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# Anisotropic diffusion and the cosmic ray anisotropy

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**Abstract.** We argue that the diffusion of cosmic rays in the Galactic magnetic field has to be strongly anisotropic. As a result, the number of CR sources contributing to the local CR flux is strongly reduced. The CR density is therefore less smooth, and the contribution of individual sources to the CR dipole anisotropy becomes more prominent. In the case of anisotropic diffusion, the observed plateau in the CR dipole anisotropy around 2–20 TeV can be explained by a 2–3 Myr old CR source which dominates the local CR flux in this energy range.

## 1. Introduction

The observed distribution of cosmic ray (CR) arrival directions is highly isotropic. Since Galactic CR sources are strongly concentrated in the Galactic disc, an efficient mechanism for the isotropisation of the CR momenta exists. Agent of this isotropisation are turbulent magnetic fields, since charged CRs scatter efficiently with resonant field modes which wavelength matches their Larmor radius. As a result, CRs perform on scales larger than the coherence length of the turbulent field a random walk, and the memory of the initial source location is mostly erased. Residual anisotropies are connected to the structure of the local magnetic field and, e.g., to a remaining net flux of CRs.

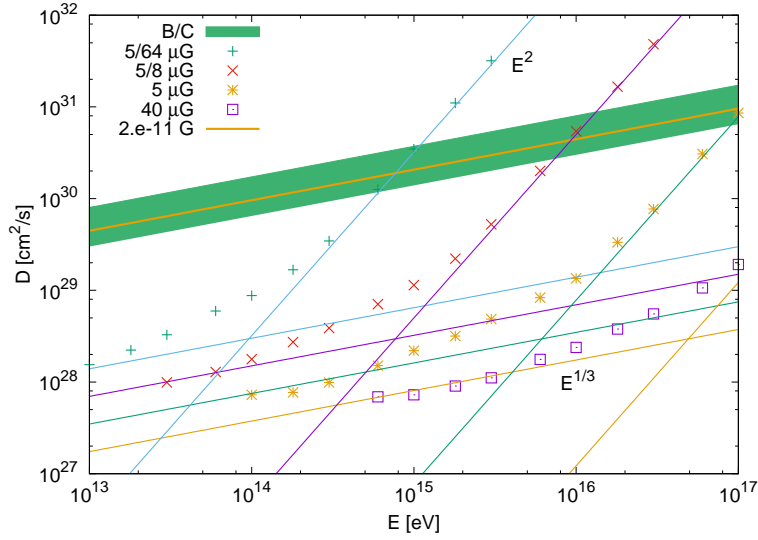
Since large wavelengths of the turbulent field modes are less abundant, CRs with higher energy are scattered less efficiently. Therefore, the diffusion picture predicts that the CR anisotropy should increase monotonically with energy. More precisely, if the turbulent field follows a Kolmogorov power law as suggested by the observed B/C ratio, the dipole anisotropy  $\delta$  should increase with energy as  $\delta \propto E^{1/3}$ . Both the energy-dependence and the absolute value of the dipole anisotropy predicted in simple isotropic diffusion models do not agree with observations. This discrepancy was dubbed the “CR anisotropy problem” by Hillas [1].

In this short review based on the results of Refs. [2, 3], we will first argue that the diffusion of CRs in the Galactic magnetic field (GMF) has to be strongly anisotropic. As a result, the number of CR sources contributing to the local CR flux is strongly reduced. Therefore, the CR density is less smooth, and the contribution of individual sources to the CR dipole anisotropy becomes more prominent than in the standard picture. Then we argue that the observed plateau in the CR dipole anisotropy around 2–20 TeV is connected to a 2–3 Myr old CR source which dominates in this energy range the local CR flux. Finally, we comment on the alternative that a young source like Vela is responsible for the observed plateau in the dipole anisotropy.

