Large scale magnetic field of the Milky Way from WMAP3 data

R. JANSSON[1], A. H. WAELKENS[2], G. R. FARRAR[1], T. A. ENSSLIN[2]
[1]*Center for Cosmology and Particle Physics, and Department of Physics*
New York University, NY, NY 10003,USA
[2]*Max-Planck-Institute für Astrophysik, Karl Schwarzschild-Str. 1, 85741 Garching, Germany*
rj486@nyu.edu

Abstract: We report on initial results from a project to constrain the large-scale and turbulent magnetic fields of the Milky Way galaxy, which eventually will incorporate all of the relevant observational data. The initial work is based on the WMAP3 polarization maps. Preliminary results on the large scale Galactic magnetic field will be presented.

Introduction

A variety of observational methods have been used to constrain the magnetic field of the Milky Way, e.g., synchrotron emission, Faraday rotation, Zeeman splitting and polarization of starlight. In a project currently underway we are making use of all relevant data available to study the Galactic magnetic field (GMF), at large and small scales. The reason for combining different types of data goes beyond having a larger number of data points when performing parameter estimation. Different types of data constrain different aspects of the magnetic field and depend on different ancillary information. For instance, synchrotron emission probes the integrated magnetic component perpendicular to the line-of-sight and requires knowledge of the relativistic electron density and spectrum; Faraday rotation and starlight polarization probe the parallel component and require knowledge of the electron and dust density distributions respectively; Zeeman splitting allows *in situ* measurements of the magnetic field.

In this paper we present first results, using polarization data from the Wilkinson Microwave Anisotropy Probe (WMAP) 3rd year data release [5].

Galactic magnetic field models

When describing models of the regular part of Galactic magnetic fields it is natural to use cylindrical coordinates (r, θ, z). Typically, the disk field is parametrized by

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

where p is the pitch angle. There has been some confusion in notation in the literature, and we will use the following conventions. A field that obeys $B(r, \theta) = B(r, \theta + \alpha)$ for any α is *axisymmetric*, while if $B(r, \theta) = -B(r, \theta + \pi)$ it is said to be *bisymmetric*. If $B(r, \theta) = B(r, \theta + \pi)$ we propose to call it *disymmetric*. Another distinction that is necessary is the model's symmetry properties under $z \to -z$, i.e., reflection at the disk plane. We denote a field as symmetric with respect to the Galactic plane if $\mathbf{B}(r, \theta, -z) = \mathbf{B}(r, \theta, z)$, and antisymmetric if $\mathbf{B}(r, \theta, -z) = -\mathbf{B}(r, \theta, z)$. This notation agrees with, e.g., [9, 3, 4], but conflicts with [8, 6]. If the disk field is generated by differential rotation from a poloidal field, then it will be antisymmetric under $z \leftrightarrow -z$.

A standard way to parametrize a bisymmetric spiral field [2] is

$$B(r, \theta) = b(r)\cos(\theta - \beta \ln \frac{r}{r_0}), \qquad (2)$$

where θ is defined to increase clockwise around the Galactic center, and $\theta = 0$ points to the Sun. The pitch angle p is positive if the clockwise tangent to the spiral is outside a circle of radius r centered on the Galactic center, and $\beta = 1/\tan p$. At the point $(r_0, \theta = 0°)$, the field reaches the first maximum in the direction $l = 180°$ outside the solar circle. In one of the earliest models, that of Han & Qiao [2], the magnetic field amplitude $b(r)$ is set to be constant within $r_{max} = 15$ kpc, and zero outside. Their best fit parameters (using rotation measures of pulsars and extragalactic radio sources) are $b = 1.8 \pm 0.3$ μG, $p = -8.2° \pm 0.5°$, $r_0 = 11.9 \pm 0.15$ kpc. They estimate the vertical scale height of the magnetic disk to be about 1.2 ± 0.4 kpc.

Stanev [8] defines a bisymmetric spiral field in the same way as eq. (2), but takes $b(r)$ to be $3R/r$ μG for $r > 4$ kpc and $3R/4$ μG for $r < 4$ kpc, where $R = 8.5$ kpc is the galactocentric distance to the solar system. The field is given two vertical scale heights, with

$$B(r,\theta,z) = \begin{cases} B(r,\theta)e^{-|z|} & \text{if } |z| \le 0.5 \text{ kpc} \\ B(r,\theta)e^{-|z|/4-3/8} & \text{if } |z| > 0.5 \text{ kpc}, \end{cases}$$

where the factor $e^{-3/8}$ is needed to make the field continuous. Different authors generate disymmetric fields in different ways, e.g. by taking the absolute value of the cosine in eq. 2 (Stanev) or taking cosine-squared instead. These fields have two variants: symmetric in z if the field directions are preserved when crossing the Galactic disk, and antisymmetric in z if the sign changes. Various modifications to these field models have been proposed, e.g., single scale height [9] and addition of toroidal halo fields and dipole in Galactic center [6].

