Can Ultrahigh Energy Cosmic Rays Come from Gamma-Ray Bursts? Constraints on Galactic sources such as long GRB

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DOI: 10.7529/ICRC2011/V08/0138

Abstract: We study the propagation of ultra-high-energy cosmic rays (UHECR) in the Galaxy, concentrating on the energy range below the ankle. A Monte-Carlo method based on analytical solutions to the time-dependent diffusion problem is used to account for intermittency. Assuming a source population that scales as Galactic baryon density, we derive constraints arising from intermittency and the requiring to satisfy observational limits on the composition and anisotropy. It is shown that the composition and anisotropy at 1e18 eV are difficult to reproduce and require that either the particle mean free path is unusually small of the composition is heavier than suggested by recent Auger data. We therefore consider it highly desirable that steps be taken to reduce the systematic uncertainty in the experimental derivation of the UHECR composition around 1e18 eV.

Keywords: GRB, cosmic rays

1 Introduction

At what energy we observe the transition from a Galactic to an extragalactic origin of particles? A closely related question is which sources in the Galaxy contribute ultra-high energy cosmic rays (UHECR). The limit on inferred source power per unit baryon mass required to sustain Galactic UHECR in the [4-40] EeV range that is imposed by the observed anisotropy limits is smaller by nearly 3 orders of magnitude than what is required for an extragalactic origin [10], and it corresponds to the power per unit mass of gamma rays from GRB [11]. This numerical coincidence fits the hypothesis of a GRB origin for the Galactic component of UHECR [16], without invoking a much larger unseen energy reservoir for GRB. In fact, it would allow a Galactic origin for UHECR above the ankle were it somehow possible to trap these CR within the Galaxy effectively enough to obey the isotropy constraint. It remains to be shown that applying the hypothesis of UHECR from Galactic GRB to subankle Galactic CR, for which there is no extra-Galactic alternative, obeys the isotropy constraint, and the analysis of this matter is done in this paper.

We study the time-dependent diffusive transport of UHECR in the Galaxy using the method of Monte-Carlo to account for the unknown location and explosion time of GRB or other sources with similar population statistic. This approach permits us to accurately account for intermittency effects in the local UHECR spectrum and thus goes beyond the scope of earlier publications [16, 20, 9].

We assume the propagation in the Galaxy of cosmic rays at energies 10^{15} eV to 10^{18} eV can be accurately described as isotropic diffusion. This requires, a) turbulence at the scale of the CR gyroradii to provide resonant scattering and b) that the particle mean free path, $\lambda_{\rm mfp}$, be much smaller than a few kpc, the typical distance between the solar system and a GRB in the Galaxy. When condition b) does not hold, the isotropy problem derived in this paper can only be exacerbated. The Larmor radius of a proton in a 10 μG field reaches $\sim$ 100 pc at 10^{18} eV, and therefore the first condition should hold for UHECRs of any composition below $\approx 10^{18}$ eV. The second condition requires that $\lambda_{\rm mfp}$ be within a factor of 10 of the Larmor radius. If the magnetic field in the Galaxy were highly ordered, isotropic diffusion would not apply, but it likely would not help confine or isotropize CRs because free streaming and particle drift in any case lead to rapid escape (Kumar and Eichler, in prep.).

2 UHE Cosmic-ray propagation

To evaluate the level of systematic uncertainties in our model, we explore various geometric forms of the propagation volume of UHECR in the Galaxy. A disk-like geometry, which appears to be a more accurate assumption than is spherical symmetry, renders the observational constraints on anisotropy and composition more difficult to meet.

