MAGNETIC FIELDS AND COSMIC-RAY ANISOTROPIES AT TeV ENERGIES

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ABSTRACT

Several cosmic-ray (CR) observatories have provided high-accuracy maps of the sky at TeV–PeV energies. The data reveal an \( O(0.1\%) \) deficit from north galactic directions that peaks at 10 TeV and then evolves with the energy, together with other anisotropies at smaller angular scales. Using the Boltzmann equation, we derive expressions for the CR flux that fit these features. The anisotropies depend on the local interstellar magnetic field \( \mathbf{B}_{\text{IS}} \), on the average galactic field \( \mathbf{B}_G \) in our vicinity, and on correlations between fluctuating quantities. We show that the initial dipole anisotropy along \( \mathbf{B}_{\text{IS}} \) can be modulated by changes in the global CR flow, and that a variation in the dipole direction would imply a given radius of coherence for the local \( \mathbf{B}_{\text{IS}} \). We also show that small- and medium-scale anisotropies may appear when the full-sky anisotropy finds a field configuration acting as a magnetic lens.

Key words: cosmic rays – ISM: magnetic fields

1. INTRODUCTION

We observe charged cosmic rays (CRs; protons and atomic nuclei) with energies of up to \( 10^{11} \) GeV. Although in their way to the Earth these particles lose directionality, they carry important information about their sources and about the environment where they have propagated. For example, the observation that boron is more frequent in CRs than in the solar system suggests that it is produced when heavier nuclei break on their way to the Earth, implying that they cross an average depth of 10 g cm\(^{-2}\) of interstellar (IS) baryonic matter in their trajectory from the dominant sources (Reeves et al. 1970).

At TeV energies magnetic fields trap charged CRs in the IS medium, and their transport is usually modeled by a diffusion equation (Shalchi 2009). One expects that the CR gas propagates along the parallel and the perpendicular directions to the background field \( \mathbf{B} \) with different diffusion coefficients, scattering with the magnetic turbulences \( \delta \mathbf{B} \) in the plasma. In particular, if we define the Larmor radius as

\[
r_L = \frac{E}{Q B c} = \left( \frac{E}{1 \text{ TeV}} \right) \left( \frac{1 \mu \text{G}}{B} \right) \left( \frac{e}{Q} \right) 1.1 \times 10^{-3} \text{ pc},
\]

a CR will predominantly be diffused by magnetic irregularities of wavenumber \( k \approx 1/r_L \). In a first approximation, one may picture its trajectory as a helix along \( \mathbf{B} \) of radius \( r_L \sqrt{1 - \mu^2} \) and velocity

\[
v_\parallel = c \mu, \quad v_\perp = c \sqrt{1 - \mu^2},
\]

with random changes in \( v_\parallel \) after a parallel mean free path \( \lambda_1 \). Such change will also imply a variation in the field line trapping the CR, i.e., \( \lambda_1 \propto r_L \).

A diffusion equation admits a multipole expansion (Jones 1990) with isotropy at order zero and a dipole along the gradient direction at first order. However, this information is deduced a posteriori, as in a diffusion equation the momenta of the gas particles have been averaged. The Boltzmann equation, instead, gives the evolution in phase space of the statistical distribution function \( f(r, p; t) \) (density of particles at \( r \) with momentum \( p \)), providing a microscopic description of the fluid (Battaner 2009; Ahlers 2014). It is easy to see that when we measure the CR differential flux \( F(u, E; t) \) (number of particles crossing the unit area from a given direction \( u \) per unit solid angle, energy, and time), we can directly read the distribution function:

\[
f \left( r_{\text{Earth}}, \frac{E}{c} u; t \right) = \frac{c^2}{E^2} F(u, E; t).
\]

where we have taken the relativistic limit with \( E = cp \). Therefore, it is interesting to explore how the appearance of anisotropies may be explained with the Boltzmann equation, especially in an environment with regular magnetic fields at different scales (see below).

