Distribution for the Regular Component of the Galactic Magnetic Field Using 5-Year WMAP Data

B. Ruiz-Granados, J.A. Rubiño-Martín, and E. Battaner

Abstract We have studied the spatial structure of the three dimensional large-scale pattern of the Galactic Magnetic Field using the polarization maps obtained by the WMAP satellite at 22 GHz. By using different models of the large-scale magnetic field of the Milky Way and a certain model for the cosmic rays electron distribution, we predict the expected polarized synchrotron emission. Using a Maximum Likelihood method, we explore the parameter values which best reproduce the WMAP data and obtain the marginal probability distribution for each of them. The model that better reproduces the observed map of polarization is an Axisymmetric model with radial dependence of the strength of the magnetic field.

1 Introduction

Our galaxy has a large-scale magnetic field. The Galactic Magnetic Field (GMF) influences the dynamics of the Galaxy and is a possible relic of primordial fields and its knowledge is essential to interpret the cosmic ray anisotropy. Comprehensive reviews are [1, 2, 3, 4]. WMAP mission provides an important dataset to improve the knowledge of the GMF.

B. Ruiz-Granados and E. Battaner
Dpto. Física Teórica y del Cosmos. Edif. Mecenas, planta baja, Campus Fuentenueva, E-18071. Universidad de Granada, Granada(Spain)
Instituto de Física Teórica y Computacional Carlos I, Granada(Spain)
e-mail: bearg@ugr.es,battaner@ugr.es

J.A. Rubiño-Martín
Instituto de Astrofísica de Canarias (IAC), C/Vía Láctea, s/n, E-38200, La Laguna, Tenerife (Spain)
e-mail: jalberto@iac.es

2 Model of the galactic magnetic field

Different models for the GMF have been proposed after the study of catalogues of RM of EGRS and pulsars. In this work, we try to constrain the regular component of the GMF by fitting the polarized synchrotron emission at 22 GHz observed by WMAP, by exploring different proposed models.

To predict the GMF, two ingredients are needed: the cosmic rays electron distribution and a model of the GMF structure. For the first one, we follow [**?**] and use:

$$N_e = N_0 \exp\left(\frac{-r}{5kpc}\right) sech^2\left(\frac{z}{1kpc}\right) \tag{1}$$

where $N_0 \approx 10^{-13} cm^{-3}$ and (r,z) are the radial and the vertical coordinates. In the following subsections, we summarize the models we consider here, all in cylindrical galacto centric coordinates.

2.1 Logarithmic Spiral Arms Model (LSA)

This is the model used by [6] to fit the direction of the polarization angle (PA, hereinafter) at 22 GHz of the WMAP 3-year data.

$$B_r = B_0 \cos\psi(r) \cos\chi(z) \tag{2}$$

$$B_\phi = B_0 \sin\psi(r) \cos\chi(z) \tag{3}$$

$$B_z = B_0 \sin\chi(z) \tag{4}$$

being B_0 the strength of the magnetic field in the solar neighbourhood, which is assumed to be constant with a value of $\sim 3\mu G$. $\psi(r)$ is given by:

$$\psi(r) = \psi_0 + \psi_1 ln\left(\frac{r}{8kpc}\right) \tag{5}$$

where ψ_0 and ψ_1 are free parameters representing the pitch angle of the magnetic field. Finally, $\chi(z)$ is given by:

$$\chi(z) = \chi_0 tanh\left(\frac{z}{1kpc}\right) \tag{6}$$

where χ_0 give us the tilt angle.

2.2 Bisymmetric Model (BSS)

This model is assumed to be representative of a primordial origin of the magnetic field and it has been used to fit the catalogue of RM of pulsars measured by [7]. In this case, the GMF is described by:

$$B_r = B_0(r)\cos\left(\phi - \beta\ln\left(\frac{r}{R_0}\right)\right)\sin(p)\cos(\chi(z)) \tag{7}$$

$$B_\phi = B_0(r)\cos\left(\phi - \beta\ln\left(\frac{r}{R_0}\right)\right)\cos(p)\cos(\chi(z)) \tag{8}$$

$$B_z = B_0(r)\sin(\chi(z)) \tag{9}$$

where $\beta = 1/\tan(p)$ and p is the pitch angle; R_0 is the distance between the Sun and the Galactic Center ($\approx 8.0 kpc$); $\chi(z)$ is given by(6) and $B_0(r)$ has been assumed here to the radial dependence given by:

$$B_0(r) = \frac{B_1}{1+\frac{r}{r_1}} \tag{10}$$

This expression has the correct asymptotic behaviours, and we recover a finite value when r is close to the galactic center ($r \rightarrow 0$) and it is $\propto 1/r$ when $r \rightarrow \infty$ as suggested in [8]. We must note that in (10), B_1 and r_1 are related through the value of the strength in the solar neighbourhood given in 2.1. So, we obtain:

