Ultra-High Energy Cosmic Rays and Neutron-Decay Halos from Gamma Ray Bursts

C. D. Dermer

Code 7653, Naval Research Laboratory, 4555 Overlook Ave., SW, Washington, DC 20375-5352 USA

Abstract. Simple arguments concerning power and acceleration efficiency show that ultra-high energy cosmic rays (UHECRs) with energies \( \gtrsim 10^{19} \) eV could originate from GRBs. Neutrons formed through photo-pion production processes in GRB blast waves leave the acceleration site and travel through intergalactic space, where they decay and inject a very energetic proton and electron component into intergalactic space. The neutron-decay protons form a component of the UHECRs, whereas the neutron-decay electrons produce optical/X-ray synchrotron and gamma radiation from Compton-scattered background radiation. A significant fraction of galaxies with GRB activity should be surrounded by neutron-decay halos of characteristic size \( \sim 100 \) kpc.

1 Introduction

Gamma-ray bursts produce enough power within the Greisen-Zatsepin-Kuzmin (GZK) photopion production radius to power the UHECRs [1,2,3]. Stochastic gyroresonant acceleration of protons and ions by turbulence generated in relativistic blast waves can accelerate particles to ultra-high energies [4]. Energetic neutrons are formed by photopion interactions of accelerated hadrons with nonthermal synchrotron radiation in GRB blast waves. The neutrons travel through intergalactic space and decay, and the neutron-decay electrons form synchrotron and Compton halos around galaxies with GRB activity. The discovery of neutron-decay halos around galaxies with vigorous star-forming activity will provide strong evidence for a GRB origin of the UHECRs [3].

2 GRB Origin of UHECRs: Power and Acceleration

As a consequence of Beppo-SAX results, we now know that GRBs are extragalactic and originate from sources with a broad distribution of redshifts and mean redshift \( \bar{z} \approx 1 \). Beppo-SAX has a much smaller field-of-view than BATSE, but triggers on nearly the same sample of long-duration (\( t_{50} \gtrsim 1 \) s) GRBs. If UHECRs originate from GRBs, then the product of the UHECR energy density \( u_{UH} \) and the characteristic source volume \( V \) is equal to the product of the GRB power \( L_{GRB} \), the loss time from the source volume, and the efficiency \( \epsilon \) to convert GRB energy into UHECRs. For protons with energies \( \gtrsim 10^{20} \) eV, the GZK radius is \( \sim 140 \) Mpc [5]. Thus the loss time \( t_{p\gamma} \approx 140 \) Mpc/c \( \approx 1.4 \times 10^{16} \) s. Hence \( u_{UH} \approx \epsilon f L_{GRB} t_{p\gamma} / V \), where \( f \) is a factor that takes into account present
day star-formation activity compared with that occurring at \( \bar{z} = 1 \), then \( f \equiv 1/6 \).

Let \( d = 10^{28} d_{28} \) cm represent the average luminosity distance to observed GRBs, so that \( V \equiv 4\pi d^2/3 \). The power of GRBs into the volume \( V \) is given by the typical GRB energy \( E_{GRB} \) multiplied by the GRB rate. BATSE is sensitive to GRBs with peak fluxes \( \phi \gtrsim 10^{-7} \phi_{-7} \) ergs cm\(^{-2}\) s\(^{-1}\). The observed mean duration of the long duration GRBs is \( t_{dur} = 30 t_{30} \) s. Thus \( E_{GRB} \approx 4\pi d^2 \cdot 10^{-7} \phi_{-7} \cdot 30 t_{30}(1+\bar{z})/(0.1 \eta_{-1}) \approx 4 \times 10^{32} d_{28}^2 \phi_{-7} t_{30}(1+\bar{z})/\eta_{-1} \) ergs, where \( \eta = 0.1 \eta_{-1} \) is the efficiency for transforming the GRB explosion energy into \( \gamma \) rays in the BeppoSAX and BATSE energy bands. The long-duration GRBs occur at a rate of \( \approx 1/(t_{day} \text{ day}) \), with \( t_{day} \approx 1 \), so that \( L_{GRB} \approx 4 \times 10^{47} d_{28}^2 \phi_{-7} t_{30}(1+\bar{z})^2/(\eta_{-1} t_{day}) \) ergs s\(^{-1}\). We therefore find that

\[
u_{UH} \text{ (ergs cm}^{-3}\text{)} \approx 1.5 \times 10^{-21} \frac{k \epsilon f \phi_{-7} t_{30}(1+\bar{z})^2}{\eta_{-1} t_{day} d_{28}}. \tag{1}
\]

The factor \( k \) represents the energy released by the dirty and clean fireballs which do not trigger the BATSE detector. Detailed calculations within the context of the external shock model show that \( k \approx 3 \) [5].

Observations show that \( u_{UH} \approx 10^{-20} \) and \( 2 \times 10^{-21} \) ergs cm\(^{-3}\) for cosmic rays with \( E \gtrsim 10^{19} \) eV and \( 10^{20} \) eV, respectively. (For protons with energies \( \gtrsim 10^{19} \) eV, \( t_{\gamma} \approx 1000 \text{ Mpc}/c \).) If an efficient mechanism for converting the energy of the relativistic outflows into UHECRs exists, then there is sufficient power in the sources of GRBs to power the UHECRs. Detailed calculations [3,6,7] verify this result.