## 2. Galactic magnetic field and anisotropic diffusion

In the diffusion approach to CR propagation one considers typically the CR density in the stationary limit. The measured ratios of CR isotopes like  $\text{Be}^{10}/\text{Be}^9$  and of secondary/primary ratios like B/C indicate a residence time of CRs with rigidity  $\mathcal{R}$  of order  $\tau_{\text{esc}} \simeq \text{few} \times$





**Figure 1.** CR diffusion coefficient  $D(E)$  in pure isotropic Kolmogorov turbulence with  $L_{\max} = 25$  pc for four values of the strength  $B_{\text{rms}}$  of the turbulent field. The green band shows the range of magnetic field strengths for which the diffusion coefficient satisfies  $D_0 = (3 - 8) \times 10^{28} \text{ cm}^2/\text{s}$  at  $E_0 = 10$  GeV; from Ref. [3].

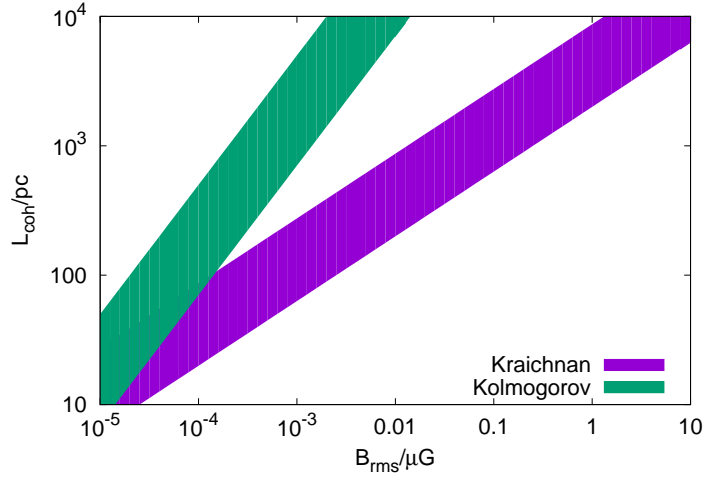
$10^7 \text{ yr} (\mathcal{R}/5 \text{ GV})^{-\beta}$  with  $\beta \simeq 1/3$ . Then the flux from some  $10^4$  sources accumulates at low rigidities, forming a “sea” of Galactic CRs, if one assumes that the main CR sources are supernovae (SN) injecting  $\simeq 10^{50}$  erg every  $\simeq 30$  yr in the form of CRs. Since many sources contribute, the discrete nature of the CR sources can be neglected. Assuming additionally that the turbulent magnetic field dominates relative to the regular field, one often replaces the diffusion tensor  $D_{ij}$  by a scalar diffusion coefficient  $D$ .

The diffusion approach based on the approximations described above has been sufficient to describe the bulk of experimental data obtained until  $\simeq 2005$ . With the increased precision of newer experiments, several discrepancies like the “positron excess” or breaks in the CR spectra of nuclei have been emerged. Here we will discuss a more theoretical challenge for the approximations employed in the standard diffusion approach, which has also the potential to solve other observational anomalies.

In Fig. 1, we show the diffusion coefficient

$$D_{ij} = \lim_{t \rightarrow \infty} \frac{1}{2Nt} \sum_{a=1}^N (x_i^{(a)} - x_{i,0})(x_j^{(a)} - x_{j,0}) \quad (1)$$

calculated numerically following the trajectories  $x_i^{(a)}(t)$  of  $N$  CRs injected into a pure random field with a Kolmogorov power spectrum with  $L_{\max} = 25$  pc for various field strengths. The transition at  $R_L(E_{\text{cr}}) = L_{\max}$  between the asymptotic low-energy ( $D \propto E^{1/3}$ , large-angle scattering) and high-energy ( $D \propto E^2$ , small-angle scattering) behaviour is clearly visible. However, for all used field strengths the diffusion coefficients are much smaller than those extracted using e.g. Galprop [4] or DRAGON [5]. Therefore CR propagation cannot be isotropic, because otherwise CRs overproduce secondary nuclei like boron for any reasonable values of the strength and the coherence scale of the turbulent field, cf. with Fig. 2. Such an anisotropy



