Faraday rotation constraints on large scale Halo model

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1. An extended Galactic halo magnetic field ?

The global structure of the magnetic field inside the disk of our Galaxy is quite well described by dynamo action and constrained by Faraday rotation measurements. The Halo, on the other hand, is much more of an enigma. Other face-on spiral galaxies show spiral magnetic structures in their disk, like the Milky Way, showing that our magnetic field is a rather typical feature for such class of galaxies. Furthermore, RM-synthesis of CHANGE-ES observations shows an increasing number of edge-on spiral galaxies presenting X-shaped structures surrounding the disk and extending orderly to distances of up to tens of kpc. Although the 3-dimensional topology of those magnetized halos and their physical nature is still unclear, they hint to the strong possibility that our galaxy also has a large and well organized magnetized Halo. The possibility of an extended and topologically well organized magnetic field in the Halo has not been studied for the Milky Way. Specifically, the models in current use only take into account the Disk field, supplemented by a component that extends very little away from the plane and decays rapidly with height.

2. Simple model of the Galactic magnetic field

We model the Galactic magnetic field $\mathbf{B}$ as a linear superposition of the disk field $\mathbf{B}_{\text{D}}$ and the halo field $\mathbf{B}_{\text{H}}$:

$$\mathbf{B} = \mathbf{B}_{\text{D}}(1 - T(z, z_0)) + \mathbf{B}_{\text{H}} T(z, z_0)\,, \quad (1)$$

where $T(z, z_0) = 1/(1 + \exp(-k(|z| - z_0)))$ is a smooth step function represented by the logistic function.

$$\mathbf{B}_{\text{D}} = (\sin p\, \hat{\boldsymbol{u}}_{\boldsymbol{r}} + \cos p\, \hat{\boldsymbol{u}}_{\boldsymbol{\varphi}}) \cos\left(\varphi - b \ln \frac{r}{r_\odot} + \Phi\right) B(r, \varphi) \quad (2)$$

$$B(r, \varphi) = \frac{B_0^{\text{D}}}{\cos \Phi} \begin{cases} r_\odot / r_c, & r < r_c \\ r_\odot / r, & r \geq r_c \end{cases} \quad (3)$$

where $r_\odot$ is the Galactocentric distance of the Sun, taken as 8.5 kpc, and $b = 1/\tan p$ and $\Phi = b \ln(1 + d/r_\odot) - \frac{\pi}{2}$, d is the distance for the first field reversal, p is the pitch angle, B_{D}^0 is the local field strength at the Sun position and r_c the characteristic radius of the central region where the field is assumed constant ($r_c \geq 1$ kpc).
As regards the halo field is modeled with an Archimedean spiral that is consistant with a large scale magnetic field due to winds and defined in spherical coordinates as:

$$\mathbf{B}_{\text{H}} = \begin{cases} 0, & \rho < \rho_0 \\ \frac{|z|}{z} B_0^{\text{H}} \left(\frac{\rho_0}{\rho}\right)^2 \left(\hat{\boldsymbol{u}}_{\boldsymbol{r}} - \frac{\rho}{\rho_1} \sin\theta\, \hat{\boldsymbol{u}}_{\boldsymbol{\varphi}}\right), & \rho \geq \rho_0 \end{cases} \quad (4)$$

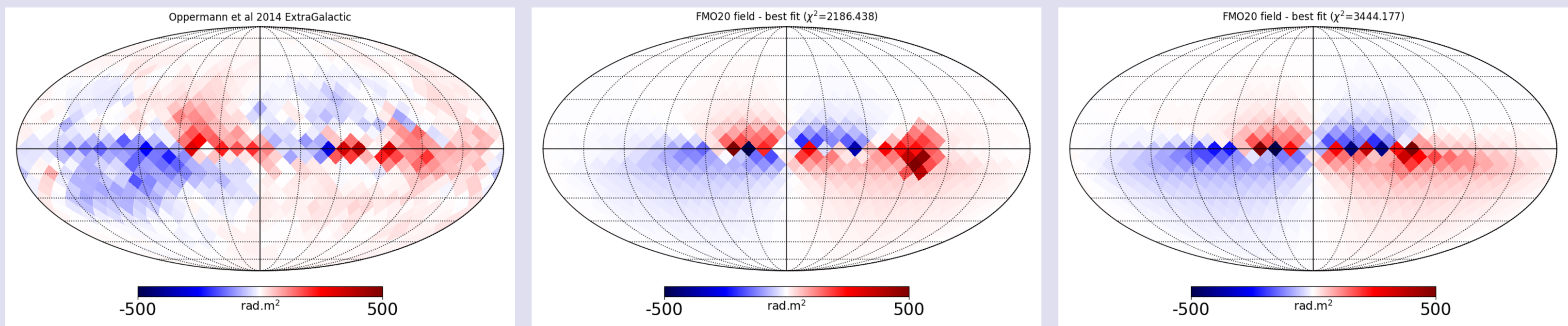
where B_0^{H} is the magnetic field strength, ρ_0 is the spherical radius at which B_0^{H} is defined, and ρ_1 is the typical distance where the halo goes from a radial to an azimuthal field.
The overall structure can be seen in the next section on the right.

