

The Large Scale Structure of the Galactic Magnetic Field and High Energy Cosmic Ray Anisotropy

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Abstract. Measurements of the magnetic field in our Galaxy are complex and usually difficult to interpret. A spiral regular field in the disk is favored by observations, however the number of field reversals is still under debate. Measurements of the parity of the field across the Galactic plane are also very difficult due to the presence of the disk field itself. In this work we demonstrate that cosmic ray protons in the energy range 10^{18} to 10^{19} eV, if accelerated near the center of the Galaxy, are sensitive to the large scale structure of the Galactic Magnetic Field (GMF). In particular if the field is of even parity, and the spiral field is bi-symmetric (BSS), ultra high energy protons will predominantly come from the Southern Galactic hemisphere, and predominantly from the Northern Galactic hemisphere if the field is of even parity and axi-symmetric (ASS). There is no sensitivity to the BSS or ASS configurations if the field is of odd parity.

1. Introduction

The position of the Solar system makes it difficult to measure the Galactic Magnetic Field (GMF) global structure and to distinguish local small-scale features from large-scale ones [1, 2, 3]. Faraday rotation measures (RM) of pulsars in our Galaxy and of polarized extragalactic radio sources are one of the best probes of the large scale structure of the GMF in the Galactic disk and the halo.

Cosmic ray propagation in the Galaxy is strongly affected by the GMF. The gyroradius of a proton of energy $E = 10^{18}$ eV in a $3 \mu\text{G}$ field is of the order of 300 pc, the typical thickness of the Galactic disk. For energies $E < 10^{18}$ eV cosmic rays diffuse in the GMF, they get isotropized, and hence are also fairly insensitive to the large features of the GMF. At energies above 10^{19} eV cosmic rays have long been thought to be of extragalactic origin [4]. Even if their sources were inside the Galaxy, there would exist a clear anisotropy in the arrival direction of cosmic rays in the case of protons that is not supported by data. An extremely interesting energy range is that from 10^{18} to 10^{19} eV where cosmic ray propagation through the GMF is thought to change from diffusive to ballistic, composition is thought to change from heavy to light, and cosmic ray origin is thought to change from Galactic to extragalactic [5].

In this work we show that protons in the energy range from 10^{18} to 10^{19} eV, if accelerated at galactocentric distances typically smaller than the radius of the Solar system orbit around the Galactic center, are sensitive to the large scale structure of the GMF. The center of our Galaxy provides a natural candidate for acceleration of cosmic rays to very high energies. There is some evidence for the presence of a supermassive black hole [6], and also for the existence of what may be the remnant of a powerful supernova [7]. Both sites are candidate sources of ultra high energy protons [8].

2. The Galactic Magnetic Field

We briefly summarize here the current knowledge on the GMF. More details can be found in [2, 3, 9]. Faraday RMs of pulsars inside the Galaxy and from extragalactic sources reveal that the GMF has two components: a regular component with strength \sim few μG , and a turbulent or random component of the same or perhaps even larger strength [10]. There seems to be agreement on the spiral structure of the regular field in the Galactic plane, although not on the exact shape of the spiral field, axi-symmetric (ASS) or bi-symmetric (BSS) [2, 9]. The number of field reversals is still under debate. The parity (even or odd) of the GMF across the Galactic plane suffers from the lack of observational surveys of the direction and strength of the field in the thick disk of height 1.5 kpc above and below the Galactic plane. An ASS model with a single reversal and even parity seems to be preferred by observations [11]. There is also disagreement on the existence of a possible halo field. An A0 dipole field directed towards the North Galactic Pole (NGP) was suggested as a halo field [12], although an azimuthal toroidal field with no component perpendicular to the Galactic plane might be more important [13].

In this work we use a generic conservative model of the regular magnetic field in the disk which assumes a two-arm logarithmic spiral, that can be either ASS or BSS, and even or odd across the Galactic plane (Fig. 1). Our main purpose is to show that cosmic rays are sensitive to the gross features of the GMF. In all models, the local regular GMF in the vicinity of the Solar System is assumed to be $\sim 1.5 \mu\text{G}$ in the direction $l = 80^\circ$ [14]. The field decreases with Galactocentric distance as $1/r_{\parallel}$ and vanishes for $r_{\parallel} > 20$ kpc. In the region around the Galactic center ($r_{\parallel} < 4$ kpc) we assume the field is constant and equal to its value at $r_{\parallel} = 4$ kpc. Following ([15]) the spiral field strengths above and below the Galactic plane are taken to decrease exponentially with two scale heights. We do not model the toroidal or the possible dipole components of the field in the Galactic center. The equations describing the functional form of the field strength for the spiral component have been published elsewhere [15, 16].

