On the Spectrum of Ultrahigh Energy Cosmic Rays and the Gamma Ray Burst Origin Hypothesis

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Abstract

It has been suggested that cosmological γ-ray bursts (GRBs) can produce the observed flux of cosmic rays at the highest energies. However, recent studies of γ-ray bursts indicate that their redshift distribution likely follows the average star formation rate of the universe and that GRBs were more numerous at high redshifts. As a consequence, we show that photomeson production energy losses suffered by ultrahigh energy cosmic rays coming from GRBs would produce too sharp a spectral energy cutoff to be consistent with the air shower data. Furthermore, we show that cosmological GRBs fail to supply the energy input required to account for the cosmic ray flux above $10^{19}$ eV by a factor of 100-1000.

Key words: gamma-ray bursts; cosmic rays; theory

1 Introduction

Ultra-high energy cosmic rays (UHECRs) are among the most energetic form of radiation ever detected, with energies apparently reaching beyond $10^{20}$ eV. Cosmic rays with ultrahigh energies were first detected over 35 years ago by the Volcano Ranch experiment [1]. With typical event rates of one per km$^2$ per century, subsequent experiments including the Fly’s Eye [2] and AGASA [3][4] experiments have observed only a double digit number of events. However, in spite of the paucity of data, a surprising characteristic in the UHECR spectrum has been observed, viz., its apparent smooth continuation beyond $10^{20}$ eV. UHECRs appear to be distributed isotropically, indicating an extragalactic...
origin. Protons traveling from intergalactic distances should experience energy losses owing to photopion production interactions with the 2.7K cosmic background radiation. For a uniform distribution of protons in the universe, even neglecting redshift effects and cosmological source evolution, these interactions would be expected to produce a cutoff in the observed spectrum of UHECRs at $\sim 6 \times 10^{19}$ eV, commonly referred to the Greisen-Zatsepin-Kuzmin (GZK) cutoff\[5\][6]. This is because of the strong energy dependence in the energy loss rate with energy from photomeson production interactions. As a result, above $\sim 10^{20}$ eV, only protons from within the relatively nearby distance of $\leq 100$ Mpc will survive at these energies to reach the Earth \[7\]. The present data indicate, however, a flattening of the spectrum above $\sim 10^{19}$ eV\[8\] and no obvious cutoff out to an energy of $\sim 3 \times 10^{20}$ eV.

Two classes of theories have emerged to explain this phenomenon. In one class of theories, “top down”, a small branching ratio into high energy nucleons would result from the decays of unstable or meta-stable supermassive particles originating at the grand unified scale or in topological defects produced at that scale. (Most of the energy from these decays goes into the production of pions which, in turn, decay to produce much larger numbers of neutrinos, photons and electrons.)

In the other class of theories, “bottom up”, protons achieve their high energies through conventional electromagnetic acceleration processes. Only a few astrophysical sources are presently considered to have the possibility to accelerate particles to ultrahigh energies of the order of $10^{20}$ eV. Suggested possible acceleration sites include AGN jets and hot spots at the ends of radio galaxy jets. For reviews, see Ref. [9].

Among other origin hypotheses, it has been suggested that $\gamma$-ray bursts (GRBs) can produce the observed flux of UHECRs\[10\]. In such scenarios, it has been speculated that UHECRs would be emitted by GRBs fireballs with roughly the same amount of total emitted energy as the observed $\gamma$-rays in the keV to MeV range. Based on this assumption, and also assuming that the GRB rate is independent of redshift, it has been argued that the flux and spectrum of UHECRs with energies above $10^{19}$ eV (a putative extragalactic component which could account for the flattening and possible composition change above $10^{19}$ eV\[8\]) is consistent with their production by GRBs \[11\].

In recent years, X-ray, optical, and radio afterglows of about a dozen GRBs have been detected leading to the subsequent identification of the host galaxies of these objects and consequently, their redshifts. The regions in the host galaxies where the bursts are located have also been identified as regions of very active ongoing star formation. One of us \[12\] has therefore argued that a more appropriate redshift distribution to take for GRBs is that of the average star formation rate. One consequence of most GRBs being at moderate to
high redshifts, is that the GZK effect in the UHECR spectrum produced by GRBs would materialize at lower energies and be more pronounced, in stark contradiction to the data. In this Letter, we present a detailed calculation of the expected UHECR spectrum which would result from GRBs with a more realistic redshift distribution, one following the star formation rate.

