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

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Abstract. The magnetic field in our Galaxy is not well known and is difficult to measure. A spiral regular field in the disk between the Galactic arms is favored by observations, however it is still controversial if the field reverses from arm to arm. The parity of the field across the Galactic plane is also not well established. In this letter we demonstrate that cosmic ray protons in the energy range $10^{18}$ to $10^{19}$ eV, if accelerated near the center of the Galaxy, can probe the large scale structure of the Galactic Magnetic Field. In particular if the field is of even parity, and the spiral field reverses direction from arm to arm, i.e. if it 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.

Key words. cosmic rays – magnetic fields

1. Introduction

The Galactic Magnetic Field (GMF) is not well known and is hard to study (Han 2002, Vallée 2004, Wielebinski 2005). The position of the Solar system makes it difficult to measure its global structure and to distinguish local small-scale features from large-scale ones. 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. From this measurements it is derived that the GMF has two components: a regular component with strength $\sim$ few $\mu$G, and a turbulent or random component of the same or perhaps even larger strength (Beck 2001). There seems to be agreement on the spiral structure of the regular field in the Galactic plane between the Galactic arms, although not on the exact shape of the spiral field, axi-symmetric (ASS) or bi-symmetric (BSS) (Han 2003, Vallée 2004). There is some controversy on the number of field reversals from arm to arm. The controversy extends to the parity (even or odd) of the GMF across the Galactic plane. 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 (Han et al. 1997).

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 $\mu$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 do not reveal the sources where they were accelerated. Such cosmic rays are also fairly insensitive to the large features of the poorly-known GMF. At energies above $10^{19}$ eV cosmic rays have long been thought to be of extragalactic origin because there are no astrophysical objects with high magnetic fields on the large scale needed for their acceleration (Cocconi 1956). 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. Heavier nuclei such as iron would not be ruled out as having a Galactic origin, because with their lower rigidity they would become isotropized in the GMF even in this energy range. However, their presence in the cosmic ray spectrum above $10^{19}$ eV is less favored by composition measurements (Abbasi 2005). An extremely interesting energy range is that from $10^{18}$ to $10^{19}$ eV. In this energy bin cosmic ray propagation through the GMF is thought to change from diffusive to ballistic, cosmic ray composition is thought to change from heavy to light, and cosmic ray origin is thought to change from Galactic to extragalactic (Nagano & Watson 2000).

The center of our Galaxy, where there is some evidence for the existence of a very massive black hole, provides a natural candidate for acceleration of cosmic rays to very high energies. The high energy astrophysical activity at the Galactic center is
supported by the recent observation by the HESS telescope of a TeV gamma-ray source near the location of Saggittarius A* (Aharonian 2004).

In this work we demonstrate 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. In particular, if the GMF is of even parity, i.e. does not change sign across the Galactic plane, their distribution in arrival direction reveals the axi-symmetric (ASS) or bi-symmetric (BSS) configuration of the spiral field. In the first case we will show that protons are observed to arrive predominantly from the Northern Galactic hemisphere, while in the second they are seen to come predominantly from the Southern Galactic hemisphere. However, as we demonstrate below, there is no sensitivity to the GMF configuration if the field changes sign across the Galactic plane, i.e. if it is of odd parity.

This letter is structured as follows: In Section 2 we briefly review the current knowledge on the GMF, and describe the GMF configurations used in this work. In Section 3 we briefly describe how we performed our calculations. In section 4 we demonstrate the sensitivity of cosmic ray propagation to the large scale features of the GMF.