We also assume a significant turbulent component of the GMF, B_{ran} . Its strength is comparable or possibly larger than the regular field ([10]). To simulate it we add to the spiral component a random field with a strength of 50% of the local regular field strength with coherence length of 100 pc.

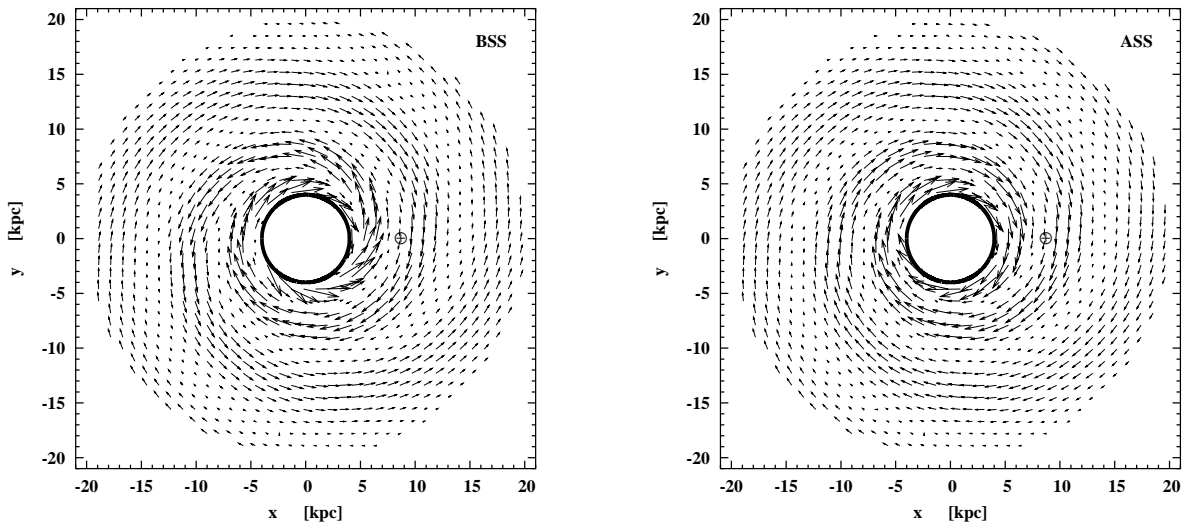


Figure 1. Spiral component of the regular GMF in the Galactic plane in two generic models. The vectors indicate the field direction and their length is proportional to its magnitude. Left panel: Bi-symmetric spiral field. Right panel: Axi-symmetric spiral field without reversals. The position of the Solar system is indicated with an open circle with a cross inside. The solid thick circle is the ring in the Galactic plane of radius $r = 4$ kpc around the Galactic center where the sources are assumed to be located. The magnetic field lines inside this circle are not plotted for clarity purposes.

3. Calculation technique

We sample protons with energies greater than $E = 10^{18}$ eV from a $dN/dE \propto E^{-2.7}$ energy spectrum. We inject 100 protons per source isotropically from sources assumed to be distributed homogeneously in a ring of radius $r_{\parallel} = 4$ kpc around the Galactic center in the Galactic plane. The GMF near the Galactic center is less certain, and we avoid this region by placing the sources in the ring where the toroidal or the possible dipole components of the field are expected to be smaller than the spiral component. Anyway our results show little sensitivity to the exact radius of the ring $r \sim 3 \dots 5$ kpc. We forward (not backward) propagate protons from the sources by numerically integrating the equations of motion in the GMF. There is no energy loss on propagation. We stop the propagation and sample a new proton energy when the proton trajectory intersects our detector – a 1 kpc radius sphere around the Solar system position – when it reaches Galactocentric distances $r_{\parallel} > 20$ kpc, or when it travels a total pathlength larger than 4 Mpc. If a proton hits the detector, we keep its arrival direction in Galactic coordinates. A total number of 50,000 protons are collected for each configuration of the GMF we have explored. We have checked that the use of a smaller detector does not change our conclusions.

