GALACTIC MAGNETIC FIELDS AND THE LARGE-SCALE ANISOTROPY AT MILAGRO

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ABSTRACT
The air-shower observatory Milagro has detected a large-scale anisotropy of unknown origin in the flux of TeV cosmic rays. We propose that this anisotropy is caused by galactic magnetic fields and, in particular, that it results from the combined effects of the regular and the turbulent (fluctuating) magnetic fields in our vicinity. Instead of a diffusion equation, we integrate Boltzmann’s equation to show that the turbulence may define a preferred direction in the cosmic ray propagation that is orthogonal to the local regular magnetic field. The approximate dipole anisotropy that we obtain explains Milagro’s data well.

Key words: cosmic rays – ISM: magnetic fields – solar neighborhood

1. INTRODUCTION

High-energy cosmic rays are of great interest in astrophysics, as they provide a complementary picture of the sky. When they are neutral particles (photons or neutrinos), they carry direct information from their source (Weekes, 2008; Voelk & Bernloehr 2009; Achatzberg et al. 2006). During the past 30 years, gamma rays, in particular, have revealed a large number of astrophysical sources (quasars, pulsars, blazars) in our Galaxy and beyond. In contrast, when they are charged particles (protons, electrons, and atomic nuclei) cosmic rays lose directionality due to interactions with the μG magnetic fields that they face along their trajectory (Strong et al. 2007). In this case, however, they bring important information about the environment where they have propagated. For example, the simple observation that Boron is abundant in cosmic rays while rare in solar system nuclei is a very solid hint that cosmic rays have crossed around 10 g cm$^{-2}$ of interstellar (baryonic) matter before they reach the Earth.

A very remarkable feature in the proton and nuclei fluxes is its isotropy. It is thought that cosmic rays of energy below 10$^9$ GeV are mainly produced in supernova explosions, which is its isotropy. It is thought that cosmic rays of energy below 10$^9$ GeV are mainly produced in supernova explosions, which is much smaller than the typical region of coherence. Therefore, this proton sees the superposition of both components as a regular magnetic field:

$$\vec{B}_{\text{galactic}} + \vec{B}_{\text{random}} = \vec{B}_{\text{regular}} \equiv \vec{B}.$$ (4)

Note that the determination of the galactic field using WMAP data (Page et al. 2007; Jansson et al. 2009; Ruiz-Granados et al. 2009) gives $\vec{B}_{\text{galactic}}$. In contrast, estimates from Faraday rotations of pulsars would be sensitive to the same regular $\vec{B}$ that affects the cosmic proton. According to Han and collaborators (Han et al. 1999; Han 2009), the local $\vec{B}$ should be nearly contained in the galactic plane and clockwise as seen from the north galactic pole (i.e., following the direction of the disk rotation), although with a small vertical component or $\text{tilt}$ angle.

At these small scales, the 10 TeV proton is $\text{diffused}$ by scattering on random fluctuations in the magnetic field

$$\delta B \ll B.$$ (5)

The interaction is of resonant character, so that the particle is predominantly scattered by those irregularities of the magnetic field of wavenumber $k \approx 1/r_g$. Estimates from the standard theory of plasma turbulence (Casse et al. 2002) that $\delta B$ falls as a power law for larger wavenumbers (Han 2009), so this component is smaller than the regular $B$.

In this Letter, we argue that the detailed observation of the TeV cosmic-ray flux obtained by Milagro (Abdo et al. 2008, 2009) also may provide valuable information about $\vec{B}$ and $\delta B$. In particular, the analysis of over 10$^{11}$ air showers has produced a map of the sky showing a large-scale anisotropy (a north galactic deficit) of order 10$^{-3}$. This map, which is consistent with previous observations (Aglietta et al. 1996; Amenomori et al. 2006), remains basically unexplained. Abdo et al. have discussed several possible origins:

(i) The Compton–Getting (CG) effect (Compton & Getting 1935), a dipole anisotropy that arises due to the motion of the solar system around the galactic center and through the cosmic-ray background. The anisotropy observed in Milagro’s map, however, cannot be fitted by the predicted CG dipole. In addition, the CG anisotropy should be energy independent, which does not agree with the data either.

(ii) The heliosphere magnetic field could produce anisotropies (Nagashima et al. 1998; Schlickeiser et al. 2007) that can
also be ruled out. The Larmor radius \( r_L \) sets the size of the coherence cells, and for 10 TeV protons it is around \( 2 \times 10^{-3} \) pc, significantly larger than the 5 \( \times 10^{-4} \) pc (100 AU) of the heliosphere. Moreover, as pointed out in Abdo et al. (2009), the anisotropies persist at higher energies (i.e., for larger distance scales), supporting the hypothesis that if magnetic fields are involved they are extra-heliospheric.

