PHYSICAL REVIEW D **90,** 041302(R) (2014)

Explaining the spectra of cosmic ray groups above the knee by escape from the Galaxy

G. Giacinti,[1] M. Kachelrieß,[2] and D. V. Semikoz[3]

[1]University of Oxford, Clarendon Laboratory, Oxford OX1 3PU, United Kingdom
[2]Institutt for fysikk, NTNU, Trondheim N-7491, Norway
[3]AstroParticle and Cosmology (APC), Paris F-75205, France

(Received 16 June 2014; published 20 August 2014)

We investigate the possibility that the cosmic ray (CR) knee is entirely explained by the energy-dependent CR leakage from the Milky Way. We test this hypothesis calculating the trajectories of individual CRs with energies between $E/Z = 10^{14}$ eV and 10^{17} eV propagating them in the regular and turbulent Galactic magnetic field. We find a knee-like structure of the CR escape time $\tau_{\rm esc}(E)$ around $E/Z =$ few $\times 10^{15}$ eV for a coherence length $l_c \simeq 2$ pc of the turbulent field, while the decrease of $\tau_{\rm esc}(E)$ slows down around $E/Z \simeq 10^{16}$ eV in models with a weak turbulent magnetic field. Assuming that the injection spectra of CR nuclei are power laws, the resulting CR intensities in such a turbulence are consistent with the energy spectra of CR nuclei determined by KASCADE and KASCADE-Grande. We calculate the resulting CR dipole anisotropy as well as the source rate in this model.

DOI: 10.1103/PhysRevD.90.041302 PACS numbers: 98.70.Sa, 96.50.sb, 98.35.Eg

I. INTRODUCTION

The cosmic ray (CR) energy spectrum follows a power law on more than ten decades in energy. Only a few breaks, such as the knee at $E_k \approx 4$ PeV, provide possible clues to how CRs propagate and to what their sources are. In addition to this feature, seen in the total CR flux, the elemental composition of the CR flux in the energy range 10^{15}–10^{17} eV is especially useful to constrain theoretical models for the knee. Such data had been missing, but recently the KASCADE-Grande collaboration has extended the measurements of the intensity of individual groups of CR nuclei up to 10^{17} eV [1,2]. In the future, the IceCube experiment with its IceTop extension will provide additional constraints on the mass composition around the knee [3]. It is therefore timely to compare not only the predictions for the total CR flux and global quantities such as the elongation rate to the experimental data, but also to consider the intensity of individual groups of CR nuclei.

Three competing explanations for the origin of the knee have been advanced: First, there have been speculations that interactions may change in the multi-TeV region, thereby suppressing the CR flux. This possibility is now excluded by the LHC data. Second, the knee may correspond to the maximum rigidity to which the dominant population of Galactic CR sources can accelerate CRs [4]. In a variation of this suggestion, the knee is caused by the maximal energy of a single nearby source such as Monogem [5]. While it is very natural to expect that differences in supernovae types and their environments lead to a distribution of reachable maximal rigidities, this proposal does not predict the exact energy of the knee or the strength of the flux suppression, without a better knowledge of CR confinement and escape [6].

Finally, the knee may be caused by a change of the diffusion properties of charged CRs [7,8]. For instance, the knee may correspond to the rigidity at which the CR Larmor radius r_L starts to be of the order of the coherence length l_c of the turbulent Galactic magnetic field (GMF). Thence the behaviors of the CR diffusion coefficient and confinement time change, which in turn would induce a steepening in the spectrum. Both small-angle scattering [7] and Hall diffusion [8] have been proposed as models for the energy dependence of the diffusion coefficient in this regime. This phenomenological approach to CR escape that describes CR propagation by diffusion has two major drawbacks: First, the analytical connection between the diffusion tensor and the underlying magnetic field is know only in certain limiting regimes. Second, the diffusion approximation is not justified at the highest energies we are interested in.