In this article we will attempt a description of several large- and medium-scale anisotropies observed in the CR flux by several experiments. The combined results from TIBET (Aménomori et al. 2006), MILAGRO (Abdo et al. 2008), ARGO-YBF (Di Sciaccio et al. 2012), SuperKamiokande (Guillian et al. 2007), ANTARES (Mangano 2009), IceCube (Aartsen et al. 2013; Santander 2013), and HAWC (Abeysekara et al. 2013) provide a picture of the whole sky at different energies. The data reveal that the almost perfect isotropy is broken by a \( O(10^{-3}) \) dipole-like feature that appears at 1 TeV and evolves with the energy, together with other irregularities at lower angular scales (Zotov & Kulikov 2012; Iuppa 2012).

It seems clear that the direction of the local IS magnetic field \( \mathbf{B}_{\text{IS}} \) should be a key ingredient in the explanation of these anisotropies (Schwadron et al. 2014). Voyager data (Ratkiewicz et al. 2008) on the heliospheric boundary provide an estimate for the direction of \( \mathbf{B}_{\text{IS}} \):

\[
\ell_B = 217^\circ \pm 14^\circ; \quad b_B = -49^\circ \pm 8^\circ
\]

(in galactic coordinates), whereas IS atom measurements with the Interstellar Boundary Explorer (IBEX) (Frisch et al. 2012) imply

\[
\ell_B = 210^\circ \pm 2^\circ; \quad b_B = -57^\circ \pm 1^\circ.
\]

Although the region of coherence of such a field is unknown (it could vary from 0.01 to 10 pc), it is much larger than the gyroradius of a TeV CR (in Equation (1)). At even larger distances (above 10 pc) the average magnetic field \( \mathbf{B}_G \) can be measured using a variety of methods (Beck 2005; Wielebinski 2005; Han 2009; Battaner 2009; Ruiz-Granados et al. 2010): polarized
2. LARGE-SCALE ANISOTROPIES

Let us first consider the simplest flux: a CR gas from a point-like source $S$ propagating through a turbulent but homogeneous and isotropic medium. Such a medium would correspond to the absence of a regular magnetic field $B_{IS}$ (or to the presence of a field weaker than the fluctuations $\delta B$ of wavenumber $k \approx 1/r_L$), and it implies the same diffusion coefficient $\kappa$ in all directions. The trajectories will define in this case a three-dimensional random walk of step $\lambda = 3\kappa/c$. The mean displacement $D$ from the source that a particle reaches after a (large) time $t$ is then (Shalchi 2009)

$$D = \sqrt{2\kappa t}.$$  (6)

The expression above implies that the radial velocity of the gas (we call it the CR flow, since an observer moving at that velocity would observe an isotropic flux) will decrease like $1/\sqrt{t}$ with the distance $D$ from $S$:

$$v_{\text{gas}} \approx \sqrt{\frac{2\kappa}{1 + 2\kappa/c^2}} = c \left( \frac{c^2D^2}{4\kappa^2} + 1 \right)^{-1/2}.$$  (7)

The relative difference between the CR flux going away and toward the source (the forward-backward asymmetry $A^{FB}$) can then be estimated as the ratio

$$A^{FB} \approx \frac{v_{\text{gas}}}{c} \approx \frac{2\kappa}{cD}.$$  (8)

This means that the point-like source will introduce an anisotropy in the CR flux proportional to $1/D$ and to $\lambda$. Basically, it is a dipole anisotropy with the excess pointing toward $S$:

$$F(u) = F_0 (1 + u \cdot \hat{d}),$$  (9)

where

$$\hat{d} = \frac{A^{FB}}{2\pi} u_S.$$  (10)

When there are several sources $S_i$, it is straightforward to show that the addition of the corresponding dipole anisotropies $d_i$ gives another dipole $d$ (Giaccinti et al. 2012)

$$d = \frac{\sum_i F_0^{(i)} d_i}{\sum_i F_0^{(i)}}.$$  (11)

In summary, for an isotropic CR propagation we may expect a dipole anisotropy pointing toward the average CR source (Pohl & Eichler 2013), with its intensity inversely proportional to the distance to these sources and proportional to the mean free path between collisions. Notice, however, that the presence of a regular magnetic field $B_{IS}$ will introduce an asymmetry between the parallel and the perpendicular diffusion coefficients ($\kappa_\parallel$ and $\kappa_\perp$) that will change this result.