In the energy band of interest, escape is the dominant loss process of cosmic rays in the Galaxy. The halo size, H, is not well known. We use $H = 5$ kpc, which is at the high end of the range of likely values. We thus probably underestimate the flux suppression arising from a finite halo size; consequently our results on spectral structure and anisotropy are conservative for the arguments that follow. Instead of a computationally expensive full solution of the diffusion problem in disk geometry [8], we use a steady-state solution to rewrite the propagation equation in terms of the mid-plane cosmic-ray density, N_0, as well as turn the diffusive flux at the halo boundaries ($z = \pm H$) into a simple catastrophic loss term,

$$\tau_{\rm esc} = \frac{H^2}{2\,D} \simeq (10^6\ {\rm yr})\,\left(\frac{H}{5\ {\rm kpc}}\right)^2\,\left(\frac{\lambda_{\rm mfp}}{0.1\ {\rm kpc}}\right)^{-1}\ . \quad (1)$$

Ignoring variations in the diffusion coefficient within the Galactic plane, the problem depends only on the in-plane distance between source (GRB) and observer, ρ, and can be recast as 2-D diffusion equation for the mid-plane cosmic-ray density around a point source,

$$\frac{\partial N_0}{\partial t}+\frac{N_0}{\tau_{\rm esc}}-\frac{1}{\rho}\,\frac{\partial}{\partial \rho}\left(\rho\,D\,\frac{\partial N_0}{\partial \rho}\right) = \frac{Q(E)\,\delta(t)\,\delta(\rho)}{2\pi\,\rho\,H}\ , \quad (2)$$

whose solution is

$$N_0(\rho,t,E) = \frac{Q(E)}{4\pi\,D\,t\,H}\ \exp\left[-\frac{\rho^2}{4\,D\,t}-\frac{t}{\tau_{\rm esc}}\right]\ . \quad (3)$$

The anisotropy in the case of a single GRB is

$$\delta \simeq \lambda_{\rm mfp}\,\frac{1}{N_0}\,\left|\vec{\nabla}N_0\right| \simeq \frac{3\,\rho}{2\,c\,t} \quad (4)$$

Heavier nuclei have a smaller rigidity at the same total energy, $R \propto E/Z$. The mean free path of an ultra-high-energy particle should only depend on the rigidity, and in the absence of energy losses a nucleus of charge Z and energy E_Z should behave like a proton of energy $E = E_Z/Z$. Thus equation 3 also describes the distribution of heavy nuclei in the Galaxy, provided the appropriate scaling is applied to the energy and the source rate.

Generally, GRBs in the Galaxy are expected every million years or so, the exact rate depending on the beaming fraction and the detailed scaling of long GRB with star formation and metallicity (For a review see [12]). Therefore, only a small number of GRB can contribute to the particle flux at the solar circle, and their relative contribution depends on the location and explosion time of the GRB. Variations in the local particle flux must be expected, and neither the particle spectrum from an individual GRB nor the spectrum calculated for a homogeneous source distribution are good proxies. To fully account for discreteness of GRBs in space and time, we can use the method of Monte-Carlo to randomly place GRBs in the Galaxy with given rate and spatial probability distribution in galactocentric radius

$$P(r_{GC}) = \frac{2\,r_{GC}}{r_0^2}\ \exp\left(-\frac{r_{GC}^2}{r_0^2}\right) \quad (5)$$

with scale $r_0 = 5$ kpc. We have calculated spectra for 10^4 random sets of GRBs, going back 6 Gyr in time, but

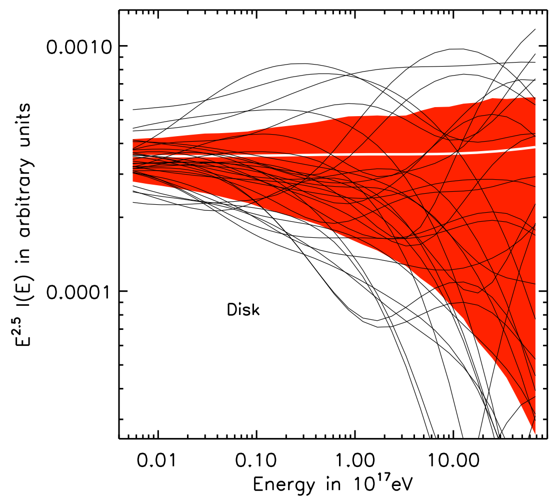

Figure 1: Proton spectra at the solar circle expected for a diffusion coefficient scaling with $\sqrt{E}$ in disk geometry. The red band indicates the central 68% containment region for the particle flux at the given energy.The GRB rate is set to 5 $\rm Myr^{-1}$. We have plotted 31 individual, randomly selected spectra. The average spectrum is given by the thick white line.