The goal of this paper is therefore to study CR escape from our Galaxy by propagating individual CRs in detailed GMF models. Given a specific GMF model, this approach allows us to predict the position and the shape of the knee for CR nuclei as a function of E/Z. We determine three main observables: The time-averaged grammage $X(E)$ traversed by CRs before escape, the time-dependent intensity of CR nuclei at the position of the Sun, and the amplitude d of the dipole anisotropy. Extrapolating $X(E)$ toward its measured value at low energies, we constrain first the strength of the turbulent Galactic magnetic field. Then we use the CR dipole anisotropy as an indication for the transition from Galactic to extragalactic CRs. Finally, we calculate the CR nuclei energy spectra, and compare them to the intensity of groups of CR nuclei determined by KASCADE and KASCADE-Grande, examining the consistency of the proposed scenario. Our results suggest that the turbulent GMF is weaker than in GMF models as [9] and has a small coherence length. Improving our understanding of the GMF has important impacts on fields outside CR research as e.g. indirect DM searches, where our results support the use of a large GMF halo and a large diffusion coefficient.

II. SIMULATION PROCEDURE

For the propagation of CRs in the GMF, we use the code described and tested in [10]. For the present work, we have implemented the most recent GMF models [9,11], but a more important change is the use of a reduced coherence length, $l_c = 2$ pc, for the turbulent field. Such a value is in line with recent measurements of l_c in some regions of the Galactic disk, see e.g. [12]. We model the random field as isotropic Kolmogorov turbulence, $\mathcal{P}(k) \propto k^{-5/3}$ extending down to a minimal length scale $l_{\rm min} \lesssim 1$ AU.

We assume that the surface density of CR sources follows the distribution of supernova remnants [13],

$$n(r) = (r/R_\odot)^{0.7} \exp[-3.5(r - R_\odot)/R_\odot], \qquad (1)$$

with $R_\odot = 8.5$ kpc as the distance of the Sun to the Galactic center.

III. GRAMMAGE

An important constraint on CR propagation models comes from ratios of stable primaries and secondaries produced by CR interactions on gas in the Galactic disk. In particular, the B/C ratio has been recently measured by the AMS-02 experiment up to 670 GeV/nucleon [14]. Above $E \gtrsim 10$ GeV, it is consistent with a straight power law.

Using the leaky-box formalism, various propagation models including plain diffusion, diffusion with convection and reacceleration were fitted in Ref. [15] to earlier data. In all cases, the grammage traversed by CRs at reference energies $E_0/Z = 5$–15 GeV was found to lie in the range 9–14 g/cm^2. In their model with reacceleration, the grammage decreases as $X(E) = X_0(E/E_0)^{-0.3}$ above energies $E_0 > 20$–30 GeV per nucleon, while the best-fit value for the normalization constant X_0 of the grammage was determined to be $X_0 = 9.4$ g/cm^2.

We calculate the average grammage $\langle X\rangle = N^{-1} c \sum_{i=1}^{N} \int dt \rho(\boldsymbol{x}_i(t))$ by injecting N cosmic rays according to the radial distribution (1) at $z = 0$ in the Galaxy, and following their trajectories $\boldsymbol{x}_i(t)$ until they reach the edge of the Galaxy. As a model for the gas distribution in the Galactic disk, we use $n(z) = n_0 \exp(-(z/z_{1/2})^2)$ with $n_0 = 0.3/\mathrm{cm}^3$ at $R_\odot$ and $z_{1/2} = 0.21$ kpc, inspired by [16]. We set $n = 10^{-4}$ g/cm^3 as minimum gas density up to the edge of the Milky Way at $|z| = 10$ kpc. Since the grammage $X(E) \propto E^{-\delta}$ scales as the confinement time $\tau(E) \propto E^{-\delta}$, we can use this quantity also as an indicator for changes in the CR intensity induced by a variation of the CR leakage rate.

In Fig. 1, we show the grammage traversed by CRs, with energies E/Z between 10^{14} eV and 10^{17} eV, propagated in the GMF model of Ref. [9]. The upper (green) line corresponds to computations using both the regular and the turbulent fields proposed in [9], while for the lower (red) curve we rescaled the turbulent field strength by a factor 0.1 ($B_{\rm rms} \to B_{\rm rms}/10$). The two lowest-energy data points shown here are consistent with the $X(E) \propto E^{-1/3}$ behavior expected for a turbulent magnetic field with a Kolmogorov power spectrum. Around a few PeV, the grammage steepens to an approximate power law $X(E) \propto E^{-1.3}$ which lies in between the expectations for Hall diffusion $[X(E) \propto E^{-1}]$ and small-angle scattering $[X(E) \propto E^{-2}]$. The transition energy agrees well with the theoretical expectation: A steepening of the grammage is expected at the characteristic energy E_c where the Larmor radius $r_{\rm L}$ equals the coherence length l_c. For $l_c = 2$ pc and $B \approx 3\ \mu$G, the value of the critical energy is $E_c/Z \approx 6 \times 10^{15}$ eV, which is only slightly higher than what we find numerically. Finally, the turnover of the grammage which is visible in the lower curve at the highest energies corresponds to the approach of its asymptotic value obtained for straight line propagation in the limit $E \to \infty$. As a consequence, the predicted CR spectra above $E/Z \simeq 10^{16}$ eV should harden by approximately one power, $\Delta\delta \sim 1$, using the model of Ref. [9] with a *reduced* turbulent field.