To find out how, let us assume a local $B_{IS}$ coherent over distances $r_{IS} \gg r_L$, with $\lambda_\parallel = 3\kappa_\parallel/c$. We will treat the CRs (protons of energy between 1 and 1000 TeV) as a fluid that only interacts with the magnetic fields. To obtain the average CR anisotropy in our vicinity, we will separate the magnetic field and the distribution function into a regular plus a turbulent component,

$$f \rightarrow \tilde{f} + \delta f,$$

$$B \rightarrow B_{IS} + \delta B,$$  (12)

and we will average the Boltzmann equation over nearby points. Given the relatively small distance and timescales, we will take stationary and homogeneous magnetic field $B_{IS}$ and distribution function $\tilde{f}$. We are then assuming that the CR sources are far enough so that the spatial gradient $\nabla \cdot \tilde{f}$ is negligible (i.e., smaller than $\delta f/R_{IS}$), and that the changes in $\tilde{f}$ occur on timescales much larger than the period of data taking (the movement of the Earth around the Sun introduces irregularities of order $10^{-4}$, i.e., a 10% correction to the large-scale anisotropy under consideration), and we ignore energy loss or collisions with IS matter. For a fixed CR energy, $\tilde{f}$ must satisfy the Boltzmann equation:

$$F \cdot \nabla_u \tilde{f}(u) = \epsilon (u \times B) \cdot \nabla_u \tilde{f}(u) = 0,$$  (14)

where $\epsilon = p/p$ and $p$ is the momentum of the CR. The equation above can also be written as

$$u \cdot (B \times \nabla_u \tilde{f}) = 0,$$  (15)

which admits the generic solution

$$\tilde{f}(u) = \tilde{f}(u \cdot \hat{b}).$$  (16)

Any stationary and homogeneous solution must then be a function with symmetry around the axis of the magnetic field: $B_{IS}$ will isotropize the flux in the directions orthogonal to its axis. In particular, these solutions may accommodate a dipole along $u_b$,

$$\tilde{f}(u) = f_0 (1 - u \cdot \hat{d}),$$  (17)

with

$$d = \frac{A^{FB}}{2\pi} u_b.$$  (18)

This distribution function will define (see Equation (3)) the dipolar flux in (9) with $u_S \rightarrow u_b$ and $F_0 = f_0(E/c)^2$, i.e., it is $B_{IS}$ (and not the position of the sources) that fixes the direction of the CR flow in our frame, defined as

$$v_0/c = \frac{1}{N} \int d\Omega / f(u) u,$$  (19)

with $N = \int d\Omega / f(u)$.

1 Notice that an observer moving at $v_0$ will see no net flux and complete isotropy. This velocity may coincide or not (for example, owing to an asymmetry in the location of CR sources) with the velocity of the local plasma wind.
The (forward or backward) direction along \( B_{\text{IS}} \) and the intensity of this dipole anisotropy will depend on boundary conditions that, in turn, will reflect the average direction of the CR flow (Biermann et al. 2013; Qu et al. 2012) at larger scales.

In Figure 1 we plot a scheme of the CR flow within different cells that contain a regular \( B_{\text{IS}} \). This field may change randomly from cell to cell, although it has an average value \( B_R \) at kiloparsec scales (Han 2009). Our result above has been obtained for an observer at rest within our local IS medium. The CR anisotropy in each cell (which may have a velocity relative to us) will then follow the \( B \) obtained for an observer at rest within our local IS medium.