ignoring energy losses. Overall, the method is the same as that used to model the transport of cosmic-ray electrons in the Galaxy [19, 18]. Results are shown in Figure 1 for an injection index $s = 2$. More details are found in an upcoming publication (Pohl & Eichler, subm.).

It is the energy dependence of the diffusion coefficient that determines the particle spectrum. Structure in the observed spectrum could thus arise from changes in the energy dependence, e.g. from shallow at lower energies to Bohmian at higher energies, without requiring any structure in the source spectrum [9]. Intermittency is strong for a GRB rate below 1 per Myr, in particular for the more realistic disk geometry. In essence, the local UHECR spectrum from galactic GRBs is unpredictable if the scattering mean free path exceeds about 100 pc, which for the parameters used here is the case above 10^{17} eV for protons, and above $3\cdot10^{18}$ eV for iron. Model fits of single-source spectra [20] can thus be very misleading. The actually expected spectra display bumps unrelated to both source and propagation physics, some of which may indeed be observed [5]. The absence of very large bumps in the observed UHECR spectra suggests that either the mean free path for scattering is smaller than assumed here, or the rate of cosmic-ray producing GRBs in the Galaxy exceeds 1 per Myr. Generally, careful accounting of the statistical fluctuations is mandatory for properly estimating the local UHECR spectrum from GRBs [9].

3 A possible model

We now try to construct a model that reproduces the spectrum of cosmic rays between 10^{15} eV and 10^{19} eV to-

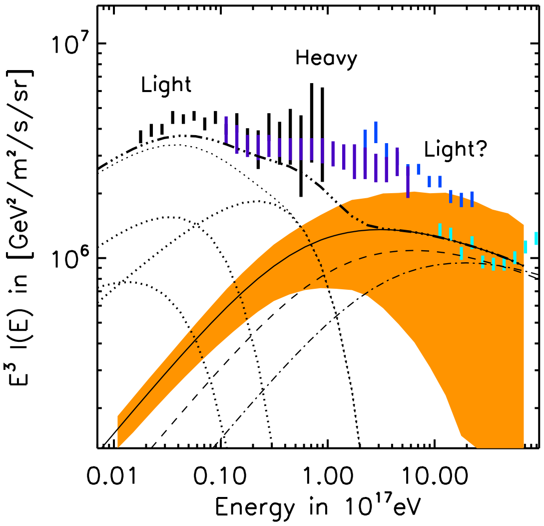

Figure 2: Example of model spectra for cosmic-ray protons, helium, and carbon nuclei, including the 68% variation range in the case of protons. The solid line denotes the average spectrum of hydrogen, the dashed line displays the same for helium, and the dash-dotted line is for carbon. The mean free path follows equation 6 and is Bohmian above 10^{17} eV. Also shown are the spectra measured with KASCADE-Grande, HiRes, and Auger, together with labels indicating the composition. For comparison, we also display simple mock spectra of hydrogen, helium, and C-Fe-group particles possibly produced in SNR. The thick triple-dot-dashed line indicates the total of hydrogen from GRB and all particles from SNR.

