

High Energy Cosmic Rays from Local GRBs

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Abstract. We have developed a model that explains cosmic rays with energies E between $\sim 0.1 - 1$ PeV and the energy of the second knee at $E_2 \sim 3 \times 10^{17}$ eV as originating from a recent Galactic gamma-ray burst (GRB) that occurred ~ 1 Myr ago within 1 kpc from Earth. Relativistic shocks from GRBs are assumed to inject power-law distributions of cosmic ray (CR) protons and ions to the highest ($\gtrsim 10^{20}$ eV) energies. Diffusive propagation of CRs from a recent (~ 1 Myr old) GRB explains the CR spectrum near and above the first knee at $E_1 \sim 3 \times 10^{15}$ eV. The first and second knees are explained as being directly connected with the injection of plasma turbulence in the interstellar medium on ~ 1 pc and ~ 100 pc scales, respectively. Transition to CRs from extragalactic GRBs occurs at $E \gtrsim E_2$. The origin of the ankle in the CR spectrum at $E_{\text{ank}} \simeq 4 \times 10^{18}$ eV is due to photopair energy losses of UHECRs on cosmological timescales, as also suggested by Berezhinsky and collaborators. The rate density of extragalactic GRBs is assumed to be proportional to the cosmological starburst activity in the universe. Any significant excess flux of extremely high energy CRs deviating from the exponential cutoff behavior at $E > E_{GZK} \simeq 6 \times 10^{19}$ eV would imply a significant contribution due to recent GRB activity on timescales $t \lesssim 10^8$ yrs from local extragalactic sources within ~ 10 Mpc.

1. Introduction

There is general consensus that acceleration of CRs by supernova remnants (SNRs) is the main contributor of galactic CRs at energies below ~ 100 TeV (e.g. [1, 2]). It is also generally thought that all CRs with energies up to at least the second knee in the CR spectrum at $E_2 \sim 3 \times 10^{17}$ eV (e.g. [3, 4]), or even up to the ankle at $E_{\text{ank}} \simeq 3 \times 10^{18}$ eV, are produced in our Galaxy (see e.g. [5] for a recent review). Meanwhile, CR acceleration to energies significantly exceeding 0.1 PeV with the conventional mechanism of nonrelativistic first-order shock acceleration by SNRs from typical (Type Ia and II) supernovae (SNe) is problematic [6, 7]. The origin of the knee in the CR spectrum, in the form of a spectral-index break in the power-law all-particle spectrum by ≈ 0.3 units at $E_1 \simeq 3 \times 10^{15}$ eV, accompanied with a change in the CR composition, seems to suggest a new contribution to CRs in the Galaxy at these energies.

We have recently proposed a model [8] that explains the entire CR spectrum from GeV up to ultra-high energies (UHE) with a single population of sources, namely SNe. It is important to realize that SNe consist of various types, not only the thermonuclear Type Ia SNe, but also the core-collapse Type II and Ib/c SNe. Observations indicate that long-duration gamma-ray bursts (GRBs) are formed by a subset of Type Ib/c SNe that collapse to black holes. These black-hole formation events are observed as GRBs if the Earth happens to fall within the narrow opening angles of their relativistic beams (see [9] for a review).

GRBs have been proposed as effective accelerators of CRs in the universe [10, 11, 12], and as probable sources of CRs up to ultra-high energies in our Galaxy [13, 14]. Our model assumes that CRs with energies below ~ 100 TeV are produced in the conventional quasi-stationary scenario of continuous injection due to nonrelativistic shock acceleration by SNRs formed in all types of SNe, with subsequent modification of the source spectrum through energy-dependent propagation (see [1, 2, 15]). The principal proposal of our model is that up to the second knee, high-energy cosmic rays (HECRs) at $E \gtrsim 0.1$ PeV are mostly due to a single (or a few) relatively recent Galactic GRB supernova event that occurred some $t_0 \lesssim 10^6$ yrs ago at distances $r_0 \lesssim 1$ kpc from us. UHECRs from extragalactic GRBs dominate at $E \gtrsim E_2$.

We note that a “single-source” model has been proposed earlier by Erlykin and Wolfendale [16], who suggested that the knee could be due to a single “normal” supernova event that occurred some $t \sim 10^4$ yr ago within $r \sim 100$ pc from us. Despite the apparent similarity in the approach, the differences between the GRB and SNR single-source models are substantial on both qualitative and quantitative levels. These include

- (i) the possibility to explain acceleration of particles up to ultra-high energies by the relativistic shocks formed by GRB outflows, which is very problematic in the case of SNRs formed in the collapse to neutron stars; and
- (ii) the much larger total energy of HECRs injected, which permits the source to have occurred at larger (~ 1 kpc) distances and from a significantly older GRB than for a single normal SN source. This makes it then easier to explain the likelihood of such an event, as well as the low degree of anisotropy observed in HECRs.