**Figure 2.** Allowed ranges of  $B_{\text{rms}}$  and  $L_{\text{coh}}$  compatible with  $D_0 = (3 - 8) \times 10^{28} \text{cm}^2/\text{s}$  at  $E_0 = 10 \text{ GeV}$  for Kolmogorov and Kraichnan turbulence. These ranges should be compared with the typical order-of-magnitude values that are relevant for the Galactic magnetic field:  $B_{\text{rms}} \sim (1 - 10) \mu\text{G}$  and  $L_{\text{coh}} \lesssim$  a few tens of pc, from Ref. [3].

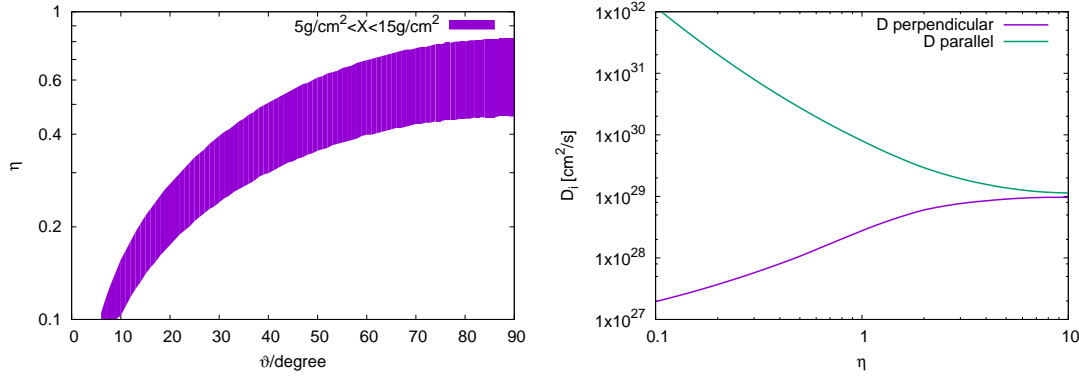
may appear if the turbulent field at the considered scale does not dominate over the ordered component, or if the turbulent field itself is anisotropic.

One can estimate the level of anisotropy required considering the following toy model: Let us adopt a thin matter disc with density  $\rho/m_p \simeq 1/\text{cm}^3$  and height  $h = 150 \text{ pc}$  around the Galactic plane, while CRs propagate inside a larger halo of height  $H = 5 \text{ kpc}$ . We assume that the regular magnetic field inside this disc and halo has a tilt angle  $\vartheta$  with the Galactic plane, so that the component of the diffusion tensor relevant for CR escape is given by

$$D_z = D_{\perp} \cos^2 \vartheta + D_{\parallel} \sin^2 \vartheta. \quad (2)$$

Applying a simple leaky-box approach, the grammage follows as  $X = c\rho hH/D_z$ . Using now as allowed region for the grammage  $5 \leq X \leq 15 \text{ g/cm}^2$ , the permitted region in the  $\vartheta$ - $\eta$  plane shown in the left panel of Fig. 3 follows. For not too large values of the tilt angle,  $\vartheta \lesssim 30^\circ$ , the regular field should strongly dominate,  $\eta \lesssim 0.35$ . This results in a strongly anisotropic propagation of CRs, where the diffusion coefficient perpendicular to the ordered field can be between two and three orders of magnitude smaller than the parallel one,  $D_{\perp} \ll D_{\parallel}$ . As a result, the  $z$  component of the regular magnetic field can drive CRs efficiently out of the Galactic disk. For instance, the “X-field” in the Jansson-Farrar model [6] for the GMF leads to the correct CR escape time, if one chooses as turbulence level  $\eta \equiv B_{\text{rms}}/B_0 \simeq 0.25$  [7].