gether with the anisotropy limits and the composition. We use data of the Kascade-Grande collaboration [4], HiRes [1, 13], and the Auger collaboration [3, 17]. At 10^{18} eV the anisotropy is low, $\delta \leq 0.01$ (the 99% upper limit is 0.02), and the composition is light, but not necessarily dominated by protons [2]. Figure 2 shows the spectra for a possible model configuration, where for simplicity we display only spectra for protons, helium, and carbon as proxies for light and heavy nuclei, respectively. The GRB rate is set to $P(t) = 1\ \mathrm{Myr}^{-1}$ and the source spectral index is $s = 2.1$. The mean free path transitions from a shallow energy dependence to Bohmian scaling as the particle energy increases,

$$\lambda_{\mathrm{mfp}} = \lambda_0\, E^{0.3} \left[1 + \frac{E}{60\,\mathrm{PeV}}\right]^{0.7} \qquad (6)$$

where λ_0 is chosen so a proton has a mean free path of 11 pc at 10^{17} eV, its Larmor radius in a 10-μG magnetic field. For comparison available data are displayed in the same figure. The offset between spectra from different experiments is likely due to errors in the absolute energy scale. The calculated spectrum below 10^{17} eV is by design far below the data in order to accommodate other Galactic sources of cosmic rays, such as SNR or PWN. The fluctu-

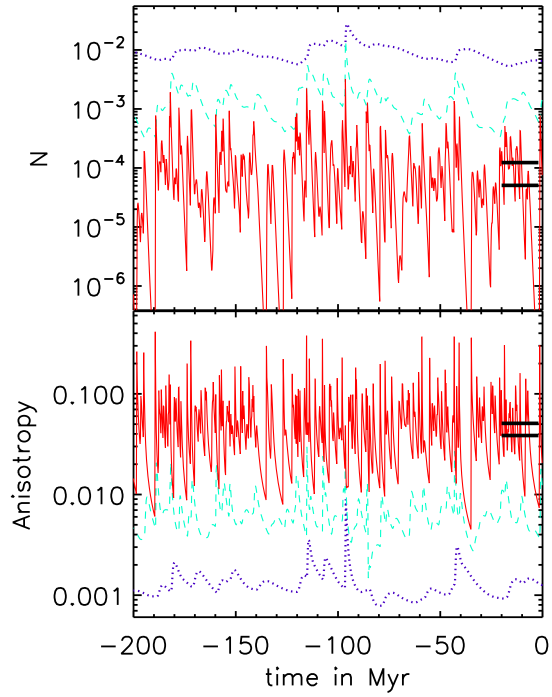

Figure 3: *Top panel:* 200-Myr lightcurve of the local proton flux at 3 different escape times relative to the inverse source rate of 1 Myr: The dotted line is for $\tau_{\mathrm{esc}} = 20$ Myr , the dashed line for $\tau_{\mathrm{esc}} = 4.5$ Myr, and the solid line for $\tau_{\mathrm{esc}} = 0.5$ Myr The units of intensity are arbitrary. *Bottom panel:* temporal variation of the anisotropy at the same escape times. For the diffusion parameters chosen in the text, where the mean free path is chosen conservatively as the gyroradius for the two highest energies, the dotted line is for 0.024 EeV, the dashed line for 0.24 EeV, and the solid line for 2.4 EeV. The two black bars on the right of the panels indicate the median and the average of the light curves at $\tau_{\mathrm{esc}} = 0.5$ Myr, where the lower bar always indicates the median.

ation amplitude at energies above 10^{17} eV is large for the GRB rate used here, one per Myr.

Galactic long GRB need only contribute about 10^{37} erg/s in accelerated particles to fully account for the currently observed particle flux at 10^{18} eV, assuming a Bohmian mean free path. This power requirement is sufficiently low to easily permit viability of the GRB scenario, in contrast to the case of extragalactic UHECRs at GZK energies [10].

