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High energy cosmic rays and the Galactic magnetic field

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We study the effect of the regular component of the Galactic magnetic field (GMF) on the arrival directions of high energy cosmic rays. Deflections in the GMF cannot be neglected even for $E = 10^{20}$ eV protons, especially for trajectories along the Galactic plane or crossing the Galactic center (GC) region. We discuss how the small-scale clustering observed by the AGASA experiment is modified by the GMF.

1. Introduction

After more than 40 years of research in the field of ultra-high energy cosmic rays (UHECRs), it is still unclear at which energy astronomy with charged particles becomes possible. In order to answer this question one has to address two issues: first, what is the chemical composition of the CR flux, i.e. are the charged primaries protons or nuclei? And second, how strong are the Galactic and extragalactic magnetic fields? Both questions can be addressed by (auto-)correlation studies of UHECRs. As an example, we shall discuss the effect of the Galactic magnetic field on the small-scale clustering observed in the data set of the AGASA experiment [1]. As our working hypothesis we shall assume throughout that deflections in extragalactic magnetic fields are negligible.

2. Galactic magnetic field models

Informations about the GMF have been extracted mainly from Faraday rotation measurements of extragalactic sources or Galactic pulsars. However, it is still not possible to reconstruct the GMF solely from observations, and instead we employ two phenomenological models for the regular component of the GMF. For a discussion of the small-scale, turbulent Galactic magnetic field we refer to Ref. [2], where it was found that deflections due to the turbulent field are subdominant.

In galactic coordinates, the field components in the disk can be parametrized as

$$B_r = B(r,\theta)\sin p\,, \qquad B_\theta = B(r,\theta)\cos p\,, \tag{1}$$

where $R_0 = 8.5$ kpc is the galactocentric distance of the Sun and p the pitch angle. The function $B(r,\theta)$ is traditionally modeled reminiscent of the spiral structure of the matter distribution in the Galaxy as

$$B(r,\theta) = b(r)\cos\left(\theta - \frac{1}{\tan p}\ln(r/\xi_0)\right)\,. \tag{2}$$

In terms of the distance d to the closest sign reversal, ξ_0 can be expressed as $\xi_0 = (R_0 + d)\exp(-\frac{\pi}{2}\tan p)$. The radial profile function $b(r)$ is generally assumed to behave as $b(r) \propto 1/r$ [3, 4], consistent with pulsar measurements. The behavior of the disk field in the inner region of the Galaxy is less known, but clearly the field has to be regularized for $r < r_{\min}$. For $r \geq r_{\max}$, the field is turned off. In the following, we will fix $r_{\max} = 20$ kpc. The vertical profile of the field outside the plane $z = 0$ is modeled by $B(r,\theta,z) = f(z)B(r,\theta)$.

TT model: Tinyakov and Tkachev (TT) examined in Ref. [4] if correlations of UHECR arrival directions with BL Lacs improve after correcting for deflections in the GMF. They assumed $b(r) \propto r^{-1}$ for $r > r_{\min} = 4$ kpc, and $b(r) = \text{const.}$ for $r \leq r_{\rm min}$. The normalization was chosen in order to obtain a local field intensity of 1.4 μG. The pitch angle was chosen as $p = -8°$ and the parameter d fixed to -0.5 kpc. They compared a BSS-A and a BSS-S model and found that the former increased the correlations. This model has an exponential suppression law, $f(z) = \text{sign}(z)\exp(-z/z_0)$, with scale $z_0 = 1.5$ kpc chosen as a typical halo-size.

HMR model: Harari, Mollerach and Roulet (HMR) used in Ref. [6] a BSS-S model with cosh profiles for both the disk and the halo field with scale heights of $z_1 = 0.3$ kpc and $z_2 = 4$ kpc,

$$f(z) = \frac{1}{2\cosh(z/z_1)} + \frac{1}{2\cosh(z/z_2)}\,. \tag{3}$$

The function $b(r)$ was chosen as $b(r) = \frac{3R_0}{r}\tanh^3(r/r_1)\,\mu$G, with $r_1 = 2$ kpc, the pitch angle was fixed to $p = -10°$, and $\xi_0 = 10.55$ kpc. Apart for the vertical profile $f(z)$, the main difference with respect to the TT model is the z-parity of the field and the negligible bulge field.

