SIGNATURES OF THE ORIGIN OF HIGH-ENERGY COSMIC RAYS IN COSMOLOGICAL GAMMA-RAY BURSTS

JORDI MIRALDA-ESCÚDÉ AND ELI WAXMAN
Institute for Advanced Study, Princeton, NJ 08540
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ABSTRACT

We derive observational consequences for the hypothesis that cosmic rays (CRs) of energy greater than $10^{19}$ eV originate in the same cosmological objects producing gamma-ray bursts (GRBs). Intergalactic magnetic fields $\gtrsim 10^{-15}$ G are required in this model to allow CRs to be observed continuously in time by producing energy-dependent delays in the CR arrival times. This results in individual CR sources having very narrow observed spectra, since at any given time only those CRs having a fixed time delay are observed. Thus, the brightest CR sources should be different at different energies. The average number of sources contributing to the total CR flux decreases with energy much more rapidly than in a model of steady CR sources, dropping to one at $E_{\text{cut}} \approx 2 \times 10^{20}$ eV with very weak sensitivity to the intergalactic magnetic field strength. Below $E_{\text{cut}}$, a large number of sources is expected, consistent with observations. Above $E_{\text{cut}}$, a source may be observed with a flux considerably higher than the time-averaged CR flux from all sources, if a nearby GRB occurred recently. If such a source is present, its narrow spectrum may produce a “gap” in the total spectrum. These signatures should be detectable by the planned “Auger” CR experiment.

Subject headings: cosmic rays — gamma rays: bursts — magnetic fields

1. INTRODUCTION

The sources of gamma-ray bursts (GRBs) and of cosmic rays (CRs) with energy $E > 10^{19}$ eV are unknown. In particular, most of the sources of CRs that have been proposed have difficulties in accelerating CRs up to the highest observed energies (e.g., Cronin 1992). Recent gamma-ray and cosmic-ray observations give increasing evidence that both phenomena are of cosmological origin (see Fishman & Meegan 1995 for GRB observations review, and Bird et al. 1994, Yoshida et al. 1995, and Waxman 1995b for CRs). Although the source of GRBs is unknown, their observational characteristics impose strong constraints on the physical conditions in the γ-ray-emitting region (Piran 1994; Mészáros 1996), which imply that protons may be accelerated in the γ-ray-emitting region to energies $10^{20} - 10^{21}$ eV (Waxman 1995a; Vietri 1995). In addition, the average rates (over volume and time) at which energy is emitted as γ-rays by GRBs and in CRs above $10^{19}$ eV in the cosmological scenario are remarkably comparable (Waxman 1995a, b). These two facts suggest that GRBs and high-energy CRs may have a common origin.

An essential ingredient of a bursting model for CRs is the time delay due to intergalactic magnetic fields. The energy of the most energetic CR detected by the Fly’s Eye experiment is in excess of $2 \times 10^{20}$ eV (Bird et al. 1994), and that of the most energetic AGASA event is above $10^{20}$ eV (Yoshida et al. 1995). On a cosmological scale, the distance traveled by such energetic particles is small: less than 100 Mpc for the AGASA event, less than 50 Mpc for the Fly’s Eye event (e.g., Cronin 1992). Thus, the detection of these events over a ~5 yr period can be reconciled with the rate of nearby GRBs (~1 per 50 yr in the field of view of the CR experiments out to 100 Mpc in a standard cosmological scenario; e.g., Cohen & Piran 1995) only if there is a large dispersion in the arrival time of protons produced in a single burst. The required dispersion, $\gtrsim 50$ yr for $10^{20}$ eV protons, may be produced by intergalactic magnetic fields (Waxman 1995a; Waxman & Coppi 1996). The deflection angle for a proton propagating a distance $D$ in a magnetic field $B$ with coherence length $\lambda$ is $\theta_c \approx 0.05 (D/\lambda)^{1/2} (\lambda/10$ Mpc)($E/10^{20}$ eV)$^{-1}$, and the induced time delay is $\tau(E) \approx 10^3$ yr $(D/10$ Mpc)($\lambda/10$ Mpc)($B/10^{-15}$ G)$^2$ $(E/10^{20}$ eV)$^{-2}$. Since the time delay is energy dependent, the large spread in proton energy, induced by the stochastic proton energy loss via pion production, results in a time broadening of the CR pulse over a time $\sim \tau(E)$. Thus, the CRs from a single burst can be received on Earth over a long time interval. Nevertheless, since the angular deflection is small, the individual sources are still detectable by measuring the arrival directions.