2. The Galactic Magnetic Field

We briefly summarize here the current knowledge on the GMF. More details can be found in Han (2003) Vallée (2004), Wielebinski (2005). At low Galactic latitudes Faraday RMs of pulsars inside the Galaxy reveal that the disk field direction is coherent over a linear scale of at least a few kpc between the Galactic arms. It is not yet clear from an experimental point of view if the field reverses direction from arm to arm (Han 2003) Vallée (2004). In particular, moving towards the Galactic Center (GC) the field direction ~ clockwise-going or anticlockwise-going as seen from the North Galactic Pole ~ between the Perseus and Perseus + I arm at galactocentric distance $r_{||} \sim 12$ kpc is still controversial. There seems to be agreement on the existence of a clockwise-going field between the Perseus and Carina-Sagittarius arm at $r_{||} \sim 8$ kpc, close to the position of the Solar System, and with a strength of $B \approx 2 \cdots 4 \mu$G. The field reverses direction in the next arm towards the Galactic Center (GC) between the Carina-Sagittarius and the Crux-Scutum arms at $r_{||} \sim 6.5$ kpc. Moving closer to the GC, the field is clockwise-going between the Crux-Scutum and Norma arms at $r_{||} \sim 5$ kpc. Finally near the Norma arm at $r_{||} \sim 4$ kpc measurements are again contradictory.

All this evidence gives support for a two-arm logarithmic spiral regular field in the disk. It is not well established whether the disk field is better described by a bi-symmetric spiral (BSS) configuration which allows for multiple field reversals, or an axi-symmetric spiral (ASS) configuration, with the BSS structure slightly favored. These two field configurations are plotted in Fig. 1.

Also it has recently been confirmed that the GC contains a highly regular polar field consistent with the presence of a dipole field in the Galaxy and compatible with being generated by an A0 dynamo (Han 2003). The presence of the dipole field could explain the vertical component of the GMF of strength $B_z \approx 0.3 \pm 0.1 \mu$G observed in the vicinity of the Sun.

At high Galactic latitudes the antisymmetric distribution of Faraday RMs is indicative of the odd parity of the field although an even parity is not excluded. At large distances from the disk $r > 1$ kpc or so, the measurements are again very difficult because of contamination by the GMF in the disk.

Given this information, in this paper we do not make strong assumptions about the large scale structure of the spiral GMF and assume all possible combinations, namely ASS without field reversals or BSS, and even or odd parity. The local regular magnetic field in the vicinity of the Solar System is assumed to be $\sim 1.5 \mu$G in the direction $l = 90^\circ + p$ where the pitch angle is $p = -10^\circ$ (Han & Qiao 1994). Some measurements discuss larger total field strengths of up to $6 \mu$G (Beck 2001), therefore our assumptions should be considered as rather conservative. The field decreases with Galactocentric distance as $1/r_{||}$ and it is zero for $r_{||} > 20$ kpc. In the region around the Galactic center ($r_{||} < 4$ kpc) the field is highly uncertain, and we assume it is constant and equal to its value at $r_{||} = 4$ kpc. Following Stan ev 1996 the spiral field strengths above and below the Galactic plane are taken to decrease exponentially with two scale heights. In this work we also assume a halo field corresponding to an A0 dipole as suggested by Han (2002). The dipole field is toroidal and its strength decreases with Galactocentric distance as $1/r^3$. The dipole field is very strong in the central region of the Galaxy, but is only $0.3 \mu$G in the vicinity of the Solar system, directed towards the North Galactic Pole. The equations describing the functional form of the field strength for both the spiral and the dipole fields have been published elsewhere (Stan ev 1996) Alvarez-Muniz et al 2002, Prouza & Smida 2003).

We also assume a significant turbulent component of the GMF, $B_{ran}$. Its strength is comparable or possibly larger than the regular field (Beck 2001). To simulate it we add to the spiral and dipole components a random field with a strength of 50% of the local regular field strength with coherence length of 100 pc. We have also performed several runs with a turbulent field twice the local regular field (i.e. four times the standard random field). The possible geometrical offset of the random and regular fields and the possible time dependence of $B_{ran}$ are neglected.

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 distributed homogeneously in a ring of radius $r_{||} = 4$ kpc around the Galactic center in the Galactic plane. We forward (not backward) propagate them from the sources in different models of the GMF by numerically integrating the equations of motion in a magnetic field. 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 $r_{||} > 20$ kpc, or when it travels a total pathlength larger than 4 Mpc. The total length of trajectories reaching Earth is al-
ways much smaller than this limit. If a proton hits the detector, we keep the proton arrival direction in Galactic coordinates, as well as the position of the source from which it was injected. Our results can be easily re-scaled in rigidity for heavier nuclei. We will show in the next section that our conclusions do not change qualitatively if we reduce the radius of the detector around the Solar System, although the detection efficiency -- the ratio of detected to injected protons -- decreases as the area of the spherical detector. For this reason we prefer to use a relatively large detector.