Our model provides a way to explain the origin and the sharpness of the knee at $E_1 \simeq 3$ PeV as the consequence of pitch-angle scattering of CRs on the plasma waves injected in the interstellar medium (ISM) through dissipation of bulk kinetic energy of SNRs effectively on the pc-scale Sedov length. Furthermore, we also explain the origin of the second knee in the spectrum of HECRs at $E_2 \simeq 4 \times 10^{17}$ eV as an unexpected but reasonable consequence of diffusive propagation due to scattering with turbulence injected on a scale of ~ 100 pc. The latter corresponds to the thickness of the Galactic disk, which therefore represents the maximum natural scale for effective injection of plasma turbulence in the Galaxy. The transition from Galactic to extragalactic CRs occurs around and above the second knee.

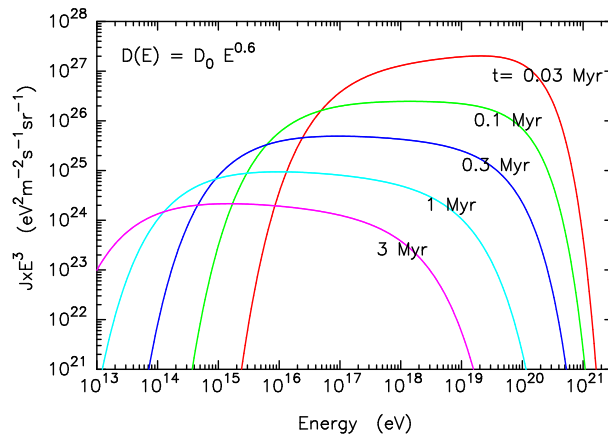


Figure 1. Time evolution of the energy distribution of CRs injected from a GRB at $r = 1$ kpc from an observer with power-law spectral index $\alpha_0 = 2.2$, with a maximum (exponential cutoff) energy $E_{max} = 10^{21}$ eV, and total energy $U = 10^{52}$ ergs. A diffusion coefficient $D(E) = D_0 E^{0.6}$ with $D_0 = 10^{29} \text{ cm}^2 \text{ s}^{-1}$ is assumed.

In this paper we present in more general terms the basic ideas and results of the model in Ref. [8], with particular emphasis on the effects of propagation and the allowed parameter space of the model.

2. Propagation Effects and Spectrum of MHD turbulence

Unlike relativistic electrons, relativistic protons and nuclei that contribute the bulk of the measured CR energy density do not suffer significant radiative energy losses during their lifetime in the Galaxy (heavier nuclei such as Fe can, however, experience substantial depletion through spallation). In particular, radiative synchrotron and Compton energy losses, which steepen the source spectra of relativistic electrons, are entirely negligible for relativistic hadrons in the ISM and galactic halo, even at ultra-high energies. This admits only one remaining possibility to explain how the spectrum of cosmic rays with power-law index $\alpha \geq 2.7$ is steepened from the $\alpha_0 \approx 2.0 - 2.3$ injection indices for CR source spectra predicted by first-order Fermi acceleration. Namely, one has to invoke spectral steepening due to *energy-dependent* diffusive propagation in the interstellar medium [2]. Spectral steepening is then possible, but only if the energy density of CRs observed locally is higher than the energy density of CRs from “outside” the source injection region. The steep spectrum of the observed CRs, in particular HECRs, implies that we are within a local “bubble” of CRs, where the CR density is significantly higher than the mean energy density throughout the Universe. At energies $E \gtrsim 5 \times 10^{17}$ eV, the extragalactic cosmic rays have a larger energy density than the cosmic rays formed within the Galaxy, so that the bulk of cosmic rays at higher energies have a universal (extragalactic) origin. Spectral modifications due to energy losses on cosmological time scales for UHECRs are then expected [15].