In addition to the data points, we show in Fig. 1 with a dotted (blue) line the extrapolation of the grammage to lower energies, assuming that $X(E) \propto E^{-1/3}$ as expected for a Kolmogorov power-spectrum. Based on this extrapolation, the GMF model [9] with full turbulence leads to a

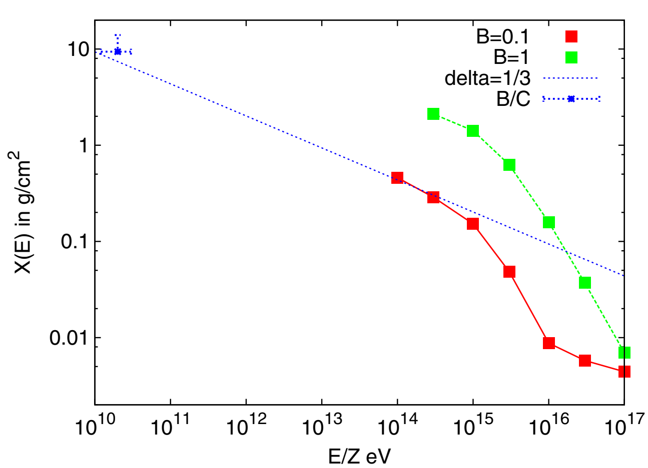

FIG. 1 (color online). Grammage $X(E)$ traversed by CR protons as a function of energy E/Z for two different levels of magnetic turbulence in the GMF model of Ref. [9], with $l_c = 2$ pc.

grammage at $E \lesssim 100$ GeV which is a factor ~10 above the determinations from e.g. B/C measurements (blue cross). This discrepancy is in line with our determination of the diffusion coefficient in a purely turbulent magnetic field with strength $B_{\rm rms} = 4\ \mu$G [17], which also disagreed by an order of magnitude with the extrapolation of the diffusion coefficient phenomenologically determined from the ratios of secondary to primary nuclei. Consistency with these measurements could be achieved, if the energy density of the turbulent magnetic field is reduced [18]. Such a rescaling is displayed as the lower (red) line in Fig. 1. In the following, we consider this case [19].

We have calculated the grammage also in the GMF model of Ref. [11]. The CR confinement time was found to be twice as large as for the GMF model of Ref. [9], leading to a stronger discrepancy between the extrapolation of the grammage to low energies and its determinations.

IV. COSMIC RAY ANISOTROPY

In the diffusion approximation, the CR dipole anisotropy d is given by $\boldsymbol{d} = 3D\nabla \ln(n)/c$. The measurements or tight experimental upper limits on d at high energies are typically difficult to reconcile with determinations of the diffusion coefficient at low energies, even for a Kolmogorov spectrum where $D(E) \propto E^{1/3}$. In our model, one expects the anisotropy to grow more rapidly above the knee. The diffusion coefficient scales there as $D \sim \frac{1}{3} l_c c (R_L/l_c)^\alpha$, with $\alpha \approx 1.3$. We compute the average anisotropy and derive the energy dependence of $D(E)$ from the escape probability calculated previously, setting $D(E/Z) \propto \tau_{\rm esc}(E/Z)$. We fix the proportionality constant by requiring that the dipole amplitude $d = \sum_k f_k d_k$ equals the dipole component $\tilde{d}$ observed by the EAS-TOP collaboration at $E = 1.1 \times 10^{14}$ eV [20]. k labels the groups of nuclei we consider, f_k is their fraction of the total CR flux, and $d_k \propto \tau_{\rm esc}(E/Z)$ is their individual dipole.