In this Letter, we examine the characteristics of CR sources that should be expected in a bursting source model, as a function of the magnetic field-dependent time delay. We find that there are characteristic signatures for such a model, which would allow us to distinguish it from a scenario where the CR sources are steady, i.e., where the sources emit a constant flux on a timescale longer than the time delay of the lowest energy CRs that are relevant. In § 2.1 we give a qualitative description of the bursting model properties, using an approximate analytic approach. In § 2.2 we present Monte Carlo simulations that demonstrate the properties discussed in § 2.1. The various tests of the bursting model and the implications for future high-energy CR experiments are discussed in § 3.

2. CHARACTERISTICS OF COSMIC-RAY BURST SOURCES

We consider a cosmic-ray burst (CRB) taking place at a distance $D$ from us, where a total number of protons $n_p(E) dE$ of energy $E$ is emitted at a single instant in time. We assume that the CRs arrive with a time delay $\tau$, relative to gamma rays, with a probability density $p(\xi) d\xi$, where $\xi = t/\tau(D, E)$, and $\tau(D, E) \propto D^2/E^2$ is the characteristic time delay. In general, $p(\xi)$ should depend on the structure of the intergalactic magnetic field and the mechanisms of energy loss, and may depend on $D$ and $E$. However, our results are determined mainly by the energy and distance dependence of the characteristic time delay $\tau$ and are not sensitive to the detailed form
of \( \rho(\xi) \). For energies above the pion production threshold, \( E \sim 5 \times 10^{19} \) eV, the dispersion in arrival times at a fixed energy and distance is comparable to \( \tau(D, E) \) due to the stochastic energy loss via pion production (Waxman 1995a; Waxman & Coppi 1996).

2.1. Analytic Model

We now perform a simple analytic calculation for the number of CR sources that should be seen at each energy and flux in a CRB model. For this purpose, we approximate the effect of energy losses as being negligible when CRs come from a distance \( D < D_s(E) \), and eliminating all CRs coming from \( D > D_s(E) \) (for \( E < 10^{20} \) eV, this approximation is good, and \( D_s(E) \) corresponds to the distance where the initial proton energy necessary to have an observed energy \( E \), after losses to electron-positron production, exceeds the threshold for pion production). We also assume that the sources are observed only during a time \( \tau(D, E) \) with a constant flux

\[
F(E, D) = \frac{n_p(E)}{4\pi D^2 \tau(E)} = \frac{n_p(E) D_s(E)^2}{4\pi D^2 \tau(E)},
\]

where \( \tau(E) = \tau[D_s(E), E] \). If the rate per unit volume of CRBs is \( \nu \), all emitting the same \( n_p(E) \), then the average number of bursts at distance \( D \) observed at a fixed time is \( n(D, E) dD = 4\pi \nu \tau(E) [D^4/\tau(E)]^2 dD \), giving a number of bursts at a given observed flux

\[
n(F, E) dF = 4\pi \nu D(E)^3 \tau(E) \left[ \frac{F(E)}{F} \right]^{5/4} dF,
\]

where \( F(E) = n_p(E)/4\pi \nu D(E)^2 \tau(E) \). The flux \( F(E) \) is the minimum flux observed for the sources. In our simplified model, the number of sources drops abruptly to zero below \( F_s(E) \), owing to the assumed distance cutoff \( D_s(E) \) and the “top-hat” time profile. In reality, there should be a smooth turnover near \( F_s(E) \) of the number of CRB sources at the faint end from the \( -5/4 \) power-law slope at the bright end. This result for bursting sources is in contrast to the usual \(-3/2\) Euclidean slope, which applies for steady sources.

The total average number of sources above flux \( F \) is

\[
N(F, E) = \frac{4\pi \nu}{5} D_s(E)^4 \tau(E) \left[ \frac{F(E)}{F} \right]^{5/4},
\]

and the average background flux resulting from all the sources is

\[
B(E) = 4\pi \nu D_s(E)^3 \tau(E) F_s(E) = \nu n_p(E) D_s(E).
\]

The background flux is dominated by sources with flux near \( F_s(E) \), although the contribution from brighter sources decreases only as \( F^{-1/4} \).