Our model assumes effective acceleration of CRs up to $\gtrsim 10^{20}$ eV by relativistic

shocks of typical GRBs, one of which would, with reasonable probability, have occurred in the Galaxy at a distance $r \lesssim 1$ kpc from us within the last million years. For spatially uniform diffusive propagation of cosmic rays from a single impulsive burst-type source, the time evolution of the spectrum $n(E; r, t)$ of CRs injected with initial energy distribution $N_0(E)$ at $t_0 = 0$ is given, in the absence of energy losses, by the expression

$$n(E, r, t) = \frac{N_0(E)}{\pi^{3/2} r_{dif}^3} \exp[-(r/r_{dif})^2] \quad (1)$$

[17, 18]. Here $D(E)$ is the diffusion coefficient, and r_{dif} is the energy-dependent diffusion radius of particles, given by

$$r_{dif} \equiv r_{dif}(E, t) = 2\sqrt{D(E)t}. \quad (2)$$

When an observer is inside the diffusion radius, that is, $r < r_{dif}(E, t)$, the steepening of the local hadron spectrum is the result of larger volumes $V(E) \propto r_{dif}^3(E)$ occupied by particles of higher energies due to their faster diffusion. For a power-law diffusion coefficient $D(E) \propto E^\delta$, the source spectrum is steepened by a change in power-law index $\Delta\alpha \equiv \alpha - \alpha_0 = (3/2)\delta$. Note that the total spectrum of injected particles in the entire space does not change in this approximation. This is easily checked by integration of Eq. (1) over d^3r . Without energy losses, the source spectrum is recovered if propagation occurs in an effectively infinite volume.

In Fig. 1 we show the time evolution of the spectrum of particles from a GRB at a distance $r = 1$ kpc from the observer. In this calculation, the total energy of protons injected with power-law index $\alpha_0 = 2.2$ is $U = 10^{52}$ ergs. It is assumed that the maximum energy of accelerated particles is $E_{max} = 10^{21}$ eV, and the diffusion coefficient is a single power-law with $\delta = 0.6$ and $D_0 = 10^{29}$ cm² s⁻¹. The spectral steepening above energy E at $t > t_{dif}(E)$, corresponding to $r_{dif}(E, t) > r$, results in $\alpha = \alpha_0 + (3/2)\delta = 3.1$. A gradual decrease of the position of the exponential cutoff in the spectrum at the highest energies results from the assumption that particles leak from the Galactic halo on timescales $t_{esc}(E)$ that corresponds to their diffusion to ≈ 10 kpc, so that $r_{dif}(E, t_{esc}) = 10$ kpc. This leads to an additional leaky-box type exponential modification of Eq. (1) by a factor $\exp[-t/t_{esc}(E)]$.

The magnitude of the CR flux at a given energy depends most importantly on whether the low-energy exponential cutoff in Eq. (1) has reached this energy. Because $r_{dif}(E, t) \propto \sqrt{D(E)t}$ is the single parameter that defines the spectral evolution in Eq. (1), the age of the source can be changed by assuming different absolute values of the diffusion coefficient.

The CR diffusion in our model is due to pitch-angle scattering of protons and nuclei with magnetohydrodynamic (MHD) turbulence in the Galactic disk and halo. The spectrum of this turbulence, superposed on the Galactic magnetic field B , is described by spectral energy distribution $w(k)$ in wave number k . The shape of this spectrum is key to explain the origin of both knees in the HECR spectrum.

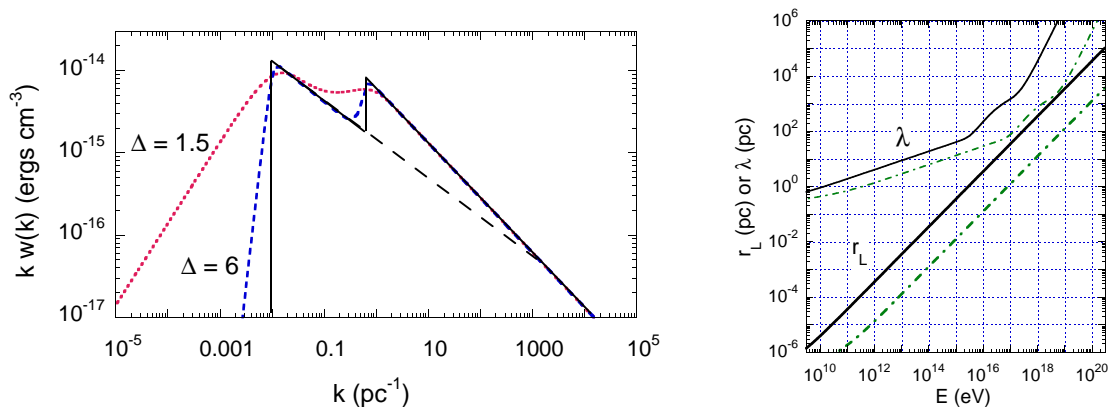


Figure 2. (a) (*left*) Wave turbulence spectrum used to model CR propagation in the Galaxy, assuming injection of turbulence at scales $k_1 = 1/1.6 \text{ pc}^{-1}$ and $k_2 = 0.01 \text{ pc}^{-1}$, followed by cascading of turbulence to smaller size scales and larger wave numbers. An idealized model is shown by the solid lines and, after smoothing, by the dotted and short-dashed curves for the smoothing parameter $\Delta = 1.5$ and 6 , respectively (see [8] for details). (b) (*right*) Larmor radius $r_L(E)$ and the mean-free-path λ of CR protons (solid curves) and Fe nuclei ($Z = 26, A = 56$; dot-dashed curves) with total energy $E = A\gamma m_p c^2$ in a magnetic field with mean strength of $3 \mu\text{G}$.

