High-Energy Cosmic Rays from Galactic and Extragalactic Gamma-Ray Bursts

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Abstract. A model for high-energy ($\gtrsim 10^{14}$ eV) cosmic rays (HECRs) from galactic and extragalactic gamma-ray bursts (GRBs) is summarized. Relativistic outflows in GRBs are assumed to inject power-law distributions of CR protons and ions to the highest ($\gtrsim 10^{20}$ eV) energies. A diffusive propagation model for HECRs from a single recent GRB within $\approx 1$ kpc from Earth explains the CR spectrum near and above the knee. The CR spectrum at energies above $\sim 10^{18}$ eV is fit with a component from extragalactic GRBs. By normalizing the energy injection rate to that required to produce the CR flux from extragalactic sources observed locally, we determine the amount of energy a typical GRB must release in the form of nonthermal hadrons. Our interpretation of the HECR spectrum requires that GRBs are hadronically dominated, which would be confirmed by the detection of HE neutrinos from GRBs.

INTRODUCTION

We summarize our model for HECRs, which assumes that HECRs are accelerated in the relativistic shocks in GRBs [1]. GRBs inject HECRs with a single power-law from a low-energy cutoff $E_{min} \approx 10^{14}$ eV to a high-energy cutoff $E_{max} \gtrsim 10^{20}$ eV. We extend previous hypotheses [2, 3] that UHECRs originate from GRBs to include HECR origin from GRBs within our Galaxy [4].

GRBs are located in the disks of active star-forming galaxies such as the Milky Way. HECRs with energies $\gtrsim 10^{18}$ eV diffuse through their host galaxy. UHECRs with energies $\gtrsim 10^{18}$ eV escape from their host galaxy and propagate almost rectilinearly in extragalactic space. UHECRs travelling over cosmological distances have their spectrum modified by energy losses. An observer in the Milky Way will measure a superposition of UHECRs from extragalactic GRBs and HECRs produced in our Galaxy.

By fitting to the measured KASCADE [5] spectra of HECRs in the knee region, we determine the properties of a Galactic GRB that produces CRs. Our fits to the UHECR spectrum [6] measured with the High-Res experiment imply that GRBs must be strongly baryon-loaded, implying a detectable number of high energy neutrinos with a km-scale neutrino detector such as IceCube.
THE MODEL

Our model of diffusive propagation of HECRs from a single nearby GRB in the Galaxy assumes pitch-angle scattering of CR trajectories in Galactic magnetic fields on which is superposed a spectrum of magnetohydrodynamic (MHD) turbulence described by a distribution in wave-number $k$. The Larmor radius of a CR propagating in a magnetic field of strength $B = B_{\mu G} \, \mu G$ is $r_L \approx A \gamma^6/(ZB_{\mu G})$ pc, where $\gamma = 10^6 \gamma_6$ is the Lorentz factor of a CR with atomic (mass, charge) $= (A,Z)$. The model assumes that the mean-free-path $\lambda$ between pitch-angle scatterings of a CR with Larmor radius $r_L$ is inversely proportional to the energy density in the MHD spectrum at wave-number $k \sim r_L^{-1}$. A two component turbulence spectrum is assumed with wave-number index $q = 5/3$ for a Kolmogorov-type (for large wave-number) and $q = 3/2$ for a Kraichnan-type (for small wave-number) turbulence. The two components give an energy-dependent break $\lambda$ at energy $E_Z(\text{PeV}) \approx ZB_{\mu G} b_{pc}$, where $B_{\mu G} = 3$ and $b_{pc} = 1.6$ is the wavelength in parsecs of the MHD waves where the spectrum changes from Kraichnan to Kolmogorov turbulence.

The diffusion radius $r_{\text{dif}} \approx 2 \sqrt{\lambda ct/3}$. When $r \ll r_{\text{dif}}$, the number density of HECRs $n(\gamma,r,t) \propto t^{-3/2} \times \gamma^{-p-1/2(3/4)}$ for $q = 5/3$ $(3/2)$. The measured spectrum is steepened by $\frac{3}{2}(2-q)$ units because the diffusion coefficient $D \propto \lambda \propto \gamma^{2-q}$ for an impulsive source. An injection spectrum with $p = 2.2$ gives a measured spectrum $n_{ZA}(\gamma;r,t) \propto \gamma^{-s}$, with $s = 2.7$ at $E \ll E_Z$ and $s = 2.95$ at $E \gg E_Z$. Because these indices are similar to the measured CR indices above and below the knee energy, we adopt this model for CR transport and investigate the implications of an injection spectrum $p = 2.2$.

Typical GRBs are thought to be beamed by a factor 500, meaning that they are $1/500 \times$ as energetic as observations imply and $500 \times$ more frequent. Accounting for the beaming factor, star formation rate (SFR) evolution, and that dirty and clean fireball transients may not be detected as GRBs, the GRB rate per $L^*$ galaxy is $(1 - 3) \times 10^{-4} \, L^{*1-4} \, \text{yr}^{-1}$. In the Milky Way we expect one GRB every 3,000 - 10,000 years with a high probability that it will be beamed away from Earth.

UHECRs produced by extragalactic GRBs lose energy from momentum red shifting and photo-pair and photo-pion production on the CMBR during propagation through a $\Lambda$-cold dark matter universe ($\Omega_{\text{matter}} = 0.3$ and $\Omega_\Lambda = 0.7$). Attenuation produces features in the UHECR flux at characteristic energies $\sim 4 \times 10^{18} \, \text{eV}$ and $\sim 5 \times 10^{19} \, \text{eV}$ for photo-pair and photo-pion, respectively, from distant sources ($\varepsilon \lesssim 1$). We take the local GRB CR luminosity density to be $\dot{E}_{CR} = f_{CR}\dot{E}_{GRB,X/\gamma}$ where $\dot{E}_{GRB,X/\gamma} = 10^{44} \, \text{erg Mpc}^{-3} \, \text{yr}^{-1}$ and $f_{CR}$ is the nonthermal baryon-loading factor required of the model.