In Fig. 2 we show the resulting dipole amplitude d as a function of energy E. As expected, the amplitude raises below the knee as $E^{1/3}$, while it increases approximately as $E^{0.7}$ above. We also plot the values of $\tilde{d}$ observed by IceCube [21], as well as the 99% C.L. upper limits on $d_\perp$ from the Pierre Auger Observatory [22,23]. Comparing our estimate for the dipole amplitude with the upper limits at high energies, we conclude that the light component of the Galactic CR flux must be suppressed above 10^{17} eV. We expect the approximation $d \propto \tau_{\rm esc}(E/Z)$ to break down for $E/Z \gtrsim 10^{17}$ eV: Close to the semiballistic regime, a calculation of the anisotropy based on trajectories would be required, but is computationally extremely expensive.

V. COSMIC RAY INTENSITY

We now use the time-dependent intensity I_k of various groups k of CR nuclei as a test of our hypothesis that the knee is entirely explained by the energy-dependent CR leakage from the Milky Way. We distribute a discrete set of sources in the Galactic disk according to Eq. (1) and a fixed rate $\dot{N}$. Each source is assumed to inject the total energy $E_{\rm p} = 1.0 \times 10^{50}$ erg in CRs. Then the individual contributions $n_{i,k}(\boldsymbol{x}, t, E)$ from each source i are added using a precalculated template in order to save computing time. We convert the total density $n_k(\boldsymbol{x}_\odot, t, E)$ at the position of the Sun into the predicted intensity $I_k(\boldsymbol{x}_\odot, t, E) = c/(4\pi) n_k(\boldsymbol{x}_\odot, t, E)$ of the CR nuclei group k as a function of time. Finally, we determine the relative fraction of energy transferred to the k.th group of nuclei and the exponent α_k of their injection spectrum $dN_k/dE \propto E^{-\alpha_k} \exp(-E/ZE_c)$ by a comparison of the predicted intensity to the measurements. We choose the energy E_c above which we assume that the source spectrum is exponentially suppressed as $E/Z = 10^{17}$ eV.

Note that $I_k(E,t)$ is predicted as a function of time. Since $I_k(E,t)$ fluctuates due to the discreteness of the sources, we show a 1σ confidence band illustrating the spread around the predicted average intensity. In contrast, the grammage is measured at relatively low energies, $E \lesssim 1$ TeV, where fluctuations due to the discrete source distribution play only a minor role and therefore only average values are relevant.

For the experimental data, we use above $E > 10^{16}$ eV the tabulated intensities of protons, helium, carbon (representing the CNO group), Si (for the SiMg group) and Fe nuclei (for Fe-Mg) from KASCADE-Grande data given in [2], while we employ in the energy range $E = 10^{15}$–10^{16} eV the KASCADE data read from Fig. 12 in [2]. Since the KASCADE and KASCADE-Grande proton data disagree in the overlapping energy range, we reduce the KASCADE-Grande proton flux by 30%, and add this 30% proton flux to the He flux, in order to achieve agreement between the two data sets. Moreover, the discriminating

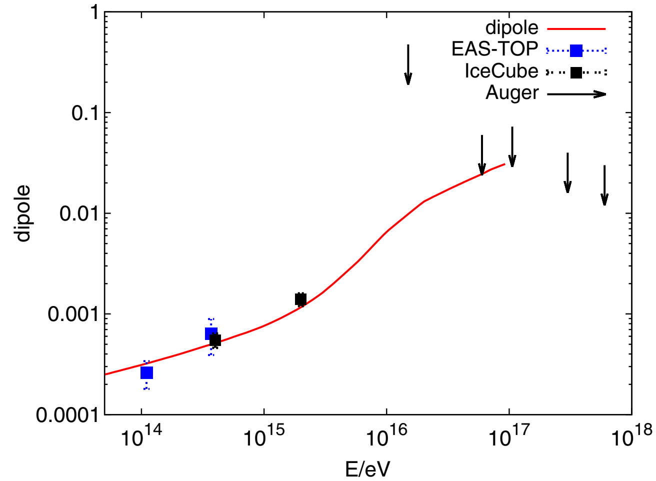

FIG. 2 (color online). Dipole amplitude $d(E)$ as a function of energy E/Z in the GMF model of Ref. [9] with reduced turbulent field and $l_c = 2$ pc.