The Larmor radius of a CR ion with total energy $E = Am_p c^2 \gamma = E_{\text{PeV}} \text{ PeV}$ and charge Z propagating in a magnetic field of strength $B = B_{\mu\text{G}} \mu\text{G}$ is

$$r_L(E) = \frac{Am_p c^2 \beta \gamma}{ZeB} \sin \theta \simeq \frac{E_{\text{PeV}}}{Z B_{\mu\text{G}}} \text{ pc} , \quad (3)$$

where θ is the pitch angle, which we have supposed to be large enough ($\sim \pi/2$) so that $\sin \theta \sim 1$ on the right side in Eq. (3). Pitch-angle scattering on MHD waves takes place through a resonance between the ion gyration radius and the wavelength k^{-1} , i.e. $k r_L \sim 1$ (see, e.g., [19, 20] for more detailed treatments). This results in the mean-free-path $\lambda(E)$, and hence the diffusion coefficient $D(E) = c\lambda/3$ of CRs with energy E , being tightly connected with the energy density in the MHD spectrum at $k \sim r_L^{-1}$, so that $\lambda = r_L U_B / \bar{k} w(\bar{k})$ [1]. Therefore a local power-law index q in the turbulence spectrum $w(k) \propto k^{-q}$ near wavenumber $k_0 = 1/r_L(E_0)$ translates to a power-law diffusion coefficient $D(E) \propto E^{2-q}$ in the vicinity of E_0 .

Fig. 2a shows the spectrum of MHD turbulence used in Ref. [8] for calculations of $\lambda(E)$. Here we assumed that MHD turbulence is injected into the Galactic disk and halo by two different processes on two distinct size scales. Injection on the $k_1^{-1} \sim 1 \text{ pc}$ scale is likely due to SNRs after reaching the Sedov phase. Turbulence injected at scales $k_2^{-1} \sim 100 \text{ pc}$, which is of the order of the characteristic thickness of the gas disk of our Galaxy, may be due to the interaction of high velocity clouds with the Galactic disk. The solid and long-dashed lines correspond to the power-law indices $q = 5/3$ and $q = 3/2$ for the Kolmogorov and Kraichnan turbulence spectra, respectively, after further cascading of the injected MHD waves from these 2 types of sources. The total spectrum of turbulence that results after application of a smoothing procedure with

parameters $\Delta = 1.5$ and $\Delta = 6$ (see [8] for details) are shown in Fig. 1a by dotted and short dashed curves, respectively.

The mean free path for scattering of CR protons and ion nuclei, calculated for the plasma turbulence spectrum plotted in Fig. 1a (for $\Delta = 1.5$), are shown in Fig. 2b. As is apparent from Eq. (3), for the characteristic Galactic magnetic field $B \simeq 3 \mu\text{G}$, the MHD turbulence near the break in the $w(k)$ spectrum at $k_1 \sim 1 \text{ pc}^{-1}$ resonates with protons with energies $E_1 \sim 3 \text{ PeV}$. This explains the origin of the first knee. The second break in the spectrum of turbulence at $k_2 \sim 1/(100 \text{ pc})$ is the cause of the second knee at $E_2 \sim 3 \times 10^{17} \text{ eV}$ in the CR spectrum. For particles of higher energies, there is not sufficient energy in resonant MHD waves to prevent rapid escape from the Galactic halo. This is seen in Fig. 2b as a very steep increase of λ with energy E above $\sim 2 \times 10^{17} \text{ eV}$ for the protons. The power-law spectrum of the MHD waves at $k < k_2$ in Fig. 2a (dotted curve) could be as hard as $q \simeq 0$.

One of the major objections to a model where the transition between the galactic and extragalactic components occurs in the vicinity of the second knee is that fine-tuning is required to smooth the transition where the galactic component exponentially cuts off and the extragalactic component emerges. This criticism is ameliorated in this model because no exponential cutoff of the galactic component is required for a propagation model, as compared to model where the maximum energy of the galactic CR source is due to acceleration and loss or escape processes. Depending on the wave turbulence spectrum at $k \lesssim 0.01 \text{ pc}^{-1}$, a break to a softer power-law may occur due to propagation effects at the second knee. This will naturally smooth any transition to a second component.