As the cosmic-ray energy is increased, the average number of bursts observed above the turnover flux \( F_s(E) \) decreases, and there is a critical energy \( E_{\text{crit}} \) where this average number of sources equals unity:

\[
\frac{4\pi \nu}{5} D_s(E_{\text{crit}})^4 \tau(E_{\text{crit}}) = 1.
\]

We can write the average number of sources in terms of \( E_{\text{crit}} \) as

\[
N_s(E, E_{\text{crit}}) = N[F_s(E, E)] = \left( \frac{E_{\text{crit}}}{E} \right)^2 \left[ \frac{D_s(E)}{D_s(E_{\text{crit}})} \right]^{5/4}.
\]

The number of sources \( N_s \) drops rapidly with energy, due to the strong dependence on the decreasing cutoff distance \( D_s(E) \). The drop is especially rapid near \( 10^{20} \) eV, where \( D_s(E) \) decreases quickly (see Fig. 1 below). Therefore, for \( E < E_{\text{crit}} \), the number of sources contributing to the flux is very large, and the overall CR flux received at any given time is near the average background \( B(E) \). The brightest source has a typical flux near \( F_s(E) = F_s(E) N_s(E)^{1/5} = [B(E)/5][N_s(E)]^{1/5} \). The flux above which there is, on average, one source, although there is a probability \( P \approx [F/F_s(E)]^{-5/4} \) to observe a source with \( F > F_s(E) \). At \( E > E_{\text{crit}} \), the total energy received in CRBs will generally be much lower than the average \( B(E) \), because there will be no burst within a distance \( D_s(E) \) having taken place sufficiently recently. A few CRBs may be the lucky survivors from sources farther than \( D_s(E) \), or they may have anomalously long time delays as a result of crossing a region of high magnetic field (probably near a galaxy). There is, however, a probability \( P \approx N_s(E) \) of seeing one CR source with \( E > E_{\text{crit}} \), having a flux \( \sim B(E)/N_s(E) \) or even brighter one with probability decreasing as \( F^{-5/4} \).

If the CR sources are steady, then the number of sources decreases with energy only as \( D_s(E)^{1/2} \), i.e., much more slowly than predicted by equation (6). This implies that, for a given critical energy, the number of bright sources at \( E < E_{\text{crit}} \) predicted by a model of steady sources is much larger than that predicted for bursting sources. At any fixed time a given burst is observed in CRBs only over

![Fig. 1.—Results of a Monte Carlo realization of the bursting sources model with \( \tau_0 = 10^{-3} \) Mpc\(^{-1} \). Thick solid line: overall spectrum in the realization. Thick dashed line: the spectrum obtained when the brightest source of this realization (dominating at \( 10^{20} \) eV) is not included. Thin solid line: average spectrum, obtained when the emissivity is spatially uniform and not due to discrete sources; this curve also gives \( D_s(E) \) (see eq [4]). Dotted lines: spectra of the five sources having the largest CR flux. Thick dashed lines: spectra of the five sources that reach the highest fraction of the average flux. Crosses: Fly’s Eye data. Open circles: AGASA data (\( \sigma \) errors are shown for the flux in bins with more that one detected event, and for the energy of the highest energy CRs). The normalization of the flux is chosen to fit the observations at \( E > 2 \times 10^{19} \) eV [at lower energies, a contribution from iron cosmic rays from Galactic sources is likely to be present (Bird et al. 1994; Waxman 1995b)].](image)
a narrow range of energy, because, if a burst is currently observed at some energy $E$, then CRs of much lower energy from this burst have not yet arrived, while higher energy CRs reached us mostly in the past. Thus, bursting CR sources should have narrowly peaked energy spectra depending on the shape of $p(\xi)$, and the brightest sources should be different at different energies. This is in marked contrast to a model of steady state sources, where the brightest source at high energies should also be the brightest one at low energies, its fractional contribution to the background decreasing to low energy only as $D_c(E)^{-1}$.