$$B_0(r) = \frac{3r_1 + 24}{r_1 + r} \tag{11}$$

where r and r_1 are in kpc and $B_0(r)$ in μG

2.3 Axisymmetric Model (ASS)

This model has been proposed by [9] and [10] to constrain the RM of EGRS and pulsars too. It is given by:

$$B_r = B_0(r)\sin(p)\cos(\chi(z)) \tag{12}$$

$$B_\phi = B_0(r)\cos(p)\cos(\chi(z)) \tag{13}$$

$$B_z = B_0(r)\sin(\chi(z)) \tag{14}$$

where $\chi(z)$ is given by (6) and $B_0(r)$ by (10).

2.4 Concentric Circular Ring Model (CCR)

This model was used by [11] and is given by:

$$B_r = 0 \tag{15}$$
$$B_\phi = B_0 \sin((\frac{\pi}{w})(r - R_0 + D_r))\cos(\chi(z)) \tag{16}$$
$$B_z = B_0 \sin(\chi(z)) \tag{17}$$

where w is the distance between reversals, D_r is the distance to the first reversal, B_0 is the strength of the magnetic field without radial dependence and $\chi(z)$ is given by (6).

2.5 Bi-Toroidal Model (BT)

Following the arguments given by [12], this model is given by:

$$B_r = 0 \tag{18}$$
$$B_\phi = B_0(r)\arctan\left(\frac{z}{\sigma_1}\right)\exp\left(\frac{-z^2}{2\sigma_2^2}\right) \tag{19}$$
$$B_z = \text{constant} \tag{20}$$

where K, σ_1 and σ_2 are constants. B_z is assumed to be $0.2\mu G$ and $B_0(r)$ is given by (10).

This model predicts a double-torus structure above and below the galactic plane being the direction of the field opposite in both torii.

3 Method

For every considered model of GMF, we get the direction of the PA by using:

$$\gamma(\hat{n}) = 0.5\arctan\left(\frac{\int N_e(z,\hat{n})2B_x(z,\hat{n})B_y(z,\hat{n})dz}{\int N_e(z,\hat{n})[B_x^2(z,\hat{n}) - B_y^2(z,\hat{n})]dz}\right) \tag{21}$$

where B_x and B_y are the components of the GMF perpendicular to the line of sight. This assumes that the dominant emission process is synchrotron with and spectral index of ~ -2.7.

The simulations of the direction of the PA are compared with the observational direction of polarized emission at 22 GHz which is given by:

$$\gamma_{obs} = \frac{1}{2} \arctan\left(\frac{U(\hat{n})}{Q(\hat{n})}\right) \tag{22}$$

This comparison between both directions, simulated and observed respectively, is done by determining the maximum likelihood ($\mathscr{L}$). For each considered model of GMF, the parameter space is constituted by a set of free parameters. We make an exploration in the parameter space by fitting the observed direction of the PA. To the end, we computing the standard χ^2 statistics:

$$\chi^2 = \sum_i \frac{(\gamma_{obs} - \gamma_{model})_i^2}{\sigma_i^2} \tag{23}$$

which allows us to define the likelihood as: $\log \mathscr{L} \propto -0.5\chi^2$. For a given model, the marginal probability curve of a fixed parameter is obtained by integrating the likelihood over the others parameters, and the estimates of the parameters is obtained. Note that the error bars correspond to a 68% confidence level. In Table 1 we show the obtained results.

Table 1 Confidence limits (68%) on the parameters describing the GMF model derived from a Maximum Likelihood analysis.

Model	Parameters	Best fits	Min(χ^2/dof)
LSA	ψ_0, ψ_1, χ_0	$(64.0\pm^{3.9}_{3.0})^\circ, (0.5\pm^{1.0}_{1.0})^\circ, (17.0\pm^{2.0}_{2.0})^\circ$	11.68
ASS($B_0(r)$)	r_1, p, χ_0	$(0.5\pm^{3.6}_{0.2})\mu G$, $(22.0\pm^{1.2}_{4.0})^\circ$,$(30.0\pm^{1.2}_{3.9})^\circ$	11.45
ASS(B_0=const)	B_0, p, χ_0	$(2.5\pm^{3.5}_{3.3})\mu G$, $(26.0\pm^{2.0}_{2.0})^\circ$,$(18.0\pm^{3.9}_{4.2})^\circ$	11.68
BSS($B_0(r)$)	r_1, p, χ_0	$(60.5\pm^{20.2}_{20.2})\mu G$, $(28.0\pm^{0.4}_{0.2})^\circ$, $(0.0\pm^{13.5}_{13.6})^\circ$	12.47
BSS(B_0=const)	B_0, p, χ_0	$(3.5\pm^{2.5}_{2.5})\mu G, (28.0\pm^{15.3}_{23.5})^\circ, (0.0\pm^{13.5}_{13.6})^\circ$	12.49
CCR	D_r, w, B_0, χ_0	$(4.5\pm^{0.2}_{0.2})kpc, (4.1\pm^{0.4}_{0.4})kpc, (3.5\pm^{2.7}_{2.7})\mu G, (18.0\pm^{0.7}_{0.8})^\circ$	14.28
Bi-Toroidal(BT)	r_1, σ_1,σ_2	$(95.5\pm^{1.5}_{4.5})\mu G, 0.01 \pm^{0.90}_{0.00} kpc, 4.51 \pm^{1.01}_{1.01} kpc)$	248.91