3. CRs from Local GRBs and Propagation Parameters

Our model predicts a transition from the Galactic to extragalactic components near and above the second knee in the all-particle spectrum at $E \sim (3 - 5) \times 10^{17} \text{ eV}$. For CR nuclei with larger Z , the positions of both knees move to higher energies because of the smaller gyroradii for the same total particle energy, as implied by Eq. (3). Injection of HE CRs from a single GRB source also allows, as demonstrated in [8], a good fit to the cosmic-ray ion spectra measured with KASCADE (Karlsruhe Air Shower Array) [4, 21] through the first knee of the cosmic ray spectrum at energies $\approx 10^{14} \text{ eV} - 10^{17} \text{ eV}$.

The total all-particle spectrum, including both galactic and extragalactic CR components, is shown by the dotted curve in Fig. 3. The steepening of the all-particle spectrum from a power law with $\alpha \approx 2.7$ to one with $\alpha \simeq 3$ would imply steepening in the index δ of the diffusion coefficient by $\Delta\delta = (2/3)\Delta\alpha \simeq 0.2$. Assumption of a Kolmogorov spectrum for $w(k)$ at $k > k_1 \sim 1 \text{ pc}^{-1}$ results in $\delta_1 = 2 - 5/3 = 1/3$, which would imply $\delta_2 \approx 0.53$ at energies above the first knee. The latter value is very close to the index $\delta_2 = 2 - 3/2 = 0.5$ resulting from the assumption of Kraichnan turbulence at $k_2 \leq k \leq k_1$ [8]. However, the true Kraichnan-type evolution of the turbulence would

then overtake the Kolmogorov turbulence at $k \gg k_1$ as well.

The spectrum of turbulence formed at scales smaller than those of the active injection scale may not be the result of turbulent cascades to smaller scales for the turbulence injected at ~ 100 pc scales, but may rather reflect the *rates of injection* of turbulent MHD energy at different spatial scales between ~ 1 pc and ~ 100 pc. For example, considering even only SNe as sources of MHD turbulence, we note that the sizes of SNR shells reach $\gtrsim 10$ pc, such as in W44 or W50. Thus, although in Figure 2a we have assumed that SNRs inject MHD turbulence only at scales ~ 1 pc, in reality their kinetic energy is dissipated in the interstellar medium (ISM) through much larger scales. Similar wide range of spatial scales should be also expected from other potential sources of MHD turbulence, such as high velocity clouds or large scale bubbles blown by stellar winds and multiple SNe in regions of active star formation.

The spectrum of turbulence at $k > k_1$ could also be of the Kraichnan form $q \simeq 3/2$, resulting in $D(E)$ with $\delta \simeq 0.5$. This could be more preferable to explain the lower-energy part of the CR spectrum for continuous injection of CRs from SNRs. In this case, the observed spectrum has an index $\alpha = \alpha_0 + \delta$, which implies a reasonably hard source spectrum with $\alpha_0 \simeq 2.2$. The break at the knee by $\Delta\alpha \simeq 0.3$ in this case would imply a characteristic spectral index $q \simeq 1.3$ for $w(k) \propto k^{-q}$ at $k_2 < k \leq k_1$. It would also suggest a more uniform injection of turbulence over all length scales from $\simeq 1$ pc to ~ 100 pc in the ISM. In this scenario, it is important to realize that the diffusion coefficient at energies between the two knees would correspond to $\delta \simeq 0.7$, resulting in the steepening of the single-source spectrum by $\Delta\alpha \simeq 1$. Thus, this scenario suggests a rather hard injection spectrum of CRs by GRBs, namely $\alpha_0 \simeq 2-2.2$. The latter value is allowed if we take into account that the real spectrum of HECRs from the local GRB