3. Analysis method and first fitting

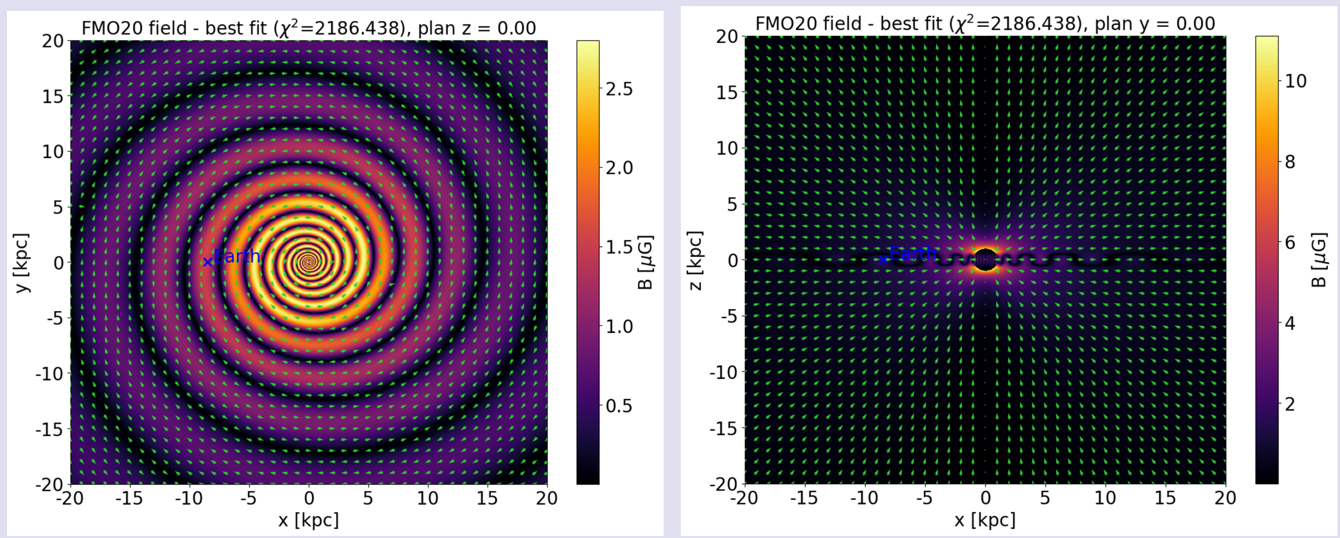
We compared the predicted Faraday rotation measurement from our simple model to full-sky map from Oppermann et al 2015 using a χ^2 minimization. Our model included a limited number of parameters (5 for the disk and 3 for the halo). Since we are interested in the extension of the halo magnetic field, we only tested a limited value for the disk so we end-up with a single disk model and see the evolution of the halo (see next section).
On the table below are summarized the parameters sets that were tested and the best parameters obtained (between parenthesis if multiple value gives equivalent χ^2). The Faraday rotation measurement is computed using two free electron density model: NE2001 and Yao et al 2017 (hereafter YMW17).

Parameter	Values tested	best fits	
		NE2001	YMW17
χ^2 (χ^2_{red})		2186 (2.88)	3445 (4.53)
disk			
B_0^{D} [μG]	1.5	1.5	1.5
R_c [kpc]	5	5	5
d [kpc]	-1, 0, 1	-1	-1
p [deg.]	-6, -8, -10	-6 (-8)	-6
z_0 [kpc]	0.5, 1, 1.5	0.5	0.5 (1)
halo			
B_0^{H} [μG]	[0.1, 60] (log step 0.1)	10 (8 → 15)	10 (7 → 15)
ρ_0 [kpc]	[1, 5] (step 1)	1 (2)	1 (2)
ρ_1 [$\times\rho_0$]	[1, 20] (log step 0.1)	1 (1 → 5)	1 (1 → 5)

On the figure below are represented the Faraday rotation sky maps predicted by the best fitted models for both free electron density models (center and right). We can see that they reproduce well the main features visible on the Oppermann et al sky map (left).

