Explanation for the Cosmic Ray Anisotropies at Small and Medium Angular Scales

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Abstract. A dipolar anisotropy in the cosmic ray (CR) arrival directions on the sky is predicted by the diffusion approximation (DA). However, the DA is not designed to predict phenomena arising on spatial scales smaller than the cosmic ray mean free path. We demonstrate here that energy-dependent smaller scale anisotropies (higher order multipoles) must naturally appear on the sky and reflect the local concrete realization of the magnetic field within the CR mean free path [1, 2]. We show that it is a viable explanation for the observed medium and small scale anisotropies. We also discuss the perspectives and priorities for the near future, and suggest that CR anisotropy measurements should become a new way of probing local interstellar and, or heliospheric fields in the future.

1. Introduction
Several experiments have detected anisotropies in the arrival directions of cosmic rays (CR) on the sky at Earth, in the ∼TeV–PeV energy range, see amongst others [3, 4, 5, 6, 7, 8]. Anisotropies have been found both on large (dipole) and smaller (higher order multipoles) angular scales.

The interstellar magnetic field in our Galaxy can be regarded as the sum of a regular and a turbulent field. The regular one is thought to follow spiral arms in the disk and typically varies on ∼kpc scales, while the turbulent one fluctuates on smaller spatial scales, from \( l_{\text{max}} \sim 100 \text{pc} \) down to a damping scale \( l_{\text{min}} \sim \) smaller than ∼1 AU [9]. CRs scatter on modes with fluctuation scales matching their gyroradius. As a consequence, the trajectories of TeV–PeV CRs resemble random walks. CR propagation in the interstellar medium of our Galaxy can be regarded as a diffusive process, described by the 'diffusion approximation' (DA). For more details, see References [10, 11].

The DA predicts the dipolar anisotropy, see Section 2, but cannot explain the smaller scale anisotropies (SSA). We show in Section 3 that the concrete realization of the magnetic field (interstellar and/or heliospheric depending on the CR rigidity \( E/Z \)) within ∼ a CR mean free path (MFP) from Earth naturally explains the presence of higher order multipoles on the sky. Indeed, the DA predictions represent an ensemble average over all possible local magnetic field configurations. Therefore, they do not reflect the exact anisotropy patterns on the sky for a specific observer. In practice, the concrete realization of magnetic fields within a CR MFP from the observer gives rise to a specific pattern of SSA, on top of a dipolar anisotropy.

This implies that observations of SSA should become in the future a new and promising way to probe our local interstellar and heliospheric fields, see Section 4.
2. The large scale anisotropy

The DA predicts a dipolar anisotropy $\delta$, whose direction and amplitude are related to the local gradient of CR density $\nabla n$ by $\delta = 3D(E/Z)/c \cdot \nabla n/n$, where $D(E/Z)$ denotes the local value of the CR diffusion coefficient. References [12, 13] put constraints on the value of the diffusion coefficient. We take $D$ value of the CR diffusion coefficient. References [12, 13] put constraints on the value of the diffusion coefficient. We take $D(E/Z) \approx 10^{28} \left( E/Z \right)^{3/4} \left( H/ \text{kpc} \right)^2 \text{ cm}^2 \text{s}^{-1}$, with $\gamma \approx 0.45$, and $H \sim 1 \text{kpc}$ as an order of magnitude of the scale height of the (magnetized) Galactic halo.

Then, if $|\nabla n/n| \sim 1/H$, this yields $|\delta| \sim 10^{-3} \left( E/Z \right)^{3/4}$. Such a value roughly corresponds to observations at $\sim (1 - 10) \text{ TeV}$ energies. For detailed studies, see References [14, 15].

In practice, the anisotropy is dominated by one (or a few) recent nearby sources [15]. Also, in a given energy range, the anisotropy does not necessarily increase with energy [15]. We also remind the reader that, at TeV–PeV energies, the CR gyroradius is negligible compared to the coherence length $l_c \sim 10 \text{ pc}$ of the interstellar turbulence. This implies that the dipole does not point in the direction of $\nabla n/n$. The diffusion approximation predicts the ensemble averaged dipole. In reality, the local magnetic field around Earth has a given configuration —which does not strongly change on the time scales and spatial scales which are relevant here. See References [16, 17, 18] for more information on the interstellar magnetic field within a few tens of parsecs from Earth.

3. Anisotropies at medium and small angular scales

The DA only predicts a dipolar anisotropy and no higher order multipoles. Previous works have proposed a variety of mechanisms that can generate SSA under some circumstances: We refer the reader to References [19, 20, 21, 22]. More recently, Reference [23] made the interesting suggestion that SSA at $\sim (1 - 10) \text{ TeV}$ may be due to heliospheric electric fields.