The anisotropy at 10^{18} eV is not easy to reconcile with the upper limit established with Auger data. The lightcurve shown in the top panel of Figure 3 shows that besides the increase in fluctuation amplitude, the fluctuation timescale decrease with particle energy (or more precisely escape rate). For the parameters used her, the escape time at 2.4 EeV is about $5 \cdot 10^5$ yr. The flux variations can be compared with the temporal behaviour of the anisotropy, shown in the bottom panel of Figure 3. Already at 0.24 EeV (the dashed, cyan line) the anisotropy hovers around 1%. A clear correlation between flux and anisotropy is not discernible at higher energies, although at 0.024 EeV some structures in flux and anisotropy coincide.

Figure 3 also indicates the median and the time average of the flux and anisotropy at 2.4 EeV, both of which are considerably in excess of the Auger limits. Only during the rare lull, lasting only several Myr, does the anisotropy dip as low as the Auger limits. During these lulls, however, the intensity dips as low as *three or four* orders of magnitude below the time average! This possibility suggests an anthropic scenario whereby we live in highly unusual times, when the present cosmic-ray intensity is far below usual conditions, which for some (possibly obscure) reason would be hostile to intelligent life and/or advanced civilization. Note that the extreme versions of this scenario, in which the present UHECR luminosity of the Galaxy is $\sim 10^{-4}$ below the average (and possibly an even larger factor below the most recent maximum), would require an average (or peak) luminosity above 100 GeV or so that compares with (or exceeds) the present day value, and hence an extremely flat Galactic source spectrum. This could possibly be tested or constrained by abundance measurements of terrestrial cosmogenic nuclei (TCN), particularly muogenic nuclei, whose production is dominated by primary energies above 100 GeV.

The Auger limits, $\delta \leq 0.01$ at 10^{18} eV, require a carbon-like composition in the case of Bohm diffusion, and the mean free path would have to be at least a factor 5 smaller than the particle Larmor radius, if the dominant particle species were protons. Auger data suggest that at 10^{18} eV the composition is indeed light, thus posing a problem for the notion that Galactic GRB (or any other source class with similar population statistic) produce the observed UHECR up to the ankle. (This measurement is not undisputed, though, for the KASCADE-Grande collaboration has just published their analysis results which seem to favor a relatively heavy composition up to nearly 10^{18} eV [5].) The UHECR composition is a very critical constraint, but its measurement is subject to considerable systematic uncertainties arising from its dependence on models for the development of air showers. It is imperative that measures be taken to better understand the air-shower physics near 10^{18} eV.

Much of the UHECR anisotropy arises from the expected location of long GRB in the inner Galaxy. Observations of GRB host galaxies suggest that regions of low metallicity and high star formation may be the preferred sites of long GRB [15, 14], which may skew the galactocentric distribution of long GRB toward the outer Galaxy. However, the large discrepancy between the predicted anisotropy and the observed upper limits would require rather fine tuning of the revised distribution, particulary if the sources are in the plane of the disk. As there is no power problem with Galactic GRB, it may be worthwhile to also consider short GRB. They provide supposedly less power as a population, but they may have a very extended spatial distribution in the Galaxy, thus reducing the anisotropy [7]. The anisotropy arising from intermittency would remain in both cases and is the subject of a forthcoming publication. For the case of intermittent sources, the spectrum varies considerably with time, and fitting the observed spectrum imposes additional constraints on the distribution of sources in the recent past.

Our results also apply to an UHECR origin in supernova remnants, assuming very efficient magnetic-field amplification can increase their ability to accelerate particles to energies significantly higher than 1 PeV [6]. The spatial distribution in the Galaxy of long GRB and SNR can be expected to be similar, and therefore the average anisotropy is the same for both long GRB and SNR. We have verified that intermittency would be negligible in case of a SNR origin (unless of course the UHECR come only from a rare subclass of supernovae) and therefore problems in simultaneously matching the composition and the anisotropy limits of UHECR are inescapable for SNR.

Support from the Israel Science Foundation, the Israel-U.S. Binational Science Foundation, and the Joan and Robert Arnow Chair of Theoretical Astrophysics is gratefully acknowledged.

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