An important question would then be what to expect for the average CR flow. Is it \( \vec{d}_R = \langle \vec{d} \rangle \), a dipole along the direction of the average magnetic field \( \vec{B}_R = \langle \vec{B}_{\text{IS}} \rangle \)? To answer this question, we again separate the magnetic field and the distribution function into a regular plus a fluctuating component, but now we average the Boltzmann equation over larger distances, which will include different (nearby) cells:

\[
\begin{align*}
\delta f & \rightarrow \delta f + \delta f, \\
\vec{B} & \rightarrow \vec{B}_R + \delta \vec{B}.
\end{align*}
\]

Although \( \delta \vec{B} \) and \( \delta f \) vary randomly from one cell to another, there may be correlations between both turbulent components (i.e., their relative value in each cell is not random). We will assume

\[
\langle e (\vec{u} \times \delta \vec{B}) \cdot \nabla_u \delta f \rangle = e \vec{u} \cdot (\delta \vec{B} \times \nabla_u \delta f) = e \vec{u} \cdot \vec{T}.
\]

The Boltzmann equation for the regular components is then

\[
u \cdot (\vec{B}_R \times \nabla_u f_R) + \frac{1}{\cos \mu} \frac{\partial f_R}{\partial \mu} u_\mu = 0.
\]

We can find consistent solutions when the correlation \( T \) is constant and orthogonal to \( \vec{B}_R \). We place the axes (see Figure 2) so that \( \vec{B}_R \) and \( T \) go along the \( x \) and the \( y \)-axis, respectively, and we use the latitude \( \mu \) and the longitude \( \phi \) to label the direction \( \vec{u} \) of a CR. Taking \( f_R(\vec{u}) = f_R(b, \mu) \) and

\[
\nabla_u f_R = \frac{\partial f_R}{\partial b} u_b + \frac{1}{\cos \mu} \frac{\partial f_R}{\partial \mu} u_\mu,
\]

with

\[
\begin{align*}
\mu &= -\sin b \cos \mu \mu_\phi - \sin b \sin \mu u_\tau + \cos b u_z; \\
\mu &= -\sin \mu u_\phi + \cos \mu u_\tau,
\end{align*}
\]

the Boltzmann equation becomes

\[
-\sin \mu \frac{\partial f_R}{\partial b} + \tan b \cos \mu \frac{\partial f_R}{\partial \mu} + \frac{T}{B_R} \cos b \sin \mu = 0.
\]

This equation can be solved analytically:

\[
f_R(b, \mu) = f_0 \left(1 + \frac{T}{f_0 B_R} \sin b\right) + \tilde{f}(\cos b \cos \mu),
\]

with \( f_0 \) a constant and \( \tilde{f} \) an arbitrary function of \( \cos b \cos \mu \). We see that the first term is just a dipole orthogonal to the plane defined by \( \vec{B}_R \) and \( T \), whereas the second term may include a dipole along \( \vec{B}_R \):

\[
f_R(b, \mu) = f_0 (1 + t \sin b + s \cos b \cos \mu),
\]

with \( t = T/(f_0 B_R) \) and \( s \) a constant depending on boundary conditions. The CR flux that corresponds to this distribution function (see Equation (5)) would be

\[
F_R(\vec{u}) = F_0 (1 + (d_z + d_\tau) \cdot \vec{u}),
\]

where \( F_0 = f_0 (E/c)^2 \), \( d_z = -t \vec{u}_R \times \vec{u}_\tau \) and \( d_\tau = -s \vec{u}_R \). Equation (28) expresses a key result: the global CR flow \( d_R \) does not necessarily flow along the average magnetic field \( \vec{B}_R \). There may appear a second dipole anisotropy orthogonal to \( \vec{B}_R \) that, added to the first dipole, could favor any direction: \( \vec{d}_R = \vec{d}_z + \vec{d}_\tau \). Moreover, the turbulent correlation \( T \) defining this second dipole may evolve with the energy and vary its...
direction, which would translate into a change in the global CR flow and then in the boundary conditions that determine the dipole anisotropy along $B_{\text{IS}}$ described above.

We would like to make some final observations concerning the evolution of the anisotropy with the energy. For a standard Kolmogorov spectrum of magnetic turbulences $\lambda_1$ grows with the energy like $\approx E^{0.6}$ (Swordy 2001), whereas $\lambda_\perp \approx r_L$ increases linearly with the CR energy. When the parallel and the transverse mean free paths become similar, the propagation becomes isotropic and we should see the global CR flow (see Figure 2). This flow, in turn, should reflect the velocity of our local IS plasma and the position and the intensity of the average CR source. Moreover, the isotropic propagation would also be a sign that $r_L$ has reached a size similar to the region of coherence of $B_{\text{IS}}$, since the fluctuations $\delta B$ of wavenumber $k \approx 1/r_L$ should be $\delta B \approx B_{\text{IS}}$.