In this work, we propose that SSA are a natural consequence of the given magnetic field configuration within roughly a CR mean free path $\lambda_{\text{mfp}}(E/Z)$ from Earth. Reference [24] supports such a view and, very interestingly, demonstrates that the observed SSA power spectrum at multi-TeV energies would be compatible with it. CRs with different rigidities $E/Z$ scatter on different wavelengths of the local turbulence. This implies that SSA must be rigidity-dependent, which is in line with observations.

In the previous Section, we have already stressed that the DA only predicts an ensemble averaged value for the dipole. The actual amplitudes and directions of the dipoles measured by observers in different realizations of the magnetic field will differ (more or less) from these predictions, even if $\nabla n/n$, $l_c$, the turbulence power spectrum and the root mean square amplitude of the field are fixed. Conceptually, this is also the reason why the DA fails to predict the higher order multipoles. From one realization of the local field to another, SSA will statistically cancel one another if averaged over a large amount of magnetic field realizations, leaving only a dipole —the ensemble averaged one, which is predicted by the DA. However, in reality, the local magnetic field has a given configuration that leads to the existence of specific SSA bearing its imprints. The interstellar magnetic field does not vary sufficiently quickly for SSA at energies $E \leq 1 \text{ TeV}$ to significantly change during the life time of experiments ($\sim 10 \text{ yr}$).

Indeed, both the velocity of the interstellar medium and the Alfvén velocity are of the order of $10 \text{ km s}^{-1}$, and $10 \text{ km s}^{-1} \times 10 \text{ yr} \lesssim r_L(\text{TeV})$, where $r_L(\text{TeV})$ is the Larmor radius of a TeV CR in a $\approx 4 \mu \text{G}$ field. Let us note that the argument presented here is valid for any magnetic field within a cosmic ray mean free path from Earth. As first realized by Desiati & Lazarian [25], the CR MFP should start to be of the order of the size of the heliotail for CRs with $E \leq 10 \text{ TeV}$. Therefore, they proposed that, below such energies, one could start to probe the configuration of heliospheric magnetic fields —see also discussion in the next Section.

1 See, amongst others, the talk given by Ming Zhang during this workshop.
We now verify numerically, with the code presented in Reference [26], that SSA do appear on top of the dipolar anisotropy, provided a local gradient of CR density $\nabla n$ exists. We propagate individual CRs with $E/Z = 10$ PeV in an isotropic turbulent magnetic field with root mean square strength $B_{\text{rms}} = 4 \mu$G. For a detailed description of the procedure, see [1]. Using a FFT, the field is precomputed on a three-dimensional grid in physical space from its power spectrum in reciprocal space —see amongst others References [27, 28] for more details on this technique.

We use here a turbulent field with a Kolmogorov spectrum ($P(k) \propto k^{-5/3}$), which contains fluctuations on scales between $l_{\text{min}} = 0.2$ pc and $l_{\text{max}} = 150$ pc. Magnetic field fluctuations are then resolved down to scales $\approx r_L(10 \text{ PeV})/10$, which ensures that the field contains modes on which CRs scatter resonantly (i.e. those with spatial fluctuation scales $\approx r_L$). Using anisotropic turbulence or changing the other parameters of the turbulence do not change the main conclusion of this work.

![Figure 1](image1.png)  
**Figure 1.** Simulated deviation $(\Delta N - \langle N \rangle)/\langle N \rangle$ of the CR flux on the sky at Earth from the average flux $\langle N \rangle$, after smoothing over $90^\circ$ circles. Result for a given realization of the local turbulent magnetic field, see text for parameters. A large scale anisotropy can be clearly seen.

![Figure 2](image2.png)  
**Figure 2.** Same as Figure 1, after subtracting the dipole and smoothing over $20^\circ$ circles. Same concrete realization of the turbulent magnetic field. Anisotropies at small and medium angular scales are visible, showing that higher order multipoles are present.

In order to diminish the computing time, we take a large relative gradient of CR density $|\nabla n/n| = (290 \text{ pc})^{-1}$. Figure 1 (respectively Figure 2) shows the resulting sky map for the large scale anisotropy (respectively the medium and small scale anisotropies). In Figure 1, we plot the relative deviation $(\Delta N - \langle N \rangle)/\langle N \rangle$ of the CR flux, after averaging over circles with $90^\circ$ radii, from the average flux on the sky $\langle N \rangle$. For Figure 2, we have subtracted the dipolar anisotropy, and we show the remaining anisotropies at smaller scales (SSA) after averaging over circles with $20^\circ$ radii.