For this choice, the diffusion coefficients satisfy  $D_{\parallel} \simeq 5D_{\text{iso}}$  and  $D_{\perp} \simeq D_{\text{iso}}/500$ , where  $D_{\text{iso}}$  denotes the isotropic diffusion coefficient  $D_{\text{iso}}$  satisfying the B/C constraints. In the regime, where the CRs emitted by a single source fill a Gaussian with volume  $V(t) = \pi^{3/2} D_{\perp} D_{\parallel}^{1/2} t^{3/2}$ , the CR density is increased by a factor  $500/\sqrt{5} \simeq 200$  compared to the case of isotropic diffusion. The smaller volume occupied by CRs from each single source leads to a smaller number of sources contributing substantially to the local flux, with only  $\sim 10^2$  sources at  $\mathcal{R} \sim 10 \text{ GV}$  and about  $\sim 10$  most recent SNe in the TeV range. This reduction of the effective number of sources may invalidate the assumption of a continuous CR injection and a stationary CR flux.



**Figure 3.** Left: Grammage  $X$  crossed by CRs in a “disc and halo” model as a function of the tilt angle  $\vartheta$  between the regular magnetic field and the Galactic plane, and of the turbulence level  $\eta$ . Right: Fit of the diffusion coefficients  $D_{\parallel}$  and  $D_{\perp}$  at  $E = 10^{15}$  eV as a function of  $\eta$ , from Ref. [3].

### 3. A local source and the cosmic ray anisotropy

In the diffusion approximation, Fick’s law is valid and the net CR current  $\mathbf{j}(E)$  is determined by the gradient of the CR number density  $n(E) = dN/(dEdV)$  and the diffusion tensor  $D_{ab}(E)$  as  $j_a = -D_{ab}\nabla_b n$ . The dipole vector  $\boldsymbol{\delta}$  of the CR intensity  $I = c/(4\pi)n$  follows then as

$$\delta_a = \frac{3j_a}{cn} = -\frac{3D_{ab}}{c} \frac{\nabla_b n}{n}. \quad (3)$$

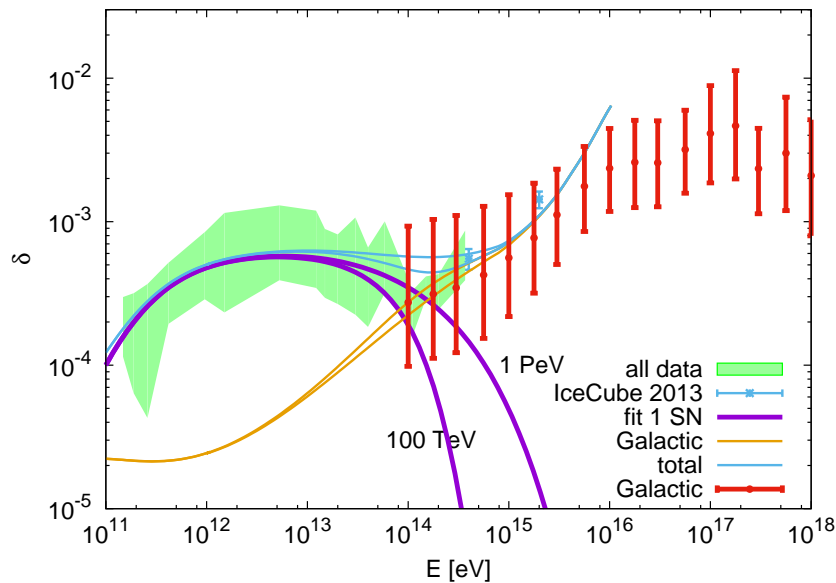
In the case of a strong ordered magnetic field  $\mathbf{B}$ , the tensor structure of the diffusion tensor simplifies to  $D_{ab} \propto B_a B_b$ . This corresponds to a projection of the CR gradient onto the magnetic field direction [8]. Hence, anisotropic diffusion predicts that the dipole anisotropy should align with the local ordered magnetic field instead of pointing to the source [8, 2]. Note that the ordered magnetic field corresponds to the sum of the regular magnetic field and the sum of turbulent field modes with wavelengths larger than the Larmor radius at the corresponding CR energy.