3. SMALL- AND MEDIUM-SCALE ANISOTROPIES

A small-scale anisotropy in the CR flux must be generated closer to the Earth (Salvati 2010; Giacinti & Sigl 2012), at distances where the diffusive regime has not been fully established yet. It is then necessary to study the image of a point-like CR source after crossing a constant magnetic field, without the magnetic turbulences that cause the diffusion.

A particle of charge $Q$ and energy $E \gg mc^2$ in a constant field $B_{\text{IS}} \parallel B_{\text{IS}} k$ will describe a helix of angular frequency $\omega = B_{\text{IS}} c Q / E$ and radius $r(\mu) = c \sqrt{1 - \mu^2} / \omega$. Choosing the coordinates such that at $t = 0$ the particle is at $S = (0, 0, 0)$, the trajectory reads

$$x = -r(\mu) \sin \phi_0 + r(\mu) \sin (\phi_0 + \omega t),$$
$$y = r(\mu) \cos \phi_0 - r(\mu) \cos (\phi_0 + \omega t),$$
$$z = c \mu t,$$

where $\mu = v_\parallel / c$ and $\phi_0$ is the initial angle with the $x$-axis:

$$\dot{x} = c \sqrt{1 - \mu^2} \cos (\phi_0 + \omega t),$$
$$\dot{y} = c \sqrt{1 - \mu^2} \sin (\phi_0 + \omega t),$$
$$\dot{z} = c \mu. \quad (30)$$

Let us consider all the trajectories connecting the source $S$ with an observer $R$ located at a transverse distance $d_\perp < c / \omega = r_L$ and a parallel distance $d_\parallel \geq 0$. We can always rotate the axes so that $R$ is at $(0, d_\perp, 0)$ and use the variables $(\mu, \phi_0, t)$ to solve $(x, y, z) = (0, d_\perp, 0)$. It turns out that there are an infinite number of such trajectories, each one characterized by an integer winding number $n \geq n_{\text{min}}$ with

$$n_{\text{min}} = \text{Integer} \left[ \frac{d_\parallel}{\pi \sqrt{4r_L^2 - d_\perp^2}} \right], \quad (31)$$

and a (positive or negative) $\phi_0$ with $|\phi_0| \leq \pi / 2$. To see this, it is instructive to first consider the case with $d_\parallel = 0$ (in Figure 3), i.e., with $S$ and $R$ in a plane orthogonal to $B_{\text{IS}}$. The trajectories in this case have $t = 0$, $\phi_0 = -\phi_0$ and reach $R$ after an arbitrary number $n$ of turns around the left or the right circles in Figure 3. Notice that higher values of $n$ correspond to longer trajectories, which will provide fainter images of $S$ (the flux scales like $1/L^2$). Adding a distance $d_\parallel$ along the $B_{\text{IS}}$ direction, the trajectories will require a nonzero value of $\mu$ to reach $R$, with $L = d_\parallel / \mu$ their total length. Trajectories with larger values of $\mu$ will be brighter, although this parameter is bounded by the condition $r_L \sqrt{1 - \mu^2} \geq d_\parallel / 2$.

In Figure 4 we plot several trajectories connecting $S$ with $R$ for a large ($d_\parallel = 35r_L$) longitudinal distance. In the limit of very large $d_\parallel$ the trajectories arrive at $R$ defining a semi-conus of directions of angle $\theta = \arccos (d_\perp / (2r_L))$, with $-\pi / 2 < \phi < \pi / 2$, and the limiting directions ($\phi = \pm \pi / 2$) defining the plane orthogonal to $B_{\text{IS}}$. It is easy to see that the trajectories with direction $\phi = 0$ and maximum $\mu$ are shorter but less dense than the ones in the extremes. As a consequence, the brightness (number of trajectories per unit length times their flux) along the semicircle scales like

$$B = B_{\text{IS}} \cos (\phi + \pi / 2). \quad (32)$$

Notice also that each trajectory reaching $R$ corresponds to a CR that left the source $S$ at a different time, so the image at $R$ would be the whole semicircle only for a constant and isotropic source.