2 Gamma Ray Burst Redshift Evolution

To date, some 15 GRBs afterglows of long duration bursts have been detected with a subsequent identification of their host galaxies. At least 14 of the 15 are at moderate to high redshifts with the highest one (GRB000131) lying at a redshift of 4.50\cite{13,14}. Redshift data on GRB host galaxies are presently available only for long duration bursts; the short duration bursts have not as yet been identified with any astronomical sources, however, their source-count distribution is also consistent with a cosmological origin \cite{24}.

The host galaxies of GRBs appear to be sites of active star formation\cite{16,17}. The colors and morphological types of these galaxies are also consistent with active star formation\cite{18} as is the detection of Ly\alpha and [OII] in several of the host galaxies\cite{19,20}. Further evidence suggests that bursts themselves are directly associated with star forming regions within their host galaxies; their positions correspond to regions having significant hydrogen column densities with evidence of dust extinction\cite{16,18}. A good argument in favor of strong redshift evolution for GRBs is made in Ref.\cite{21} based on the nature of the host galaxies. Other recent analyses have also favored a GRB redshift distribution which follows the strong redshift evolution of the star formation rate \cite{22,23}.

One argument for strong redshift evolution for GRBs which is independent of the SFR assumption has been put forward very recently. It is based on correlating the time variability of GRB events with the absolute luminosity of the events\cite{23}. The relationship is based on seven events and has been extended to a sample of 224 long, bright GRBs detected by BATSE. The GRB rate was found to scale as \((1+z)^{3.6\pm0.3}\) which is roughly consistent with the SFR for \(z < 1.5\). For higher \(z\), the SFR can not be accurately determined because it is strongly affected by dust. As we shall show in the next section, this uncertainty at such high redshifts does not strongly affect our result because contributions to the observed UHECR flux from such redshifts are negligible.

\footnote{The origin of GRB980425 is somewhat controversial; a possible X-ray source\cite{15} and an unusual nearby Type Ic supernova\cite{14} have both been put forward as candidates. Taking the supernova identification gives an energy release which is orders of magnitude smaller than that for a typical cosmological GRB.}
3 Calculations

Energy losses of high energy protons from their creation to the present epoch ($z = 0$) are a result of cosmological redshifting and by pair production ($p + \gamma \to p + e^+ + e^-$) and pion production ($p + \gamma \to \pi + n$) through interactions with cosmic background radiation (CBR) photons. We shall assume for this calculation a flat ($\Omega = 1$) Einstein-de Sitter universe with a Hubble constant of $H_0 = 70 \text{ km sec}^{-1} \text{ Mpc}^{-1}$ ($h = 0.7$) and taking $\Lambda = 0$. The relationship between time and redshift is then given by

$$t = \frac{2}{3} H_0^{-1} (1 + z)^{-3/2},$$  \hspace{1cm} (1)

and the energy loss owing to redshifting is

$$-\frac{1}{E} \frac{dE}{dt} = H_0 (1 + z)^{3/2}.$$  \hspace{1cm} (2)

Photopion production is the dominant interaction between UHECRs and the CMB for energies $> 10^{20}$ eV. Below energies of $3 \times 10^{19}$ eV, protons will lose energy mainly through pair production. The combined energy loss rate for both pion and pair production for protons in collisions with photons of the 2.7K background at the present epoch ($z = 0$) is defined as

$$\frac{1}{E} \frac{dE}{dt} \equiv \tau(E)^{-1}.$$  \hspace{1cm} (3)

The photomeson loss time is given by Stecker[7] and that for pair production is given by Blumenthal[25]. In order to compute the energy losses due to pion and pair production occurring at a redshift $z$, one must account for the increased photon densities and energies at larger $z$. The energy of photons increases as $(1 + z)$ and the photon density increases as $(1 + z)^3$. The energy loss for photons for any epoch $z$ can then be expressed as

$$\frac{1}{E} \frac{dE}{dt} = (1 + z)^3 \tau[(1 + z)E]^{-1}.$$  \hspace{1cm} (4)

We can then calculate the energy $E_0(z)$ at which a proton is created at a redshift $z$ whose observed energy today is $E$.