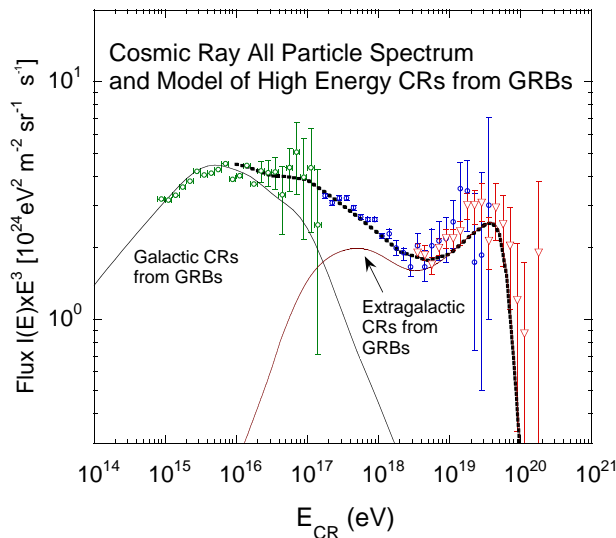


Figure 3. The total spectrum of HECRs above 100 TeV contributed by a single recent GRB (timescale $t \sim 1$ Myr), and by extragalactic sources at energies $\gtrsim 10^{17}$ eV on cosmological timescales (see Ref. [8]).

above the first knee could easily be in the range of $\alpha \sim 3.2$ if one includes a small contribution of extragalactic HECS at $E \gtrsim 10^{16}$ eV (see Fig. 3).

Thus, both Kolmogorov and Kraichnan types of turbulence at scales $k > k_1$ are possible. In the latter case an additional small steepening of the single-source spectrum below the first knee due to the relative proximity of the low-energy exponential turnover (see Fig. 1) can also be invoked. In any case, the sharpness of the spectral break at the knee directly reflects the sharpness of the spectral break in $w(k)$ at k_1 .

The important model parameters are the age of the GRB and its distance. In the spectral fit shown in Fig. 3, we have used $t = 0.2$ Myr and $r = 0.5$ kpc, with $D_0 \equiv D(1 \text{ PeV}) = 1.5 \times 10^{30} \text{ cm}^2 \text{ s}^{-1}$. The latter is calculated assuming the ratio of MHD to Galactic magnetic field energy densities $\xi = 0.03$. For these parameters, protons with $E = 1$ PeV diffuse to scales $r_{dif}(1 \text{ PeV}) \simeq 2$ kpc, i.e., well beyond the assumed distance to the source. Thus, we could also assume a distance to the source $r \sim 1$ kpc for the same total energy (10^{52} ergs), while keeping the exponential turnover of the spectrum at low energies significantly below 1 PeV. Because of the invariance of the local CR spectrum with respect to the product $D_0 \times t$, we could equally assume that the diffusion coefficient was smaller by one order of magnitude (with $\xi \sim 0.3$), but a GRB age $\gtrsim 1$ Myr. The smaller diffusion coefficient is also preferable because in that case the diffusion timescale of ~ 10 GeV CRs out of the galactic disc would be in better agreement with the generally accepted value $t_{esc} \sim 10^7$ yr for these energies.

A larger distance and age can help to improve the likelihood of a local GRB. As estimated in [8], the rate of occurrence of a GRB in our Galaxy is ≈ 1 per 10^4 yr, in agreement also with the estimates in [22]. Using this, the mean number of GRBs that would occur in the Galactic disc at $r = r_{\text{kpc}}$ kpc from us during $t = t_{\text{Myr}} 10^6$ yr is estimated as $\bar{N}_{\text{GRB}} \simeq (0.45-1.3) r_{\text{kpc}}^2 t_{\text{Myr}}$.

Another advantage of a longer age of the local GRB as large as ~ 1 Myr is the possibility to explain better the observed small anisotropy $\omega = (J_{max} - J_{min}) / (J_{max} + J_{min}) \sim (0.15 \pm 0.05)\%$ [23, 24] in the knee region (the anisotropy is, however, increased for a more distant source). For the spatial distribution of the CRs $n \equiv n(E, r, t)$ given by Eq. 1, calculations of the anisotropy [2] result in

$$\omega = \frac{3D}{cn} \frac{\partial n}{\partial r} = \frac{3r}{2ct} \simeq \frac{0.4 r_{\text{kpc}}}{t_{\text{Myr}}} \% \quad (4)$$

For $r = 0.5$ kpc and $t = 2$ Myr the anisotropy can be as small as 0.1%. An interesting point in Eq. (4) is that ω is independent of energy for a spherically symmetric single-source model.

