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 ~ 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 ϵ to convert GRB energy into UHECRs. For protons with energies $\gtrsim 10^{20}$ eV, the GZK radius is ~ 140 Mpc [5]. Thus the loss time $t_{p\gamma} \cong 140$ Mpc/c $\cong 1.4 \times 10^{16}$ s. Hence $u_{UH} \cong \epsilon f L_{GRB} t_{p\gamma}/V$, where f is a factor that takes into account present day star-formation activity compared with that occurring at $\bar{z}$. If $\bar{z} = 1$, then $f \cong 1/6$.

Let $\bar{d} = 10^{28} d_{28}$ cm represent the average luminosity distance to observed GRBs, so that $V \cong 4\pi \bar{d}^3/3$. 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 $E_{GRB} \approx 4\pi \bar{d}^2 \cdot 10^{-7}\phi_{-7} \cdot 30 t_{30}(1+\bar{z})/(0.1\eta_{-1}) \approx 4\times 10^{52} d_{28}^2 \phi_{-7} t_{30}(1+\bar{z})/\eta_{-1}$ ergs, where $\eta = 0.1\eta_{-1}$ is the efficiency for transforming the GRB explosion energy into γ rays in the Beppo-SAX and BATSE energy bands. The long-duration GRBs occur at a rate of $\approx 1/(t_{day}$ 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

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

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 $u_{UH} \cong 10^{-20}$ and 2×10^{-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, $t_{p\gamma} \cong 1000$ 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 $r_{\rm L} = (Am_pc^2/ZeB)$ $(\gamma_{max}/\Gamma) < \Delta' = f_\Delta x/\Gamma$, where γ_{max} is the maximum particle Lorentz factor measured in the explosion frame, $\Gamma = 300\Gamma_{300}$ is the blast wave Lorentz factor, Δ' is the comoving blast wave width, $f_\Delta \cong 1/12$ 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 $B \cong \sqrt{32\pi e_B n_{ISM} m_p c^2}\,\Gamma \cong 0.4\sqrt{e_B n_{ISM}}\,\Gamma$ G is defined by a magnetic-field parameter $e_B(< 1)$, and the term n_{ISM} is the particle density of the surrounding medium. Thus

$$E_{max} = Am_pc^2\gamma_{max} = ZeBf_\Delta x \simeq 3\times 10^{19} Z\sqrt{e_B n_{ISM}}\,(\frac{f_\Delta}{1/12})\; x_{16}\Gamma_{300}\,\text{eV}. \quad (2)$$

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 $v_{\rm A}$ in the relativistic shocked fluid is also relativistic (naively using the nonrelativistic expression gives $v_{\rm A}/c \cong \sqrt{2e_B\Gamma}$, 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 $\gamma_n t_n \simeq 3 \times 10^5 \gamma_{10}$ yr, where the neutron β-decay lifetime $t_n \cong 900$ s. The neutrons travel a characteristic distance $\lambda_n \simeq 90\gamma_{10}$ 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 $L_{halo} \approx 0.01 \times \mathcal{F} 10^{54} E_{54}(m_e/m_p)/(\gamma_n t_n) \approx 10^{36} E_{54}\mathcal{F}/\gamma_{10}$ 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)γ_{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 $\nu \sim 3 \times 10^{20} B(\mu\mathrm{G})\gamma_{10}^2$ Hz, where $B(\mu\mathrm{G})$ is the mean magnetic field in the region surrounding the galaxy in μG. The halo will display a cooling synchrotron spectrum at optical and soft X-ray energies. The electromagnetic cascade formed by the Compton-scattered γ rays terminates when the γ 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 $B(\mu\mathrm{G})$. 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