3. Deflections in the regular field

3.1 Deflection maps

We have followed backwards CR protons with energy $E = 4 \times 10^{19}$ eV recording their deflection angles for the two different GMF models examined. The obtained deflection maps are shown in Galactic coordinates in Fig. 1. Although the structures visible in the maps are very similar, there are important differences between the two models: First, the magnitude of the deflections differs up to a factor of two for higher latitudes. Second, the directions of the deflections differ strongly. On the southern hemisphere in particular, the deflections have nearly opposite directions because of the different z-parity of the two models. The model predictions agree better in the low-latitude regions away from the GC, where the field geometry and intensity is best known.

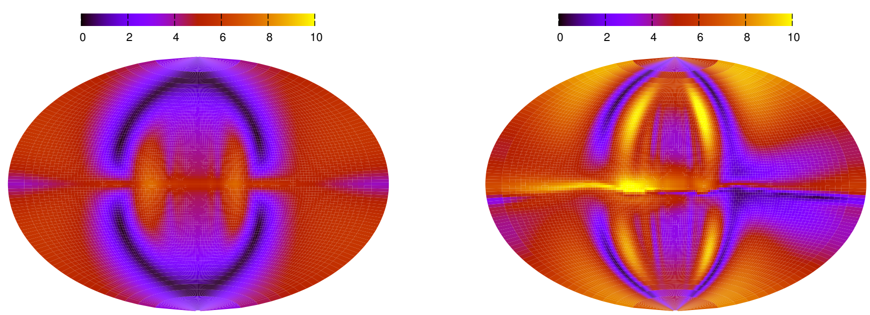

Figure 1. Deflection maps for CR protons with energy $E = 4 \times 10^{19}$ eV for the TT (left) and HMR (right) GMF model.

If one excludes the central regions of the Galaxy, the average deflections are $\approx 1°$–$2°$ for protons with $E = 10^{20}$ eV, and the differences among the different models are of the order of 50%. Thus only for the highest energy events and proton primaries the role of the GMF is negligible compared to the angular resolution of modern UHECR experiments. For lower rigidities, correcting for deflections in the GMF and a better knowledge of the GMF become crucial. Note that a reconstruction of the original arrival directions requires a relatively good measurement of the primary energy: an uncertainty of, say, 30% in the energy scale around 5×10^{19} eV leads to errors $\gtrsim 1°$ in the reconstructed position of proton primaries in most of the sky.

3.2 Exposure maps

A generalized version of the Liouville theorem holds for CRs [5] and ensures the constancy of the phase space volume along particle trajectories: When the CR flux is magnified, the angular spread of the velocity vectors increases, thus they are seen as arriving from a larger solid angle. For the flux per unit solid angle, the two effects compensate each other and as a consequence an *isotropic* flux will remain isotropic to an observer behind a magnetized environment, as long as no particles are trapped. However, following the particles that arrive at Earth backwards to their original sources, the effective exposure to the "external sky" is changed by the GMF. This effect is shown in Fig. 2, where the relative change in exposure due to (de-)focusing in the GMF is presented. More precisely, we show the ratio $\omega_B(l,b) = d\Omega_\infty(l',b')/d\Omega_\oplus(l,b)$ of an infinitesimal small cone at Earth $d\Omega_\oplus$ (around the direction l, b) and transported along the trajectory of a charged particle to the border of the Galaxy $d\Omega_\infty$ (around the new position $l'(l,b), b'(l,b)$). If $\omega_B(l,b)$ deviates significantly from one, the corrected exposure has to be used in (auto-)correlation studies. When anisotropies do exist in the primary flux, the spectral power can be redistributed among different scales by magnetic lensing phenomena and, for a relatively small number of UHECR sources, phenomena analogous to gravitational lenses are possible [6].

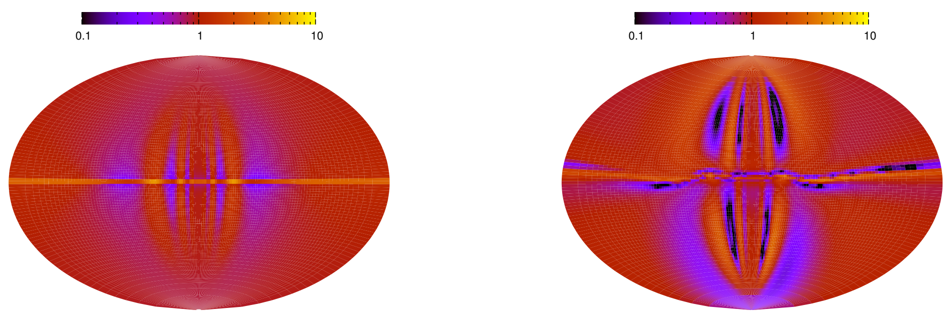

Figure 2. Maps of $\omega_B(l,b)$ for CR protons with energy $E = 4 \times 10^{19}$ eV for the TT (left) and HMR (right) GMF model.