In the case of a (three-dimensional) Gaussian CR density  $n$ , the formula (3) can be evaluated analytically. The result  $\delta = 3R/(2cT)$  for a single source with age  $T$  and distance  $R$  is independent of the regular and turbulent magnetic field. In Ref. [2], it was shown that the CR density of a single source is quasi-Gaussian, if CRs propagate over length scales  $l \gg L_{\text{coh}}$ . Numerically, the dipole anisotropy  $\delta$  of a source contributing the fraction  $f_i$  to the total observed CR flux is thus

$$\delta_i = f_i \frac{3R}{2cT} \simeq 5.0 \times 10^{-4} f_i \left( \frac{R}{200 \text{ pc}} \right) \left( \frac{T}{2 \text{ Myr}} \right)^{-1}. \quad (4)$$

In Fig. 4, we show experimental data for the dipole anisotropy from Refs. [9, 10] as a green band: The anisotropy grows as function of energy until  $E \simeq 2$  TeV, remains approximately constant in the range 2–20 TeV, before it decreases again. The plateau in the range 2–20 TeV is naturally explained by the energy-independent contribution to the dipole anisotropy of a single source. This is supported by the fact that the dipole phase remains approximately constant in this range too, before it flips by  $\sim 180^\circ$ . Such a flip is naturally explained by the projection effect on the magnetic field line, if above 20 TeV another source, which is located in the opposite hemisphere, dominates the CR dipole anisotropy.

More specifically, it was suggested in Ref. [2] that a 2–3 Myr old source at the distance 200–300 pc dominates the dipole anisotropy in the range 2–20 TeV. Previously, it was shown in



**Figure 4.** Lower and upper limit (green band) on the dipole anisotropy and data from IceCube (blue error-bars) compared to the contribution from the local source (red, for two values of  $E_{\text{max}}$ ) and from the average CR sea (magenta) as function of energy; adapted from Ref. [2].

Ref. [11] that the same source can explain the “positron excess”, as well as the breaks of the nuclei spectra and the different slope of the proton spectrum [12]. The contribution of this local source is shown by two magenta lines for two different high-energy cutoffs: In one case, it was assumed that the source can accelerate up 100 TeV, in the other that it is a PeVatron. In both cases, the CR flux was calculated following the trajectories of individual CRs, as discussed in Refs. [7, 13, 11, 12]. Additionally, the total anisotropy beyond  $10^{14}$  eV of all Galactic SNe is shown by red error-bars which is calculated in the escape model which uses the same magnetic field configuration as the one used for the local source [7, 13].

A characteristic feature of this proposal is that a relatively old source dominates the observed CR flux. This is only possible in the case of anisotropic diffusion, and requires additionally that the perpendicular distance  $d_{\perp}$  of the Sun to the magnetic field line connecting it to the source is not too large. Even for small  $d_{\perp}$ , the CR flux from the single source is suppressed at low-energies, because of the slower perpendicular diffusion. In Refs. [12], the value  $d_{\perp} \simeq 70$  pc was estimated requiring that the low-energy break in the source spectrum explains the breaks in the energy spectra of CR nuclei. For this choice of  $d_{\perp}$ , the flux of the local source is suppressed below  $\simeq 1$  TeV (cf. with Fig. 2 of Ref. [12]), leading to a decreasing  $f_i$  and the transition to the standard  $\delta \propto E^{1/3}$  behavior below this energy.