2.2. Numerical Results

We now present Monte Carlo simulations of the total number of CRs received from CRBs at some fixed time. For each realization, we randomly draw the positions (distances from Earth) and times at which cosmological CRBs occurred, assuming that the CRBs are homogeneously distributed standard candles with an average rate $\nu = 2.3 \times 10^{-3}\ h^3 \text{Mpc}^{-3} \text{yr}^{-1}$ (with $h = 0.75$), similar to that of cosmological GRBs (Cohen & Piran 1995). We assume an intrinsic CR generation spectrum $\phi_0(E) \propto E^{-3} \text{d}E$, which produces a flux above $2 \times 10^{19} \text{eV}$ consistent with the Fly’s Eye and AGASA data (below $2 \times 10^{19} \text{eV}$, a significant contribution from iron cosmic rays from Galactic sources is likely to be present; Bird et al. 1994; Waxman 1995b). We calculate the change of the spectrum due to interaction with the CMB photons in a method similar to that described in Waxman (1995b), except that, for distances less than 130 Mpc, we do not use the continuous spectrum of CMB photons. Instead, we assume that there are magnetized regions with magnetic field strengths, giving a power-law distribution of magnetic field strengths, yielding a time delay, however, depends on the unknown properties of the magnetic field, and we assume there is a power-law distribution of magnetic field strengths, giving a power-law distribution of time delays. If the typical field in the intergalactic medium is $B$ and has coherence length $\lambda$, the typical deflection angle is $\theta \propto B(D\lambda)^{1/2}$. When intercepting a region with magnetic field $B' \gg B$ and coherence length $\lambda'$, the deflection angle is $\theta' \propto B'\lambda'$, yielding a time delay $\tau' \propto \tau(B'\lambda'/BA)^2(\lambda/D)$. If $n$ is the number density of such regions, the interception probability is $n \pi\lambda^2 D$, so the index $\alpha$ is $\alpha = -\log(n \pi\lambda^2 D) \log(\langle B^2\lambda^2 \rangle/\langle (B^2\lambda^2) \rangle)$. Here, we shall use as an example $\tau_0 = \tau(D = 80 \text{Mpc}, \ E = 10^{20} \text{eV}) = 10^7 \text{yr}$, corresponding to $\lambda \approx 10 \text{Mpc}$ and $B \approx 10^{-11} \text{G}$. We also assume that there are magnetized regions with $B'\lambda' = 10^5 \text{G} \lambda^2/\lambda = 10^{-3}$, and $n = 10^{-5} \text{Mpc}^{-3}$, corresponding to typical parameters for spiral galaxies. This leads to $\alpha \approx 1$ (with a weak dependence on distance).

Figure 1 presents the CR flux obtained in one Monte Carlo realization. Most of the realizations give an overall spectrum similar to that obtained in the realization of Figure 1 when the brightest source of this realization (dominating at $10^{20} \text{eV}$) is not included (**thick dashed line**). Thus, in most cases the flux at high energies is below the background (**thin solid line**), since there is no nearby source having occurred sufficiently recently. A source similar to the brightest one in Figure 1 appears only

~5% of the time. The analytic expression in equation (3) for $N(F, E)$ provides a good approximation to the numerical results for the number of sources with flux $F$ and spectral peak at $E$, except that sources at high energy are also present at fluxes below $F_c(E)$, coming from CRBs at distances higher than $D_c(E)$ for which some high-energy cosmic rays still survive. The spectral shape of the individual sources is determined by the time-delay probability distribution we have assumed, and is slightly modified by the interaction with the microwave background (this is the reason why the shape of the spectra of different sources varies).

Figure 2 shows $N_c(E)$, calculated from the average background and equations (4) and (6). The same curve gives the typical fraction of all the CRs coming from the brightest source at different energies, for $E < E_{\text{cut}}$. Since our numerical model does not assume a sharp cutoff in the flux distribution, as we did above in the analytic model, $N_c(E)$ is here an indication of the number of sources above the turnover flux. All the characteristics of the sources depend on the CRB rate $\nu$ and on the characteristic time delay $\tau_0 = \tau(D = 80 \text{Mpc}, \ E = 10^{20} \text{eV})$ only through their product $\nu\tau_0$ or, equivalently, through the critical energy $E_{\text{cut}}(\nu\tau_0)$. For the parameters we have chosen, $\nu\tau_0 = 10^{-3} \text{Mpc}^{-3}$, Figure 2 shows that $E_{\text{cut}} \approx 1.4 \times 10^{19} \text{eV}$. The dependence of $E_{\text{cut}}$ on $\nu\tau_0$ is easily determined from Figure 2, since $N_c \propto \nu\tau_0$ (see eqs. [5] and [6]), and therefore the curve in Figure 2 shifts vertically as $\nu\tau_0$. If the CRBs with $E > 10^{19} \text{eV}$ are indeed produced by GRBs, then $\nu$ is determined by the GRB flux distribution. The time delay, however, depends on the unknown properties of the intergalactic magnetic field, $\tau_0 \propto B^2\lambda$. As mentioned in §1, current data requires $\tau_0 \approx 50 \text{yr}$ or, equivalently, $E_{\text{cut}} \approx 10^{20} \text{eV}$, which corresponds to $B\lambda^{1/2} \approx 10^{-11} \text{G} \text{Mpc}^{1/2}$. The current upper limit for the intergalactic magnetic field, $B\lambda^{1/2} \approx 10^{-9} \text{G} \text{Mpc}^{1/2}$ (Kronberg 1994; Vallee 1999), allows a much larger delay, $\tau_0 \approx 10^9 \text{yr}$. However, the rapid decrease
of \(N_c(E)\) with energy near \(10^{20}\) eV implies that \(E_{\text{crit}}\) is not very sensitive to \(\nu \tau_0\). Thus, for the range allowed for the GRB model, \(5 \times 10^{-7}\) Mpc \(^{-3}\) \(\leq \nu \tau_0 \leq 10^{-2}\) Mpc \(^{-3}\), the critical energy is limited to the range \(10^{20}\) eV \(\leq E_{\text{crit}} \leq 3 \times 10^{20}\) eV.