3.3 Analysis of the AGASA data set

The AGASA experiment has published the arrival directions of their data until May 2000 with zenith angle $< 45°$ and energy above 4×10^{19} eV [7]. This data set consists of $N = 57$ CRs and contains a clustered component with four pairs and one triplet within $2.5°$ [1] that has been interpreted as first signature of point sources of UHECRs. Since already for protons both deflections and the (de-)magnification of the exposure are considerable at energies 4×10^{19} eV, we discuss now how the small-scale clustering observed by the AGASA experiment is modified by the GMF.

Neglecting the influence of the GMF (or assuming neutral primaries), one generates a large number of Monte Carlo sets of CRs, each consisting of N CRs distributed according to the geometrical exposure $\omega_{\rm exp}$ of AGASA. The fraction of MC sets that has a value of the first bin w_1 of the autocorrelation function larger or equal to the observed one, w_1^*, is called the chance probability P of the signal. For a nonzero GMF, one uses the back-tracing method: the observed arrival directions on Earth are back-traced following a particle with the opposite charge to the boundary of the GMF. Then the value w_1 of the autocorrelation function is calculated. Since also the exposure is changed by the GMF, the CRs of the Monte Carlo sets have to be generated now

$E_{\rm min}/10^{19}$ eV	N	w_1	$P[\%]$	TT:	w_1	$P[\%]$	$P_0[\%]$	HMR:	w_1	$P[\%]$	$P_0[\%]$
5.0	32	4	0.22		2	8.9	8.5		2	9.5	8.5
4.5	43	6	0.05		4	1.5	1.4		4	1.8	1.4
4.0	57	7	0.18		6	0.8	0.7		5	3.3	2.4

Table 1. Number N of CRs with energy $E \geq E_{\rm min}$ and zenith angle $\theta \leq 45°$; the values of the first bin of the autocorrelation function w_1, and the chance probability $P(w_1 \geq w_1^*)$ from an isotropic test distribution are shown for the two cases with (P) and without (P_0) correction of the exposure, respectively.

using as exposure $\omega_{\rm tot}(E,l,b) = \omega_{\rm exp}(l,b)\omega_B(E,l,b)$. The resulting chance probability is called P in table 1. For illustration, we show also the chance probability P_0 calculated using only the experimental exposure (or $\omega_B = 1$) that overestimates that clusters come indeed from the same source.

Correcting for the GMF reduces for both GMF models the value of w_1. Thus, either some of the pairs are created by the focusing effect of the GMF, or the GMF and especially its halo component is not well enough reproduced by the two models. In the latter case, "true pairs" are destroyed by the the incorrect reconstruction of their trajectories in the GMF. Alternatively, our assumptions of negligible deflections in the extragalactic magnetic field and of proton as primaries could be wrong. Note that the effect of the GMF-induced exposure to the extragalactic sky is not negligible for the HMR model. The fact that P_0 is only somewhat smaller than P indicates that only a small fraction of clusters is caused by magnetic lensing. Finally, we note that the energy threshold for which the chance of clustering is minimal increases for the HMR model, while it decreases for the TT model. The changes, especially for the case of the TT model, are however rather small and a larger data set is needed for any definite conclusion.

4. Conclusions

We have found that deflections in the GMF cannot be neglected even for $E = 10^{20}$ eV protons, especially for trajectories along the Galactic plane or crossing the GC region. The magnitude as well as the direction of the deflections are model-dependent. Therefore, it might be necessary for experiments on the southern hemisphere like AUGER either to exclude some part of their data from (auto-) correlation studies or to correct for the GMF deflections. We have noted that in studies of the compatibility of small-scale clustering with an isotropic CR flux the exposure of CR experiments has to be corrected for magnetic (de-) focusing effects. We have performed an autocorrelation analysis of the AGASA data set including GMF effects.

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