Given the still controversial experimental measurements of the GMF, we study the sensitivity of cosmic ray propagation to an ASS and a BSS spiral field, that can be either of even or odd parity across the Galactic plane. In order to better understand the effect of each of the GMF components -- spiral, random and dipole -- we simulate the propagation of cosmic rays artificially switching on each component, starting with the spiral field, then adding the random component and finally switching all of them on. A total number of 50,000 protons are collected for each configuration of the GMF we have explored.

Numerical Monte Carlo procedures such as the one described above do not usually represent well the power spectrum of the random magnetic field and thus can not be used to predict the energy dependence of the diffusion coefficient. In this study we are concentrating on the propagation of protons in the transition regime between diffusive and ballistic propagation, where the random field properties are less important.

4. Results

Tables 1, 2, and 3 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), i.e. that arrive at the spherical detector from Galactic latitude $b < 0$. The numbers in parenthesis are the one sigma Poisson limits on the fraction of events, i.e. the probability that the fraction of events is outside the corresponding interval is $1/e \sim 0.37$. Typically the uncertainty increases with energy as less events are sampled at high energy due to the steep injection spectrum.

Inspection of the tables leads to several important conclusions:

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Fig. 1. Spiral component of the regular GMF in the Galactic plane. 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 located. The magnetic field lines inside this circle are not plotted for clarity purposes.
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. We inject 100 protons per source with the sources homogeneously distributed in the Galactic plane in a ring of radius $r_l = 4$ kpc around the Galactic center. 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 and dipole field. The numbers in parenthesis are the one sigma Poisson limits on the fraction of events (see text).

| $\log_{10}(E/eV)$ bin | BSS only | BSS + $B_{ran}$ | BSS + $A_0 + B_{ran}$ |
|-------------------------|----------|-----------------|------------------------|
| 18.0 - 18.1             | 99.0 (100.0, 95.4) | 95.3 (95.5, 95.1) | 70.0 (70.2, 69.8) |
| 18.1 - 18.2             | 99.1 (100.0, 95.5) | 96.3 (96.6, 96.0) | 84.7 (85.0, 84.4) |
| 18.2 - 18.3             | 100.0 (100.0, 99.8) | 96.3 (96.7, 95.9) | 94.9 (95.4, 94.5) |
| 18.3 - 18.4             | 100.0 (100.0, 99.7) | 97.6 (98.6, 96.6) | 98.6 (99.2, 98.0) |
| 18.4 - 18.5             | 100.0 (100.0, 99.5) | 98.2 (100.0, 96.2) | 99.5 (100.0, 98.9) |
| 18.5 - 18.6             | 100.0 (100.0, 96.5) | 96.7 (100.0, 92.9) | 99.9 (100.0, 99.1) |
| 18.6 - 18.7             | 100.0 (100.0, 94.8) | 95.6 (100.0, 89.9) | 100.0 (100.0, 98.8) |
| 18.7 - 18.8             | 100.0 (100.0, 94.4) | 100.0 (100.0, 94.0) | 100.0 (100.0, 98.4) |
| 18.8 - 18.9             | 100.0 (100.0, 92.8) | 100.0 (100.0, 93.7) | 100.0 (100.0, 98.0) |
| 18.9 - 19.0             | 100.0 (100.0, 88.9) | 100.0 (100.0, 89.7) | 98.2 (100.0, 95.9) |

1. If the GMF is of even parity (Table 1 and top half of Table 2), there is a very strong North-South (NS) anisotropy in the arrival direction of protons. In particular, for energies above $\sim 3 \times 10^{18}$ eV, more than 90% of the protons that are detected come from the SGH in the BSS model, and 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 or dipole components of the field as can be seen in Table 3. In this table we give the fraction of events coming from the SGH for the BSS even parity model, but using a random field twice the value of the regular field, i.e. four times the standard random field, and also doubling the strength of the dipole field with respect to its nominal value of 0.3 $\mu$G at the position of the Solar system.