4 Conclusions

The model that better reproduces the direction of the observed PA at 22 GHz is an axisymmetric model with a radial dependence of the strength given by (10). The parameters of the best fit are $r_1 = (0.5\pm^{3.6}_{0.2})\mu G$, $p = (22.0\pm^{1.2}_{4.0})^\circ$ and $\chi_0 = (30.0\pm^{1.2}_{3.9})^\circ$. In Fig. 1 appears the observational map of PA and the simulated map corresponding to the best fit.

In general, the axisymmetric types give better fits as it can be appreciated from the χ^2-test. The obtained value of the pitch angle is not compatible with those values derived from the observations of RM of pulsars and EGRS which are varying in a interval between -5° and -15°. For the LSA model, we find clear discrepancies for the values given by [6]. The others models (BSS and CCR) give good fits too and therefore they can not be rejected.

Concerning to BT model, it can not explain the GMF but it can reproduce the halo component. This component does not produce significant synchrotron emission but could affect the trajectory of cosmic rays and the primordial magnetic fields.

The inclusion of a radial dependence of the strength produce better results and they are in agreement with those found by [13]. Nevertheless we have not found big differences in the maximum likelihood with the other models. PLANCK measurements would be necessary to obtain more firm constraints.

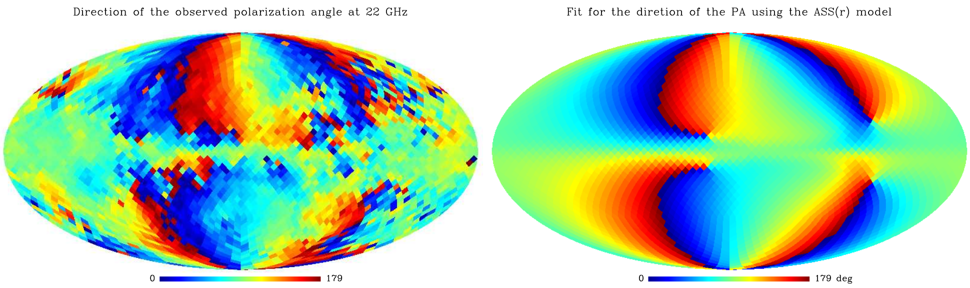

Fig. 1 Observed direction of the PA at 22 GHz and Best fit to the direction of the PA.

References

1. Wolleben, M., Landecker, T. L., Reich, W., & Wielebinski, R. 2006, A&A, 448, 411
2. Reich, W. 2008, Mapping the Galaxy and Nearby Galaxies, Astrophysics and Space Science Proceedings, Volume . ISBN 978-0-387-72767-7. Springer Science+Business Media, LLC, 2008, p. 63, 63
3. Wielebinski, R. 2008, Mapping the Galaxy and Nearby Galaxies, Astrophysics and Space Science Proceedings, Volume . ISBN 978-0-387-72767-7. Springer Science+Business Media, LLC, 2008, p. 237, 237
4. Beck, R., Brandenburg, A., Moss, D., Shukurov, A., & Sokoloff, D. 1996, ARAA, 34, 155
5. Drimmel R. & Spergel D.N. ApJ 556 2001 181
6. Page et *al.* ApJ Supp. 170 2007 335
7. Han J.L. & Qiao G.J. A&A 288 1994 759
8. Battaner, E., & Florido, E. 2007, Astronomische Nachrichten, 328, 92
9. Poezd, A., Shukurov, A., & Sokoloff, D. 1993, MNRAS, 264, 285
10. Vallee, J. P. 1991, ApJ, 366,450
11. Rand R.J. & Kulkarni S.R. ApJ 343 1989 760
12. Battaner E. & Florido E. Fund.Cosmic Phys 21 2000 1
13. Sun, X. H., Reich, W., Waelkens, A., & Enßlin, T. A. 2008, A&A, 477, 573