Although from the previous analysis it is apparent that a nearby source could introduce small- and medium-scale anisotropies in the CR flux, we do not expect any sources at distances below 1 pc, which would probably introduce too large anisotropies. We find, however, another plausible mechanism for the generation of this type of anisotropy.

In Battaner et al. (2011) we have described the possible effects of a cosmic magnetic lens: a predominantly toroidal field configuration that may appear with a variety of sizes and magnetic strength. As deduced from Liouville's theorem, an isotropic and homogeneous flux will never become anisotropic due to the action of a magnetic field. However, the large-scale dipole anisotropy discussed in the previous section could cross a nearby field configuration acting as a magnetic lens and imply point-like anisotropies of the same order. The lens would then become equivalent to a faint source of CRs but be otherwise invisible, since it does not produce or deflect the light.

4. COMPARISON WITH THE DATA

SuperKamiokande, TIBET, ARGO-YBF, ANTARES, MILAGRO, and, more recently, HAWC have been able to distinguish from the northern sky an $O(0.1\%)$ large-scale anisotropy in the flux of $1\text{–}10\text{ TeV}$ CRs. IceTop and IceCube have observed

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\textsuperscript{2} This theorem, first applied to CRs moving inside a magnetic field in (Lemaitre & Vallarta 1933), implies that an observer following a trajectory will always observe the same differential flux (or intensity, particles per unit area and solid angle) along the direction defined by that trajectory.
with also very high statistics up to the PeV scale from the South Pole. In Table 1, we give an estimate of the results obtained in these experiments. It is remarkable that all the observations seem consistent with each other, although the higher energies seen at IceTop have not been accessible to the previous experiments or to HAWC yet. One should notice that each experiment can access all the right ascensions (e.g., $-90^\circ < \delta < -25^\circ$ in IceCube). It becomes then difficult to estimate whether the excess and the deficit in the flux are opposite to each other ($\alpha \rightarrow \alpha \pm 180^\circ$, $\delta \rightarrow -\delta$) and define a dipole. Actually, in most experiments the region of maximum excess or maximum deficit is found at the limiting declinations that are accessible, suggesting that the real maximum is out of reach. If that is the case, the nonaccessible pole will introduce a relatively less intense and broader anisotropy than the pole that can be seen by the experiment.

The data can be summarized as follows. At 1–20 TeV it reveals a dipole anisotropy that goes along $B_{IS}$. Taking all the data from the northern observatories and the low-energy IceCube results (based on the observation of atmospheric muons), we estimate

$$\ell_B = 180^\circ; \quad b_B = -60^\circ,$$

which is consistent with the values in Equations (4–5). In Figure 5 we plot in equatorial coordinates two cones of angle $30^\circ$ with the axis along and opposite to the direction of this $B_{IS}$.

At higher energies the observations from the South Pole indicate that the anisotropy weakens, becoming of order $10^{-4}$. This result is supported by TIBET (see Table 1) and, especially, by EAS-TOP (Aglietta et al. 2009), which at $E \approx 100$ TeV is able to see the movement of the Earth around the Sun (an anisotropy of amplitude $2 \times 10^{-3}$). At even higher energies (around 400 TeV) both EAS-TOP and IceCube detect an increase in the amplitude of the anisotropy and also a large change of phase, suggesting a dipole almost opposite to the initial one. Finally, at 2 PeV (Aartsen et al. 2013) the direction of the excess may have changed slightly toward the galactic center.