Table 1. Fraction of protons in different energy bins that arrive from the Southern Galactic hemisphere (SGH) at our spherical detector around the Solar system after propagating through the BSS even parity GMF model. The fraction of events when switching on different components of the GMF is shown. Second column: Spiral field only. Third column: Spiral and random field. Fourth column: Spiral and random field four times the standard random field used in the second column. The numbers in parenthesis are the one sigma Poisson limits on the fraction of events (see text).

$\log_{10}(E/\text{eV})$	Even parity		
	BSS only	BSS + B_{ran}	BSS + 4 B_{ran}
18.0 - 18.1	99.0 (100.0, 95.4)	95.3 (95.5, 95.1)	78.4 (78.5, 78.2)
18.2 - 18.3	100.0 (100.0, 99.8)	96.3 (96.7, 95.9)	85.8 (86.1, 85.4)
18.4 - 18.5	100.0 (100.0, 99.5)	98.2 (100.0, 96.2)	92.1 (93.0, 91.3)
18.6 - 18.7	100.0 (100.0, 94.8)	95.6 (100.0, 89.9)	92.6 (94.4, 90.9)
18.8 - 18.9	100.0 (100.0, 92.8)	100.0 (100.0, 93.7)	93.0 (96.0, 90.4)

Table 2. Same as in the first three columns in table 1 for the ASS even parity GMF model (left half of the table) and for the ASS odd parity GMF model (right half of the table).

$\log_{10}(E/\text{eV})$	Even parity		Odd parity	
	ASS only	ASS + B_{ran}	ASS only	ASS + B_{ran}
18.0 - 18.1	57.5 (58.7, 56.4)	87.3 (87.4, 87.0)	50.6 (50.8, 50.5)	50.4 (50.6, 50.2)
18.2 - 18.3	97.8 (98.0, 97.5)	73.3 (73.8, 72.9)	45.8 (46.1, 45.5)	50.0 (50.3, 49.7)
18.4 - 18.5	87.5 (88.0, 87.0)	31.8 (32.5, 31.1)	51.8 (52.2, 51.3)	53.2 (53.7, 52.7)
18.6 - 18.7	3.2 (4.0, 2.6)	2.5 (3.4, 1.9)	49.5 (50.3, 48.7)	48.9 (49.8, 48.1)
18.8 - 18.9	0.0 (2.8, 0.0)	0.0 (2.5, 0.0)	51.1 (52.8, 49.6)	50.8 (52.6, 49.2)

4. Results

Tables 1 and 2, summarize the main results of our work. In all of them we give the fraction of cosmic rays in different energy bins coming from the Southern Galactic hemisphere (SGH) The probability that the fraction of events is not between the numbers in parenthesis is ~ 0.37 . Inspection of the tables leads to several conclusions:

- (i) If the GMF is of even parity (Table 1 and left half of Table 2), there is a very strong North-South (NS) anisotropy in the arrival direction of protons. In particular, for