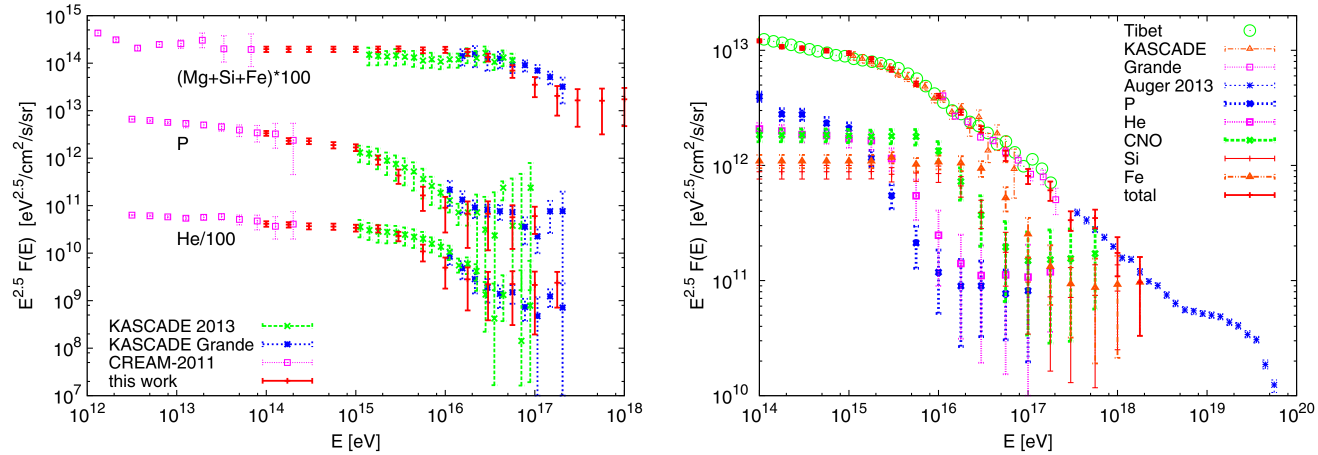

FIG. 3 (color online). Left: The (rescaled) intensity $I(E)$ of CR protons, He and Fe nuclei compared to the experimental data from KASCADE [2], KASCADE-Grande [2] and CREAM [26], using the rescaled turbulent GMF. Right: Intensity $I(E)$ of CR protons, He, CNO, MgSi and Fe nuclei as a function of energy E per nucleus, obtained using the same GMF.

power between Si and Fe in KASCADE was relatively poor and the absolute Si + Fe abundance is small close to 10^{15} eV, and therefore we analyze these two groups of elements jointly [24,25]. Finally, we determine the slope α_k and the normalization of the intensities for individual CR groups with measurements at energies below the knee using the data from the CREAM experiment [26].

In the left panel of Fig. 3, we show our results (red solid points with error bars) for the intensity of p, He, and the combined intensity of the MgSi and Fe groups compared to experimental data. Overall, we find that the assumptions used, a GMF model with rescaled Kolmogorov turbulence and $1/E^{\alpha_k}$ injection spectra, lead to a consistent CR intensity in the full energy range $E \sim (10^{14}–10^{17})$ eV considered not only for protons, but also for He and heavy nuclei. Since CR escape depends only on rigidity, and since the exponents α_k are determined by the data below the knee, the relative shape of the different CR elements is fixed in this scheme. Note also that the recovery of the proton and helium spectra above $E/Z \sim 10^{16}$ eV cannot be reproduced assuming power-law injection spectra and the full turbulent GMF of Ref. [9].

In the right panel of Fig. 3, we show the contribution of the CNO group and the resulting total CR intensity. The latter is compared to measurements of the total CR intensity by Tibet [27], KASCADE, KASCADE-Grande and Auger [28]: Because of the rigidity-dependent energy cutoff, Galactic CRs are dominated at the highest energies by iron, while the total intensity is exponentially suppressed above 3×10^{18} eV. Thus Galactic Fe could give a significant contribution to the total CR spectrum up to the ankle, being especially important for composition studies.

The obtained source rate $\dot{N} \sim 1/180$ yr is only a factor six smaller than the Galactic SN rate and makes a GRB origin of Galactic CRs unlikely. Taken at face value, these numbers would require that a large fraction of SNe can accelerate protons up to $E \sim 10^{17}$ eV.

VI. CONCLUSIONS

The two main explanations for the knee are (i) a change in the CR confinement time in the Galaxy when their Larmor radius starts to be of the order of the coherence length l_c of the interstellar turbulence, and (ii) a change in the number of sources able to accelerate CRs above ≈4 PeV. We have shown that, if the coherence length in the Galactic disk is of the order of $l_c = 2$ pc as suggested by Refs. [12], the CR escape time $\tau_{esc}(E) \sim X(E)$ and as a consequence the total CR intensity steepens at the correct energy. Moreover, the resulting rigidity-dependent knees in the individual intensities of the considered CR groups (p, He, CNO, and MgSiFe) agree well with measurements.