Our results in Section 2 provide a framework with which to interpret these observations. Above 1 TeV the effect of the heliosphere on the CR trajectories is subleading, and the dominant magnetic field is the $B_{IS}$ in Equation (33). The modulation above 10 TeV can then be explained if the global CR flow varies its direction with the energy, in particular, if its component along $B_{IS}$ changes sign at $\approx 100$ TeV. At these energies other effects, like the Compton–Getting irregularities of order $10^{-4}$ due to the velocity of the Earth, become relatively important. As the CR energy grows, the possible misalignment of the anisotropy with $B_{IS}$ would indicate that $r_L \approx R_{IS}$, where $R_{IS}$ is the radius of coherence of the local IS magnetic field (see Figure 2). For $B_{IS} \approx 3 \mu G$ (Schwadron et al. 2014) and $E \approx 1$ PeV we obtain $R_{IS} \approx 0.3$ pc. The propagation then becomes isotropic (Casse et al. 2002), and the dipole anisotropy should follow the direction of the global CR flow, which is driven...
by a correlation of turbulent quantities (at this scale, $\delta B = B_{IS}$ and the fluctuation $\delta f$ generated by the movement of our local IS cell relative to our neighbors) and by the average magnetic field $B_{IS}$. The radius $R_{IS} \approx 0.3$ pc of our local IS plasma could also be related to the appearance of the knee in the CR spectrum, as CRs of energy above 1 PeV could not be trapped by $B_{IS}$ in our vicinity.

As for the low-scale anisotropies, we have described in Section 3 how the image of the dipole through a cosmic magnetic lens may introduce irregularities. These could consist of pointlike and/or longitudinal structures similar to the ones discovered by some experiments: the two regions observed by TIBET (Amenomori et al. 2006) and MILAGRO (Abdo et al. 2008) or the four regions (which include the two former regions) found by ARGO (Bartoli 2013). The lens could focus the CR wind (see Figure 1) and define anisotropies of order $5 \times 10^{-4}$, the amplitude that has been observed. Notice also that, since the effect of the magnetic lens on a more energetic CR will be smaller (Battaner et al. 2011), the irregularities will slightly change their position and finally disappear when the energy grows. We think that region 2 in Bartoli (2013)—region $B$ in (Abdo et al. 2008)—could be related to the effect that we described (region 1, the most intense, seems linked to an effect of the heliotail; Lazarian & Desiati 2010).

5. SUMMARY AND DISCUSSION

The appearance of anisotropies in the flux of charged CRs provides information about the distribution of sources and about the magnetic plasma where they have propagated on their way to the Earth. The $O(10^{-3})$ deficit from north galactic regions discovered by TIBET and MILAGRO seems to follow the direction of $B_{IS}$. Using the Boltzmann equation, we have justified this observation and have shown that the CR flow at more global scales may modulate this anisotropy, reducing its intensity and even inverting its direction at higher energies. These features seem consistent with IceCube observations in the Southern Hemisphere. We have argued that a misalignment of the dipole anisotropy with $B_{IS}$ could be used to estimate the region of coherence of the local IS plasma. Although the appearance of anisotropies can also be understood using a diffusion equation, we think that our approach provides an alternative (and simpler) framework.

In particular, the Boltzmann equation averaged over different scales provides a useful picture able to describe the changes in the anisotropy with the energy.

We have also suggested a mechanism that would relate the large- and the small-scale anisotropies: these would appear as the image of the global dipole provided by nearby cosmic magnetic lenses (Battaner et al. 2011), which would focus the CR flow. Notice that the lens acts as a CR source, but that the real source would be the large-scale anisotropy. In particular, if this is $O(0.1\%)$, then the low-scale anisotropy will be of the same order. If the lens is seen from the Earth under a sizable solid angle, the magnetic field $B_{IS}$ can define linear structures like the ones described in (Bartoli 2013).

The simplified scheme proposed here uses a number of approximations: all CRs are protons (heavier nuclei of the same energy would have smaller $r_{L}$), all CRs in the same data set have equal energy, or the effect of the heliosphere (Lazarian & Desiati 2010) is negligible. We think, however, that it provides an acceptable qualitative description of the data. In the near future HAWC observations from the Northern Hemisphere could confirm that the TIBET/MILAGRO dipole is modulated and changes sign at energies above 100 TeV.

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