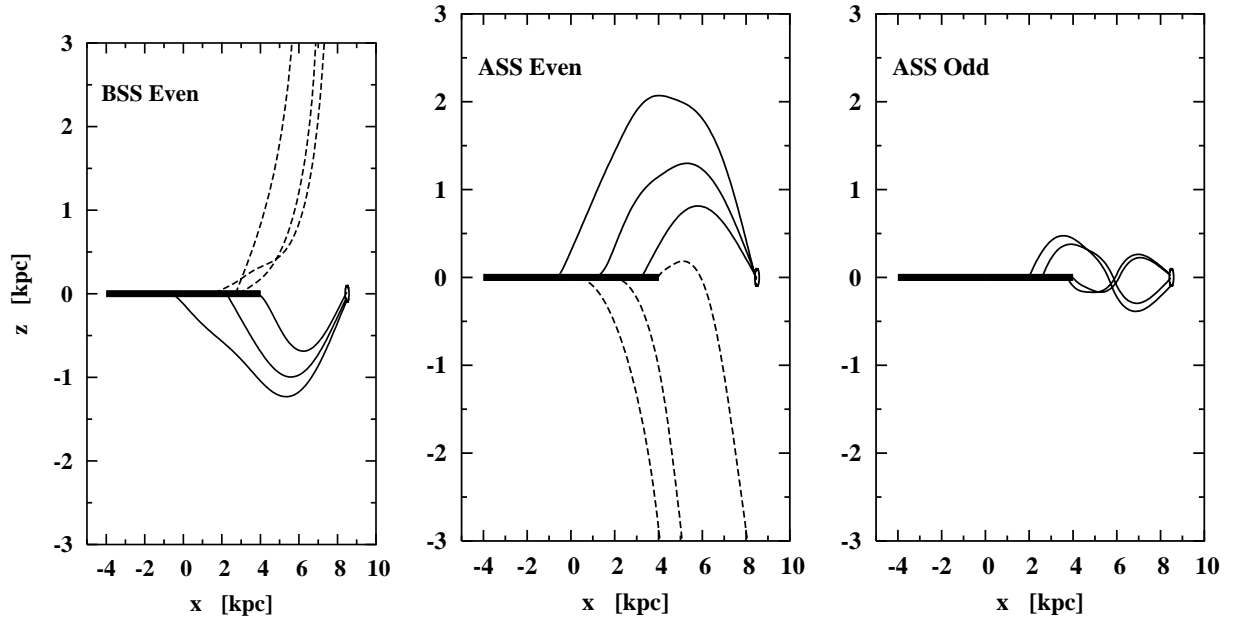


Figure 2. Examples of detected (solid lines) and non detected (dashed lines) proton trajectories projected onto a plane perpendicular to the Galactic disk that contains the Solar system (small open circle at $x = 8.5$ kpc) and the Galactic center (at $x=0$, $z=0$). Proton energy is $E = 10^{19}$ eV for all tracks. The thick solid line parallel to the x -axis is the ring in the Galactic plane of radius $r = 4$ kpc around the Galactic center where the sources are assumed to be located. The random component of the field has been switched off to make this plot, and we have used a 100 pc radius detector.

energies above $\sim 3 \times 10^{18}$ eV, more than 90% of the arriving protons come from the SGH in the BSS model, and more than $\sim 75\%$ from the Northern Galactic hemisphere (NGH) in the ASS model. This is a clear tendency that does not depend very much on the strength of the random component of the field as can be seen in the last column of Table 1 where we give the fraction of events coming from the SGH for the BSS even parity model, but using a random field four times the standard random field. This result is very stable, and mostly dependent on the model of the regular field. The insufficient representation of the turbulence of the random field thus does not affect the conclusions of this study. The NS anisotropy seen in Tables 1, and 2 is significantly reduced at energies below $\sim 3 \times 10^{18}$ eV, especially in the ASS model. Clearly in the lower energy bins, proton propagation is more affected by the random component of the GMF.

- (ii) If the field is of odd parity (right half of Table 2) there is no sensitivity to the ASS or BSS character of the spiral field as modeled in our work. About half of the protons in all energy bins come from the SGH in both the ASS (bottom half of Table 2) and BSS (values not given) odd parity configurations.

In order to understand how this strong anisotropy is actually realized, we show in Fig.2 the projection onto a plane perpendicular to the Galactic disk containing the Solar system position and the Galactic center, of a sample of detected and non detected

proton trajectories at 10^{19} eV in the BSS and ASS (spiral field only) even and odd parity configurations. In the BSS even parity configuration, the GMF is directed towards $l \sim 270^\circ$ in the first magnetic arm that protons encounter on their paths to the Solar system (Fig.1), so that their tracks tend to be concave. If a proton is injected from a source towards north, the GMF bends the trajectory so that it escapes from the Galaxy (dashed lines in the left panel of Fig. 2). If the proton is injected towards south, the GMF will bend its track towards north so that it may hit the Solar system and will appear as coming from the SGH (solid lines in the left panel of Fig. 2). The opposite behavior is true for the ASS even parity configuration, i.e. the tracks tend to be convex (middle panel in Fig.2) because the GMF points towards $l \sim 90^\circ$ in the first magnetic arm between the sources and the Solar system (Fig.1). As a consequence only protons injected towards north and bending back towards south can be detected, and will appear to come from the Northern Galactic hemisphere. If the field changes sign across the Galactic plane (odd parity), both concave and convex trajectories are possible and there is no preferred arrival direction. In fact typical proton trajectories arriving at the detector cross the Galactic plane (right panel in Fig.2).

We have shown that the arrival distribution of high energy protons (if accelerated near the center of the Galaxy) might provide useful information which might help confirming or ruling out models of the GMF.

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