\), and large magnetic field energy density in the fireball plasma, \(u_B/u_e\) of order unity (see § 2.2). These constraints are consistent with those previously inferred from \(\gamma\)-ray observations and with the constraints imposed by the requirement to allow proton acceleration to greater than \(10^{20} \text{ eV}\).

The local, \(z = 0\), \(\gamma\)-ray energy generation rate by GRBs is \(\approx 10^{44} \text{ ergs Mpc}^{-3} \text{ yr}^{-1}\) (see eqs. [3] and [4]). Afterglow observations allow one to determine this rate to within a factor of a few. The main uncertainty is due to uncertainties in the redshift evolution of the GRB rate (see § 3.1). The local rate of energy generation in high-energy protons required to account for the observed UHECR flux is determined by observations with smaller uncertainty and is also \(\approx 10^{44} \text{ ergs Mpc}^{-3} \text{ yr}^{-1}\) (see § 3.2, eqs. [6] and [7]).

Prior to direct GRB redshift measurements, which became possible with the detection of afterglows, estimates of the GRB rate ranged from \(\sim 3 \text{ Gpc}^{-3} \text{ yr}^{-1}\) (Piran 1992) to \(\sim 30 \text{ Gpc}^{-3} \text{ yr}^{-1}\) (Mao & Paczynski 1992). These estimates were subject to large uncertainties, since the \(\gamma\)-ray luminosity function as well as the evolution of GRB rate with redshift were poorly constrained. The measurements of GRB redshifts allow a more accurate estimate, \(0.5 \text{ Gpc}^{-3} \text{ yr}^{-1}\) at \(z = 0\). Although this rate is significantly lower than the pre-afterglow estimates, the estimated rate of energy generation in \(\gamma\)-rays by GRBs is similar to the pre-afterglow estimate, which was \(\approx 10^{44} \text{ ergs Mpc}^{-3} \text{ yr}^{-1}\). This is due to the fact that the average \(\gamma\)-ray energy release in a single GRB is larger than the pre-afterglow estimates, \(10^{43} \text{ ergs}\) instead of \(\approx 10^{42} \text{ ergs}\).

The numbers quoted above for the GRB rate density and \(\gamma\)-ray energy release are based on the assumption that GRB \(\gamma\)-ray emission is isotropic. If, as now commonly believed (see Frail et al. 2001 and references therein), the emission is confined to a solid angle \(\Delta \Omega < 4\pi\), then the GRB rate is increased by a factor \((\Delta \Omega/4\pi)^{-1}\) and the GRB energy is decreased by the same factor. However, their product, the energy generation rate, is independent of the solid angle of emission.
The local GRB rate implies that the rate of GRBs out to a distance from which most protons of energy exceeding $10^{20}$ eV originate, $\sim 90$ Mpc (see Fig. 2 in Waxman 1995a), is $\sim 10^{-3}$ yr$^{-1}$. The number of GRBs contributing to the observed flux at any given time is given by the product of this rate and the spread in arrival time of protons, due to the combined effect of stochastic propagation energy loss and deflection by magnetic fields (Waxman 1995b). This time spread may be as large as $10^7$ yr for $10^{20}$ eV proton originating at 90 Mpc distance, implying that the number of GRBs contributing to the greater than $10^{20}$ eV flux at any given time may reach $\sim 10^4$ (Waxman 2001). The upper limit on the strength of the intergalactic magnetic field, combined with the low local rate of GRBs, leads to unique predictions of the GRB model for UHECR production (Miralda-Escudé & Waxman 1996; Waxman & Miralda-Escudé 1996) that may be tested using operating (Abu-Zayyad et al. 2002), under construction (Kirk et al. submitted (astro-ph/0208243)), and planned (Teshima et al. 1992) large-area UHECR detectors. In particular, a critical energy is predicted to exist, $10^{20}$ eV $\lesssim E_0 < 4 \times 10^{20}$ eV, above which a few sources produce much of the UHECR flux, and the observed spectra of these sources is predicted to be narrow, $\Delta E/E \sim 1$: the bright sources at high energy should be absent in UHECRs of much lower energy, since particles take longer to arrive the lower their energy. The model also predicts the emission of high-energy, greater than 1 TeV neutrinos (Waxman & Bahcall 1997), a prediction that may be tested using operating (AMANDA), under construction (ANTARES, IceCube, NESTOR) and planned (NEMO) large-volume neutrino telescopes (see Halzen & Hooper 2002 for review). For more detailed discussion of model predictions, see Waxman (2001).

At energies greater than $10^{20}$ eV, the predicted number, $N$, of events in conventional models is uncertain because of the unknown clustering scale, $r_0$, of the sources, $\sigma(N_{\text{predicted}})/N_{\text{predicted}} = 0.9(r_0/10$ Mpc)$^{0.9}$ (Bahcall & Waxman 2000). For GRBs, in particular, the flux above $3 \times 10^{20}$ eV is expected to be dominated by few sources (Miralda-Escudé & Waxman 1996), and hence large deviations from a homogeneous source distribution may be expected (see Waxman 2001 for detailed discussion).

E. W. thanks J. N. Bahcall for useful discussions and the IAS for hospitality. This research was partially supported by MINERVA and AEC grants.

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