\footnote{Taking a $\Lambda = 0.7$ model does not significantly affect the results.}
In order to calculate the (number) flux of protons observed on earth of energy $E$, we follow the formalism derived in Berenzinsky and Grigor’eva [26]. Because of their high energies, we will assume that these protons will propagate along roughly straight lines from their source to the observer, unaffected by small intergalactic magnetic fields. (Dropping this assumption increases their propagation time and energy losses so that it would only strengthen our argument.)

The observed flux from a volume element of the sphere $dV = R(z)^2 dr d\Omega$ is

$$\frac{dj}{dE}dE = \frac{F(E_0, z) n(z) dV}{(1+z)4\pi R_0^2 r^2}.$$  \hfill (5)

where $F(E_0, z)$ is the flux of particles emitted at $z$ of energy $E_0$ and $n(z)$ is the density of GRBs as a function of redshift. We will take this function to be of the form

$$n(z) = (1+z)^{(3+q)} n(0).$$  \hfill (6)

Furthermore with $R_0 = R(z)(1+z)$ and $R(z)dr = cdt$, changing time to redshift dependence utilizing (1), and by integrating (5) to the edge of the sphere (i.e. out to a maximum redshift $z_{\text{max}}$) one obtains

$$j(E) = \frac{3}{8\pi} R_0 n(0) F(E) \int_0^{z_{\text{max}}} (1+z)^{(q-5/2)} \left( \frac{E_0}{E} \right)^{-\alpha} \frac{dE_0}{dE} dz.$$  \hfill (7)

assuming a power-law spectrum of index $\alpha$ for $F(E)$ to be generated by the GRBs, where $F(E)$ is the total number of particles per second with energy $E$ observed.

Above $\sim 10^{19}$ eV, the Fly’s Eye[2] and AGASA data[3][4] are well fit by a spectrum with a power law $\propto E^{-2.75}$. The “GZK cutoff energy” for UHECRs versus redshift of origin is plotted in Figure 1. We have defined this as the energy at which the spectrum drops to $1/e$ of its original value owing to photomeson production. It can be seen from Figure 1 that the protons of energy above ($> 10^{20}$ eV) can have originated no further than a redshift of $z = .034$ or a distance of 130 Mpc.

For the redshift distribution of GRBs, we have have considered three scenarios and corresponding values for the evolution index, $q$. In the first two cases, we assume a value for $\alpha$ of 2.75 which fits the data above $10^{19}$eV. For the first case, we take an isotropic comoving source density distribution corresponding to $q = 0$ out to a maximum redshift of 2.5. In a second case, we take a redshift
dependence proportional to the star formation rate corresponding to $q = 3$ out to a redshift of 2.5.

For our third case, we take the redshift distribution for GRBs derived from the time variability-redshift relationship for GRBs\cite{21}. This corresponds to taking $q = 3.6$ out to a redshift of 3.6. (It should be noted that there is no observable contribution to the cosmic ray flux from redshifts beyond 2.5 in any case.) For this case, we assume a flatter source spectrum with a smaller value for $\alpha$ of 2.35. This gives a better fit to the data between $10^{18}$ and $10^{19}$ eV, but requires a larger energy input. (If we take $\alpha = 2.75$ for this case, we get a very similar result to the second case, but slightly lower fluxes.)

We have normalized our resulting spectra to the Fly’s Eye data at $E = 10^{18}$ eV and calculated the corresponding UHECR spectra observed at Earth under the assumptions for the three scenarios described above. The results of these scenarios are plotted against the Fly’s Eye and AGASA data in figure 2. The failure of all three scenarios to fit the observed observed spectrum, particularly for energies above $10^{20}$ eV, is evident. In the scenarios where the source rate follows the star formation rate as a function of redshift, the spectrum is significantly steepened from the source spectrum above $10^{18}$ eV, a situation which does not occur in the case of a uniform distribution independent of redshift.