The GRB cosmic rate-density evolution is assumed to follow the SFR history derived from the blue and UV luminosity density of distant galaxies (see [11]). To accommodate uncertainty in the SFR evolution we take two models, one based on optical/UV measurements without extinction corrections (lower SFR), and the other with extinction corrections (upper SFR). The upper SFR is roughly a factor of 3(10) greater than the lower SFR at red-shift $z = 1(2)$. For $> 10^{20} \, \text{eV}$ CRs, both evolution models give the same flux, but the upper SFR contributes a factor $\sim 3$ more CR flux over the lower SFR at energies $\lesssim 10^{18} \, \text{eV}$. 

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FIGURE 1. Data points show preliminary KASCADE measurements of the CR proton (panel a), He (panel b), Carbon (panel c), Fe (panel d), and the all-particle spectrum (panel e), along with model fits (dotted curves) to the CR ionic fluxes. In the model, a GRB that occurred $2.1 \times 10^5$ years ago and at a distance of 500 pc injects $10^{52}$ ergs in CRs. The CRs isotropically diffuse via pitch-angle scattering with an energy-dependent mean-free-path $\lambda$ in an MHD turbulence field.

RESULTS

The preliminary (2001) KASCADE data are fit in Fig. 1 using the diffusion model described above with a GRB source a distance $r \approx 500$ pc away that exploded $\approx 2 \times 10^5$ yrs ago. The break in the CR particle spectrum $\propto$ ionic charge $Z$ is apparent in the
FIGURE 2. Best fit to the KASCADE (black points), HiRes-I Monocular (red points), and HiRes-II Monocular (blue points) data assuming a spectral cutoff at the source of $E_{\text{max}} = 10^{20}$ eV and using the upper limit to the SFR evolution. We also show the AGASA data [12] (green points) but do not include these in our fits. The cutoff energy for the halo component is $E_{\text{halo}} = 10^{17.07}$ eV and $\chi^2_r = 1.03$. The requisite baryon loading factor is $f_{\text{CR}} = 746(70.3)$ for a low energy cutoff at the source of $E_{\text{min}} = 10^9(10^{14})$ eV. This fit implies that the transition from Galactic to extragalactic CRs occurs near the second knee ($10^{17.6}$ eV) and that the ankle ($10^{18.5}$ eV) is associated with photo-pair production.

We did not perform a rigorous fit to the data, but instead adjusted the wavenumber $k_1$ (where the turbulence spectrum breaks) and the compositions of the ionic species until a reasonable fit was obtained. The best fits were obtained with $k_1 \approx 1/1.6$ pc and composition enhancements by a factor of 50 and 20 for C and Fe, respectively, over Solar photospheric abundances. The likelihood for such an event is reasonable, and the corresponding anisotropy of the CRs from a single source is shown to be consistent with observations [1]. The combined KASCADE, HiRes-I and HiRes-II Monocular data between $\approx 2 \times 10^{16}$ eV to $3 \times 10^{20}$ eV are fit in Fig. 2. We investigated 8 separate cases [1] with cutoff energy $E_{\text{max}} = 10^{20}$ eV and $10^{21}$ eV, spectral indices of $p = 2.0$ and $p = 2.2$ (for
optimizing KASCADE fits), and upper vs. lower SFR evolution. The free parameters we vary are the galactic-halo-cutoff $E_{\text{halo}}$, the baryon loading $f_{\text{CR}}$, and the intensity of the galactic halo CR component. We give values of $f_{\text{CR}}$ corresponding to $E_{\text{min}} = 10^9$ eV and $10^{14}$ eV. Fig. 2 shows our best case, with $p = 2.2$, $E_{\text{max}} = 10^{20}$ eV, and the upper SFR. The $p = 2.0$ spectrum provides a worse fit than the $p = 2.2$ case, although the CR energy demand is less in this case because CRs are injected equally per unit decade in particle energy. The transition between galactic and extragalactic CRs is found in the vicinity of the second knee ($10^{17.6}$ eV), consistent with a heavy-to-light composition change [13]. The ankle ($10^{18.5}$ eV) is interpreted as a suppression from photo-pair losses, analogous to the GZK suppression.

Our results imply that GRB blast waves are baryon-loaded by a factor $f_{\text{CR}} \gtrsim 60$ compared to the energy injected and emitted by the primary electrons that is inferred from hard X-ray and soft $\gamma$-ray measurements of GRBs. For the large baryon load required for this model, calculations show that 100 TeV – 100 PeV neutrinos could be detected several times per year from all GRBs with kilometer-scale neutrino detectors such as IceCube [14, 1]. Detection of even 1 or 2 neutrinos from GRBs with IceCube or a northern hemisphere neutrino detector would unambiguously demonstrate the high nonthermal baryon load in GRBs, and would provide compelling support for this scenario for the origin of cosmic rays.

The work of S.D.W. was performed while he held a National Research Council Research Associateship Award at the Naval Research Laboratory (Washington, D.C). The work of C.D.D. is supported by the Office of Naval Research and NASA GLAST science investigation grant DPR # S-15634-Y. A.A. acknowledges support and hospitality during visits to the High Energy Space Environment Branch.

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