In contrast, the change in the slope of $X(E/Z) \sim \tau(E/Z)$ would be shifted to energies above $E/Z \simeq 10^{16}$ eV for a coherence length l_c of the order of $l_c = 50$ pc in the Galactic disk. In this case, the knee would have to be explained by the possibility (ii), yielding precious information on Galactic CR accelerators. More measurements of the coherence length of the turbulence as expected from e.g. SKA [29] will solve this crucial question.

A large coherence length l_c would worsen the tension between our computations of the grammage in GMF models like [9,11] and its determination from B/C at low energies. In this paper, we have therefore considered the possibility that the average strength of the turbulent magnetic field is reduced by a factor ≃5–10. In this case, we found agreement between our calculation of the escape time τ_{esc} and determinations of the grammage $X(E)$ at lower energies from the B/C ratio. More importantly, the turnover of the grammage $X(E)$ leads to a hardening of the intensity of the nuclei with charge Z around

$E/Z \simeq 10^{16}$ eV. This energy behavior is very similar to the one seen in KASCADE-Grande measurements [1]: As a result, the observed energy dependence of various groups of CR nuclei can be explained in the energy range between 10^{14} and 10^{17} eV as the modulation of power-law injection spectrum via CR leakage from the Galaxy.

The source rate in our scenario is relatively large, $\dot{N} \sim 1/180$ yr, and requires that a large fraction of SNe can accelerate protons up to $E \sim 10^{17}$ eV. Our estimate for the dipole anisotropy suggests on the other hand that CRs with energies beyond $E/Z \sim 10^{17}$ eV are not predominantly Galactic, which requires an early transition to extragalactic CRs, before the ankle as e.g. in the dip model [30]. A hint about this is also given by KASCADE-Grande [31]. Finally, we note that the suggested weakness of the turbulent GMF would facilitate the search for ultra-high energy CR sources by a smaller spread of their images on the sky [32].

ACKNOWLEDGEMENTS

We thank P. Blasi for raising the grammage question, and S. Ostapchenko and A. Strong for useful discussions. We are grateful to A. Haungs for advice about the KASCADE data. G. G. acknowledges funding from the European Research Council (Grant agreement No. 247039). The work of D. S. was supported in part by Grant RFBR No. 13-02-12175-ofi-m.

[1] W. D. Apel *et al.* (KASCADE-Grande Collaboration), Phys. Rev. Lett. **107**, 171104 (2011); Astropart. Phys. **36**, 183 (2012).

[2] W. D. Apel *et al.* (KASCADE-Grande Collaboration), Astropart. Phys. **47**, 54 (2013).

[3] R. Abbasi *et al.* (IceCube Collaboration), Astropart. Phys. **42**, 15 (2013); M. G. Aartsen *et al.* (IceCube Collaboration), Phys. Rev. D **88**, 042004 (2013).

[4] T. Stanev, P. L. Biermann, and T. K. Gaisser, Astron. Astrophys. **274**, 902 (1993); A. M. Hillas, J. Phys. G **31**, R95 (2005).

[5] A. D. Erlykin and A. W. Wolfendale, J. Phys. G **23**, 979 (1997); Astropart. Phys. **22**, 47 (2004).

[6] For a work in this direction see e.g. A. R. Bell, K. Schure, B. Reville, and G. Giacinti, Mon. Not. R. Astron. Soc. **431**, 415 (2013); see also K. Kobayakawa, Y. Sato, and T. Samura, Phys. Rev. D **66**, 083004 (2002); L. G. Sveshnikova, Astron. Astrophys. **409**, 799 (2003); V. S. Ptuskin and V. N. Zirakashvili, Astron. Astrophys. **429**, 755 (2005).

[7] V. L. Ginzburg and S. I. Syrovatskii, *The Origin of Cosmic Rays* (Pergamon Press, New York, 1964).

[8] V. S. Ptuskin *et al.*, Astron. Astrophys. **268**, 726 (1993); J. Candia, E. Roulet, and L. N. Epele, J. High Energy Phys. 12 (2002) 033; J. Candia, S. Mollerach, and E. Roulet, J. Cosmol. Astropart. Phys. 05 (2003) 003.