4. Extragalactic Cosmic Rays

The rapid decline of the CR flux from local GRBs above the second knee results in the contribution of extragalactic component in the all-particle spectrum dominating near and above the second knee. Calculations of the extragalactic component as shown in

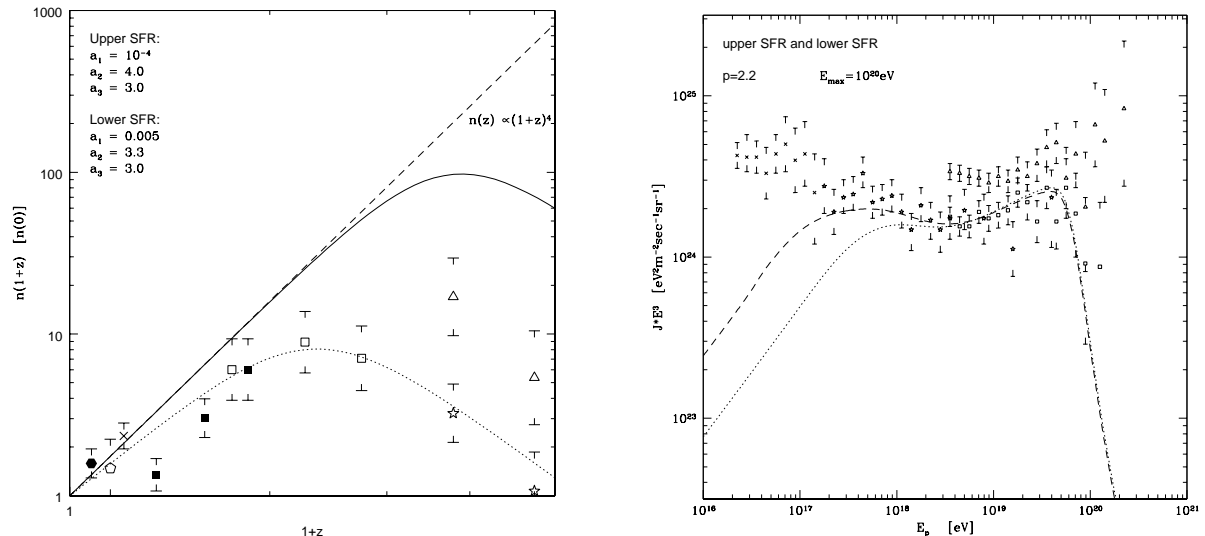


Figure 4. (a) (*left*) The history of evolution of the star formation rate (SFR) in the universe as a function of redshift $1+z$, normalized to the current SFR. The dotted curve shows the lower limit to the SFR evolution implied by measurements of the blue and UV energy density, and the solid curve shows the SFR corrected for dust extinction (see [8] for detailed discussion). The dashed line displays the relation $n(z) = n(0)(1+z)^4$ used by [27] for calculations of the fluxes of extragalactic CRs. (b) (*right*) Calculated fluxes of extragalactic CRs assuming that the injection of UHECRs in the universe was due to GRBs with a rate density proportional to the minimum (dotted curve) and maximum (solid curve) SFR functions shown in Figure 4a. Note that the spectra are not normalized to each other at high energies. Instead, the normalization for both of them corresponds to the same value for the current ($z = 0$) injection rate.

Fig. 3 for our model of CRs from GRBs includes photomeson interactions, $e^+ - e^-$ pair production, and adiabatic cooling of UHECRs [15]. We assume that the rate density of GRBs is proportional to the cosmological star formation rate (SFR) history of the universe [25]. For the two rates shown in Fig. 4a that correspond to minimum and maximum SFRs, calculations in [8] result in the two spectra for the extragalactic component shown in Fig. 4b. An interesting result here is that in the framework of this model, the ankle in the spectrum of CRs observed at $E \simeq 3 \times 10^{18}$ eV is formed in the process of cooling of UHE protons on cosmological timescales.

Similar spectral behavior for the extragalactic CR component at $E \geq 10^{18}$ eV as shown in Fig. 4b, where the ankle is explained as a consequence of photopair losses of UHECRs formed at high redshift, were also derived by Berezhinsky and collaborators (e.g. see [26, 27] and references therein). These authors [27] consider a model where UHECRs are accelerated by active galactic nuclei and assume cosmological evolution of the injection rate of UHECRs $\propto (1+z)^4$ (see Fig. 4a). It remains to be studied if these two principal options (GRBs and AGNs) for the sources of UHECRs in the universe can be distinguished from each other observationally as a result of differences in their evolutionary histories.