Here we explore the effect of the local (regular and fluctuating) magnetic fields on the propagation of TeV cosmic rays reaching the Earth. Most analyses model cosmic-ray propagation with a diffusion equation (Ptuskin et al. 2006; Strong et al. 2007; Schlickeiser et al. 2007), assuming a certain spatial distribution of sources and a diffusion tensor often simplified to an isotropic scalar coefficient. This provides the flux over an extended region around the solar neighborhood. Here we intend a different approach. The diffusion equation derives from Boltzmann’s equation, which contains \textit{more} information. The solution of Boltzmann’s equation in the vicinity of the Earth gives the statistical distribution function \( f(\vec{r}, \vec{p}, t) \) of particles moving in the six-dimensional phase space (Battaner, 1996). In our case this is just

\[
\vec{F} \cdot \nabla f(\vec{u}) = e(\vec{u} \times \vec{B}) \cdot \nabla f(\vec{u}) = 0.
\]

Now, we separate the regular and the turbulent components both in the distribution function and in the magnetic field:

\[
f \rightarrow f + \delta f, \quad \vec{B} \rightarrow \vec{B} + \delta \vec{B}. 
\]

The components \( \delta \vec{B} \) and \( \delta f \) vary randomly from one cell to another and have a vanishing average value,

\[
[\delta \vec{B}] = [\delta f] = 0.
\]

However, there may be correlations between both fluctuating quantities. In particular, we will assume a non-zero value of

\[
[\tilde{e}(\vec{u} \times \delta \vec{B}) \cdot \nabla f] = e \tilde{u} \cdot [\delta \vec{B} \times \nabla \delta f] = e \tilde{u} \cdot \tilde{T}.
\]

Boltzmann’s equation for the regular component is then

\[
(\vec{u} \times \vec{B}) \cdot \nabla f + \tilde{u} \cdot \vec{T} = 0.
\]

This equation can also be written as

\[
\tilde{u} \cdot (\vec{B} \times \nabla f) + \tilde{u} \cdot \vec{T} = 0.
\]

As \( \tilde{u} \) is any direction, this implies \( \vec{B} \times \nabla f = \tilde{T} \), i.e., the vector \( \vec{T} \) must be orthogonal to \( \vec{B} \). Taking \( \vec{T} \) in the galactic plane,

\[
\tilde{u} \cdot \vec{T} = T \cos b \sin \mu,
\]

and expressing

\[
\nabla f(\vec{u}) = \frac{\partial \delta f}{\partial b} \tilde{u}_b + \frac{1}{\cos b} \frac{\partial \delta f}{\partial \mu} \tilde{u}_\mu,
\]

with

\[
\tilde{u}_b = - \sin b \cos \mu \tilde{u}_\phi - \sin b \sin \mu \tilde{u}_r + \cos b \tilde{u}_z; \quad \tilde{u}_\mu = - \sin \mu \tilde{u}_\phi + \cos \mu \tilde{u}_r,
\]

Equation (11) becomes

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

This equation can be solved analytically:

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

with \( f_0 \) being a constant that normalizes \( f \) to the number of particles per unit volume and the second term any arbitrary function of the variable \( \cos b \cos \mu \). From the direction \( \tilde{u} \) we observe cosmic rays with \( \tilde{p} = -p \tilde{u} \); it is straightforward to find the relation between the distribution function and the flux.
The dominant magnetic field \( \vec{B} \) in the galactic plane, whereas \( \vec{d} \) and \( \vec{T} \) have latitudes \( b_0 \) and \( 90^\circ - b_0 \), respectively.

\( F(b, \mu) \) of particles observed at Milagro per unit area, time, solid angle, and energy:

\[
F(b, \mu) = \frac{E^2}{c^2} f(-b, \mu + \pi) .
\]

This implies that

\[
F(b, \mu) = F_0 (1 - t \sin b) + \bar{F} (\cos b \cos \mu) ,
\]

where \( t = T/(f_0 B) \) and \( F_0 = (E/c)^2 f_0 \). Finally, we will expand \( \bar{F} \) to second order:

\[
\bar{F} (\cos b \cos \mu) \approx F_1 \cos b \cos \mu + F_2 (\cos b \cos \mu)^2 .
\]

The solution in terms of the galactic longitude is obtained just by expressing \( \mu = l - l_B \).

Several comments are here in order.

(i) If \( F_1 = F_2 = 0 \), then the solution is a dipole anisotropy, with the minimum/maximum in the north/south galactic poles. This dipole is then modulated by the constants \( F_{1,2} \), that introduce an anisotropy proportional to \( \cos b \cos \mu \) (i.e., the additional anisotropy coincides along the directions \( \vec{u} \) with equal projection on \( \vec{B} \)).

(ii) The dipole anisotropy would vanish if there were no turbulence (\( t = 0 \)); \( \vec{B} \) implies an isotropy broken by the turbulence in the orthogonal plane. In contrast, the equation does not say anything about the direction along \( \vec{B} \). For different boundary conditions one can find solutions with a forward–backward asymmetry (implying diffusion along \( \vec{B} \)) or symmetric solutions. In particular, \( F_1 \) creates an asymmetry between the \( (b = 0, \mu = 0) \) and \( (b = 0, \mu = 180^\circ) \) directions, whereas the \( F_2 \) solution is symmetric.