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.

2. If the field is of odd parity (bottom half of Table 2) there is no sensitivity to the ASS or BSS character of the spiral field. 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. The non-observation of a large NS anisotropy in the highest energy bins for protons having Galactic longitude in a fairly wide angular bin around $l = 0^\circ$ could be favoring an odd parity GMF.

3. 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 and dipole components of the GMF. The dipole field seems to be more important in reducing the NS anisotropy at low energies, possibly due to its large strength near the Galactic center (Yoshiguchi et al. 2004).

To understand how this strong anisotropy is actually realized, we show in Fig. 1 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. What is shown is the projection of the proton trajectories through the GMF onto a plane perpendicular to the Galactic disk containing the Solar system position and the Galactic center. In the BSS even parity configuration, the GMF is directed towards $l \sim 270^\circ$ in the first arm that protons encounter on their paths to the Solar system as can be seen in 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 top 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 Southern Galactic hemisphere (solid lines in the top 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) due to the GMF pointing towards Galactic longitude $l \sim 90^\circ$ in the first magnetic arm between the sources and the Solar system (see right panel of 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 due
Table 2. Same as in table [ ] for the ASS even parity GMF model (top half of the table) and for the ASS odd parity GMF model (bottom half of the table).

| log_{10}(E/eV) bin | ASS only | ASS + B_{ran} | ASS + A0 + B_{ran} |
|--------------------|----------|---------------|-------------------|
| 18.0 - 18.1        | 57.5 (58.7, 56.4) | 87.3 (87.4, 87.0) | 72.6 (72.7, 72.4) |
| 18.1 - 18.2        | 36.5 (37.4, 35.6) | 84.2 (84.5, 83.9) | 56.9 (57.2, 56.6) |
| 18.2 - 18.3        | 97.8 (98.0, 97.5) | 73.3 (73.8, 72.9) | 29.1 (29.4, 28.9) |
| 18.3 - 18.4        | 97.8 (98.0, 97.6) | 49.0 (49.5, 48.5) | 15.1 (15.3, 14.8) |
| 18.4 - 18.5        | 87.5 (88.0, 87.0) | 31.8 (32.5, 31.1) | 4.8 (5.1, 4.5) |
| 18.5 - 18.6        | 25.4 (26.4, 24.6) | 26.4 (27.6, 25.4) | 0.9 (1.4, 0.6) |
| 18.6 - 18.7        | 3.2 (4.0, 2.6)    | 2.5 (3.4, 1.9)   | 0.0 (2.3, 0.0) |
| 18.7 - 18.8        | 0.0 (0.8, 0.0)    | 0.0 (0.9, 0.0)   | 0.0 (0.2, 0.0) |
| 18.8 - 18.9        | 0.0 (2.8, 0.0)    | 0.0 (2.5, 0.0)   | 0.0 (0.1, 0.0) |
| 18.9 - 19.0        | 0.0 (3.7, 0.0)    | 0.0 (4.2, 0.0)   | 0.0 (0.2, 0.0) |

| log_{10}(E/eV) bin | ASS only | ASS + B_{ran} | ASS + A0 + B_{ran} |
|--------------------|----------|---------------|-------------------|
| 18.0 - 18.1        | 50.6 (50.8, 50.5) | 50.4 (50.6, 50.2) | 49.9 (50.1, 49.8) |
| 18.1 - 18.2        | 52.1 (52.3, 51.8) | 49.9 (50.1, 49.7) | 49.1 (49.3, 49.0) |
| 18.2 - 18.3        | 45.8 (46.1, 45.5) | 50.0 (50.3, 49.7) | 50.3 (50.6, 50.0) |
| 18.3 - 18.4        | 51.8 (52.2, 51.4) | 49.5 (49.9, 49.1) | 49.8 (50.2, 49.4) |
| 18.4 - 18.5        | 51.8 (52.2, 51.3) | 53.2 (53.7, 52.7) | 48.0 (48.5, 47.5) |
| 18.5 - 18.6        | 47.7 (48.5, 47.0) | 48.6 (49.4, 47.9) | 52.8 (53.5, 52.1) |
| 18.6 - 18.7        | 49.5 (50.3, 48.7) | 48.9 (49.8, 48.1) | 49.9 (51.0, 48.9) |
| 18.7 - 18.8        | 55.3 (56.5, 54.2) | 54.0 (55.3, 52.9) | 45.1 (46.5, 43.9) |
| 18.8 - 18.9        | 51.1 (52.8, 49.6) | 50.8 (52.6, 49.2) | 55.4 (57.1, 53.7) |
| 18.9 - 19.0        | 42.3 (44.6, 40.3) | 43.4 (45.7, 41.4) | 53.2 (56.1, 50.8) |