3. DISCUSSION

We have analyzed a model where the CRs with \(E > 10^{19}\) eV are produced by cosmological sources bursting at a rate comparable to GRBs. We have found that, in this model, the average number of CR sources contributing to the flux decreases with energy much more rapidly than in the case where the CR sources are steady. We have shown that a critical energy exists, \(10^{20}\) eV \(\leq E_{\text{crit}} < 3 \times 10^{20}\) eV, above which a few sources produce most of the CRs, and that the observed spectra of these sources is very narrow: the bright sources at high energy should be totally absent in CRs of substantially lower energy, since particles take longer to arrive the lower their energy. In contrast, a model of steady sources predicts that the brightest sources at high energies should also be the brightest ones at low energies.

Above \(E_{\text{crit}}\), there is a significant probability to observe one source with a flux considerably higher than average. If such a source is present, its narrow spectrum may produce a "gap" in the overall spectrum, as in Figure 1. Recently, Sigl et al. (1995) argued that the observation of such an energy gap would imply that the sources of the CRs with \(E > 10^{20}\) eV are different from the sources at lower energy, hinting that the highest energy CRs are produced by the decay of a new type of massive particle. We see here that this is not the case when bursting sources are allowed, owing to the time variability. If such an energy gap is present, our model predicts that most of the CRs above the gap should normally come from one source.

If our model is correct, then the Fly's Eye event above \(2 \times 10^{19}\) eV suggests that we live at one of the times when a bright source is present at high energies. However, the absence of such a source cannot be ruled out, since, for example, the probability of detecting the Fly's Eye event in the realization of Figure 1, in the absence of the brightest source (thick dashed line), is \(\sim 3\%\). The highest energy AGASA event might more easily be produced by a common, faint source. Furthermore, notice that, given the detection of only one cosmic ray with \(E > 10^{20}\) eV by the Fly's Eye, we already know that the AGASA cosmic ray had a low probability of being detected; within the measurement error, its energy might be not much above \(10^{20}\) eV.

Given the present scarcity of ultra–high-energy CRs, no solid conclusions can be drawn. However, with the projected Auger experiment (Cronin 1992), the number of detected CRs would increase by a factor \(\sim 50\). If \(E_{\text{crit}}\) is \(2 \times 10^{20}\) eV, then a few bright sources above \(10^{20}\) eV should be identified; in addition, the brightest source at \(E = 2 \times 10^{19}\) eV should produce \(\sim 1\%\) of the background (Fig. 2), easily detectable once a few thousand cosmic rays at that energy have been measured, which Auger should do in a few years of exposure. In contrast, a steady source model with the same \(E_{\text{crit}}\) would predict \(\sim 10\) sources of this flux.

The observed characteristics of high-energy CR sources depend on the bursting rate \(\nu\) and on the typical time delay \(\tau_0\) only through their product \(\nu \tau_0\). However, \(\nu\) and \(\tau_0\) may be measured separately, if the time delay is either very short, \(\tau_0 \leq 50\) yr, or very long, \(\tau_0 \sim 10^6\) yr. In the former case, time variability of high-energy sources may be detected, while in the latter, which implies large magnetic fields, dispersion in CR arrival directions could be measured. The magnetic field of our Galaxy can also have interesting observable effects: the images of CRB sources should appear elongated perpendicular to the direction of the magnetic field, with a predictable correlation of the cosmic-ray position and energy. For example, a cosmic ray with \(E = 3 \times 10^{19}\) eV could be deflected by \(\sim 10^6\) when arriving along the plane of the Galaxy.

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