(iii) The dominant magnetic field \( \vec{B} \), the turbulence \( \vec{T} \), and the dipole \( \vec{d} \) are always orthogonal to each other. For \( \vec{B} \approx Bu_\phi \) the symmetry of the galactic disk could favor a radial turbulence, \( \vec{T} \approx T \vec{u}_r \), like the one that we have assumed above (see Figure 1).\(^2\) However, one can change the latitude \( b_0 \) of the dipole while keeping \( \vec{B} \) on the galactic plane just by taking the turbulence \( \vec{T} \) out of the plane. In particular, the dipole will point toward the arbitrary direction \( b_0 \) (see Figure 2) if

\[
\vec{u} \cdot \vec{T} = T (\sin b_0 \cos b \sin \mu - \cos b_0 \sin b) .
\]

\(^2\) Buoyancy will mainly produce ascending turbulent cells; since Coriolis forces are negligible at these small timescales the compression of the (frozen-in) azimuthal field lines may result into a \( \delta \vec{B} \) also azimuthal and a vertical \( \nabla_u \delta f \), which imply a radial \( \vec{T} \).
Therefore, we can check if this dipole observed at Milagro and the local regular magnetic field $\vec{B}$ (also an observational output) are perpendicular. We will consider the values of $\vec{u}_B$ given by Han (Han et al. 1999; Han 2009). It is found that $\vec{B}$ is basically azimuthal clockwise (a pitch angle of either 0° or 180° depending on the definition, which changes for different authors). However, the observations also indicate the presence of a non-null tilt angle of 6° (a vertical component of order 0.3 $\mu$G) taking the magnetic field out of the plane. We obtain an unitary vector

$$\vec{u}_B = 0.99 \vec{u}_\phi + 0.00 \vec{u}_r + 0.10 \vec{u}_z,$$

which implies a remarkable

$$\vec{u}_d \cdot \vec{u}_B = -0.18. \quad (28)$$

We think that the approximate orthogonality of these two observational vectors (we obtain an angle of 100°) provides support to the model presented here.

Note that our framework could also accommodate other anisotropies in the flux, added to the dipole one, as far as they have the same value in all the points with equal projection ($\cos b \cos \mu$) on $\vec{B}$. To explain a point-like anisotropy like the one named as region A in Abdo et al. (2008), the anisotropy itself should be along the direction of the dominant magnetic field $\vec{B}$ (orthogonal to $\vec{d}$). Region A, however, is at ($b_A \approx -30^\circ$, $l_A \approx 215^\circ$), forming an angle of 58° with the dipole.

4. SUMMARY AND DISCUSSION

Although charged cosmic rays do not reveal their source, the study of their flux from different directions is of interest in astrophysics because it brings valuable information about the interstellar medium. In particular, the per mille deficit observed by Milagro could be caused by the local (at distances of order $r_g$) magnetic fields.

Using Boltzmann’s equation we have shown that the interplay between the regular and the turbulent components in these magnetic fields always produces a dipole anisotropy in the cosmic-ray flux. We find that (i) the direction of this anisotropy is orthogonal to the regular $\vec{B}$ and (ii) its intensity is proportional to the fluctuations $\delta B/B$ at the wavenumber $k = 1/r_g$. These two simple results have already non-trivial consequences. In particular, (i) implies that a north–south galactic anisotropy would only be consistent with a dominant $\vec{B}$ laying in the galactic plane, whereas (ii) explains that the anisotropy is larger for more energetic cosmic rays: their gyroradius $r_g$ is larger, the resonant wavenumber $k$ smaller, so the expected value of $\delta B/B$ will be larger.

We have argued that Milagro’s data can be interpreted as a dipole anisotropy pointing to a well-defined direction in the north galactic hemisphere, namely ($b_0 \approx 72^\circ$, $l_0 \approx 293^\circ$). Our model provides a remarkable fit of the data, so we conclude that it explains satisfactorily the large-scale anisotropy found by Milagro. The model implies that the dominant magnetic field near our position must be in the plane orthogonal to the dipole ($\vec{B}$, the turbulence correlation $\vec{T}$ and $\vec{a}$ define a trihedron). This plane forms an angle $\theta = 23^\circ$ with the galactic disk.

The data obtained by Milagro (energy, direction, and nature of over $10^{11}$ primaries) show that the $10^{-3}$ deficit in the cosmic-ray flux from the north galactic hemisphere already seen in previous experiments (Aglietta et al. 1996; Amenomori et al. 2006) is actually very close to a dipole anisotropy. We think that the analysis of the flux after subtracting this dipole anisotropy could reveal further correlations.

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