[9] R. Jansson and G. R. Farrar, Astrophys. J. **757**, 14 (2012); Astrophys. J. **761**, L11 (2012).

[10] G. Giacinti, M. Kachelriess, D. V. Semikoz, and G. Sigl, J. Cosmol. Astropart. Phys. 07 (2012) 031.

[11] M. S. Pshirkov, P. G. Tinyakov, P. P. Kronberg, and K. J. Newton-McGee, Astrophys. J. **738**, 192 (2011); M. S. Pshirkov, P. G. Tinyakov, and F. R. Urban, Mon. Not. R. Astron. Soc. **436**, 2326 (2013).

[12] M. Iacobelli *et al.*, Astron. Astrophys. **558**, A72 (2013); see also G. Bernardi, A. G. de Bruyn, G. Harker *et al.*, Astron. Astrophys. **522**, A67 (2010); A. Ghosh, J. Prasad, S. Bharadwaj, S. S. Ali, and J. N. Chengalur, Mon. Not. R. Astron. Soc. **426**, 3295 (2012).

[13] D. A. Green, IAU Symposium **9**, 188 (2014).

[14] A. Oliva *et al.* (AMS-02 Collaboration), in *Proceedings of the 33rd ICRC, 2013* (to be published).

[15] F. C. Jones, A. Lukasiak, V. Ptuskin, and W. Webber, Astrophys. J. **547**, 264 (2001).

[16] H. Nakanishi and Y. Sofue, Publ. Astron. Soc. Jpn. **55**, 191 (2003); **58**, 847 (2006); see also the comparison in C. Evoli, D. Grasso, and L. Maccione, J. Cosmol. Astropart. Phys. 06 (2007) 003.

[17] G. Giacinti, M. Kachelriess, and D. V. Semikoz, Phys. Rev. Lett. **108**, 261101 (2012).

[18] The GMF model of Ref. [9] is currently being revised, taking into account correlations between the electron density and the magnetic field. As a result, the turbulent field will be reduced by a factor 5–6; G. Farrar (private communication).

[19] We have also performed calculations for $l_c = 5$ pc. In this case, the turbulent field has to be rescaled only by a factor 0.2.

[20] M. Aglietta *et al.* (EAS-TOP Collaboration), Astrophys. J. **692**, L130 (2009).

[21] R. Abbasi *et al.* (IceCube Collaboration), Astrophys. J. **746**, 33 (2012).

[22] P. Abreu *et al.* (Pierre Auger Collaboration), Astrophys. J. **762**, L13 (2013); I. Sidelnik *et al.* (Pierre Auger Collaboration), in *Proceedings of the 33rd ICRC, 2013* (to be published).

[23] Note that the experimental values $\tilde{d}$ are connected to the true dipole amplitude d as $\tilde{d} = d_\perp/\langle\cos(\delta)\rangle$, where $d_\perp$ is the dipole component in the equatorial plane and $\langle\cos(\delta)\rangle$ the average declination of the events used in the harmonic analysis based only on R.A.; See J. Aublin and E. Parizot, Astron. Astrophys. **441**, 407 (2005).

[24] A. Haungs, (private communication).

[25] T. Antoni *et al.* (KASCADE Collaboration), Astropart. Phys. **24**, 1 (2005).

[26] Y. S. Yoon *et al.*, Astrophys. J. **728**, 122 (2011).

[27] M. Amenomori *et al.* (TIBET III Collaboration), Astrophys. J. **678**, 1165 (2008).

[28] A. Aab *et al.* (Pierre Auger Collaboration), arXiv:1310.4620.

[29] C. Carilli and S. Rawlings, New Astron. Rev. **48**, 979 (2004).

[30] V. S. Berezinsky, S. I. Grigorieva, and B. I. Hnatyk, Astropart. Phys. **21**, 617 (2004); V. Berezinsky, A. Z. Gazizov, and S. I. Grigorieva, Phys. Lett. B **612**, 147 (2005); Phys. Rev. D **74**, 043005 (2006); R. Aloisio, V. Berezinsky, P. Blasi, A. Gazizov, S. Grigorieva, and B. Hnatyk, Astropart. Phys. **27**, 76 (2007).

[31] W. D. Apel *et al.*, Phys. Rev. D **87**, 081101 (2013).

[32] G. Giacinti, M. Kachelrieß, D. V. Semikoz, and G. Sigl, Astropart. Phys. **35**, 192 (2011).