We verified that these SSA are rigidity-dependent. In reality, experiments such as IceCube present results for broad energy ranges (and different charges), see Figure 3 of Reference [7]. SSA from CRs with different rigidities add up non-constructively. Observed SSA are then expected to have an amplitude smaller than the amplitude of the dipole. We find that for a CR distribution with a median energy $E_m = 10$ PeV and width $\Delta E/E_m$ set to that for the IceCube observations at $E_m = 20$ TeV, the amplitude of SSA is roughly 10 times smaller than the dipole, which agrees with observations.

For a quantitative and detailed theoretical explanation for the origin of SSA, we refer the reader to our main work [1]. Very qualitatively, if CRs were travelling on straight lines from a ‘last scattering surface’ at $\lambda_{\text{mfp}}(E/Z)$ from Earth, only a dipole would be present: It would point to the direction of the local gradient of CR density $\nabla n$. In reality, their trajectories are curved in the given configuration of the local magnetic field within $\approx \lambda_{\text{mfp}}(E/Z)$ from Earth,
which reshuffles parts of the dipole to smaller patches in different directions on the sky: the SSA.

**Figure 3.** Trajectories of four CRs that reach Earth in four different directions on the sky: (l, b) = (180°, 0°) — red line, (181°, 0°) — green line, (199°, 0°) — blue line, and (200°, 0°) — magenta line. Computations are done for $E/Z = 10$ PeV CRs in a concrete realization of the turbulent magnetic field, see text. Trajectories are projected on a panel of lateral size 200 pc which contains the local gradient of CR density, $\nabla n$. $\nabla n$ points towards increasing $Y$, and the Earth is located at $(X, Y) = (0, 0)$.

**Figure 4.** Zoom on Figure 3, showing CR trajectories in a panel with 60 pc lateral size. Within approximately a CR mean free path, most CRs which arrive in a SSA 'hot spot' (resp. 'cold spot') have trajectories which point back towards larger (resp. lower) $n$.

Figures 3 and 4 illustrate this: They show the trajectories of four CRs arriving at Earth, two being in a 'cold spot' of the SSA (i.e. a sky patch in which the CR flux is lower than expected if only a dipolar anisotropy were present), and two in a 'hot spot', see captions of the figures. In Figure 3, one can see that all four CRs may come from any direction, as should be expected. However, in Figure 4, which is a zoom to a region of size $\approx \lambda_{mfp}(E/Z)$ around Earth, one can see that CRs from the cold (respectively hot) spot tend to preferentially come from the direction of lower (respectively larger) CR densities $n$. Therefore, the last part of the CR trajectories within $\approx \lambda_{mfp}(E/Z)$ from Earth determines the given local configuration of SSA, which is in line with the theoretical model presented above.

4. Perspectives

We think that, to some extent, one now has the basic theoretical ingredients that are needed to build a self-consistent picture for the origin of the TeV-PeV CR dipole and SSA. Further CR anisotropy observations, as well as better knowledge/understanding of heliospheric fields and of local interstellar fields, should help in building such a picture.

Concerning the anisotropies at medium and small angular scales, some of the main questions which remain to be solved are:

- Below which energy do SSA start to probe heliospheric fields (as proposed in Reference [25])? Are TeV anisotropies at small scales due to the heliospheric fields?
- Is the effect of heliospheric electric fields on SSA (as proposed in Reference [23]) dominant or sub-dominant at $\sim (1 - 10)$ TeV energies?
• Could some simulations of heliospheric fields reproduce, or at least be somehow compatible with, the observed TeV SSA?
• What is the expected amplitude and power spectrum of SSA from the local interstellar magnetic fields, from TeV to PeV energies? And how well would it fit observations from TeV to PeV energies?
• What is the proper explanation for the anisotropy patterns observed by IceCube and IceTop at 400 TeV and 2 PeV?

In principle, one should be able to shed more light on these questions by combining the current knowledge of the local interstellar magnetic field, heliospheric fields, and checking their impact of the SSA.

We predict that, once these questions will be better understood, our field will enter a new era. Measurements of CR anisotropies on all angular scales (dipole and higher order multipoles) will enable one to deduce precious information on local magnetic fields, within the cosmic ray mean free path. In the future, this may become one of the most powerful ways to measure such fields (strength, structure, and maybe potential temporal variations).