In the WMAP polarization analysis [5] the authors adopt the simple axisymmetric model

$$\mathbf{B}(r,\phi,z) = B_0[\cos\psi(r)\cos\chi(z)\hat{r} + \sin\psi(r)\cos\chi(z)\hat{\phi} + \sin\chi(z)\hat{z}] \tag{3}$$

where $\psi(r) = \psi_0 + \psi_1 \ln(r/8\,\text{kpc})$, $\chi(z) = \chi_0 \tanh(z/1\,\text{kpc})$, and let r range from 3 kpc to 20 kpc. For a fixed radius, their $|\mathbf{B}|$ has the same value at all azimuths. The distance to the center of the Galaxy is taken to be 8 kpc. WMAP reports their best fit is found for $\chi_0 = 25°$, $\psi_0 = 35°$ and $\psi_1 = 0.9°$.

Using WMAP3 polarization data

Relativistic electrons accelerated by a magnetic field radiate synchrotron radiation [7]. For a power law distribution of cosmic ray electrons, $n(E)dE \sim E^{-p}dE$, the synchrotron emissivity is

$$j_\nu \propto B_\perp^{\frac{1+p}{2}} \nu^{\frac{1-p}{2}}. \tag{4}$$

The emission has a large degree of linear polarization.

WMAP is an all-sky survey measuring the Stokes I, Q, U parameters in five frequency bands in the 23-94 GHz range. In the K band (23 GHz, shown in figure 1) the Galactic synchrotron emission dominates the measured polarized radiation. WMAP [5] obtain the best fit parameters to their GMF model by maximizing the rms value of the correlation coefficient $r = \cos(2(\gamma_{model} - \gamma_{data}))$ averaged over all pixels, where γ is the polarization angle of the synchrotron radiation, $\gamma = \frac{1}{2}\tan^{-1}(U/Q)$. Assuming a simple exponential disk model of the cosmic ray electron density (see [1]) to calculate γ_{model}, and applying a mask covering 25.7% of the sky (essentially the Galactic disk and the North Galactic Spur) a best-fit yields an rms average over all pixels of $r = 0.76$ when fitted to the K band data.

In our analysis we determine the best fit parameters by minimizing χ^2 for Q and U. The resolution in the K band is $\sim 1°$, but to better probe the large scale regular field while removing the noise from random fields, we smooth the data to $\sim 4°$. For each $4°$ pixel we calculate the variance of the $1°$ pixels within a radius ρ from the center of the larger pixel. This way we obtain σ_Q and σ_U for the $4°$ maps. Regions with large turbulence and irregular structures have a larger variance and thus are de-weighted in the χ^2 fit. We thereby avoid masking out the Galactic disk, which is essential to be able to probe the magnetic structure in the plane of the Galaxy.

For a given Galactic magnetic field type and electron distribution from ref. [1] we calculate the polarized synchrotron emission Q and U using the Hammurabi code [10]. We measure the goodness-of-fit by

$$\chi_Q^2 = \sum_{i=1}^{pixels} \frac{(Q_i^{model} - Q_i^{data})^2}{\sigma_{Q,i}^2}, \tag{5}$$

and similarly for U, with $\chi^2_{QU} = \chi^2_Q + \chi^2_U$ the quantity that is minimized to obtain the best parameters for that field type.

In figure 2 a smoothed map of the WMAP3 Q parameter is shown, along with map of σ_Q obtained using $\rho = 2^\circ$.

Results

We will report results of performing a parameter search to minimize χ^2_{QU} and find the best-fit parameters for a selection of GMF models proposed in the literature and summarized above. We will also compare the minimized χ^2 for different models, to deduce what model types give the better fits to the data, e.g., symmetry or antisymmetry in z, bi- or disymmetry structure of the disk field etc..

Results will be presented at ICRC 2007.

Summary

We have reported on a project that will eventually make use of all relevant data to constrain models of the Galactic magnetic field. In this paper we outline our analysis using the WMAP3 polarization data. We improve on the previous analysis [5] of the same data by including the Galactic plane, and allow for weighting individual pixels based on the variance in the data. We also explore the full range of models for the GMF proposed in the literature, rather than restricting to one special case. In future work random fields will be introduced and the synchrotron component of I, as well as Q and U will be used in the fit.