For the $\alpha = 2.75$ cases, the required energy input in cosmic rays above $10^{19}$ eV is $2 \times 10^{45}$ erg Mpc$^{-3}$ yr$^{-1}$. This is two orders of magnitude greater than the energy release rate from GRBs in the 0.01-1 MeV range \cite{12}. For the $\alpha = 2.35$ case, the discrepancy increases to three orders of magnitude, given the required normalization and the flatter source spectrum.

One may speculate that there are numerous nearby low-flux GRBs below the \textit{BATSE} threshold. However, \textit{BATSE} has only detected one burst which may have had an energy release significantly lower than $10^{50}$ erg, even this event being in doubt \cite{8}-\cite{15}. Thus, there is no reason to believe that such a scenario could overcome the energy discrepancy shown above unless much more GRB energy is released in UHECRs than in low-energy $\gamma$-rays.

Our calculated spectrum above $\sim 10^{20}$ eV may be underestimated owing to the fact that fluctuations in the interaction rate from very nearby sources can allow more protons to reach the Earth than our continuous-energy-loss approximation indicates \cite{27}. However, even with the inclusion of this effect, the predicted energy fluxes from GRBs would be much lower than the observations indicate\cite{28}. With regard to fluctuations, it has been argued that a few nearby sources could produce the UHECRs \cite{29} but statistical studies rule this out \cite{30}.
4 Conclusions

In this paper, we have presented the predicted spectra of UHECRs assuming that the UHECR sources are GRBs and that their source density distribution follows the star formation rate. Our motivation is the recent redshift studies of GRBs which suggest a strong redshift evolution for these objects. The results indicate that GRBs can not be responsible for the UHECRs observed at Earth because their redshift evolution leads to a predicted spectrum which is well below the data, particularly for energies above $10^{20}$ eV. In fact, the “effective GZK cutoff” for UHECRs of cosmological GRB origin is found to be $\sim 3 \times 10^{19}$ eV (see Figure 2).

It should be noted that, independent of spectral considerations, if the GRB redshift distribution follows the star formation rate, GRBs can be ruled out as candidates for the UHECRs based on energetics considerations. The present star formation rate coupled with the mean energy release per burst leads to an energy release rate per volume which is more than an order of magnitude below the rate need to account for the UHECRs with energies above $10^{20}$ eV[12],[31] and, as shown in the previous section, two to three orders of magnitude below the rate needed to account for UHECRs above $10^{19}$ eV, contradicting the hypothesis advocated in Ref. [11] and strengthening the conclusion of Ref. [12].

The recently launched High Energy Transient Explorer (HETE-2) and the Swift satellite mission, projected to be launched in 2003, should eventually provide redshift information for thousands of bursts, including the short duration bursts. These missions therefore have the potential to conclusively exclude gamma ray bursts as the source of the UHECRs, should the density distribution of the bursts conclusively indicate redshift evolution.

Future and planned UHECR detectors such as the Pierre Auger Observatory, and the space-based orbiting wide-angle lens collector (OWL) satellite system should provide the coverage area necessary to determine the true particle spectrum above $10^{20}$eV. Confirmation of the lack of a pronounced GZK cutoff and an event rate similar to that indicated by present data would also spell the demise for a GRB origin of the UHECRs.

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Fig. 1. The maximum energy a proton should be observed with at Earth (i.e., “the GZK cutoff energy”) if it is produced at redshift $z$. 
Fig. 2. The highest energy region of the cosmic ray spectrum as observed by the Fly’s Eye (triangles) and AGASA (filled dots) experiments. The solid line is the expected spectrum from sources whose density distribution follows the strong redshift dependence of gamma ray bursts derived in [23], viz., \( q = 3.6, \ z_{\text{max}} = 3.6 \). Also plotted are the expected spectra from sources whose density distribution evolves as the star formation rate \( q = 3.0, \ z_{\text{max}} = 2.5 \) (thick dashed line) and from sources whose distribution is independent of redshift \( q = 0.0 \) (dotted line). For the solid-line case, we have taken a source spectral index of 2.35; for the other two cases, an index of 2.75 was chosen.