5. Conclusions
We have shown that small scale anisotropies naturally arise from the concrete local magnetic field configuration, within ~ a CR mean free path from Earth. At PeV energies, CR anisotropies probe the local interstellar turbulence within several tens of parsecs. At lower energies, below ~ 10 TeV, the same argument holds, and one may start to probe heliospheric fields [25].

We predict that the field is about to enter a new phase. In the near future, one will start to use CR anisotropy observations on different angular scales in order to gain information of the still rather poorly known local interstellar and heliospheric magnetic fields. Since the CR mean free path depends on the rigidity \( E/Z \), CR anisotropy observations at different energies will in principle enable one to study magnetic fields at different distances from Earth, from the heliosphere to a few tens of parsecs.

Acknowledgments
The author acknowledges funding from the European Research Council under the European Community’s Seventh Framework Programme (FP7/2007 2013) / ERC grant agreement No. 247039. He thanks the Committee for organizing this fascinating and fruitful workshop, and acknowledges several interesting discussions with, amongst others, Segev BenZvi, Pasquale Blasi, Paolo Desiati, Priscilla Frisch, Alex Lazarian, Mikhail Malkov, Philipp Mertsch, Nikolai Pogorelov, Marcos Santander and Nathan Schwadron.

References
[1] Giacinti G and Sigl G 2012 Phys. Rev. Lett. 109 071101
[2] Giacinti G 2013 Plasma Phys. Control. Fusion 55 124007
[3] Guillian G et al. [Super-Kamiokande Collaboration] 2007 Phys. Rev. D 75 062003
[4] Amenomori M et al. [Tibet AS-gamma Collaboration] 2006 Science 314 439
[5] Abdo A A et al. [Milagro Collaboration] 2008 Phys. Rev. Lett. 101 221101
[6] Abdo A A et al. [Milagro Collaboration] 2009 Astrophys. J. 698 2121
[7] Abbasi R et al. [IceCube Collaboration] 2012 Astrophys. J. 746 33
[8] Aartsen M G et al. [IceCube Collaboration] 2013 Astrophys. J. 765 55
[9] Han J-L, Ferriere K and Manchester R N 2004 Astrophys. J. 610 820
[10] Ginzburg V L, Dogiel V A, Berezinsky V S, Bulanov S V and Ptuskin V S 1990 Astrophysics of Cosmic Rays (Amsterdam: North-Holland)
[11] Strong A W, Moskalenko I V and Ptuskin V S 2007 Ann. Rev. Nucl. Part. Sci. 57 285
[12] Strong A W and Moskalenko I V 1998 Astrophys. J. 509 212
[13] Di Bernardo G, Evoli C, Gaggero D, Grasso D and Maccione L 2010 Astropart. Phys. 34 274
[14] Erlykin A D and Wolfendale A W 2006 Astropart. Phys. 25 183;
[15] Blasi P and Amato E 2012 J. Cosmol. Astropart. Phys. 1201 010
[16] Frisch P C, Andersson B-G, Berdyugin A, Funsten H O, Magalhaes M, McComas D J, Pirola V, Schwadron N A, Slavin J D and Wiktorowicz S J 2010 Astrophys. J. 724 1473
[17] Frisch P C 2012 AIP Conf. Proc. 1436 295
[18] Frisch P C, Andersson B-G, Berdyugin A, Pirola V, DeMajistre R, Funsten H O, Magalhaes A M, Seriacopi D B, McComas D J, Schwadron N A, Slavin J D and Wiktorowicz S J 2012 Astrophys. J. 760 106
[19] Drury L and Aharonian F A 2008 Astropart. Phys. 29 420
[20] Malkov M A, Diamond P H, Drury L and Sagdeev R Z 2010 Astrophys. J. 721 750
[21] Lazarian A and Desiati P 2010 Astrophys. J. 722 188
[22] Kotera K, Perez-Garcia M A and Silk J 2013 Phys. Lett. B 725 196
[23] Drury L 2013 The problem of small angular scale structure in the cosmic ray anisotropy data Preprint arXiv:1305.6752
[24] Ahlers M 2014 Phys. Rev. Lett. 112 021101.
[25] Desiati P and Lazarian A 2013 Astrophys. J. 762 44
[26] Giacinti G, Kachelriess M, Semikoz D V and Sigl G 2012 J. Cosmol. Astropart. Phys. 1207 031
[27] Casse F, Lemoine M and Pelletier G 2002 Phys. Rev. D 65 023002
[28] De Marco D, Blasi P and Stanev T 2007 J. Cosmol. Astropart. Phys. 0706 027