References

[1] R. Drimmel and D. N. Spergel. Three dimensional structure of the milky way disk. *Astrophys. J.*, 556:181, 2001.

[2] J. L. Han and G. J. Qiao. The magnetic field in the disk of our Galaxy. *A&A*, 288:759–772, August 1994.

[3] D. Harari, S. Mollerach, and E. Roulet. The toes of the ultra high energy cosmic ray spectrum. *JHEP*, 08:022, 1999.

[4] M. Kachelriess, P. Dario Serpico, and M. Teshima. The galactic magnetic field as spectrograph for ultra-high energy cosmic rays. 2005.

[5] L. Page et al. Three year wilkinson microwave anisotropy probe (wmap) observations: Polarization analysis. 2006.

[6] M. Prouza and R. Smida. The galactic magnetic field and propagation of ultra-high energy cosmic rays. *Astron. Astrophys.*, 410:1–10, 2003.

[7] Rybicki, G. B. and Lightman, A. P. *Radiative Processes in Astrophysics*. ISBN 0-471-82759-2. Wiley, 1986.

[8] T. Stanev. Ultra high energy cosmic rays and the large scale structure of the galactic magnetic field. *Astrophys. J.*, 479:290, 1997.

[9] P. G. Tinyakov and I. I. Tkachev. Tracing protons through the galactic magnetic field: A clue for charge composition of ultrahigh-energy cosmic rays. *Astropart. Phys.*, 18:165–172, 2002.

[10] A. H. Waelkens and T. A. Ensslin. In prep. 2007.

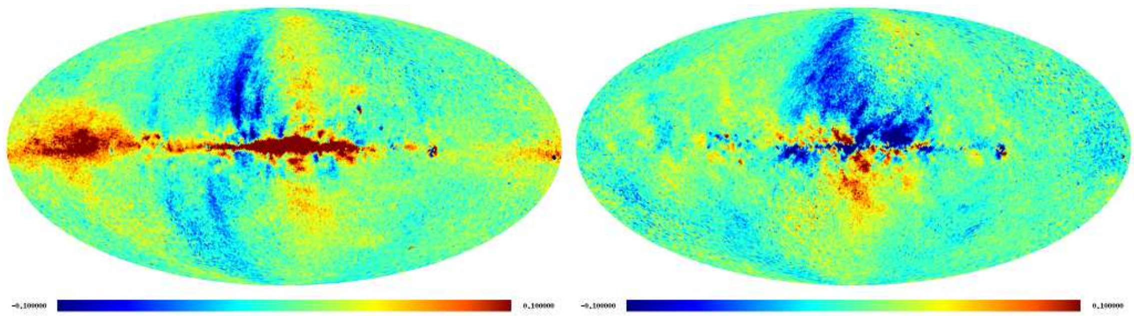

Figure 1: Stokes Q and U parameters in mK from WMAP3 in 1° resolution.

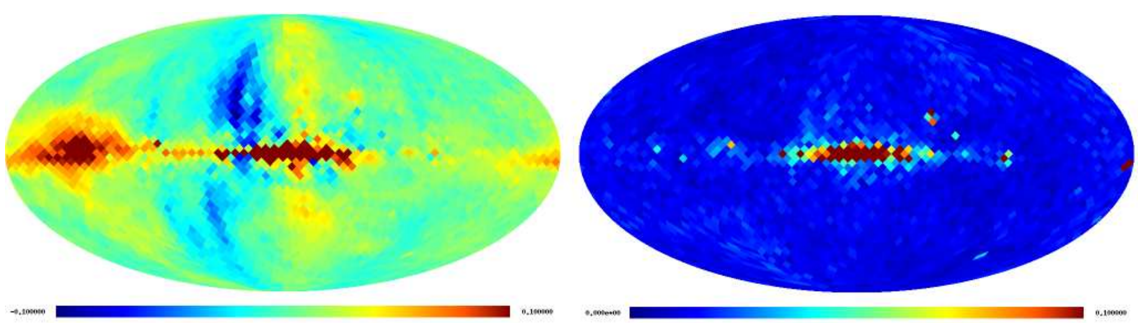

Figure 2: *Left:* Stokes Q parameter in mK from WMAP3 smoothed to 4° resolution. *Right:* σ_Q in mK calculated with $\rho = 2°$.