The spectra of UHECRs resulting from injection of UHECR protons in the universe

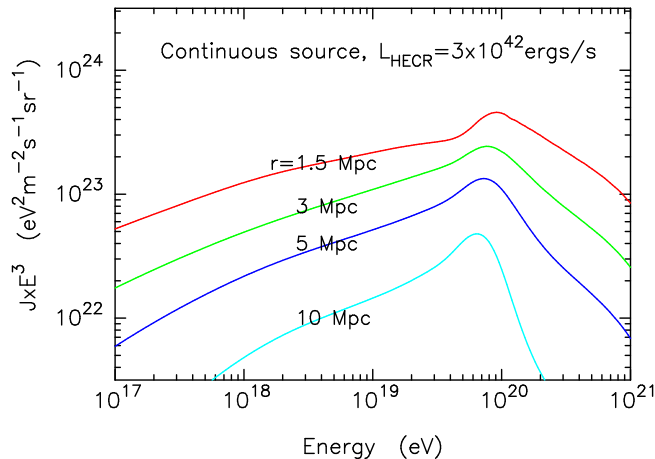


Figure 5. Fluxes of UHECRs from a local, continuous extragalactic source population at distance r that injects HEERs into the intergalactic medium with spectral index $\alpha_0 = 2.2$, a maximum (‘exponential cutoff’) energy $E_{max} = 10^{21}$ eV, and total power $L_{HECR}(E \geq 1 \text{ PeV}) = 3 \times 10^{42} \text{ ergs s}^{-1}$. Diffusive propagation with $\delta = 0.5$ and $D(10^{19} \text{ eV}) = 10^{34} \text{ cm}^2 \text{ s}^{-1}$ in the local intergalactic medium is assumed.

on cosmological timescales show a sharp (“GZK”) cutoff above the GZK energy $E \simeq 6 \times 10^{19}$ eV. The UHECR spectrum in Fig. 3 (or Fig. 4b) agrees with the HiRes data, but is in disagreement with the AGASA results at $E \sim 10^{20}$ eV. If Auger observations show any significant excess over the exponential GZK cutoff at these energies, this would imply that there are other recent ($\lesssim 10^8$ yr) local source sources of extragalactic origin in our vicinity at $\lesssim 10$ Mpc that produce this flux. One possibility is that the excess would be due to cosmic ray ions (e.g., [28]).

In the framework of our model, such extragalactic sources could be connected with starburst galaxies in the local group, such as M82 and NGC 253, both at distances $r \sim 3.5$ Mpc. Taking into account that the supernova rate in these galaxies is about 0.3 – 1 per year, and that the estimated GRB rate in our Galaxy is about (0.3 – 1)% of the supernova rate, the mean GRB rate in the starburst galaxies is estimated as one per $\sim 300 - 1000$ yrs. If the total energy of CRs accelerated by a typical GRB is indeed about 10^{52} ergs, as for our local Galactic GRB, the characteristic injection power of UHECRs from starburst galaxies averaged over the timescale of $\sim 10^8$ yr can be $\sim (1 - 3) \times 10^{42} \text{ ergs s}^{-1}$. In Fig. 5 we show the UHECR fluxes expected from a single *continuous* source (which is valid for a GRB model because of the large number of GRBs from these starburst galaxies within the last 100 Myrs) at a distance r from us. The fluxes are calculated in the framework of a diffusion propagation model from a single source, assuming a diffusion coefficient with $\delta = 0.5$ normalized at $D(10^{19} \text{ eV}) = 10^{34} \text{ cm}^2 \text{ s}^{-1}$. Note that the Larmor radius of a 10^{19} eV proton in the magnetic field $B_{extragalactic} \sim 10^{-7} \text{ G}$ would be about 3×10^{23} cm. This implies that the assumed diffusion coefficient would still be larger, by a factor of 3, than for Bohm diffusion. The assumption of a different propagation model (or diffusion coefficient) in the intergalactic space would change the fluxes shown in Fig. 5, and will require a

separate study.

5. Conclusions

We have described a complete model for cosmic rays comprising a single type of sources, namely SNe. Because of the wide diversity of SNe types, the efficiency of CR acceleration varies dramatically from Type Ia and II SNe, with SN ejecta speeds in the range of 3,000 – 30,000 km s⁻¹, to Type Ib/c SNe, with SN ejecta reaching highly relativistic velocities in the subset of Type Ib/c SNe that collapse to black holes and form GRBs. Because GRBs are found in our Galaxy, we expect that CRs to the highest energy will also be accelerated by past GRB sources in the vicinity of Earth.

The transition from the Galactic to the extragalactic component occurs at the second knee and, as also suggested by Berezhinsky and collaborators [26], the ankle is a consequence of pair-production interactions (similar conclusions have been reached in Ref. [29], but without proposing a specific source model for the high-energy CRs). As we show [8, 30], the large energy in CRs in a GRB makes it likely that GRBs will be detectable high-energy neutrino sources with IceCube [31]. Detection of even one PeV neutrino coincident with a GRB will confirm that GRBs are efficient accelerators of high-energy cosmic rays and will support this model for cosmic-ray origin.

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