Another choice for the age of the source was suggested in Refs. [14, 15]. Here, Vela with the age around 11,000 yr and distance 300 pc was proposed as the single source responsible for the plateau in the dipole anisotropy in the energy range 2–20 TeV. In this case, the contribution of Vela to the dipole amplitude has to be suppressed by a factor  $\simeq 200$ . Three mechanisms for such a suppression may be operating: First, if the regular magnetic field and the CR gradient are not parallel, the projection effect in  $D_{ab}\nabla_b n$  can reduce the dipole [16, 15]. Second, the measured CR dipole is a projection into the equatorial plane and is thus reduced compared to the true one. Finally, the CR flux contributed by Vela may be small. Calculating the CR fluxes from nearby young sources using the standard isotropic diffusion coefficient and taking into account

these effects, [15] argued that Vela leads to correct level of anisotropy. There is however a caveat in this conclusion: While Ref. [15] calculates the CR fluxes from individual sources for *isotropic* diffusion, the remaining analysis is based on strongly anisotropic diffusion. In the latter case, the CR flux depends however crucially on the perpendicular distance  $d_{\perp}$  of the source to the magnetic field line connecting it with the Sun, and a calculation of the CR flux following the lines of Refs. [2, 11, 12] is required. Moreover, the number of sources is strongly reduced and correspondingly the flux of nearby sources with small perpendicular distance strongly enhanced.

#### 4. Conclusions

We have argued that the diffusion in the GMF has to be strongly anisotropic, because otherwise CRs overproduce secondary nuclei like boron for any reasonable values of the strength and the coherence scale of the turbulent field. Therefore the number of CRs contributing to the local CR flux is strongly reduced compared to the “standard picture”. As a result, the CR density is less smooth, and the contribution of individual sources to the CR dipole anisotropy becomes more prominent. In this picture, the observed plateau in the CR dipole anisotropy around 1–20 TeV can be explained by a 2–3 Myr old CR source which dominates the local CR flux in this energy range. Such a source can explain also several other CR puzzles such as the “positron excess”, the difference in the slope of the proton and nuclei spectra as well as their breaks [12].

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#### References

- [1] Hillas A M 2005 *J. Phys.* **G31** R95–R131
- [2] Savchenko V, Kachelrieß M and Semikoz D V 2015 *Astrophys. J.* **809** L23 (*Preprint* 1505.02720)
- [3] Giacinti G, Kachelrieß M and Semikoz D V 2018 *JCAP* **1807** 051 (*Preprint* 1710.08205)
- [4] Jóhannesson G *et al.* 2016 *Astrophys. J.* **824** 16 (*Preprint* 1602.02243)
- [5] Evoli C, Gaggero D, Grasso D and Maccione L 2008 *JCAP* **0810** 018 [Erratum: *JCAP*1604,no.04,E01(2016)] (*Preprint* 0807.4730)
- [6] Jansson R and Farrar G R 2012 *Astrophys. J.* **761** L11 (*Preprint* 1210.7820)
- [7] Giacinti G, Kachelrieß M and Semikoz D V 2014 *Phys. Rev.* **D90** 041302 (*Preprint* 1403.3380)
- [8] Jones F C 1990 *Astrophys. J.* **361** 162–172
- [9] Di Sciascio G and Iuppa R 2014 (*Preprint* 1407.2144)
- [10] Ahlers M and Mertsch P 2017 *Prog. Part. Nucl. Phys.* **94** 184–216 (*Preprint* 1612.01873)
- [11] Kachelrieß M, Neronov A and Semikoz D V 2015 *Phys. Rev. Lett.* **115** 181103 (*Preprint* 1504.06472)
- [12] Kachelrieß M, Neronov A and Semikoz D V 2018 *Phys. Rev.* **D97** 063011 (*Preprint* 1710.02321)
- [13] Giacinti G, Kachelrieß M and Semikoz D V 2015 *Phys. Rev.* **D91** 083009 (*Preprint* 1502.01608)
- [14] Sveshnikova L G, Strelnikova O N and Ptuskin V S 2013 *Astroparticle Physics* **50** 33–46 (*Preprint* 1301.2028)
- [15] Ahlers M 2016 *Phys. Rev. Lett.* **117** 151103 (*Preprint* 1605.06446)
- [16] Mertsch P and Funk S 2015 *Phys. Rev. Lett.* **114** 021101 (*Preprint* 1408.3630)