Particle acceleration in GRB blast waves must satisfy the Hillas [8] condition for UHECR production, which requires that the Larmor radius be smaller than the characteristic size of the acceleration region. For GRB blast waves, this size is the blast-wave width. Hence the particle Larmor radius \( r_L = (Am_p c^2/ZeB) \) \((\gamma_{max}/\Gamma) < \Delta' = f_{\Delta} x / \Gamma \), where \( \gamma_{max} \) is the maximum particle Lorentz factor measured in the explosion frame, \( \Gamma = 300 \Gamma_{300} \) is the blast wave Lorentz factor, \( \Delta' \) is the comoving blast wave width, \( f_{\Delta} \equiv 1/12 \) from hydrodynamics, and \( x = 10^{16} x_{16} \) cm is the location of the blast wave from the explosion center. The blast-wave magnetic field \( B \approx \sqrt{32\pi \epsilon B_{n_{ISM}} m_p c^2} \Gamma \approx 0.4 \epsilon B_{n_{ISM}} \Gamma \) G is defined by a magnetic-field parameter \( \epsilon_B(<1) \), and the term \( n_{ISM} \) is the particle density of the surrounding medium. Thus

\[ E_{max} = Am_p c^2 \gamma_{max} = ZeBf_{\Delta} x = 3 \times 10^{19} Z \sqrt{\epsilon B_{n_{ISM}}(f_{\Delta}/1.12)} x_{16} \Gamma_{300} \text{ eV}. \tag{2} \]

A wide range of parameter values can satisfy the Hillas condition for accelerating UHECRs by stochastic acceleration through gyroresonant interactions with MHD turbulence in the blast wave fluid [4,9]. The Alfvén speed \( v_A \) in the relativistic shocked fluid is also relativistic (naively using the nonrelativistic expression gives \( v_A/c \equiv \sqrt{2 \epsilon_B \Gamma} \), resulting in an acceleration rate that is much more rapid for second-order than for first-order processes [9,10].
3 Neutron-Decay Halos

Accelerated protons and ions interacting with nonthermal synchrotron radiation in the blast wave will produce neutrons through the process \( p + \gamma \rightarrow n + \pi^+ \). The neutrons, unbound by the magnetic field in the blast wave, leave the acceleration site with Lorentz factors \( \gamma_n = 10^{10} \gamma_{10} \), with \( 0.1 \lesssim \gamma_{10} \lesssim 100 \). The neutrons decay on a timescale \( \gamma_n t_n \approx 3 \times 10^5 \gamma_{10} \) yr, where the neutron \( \beta \)-decay lifetime \( t_n \approx 900 \) s. The neutrons travel a characteristic distance \( \lambda_n \approx 90 \gamma_{10} \) kpc before they decay and inject highly relativistic electrons and protons into intergalactic space. Approximately 1% of the energy of a GRB explosion with \( 10^{54} E_{54} \) ergs is deposited into highly relativistic neutrons when \( E_{54} \approx 1 \) [3]. The neutron-decay electron halo surrounding a galaxy from a single GRB reaches a maximum power of \( L_{\text{halo}} \approx 0.01 \times \mathcal{F}10^{54} E_{54}(m_e/m_p)/(\gamma_n t_n) \approx 10^{36} E_{54} \mathcal{F} / \gamma_{10} \) ergs s\(^{-1}\). Detailed calculations show that \( \mathcal{F} \approx 0.1 \) [3]. The neutron-decay protons become part of the UHECRs. GRB explosions with \( E_{54} \gtrsim 0.2 \) occur at a rate of about once every 5 Myrs per \( L^* \) galaxy, implying that \( \sim (5-10)\gamma_{10} \% \) of \( L^* \) galaxies should display a neutron-decay halo at maximum power. If GRB emission is beamed, a larger fraction of galaxies will display proportionally weaker halos.

The \( \beta \)-decay electrons radiate nonthermal synchrotron emission and Compton scatter CMB photons to high energies. The maximum synchrotron frequency is \( \nu \sim 3 \times 10^{20} B(\mu G) \gamma_{10}^2 \) Hz, where \( B(\mu G) \) is the mean magnetic field in the region surrounding the galaxy in \( \mu G \). The halo will display a cooling synchrotron spectrum at optical and soft X-ray energies. The electromagnetic cascade formed by the Compton-scattered \( \gamma \) rays terminates when the \( \gamma \) rays are no longer energetic enough to pair produce with the diffuse radiation fields. The relative intensity of the synchrotron and Compton components depends on the magnitude of \( B(\mu G) \). The best prospect for discovering neutron-decay halos is by optical observations of field galaxies that display active star formation [3].

We also note that the emission of nonthermal synchrotron and Compton radiation from photopion processes by UHECRs traveling through intergalactic space will produce a nonthermal component of the diffuse radiation background, irrespective of the sources of UHECRs.

References

1. E. Waxman: Phys. Rev. Lett. 75, 386 (1995)
2. M. Vietri: Astrophys. J. Lett. 453, 883 (1995)
3. C.D. Dermer: Astrophys. J., submitted (2000), astro-ph/0005440
4. C.D. Dermer, M. Humi: Astrophys. J., in press 555 (2001), astro-ph/0012272
5. T. Stanev, R. Engel, A. Mücke, R.J. Protheroe, R. J., and J.P. Rachen: Phys. Rev. D, 62, 093005
6. M. Böttcher and C.D. Dermer: Astrophys. J. 529, 635 (2000)
7. C.D. Dermer: In Heidelberg 2000 High-Energy Gamma-Ray Workshop, ed. F.A. Aharonian and H. Völk (AIP, New York, 2000), astro-ph/0010564
8. A.M. Hillas: Ann. Rev. Astron. Astrophys. 22, 425 (1984)
9. R. Schlickeiser and C.D. Dermer: Astron. Astrophys. 360, 789 (2000)
10. C.D. Dermer: Astrophys. J. revision in preparation