Table 3. Same as in table [ ] but this time we show the fraction of protons coming from the SGH, with all GMF components switched on (second column), with $B_{ran}$ twice the regular field, i.e. four times the standard random field used in the second column (third column), and with the dipole field twice its nominal value of 0.3 μG at the Solar system position (fourth column).

| log_{10}(E/eV) bin | BSS + A0 + B_{ran} | BSS + A0 + 4 B_{ran} | BSS + 2 A0 + B_{ran} |
|--------------------|--------------------|----------------------|----------------------|
| 18.0 - 18.1        | 70.0 (70.2, 69.8) | 64.9 (65.1, 64.8)   | 43.6 (43.7, 43.4)   |
| 18.1 - 18.2        | 84.7 (85.0, 84.4) | 73.0 (73.3, 72.7)   | 41.0 (41.2, 40.8)   |
| 18.2 - 18.3        | 94.9 (95.4, 94.5) | 80.2 (80.5, 79.7)   | 40.7 (40.9, 40.4)   |
| 18.3 - 18.4        | 98.6 (99.2, 98.0) | 86.4 (87.0, 85.8)   | 44.0 (44.4, 43.7)   |
| 18.4 - 18.5        | 99.5 (100.0, 98.9) | 89.5 (90.2, 88.8)  | 52.1 (52.6, 51.5)  |
| 18.5 - 18.6        | 99.9 (100.0, 99.1) | 93.7 (94.7, 92.7)  | 57.0 (57.7, 56.3)  |
| 18.6 - 18.7        | 100.0 (100.0, 98.8) | 94.1 (95.6, 92.8) | 77.2 (78.7, 75.8) |
| 18.7 - 18.8        | 100.0 (100.0, 98.4) | 93.7 (95.5, 91.9) | 92.9 (94.7, 91.1) |
| 18.8 - 18.9        | 100.0 (100.0, 98.0) | 92.3 (94.8, 90.1) | 89.3 (91.1, 87.6) |
| 18.9 - 19.0        | 98.2 (100.0, 95.9) | 90.2 (93.1, 87.5) | 92.6 (95.1, 90.2) |
Fig. 2. Examples of detected (solid lines) and non detected (dashed lines) proton trajectories after travelling through different GMF configurations. The trajectories are projected onto a plane perpendicular to the Galactic disk that contains the position of Solar system (plotted as a small open circle at \( x = 8.5 \) kpc) and the Galactic center (located 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 located. From top to bottom the GMF configuration corresponds to BSS even parity, ASS even parity and ASS odd parity. The random and dipole fields have been switched off to make this plot, and we have used a 100 pc radius detector.

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The use of a 1 kpc radius spherical detector, being the average distance to the sources in the Galactic ring of the order of \(~ 5 \) kpc, induces an unavoidable smearing in the proton arrival angles of \(~ 10^\circ \). However this does not change our conclusions about the strong NS anisotropy we predict. The reason is that, for instance for the BSS even + \( B_{\text{tan}} \) + dipole configuration, 96% of the events coming from south in the energy bin \( \log_{10}(E/\text{eV}) \in (18.3, 18.4) \) arrive from latitudes \( b < -10^\circ \). As a result the strong NS anisotropy given in Table I is not expected to change significantly due to the \( 10^\circ \) smearing in arrival angle that may possibly shift their arrival directions so that they would actually appear to come from north.