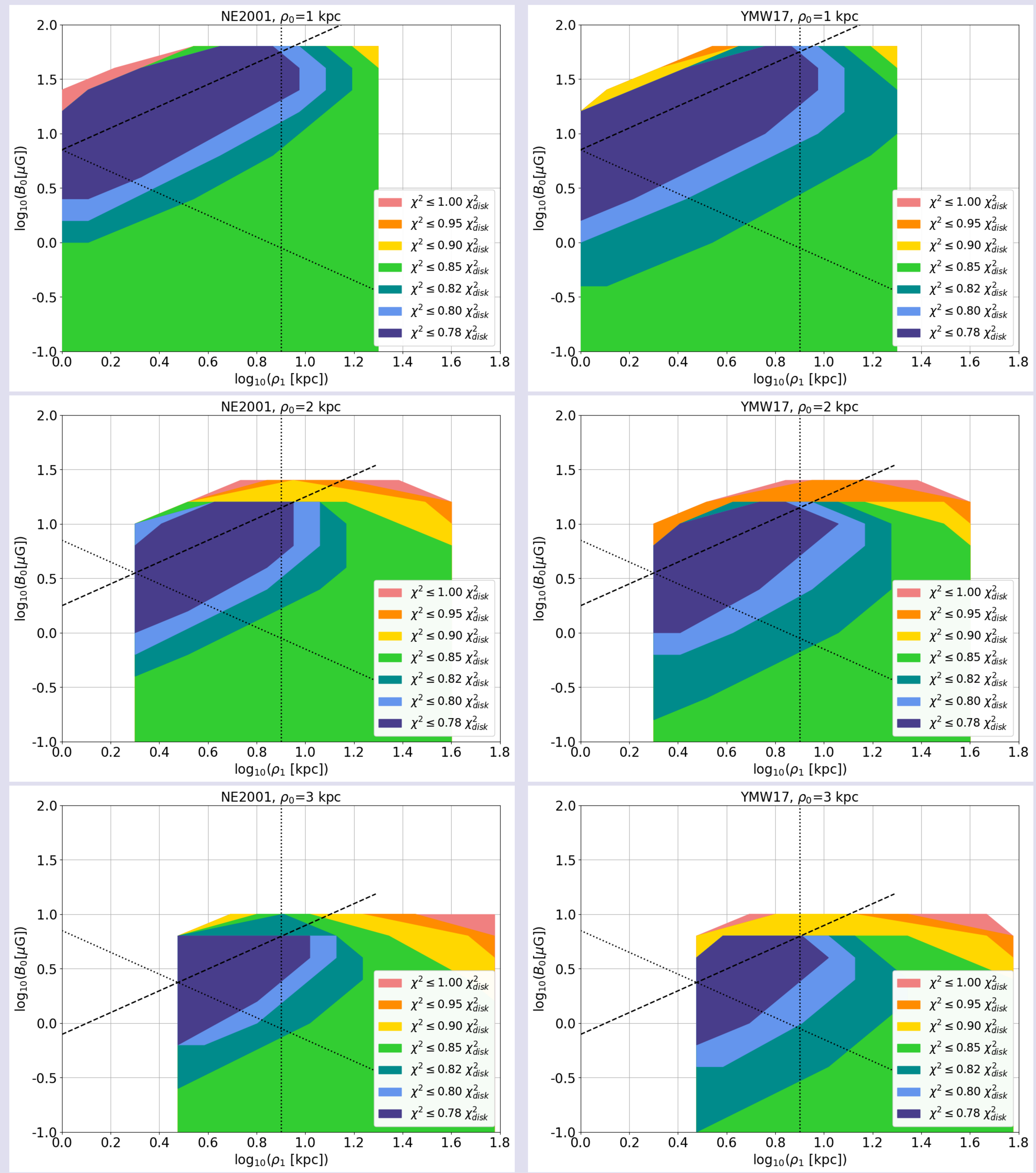


The corresponding projections (z=0 and x=0) of the "best fit" magnetic field are represented on the figures below.



4. Stressing an extended halo magnetic field

In the previous section we have fitted our model. Because we have tested only few values for the disk parameters, only one set of parameters arises as the "best fit". In this section, we will use this set as the "true" best disk model. We have computed the χ^2_{disk} corresponding to the disk only fitting. The objective is now to stress how much the adding of our halo magnetic field model can improve the fitting by comparing if we can reduce the χ^2. On figure **??**, is represented the χ^2 (color map) versus the three parameters of the halo: ρ_0, ρ_1 and B_0^{H}. Each figure is done for a value of ρ_0 (1, 2, 3 kpc in raw) and for one model of the free electron density (NE2001 on the left, YMW17 on the right). The blue area giving the improvement of the fitting compare to a disk only model shows a certain degeneracy.



Dashed and dotted lines allowed us to roughly adjust the dependancy following the equation:

$$B_H^0(best) = 7 \left(\frac{\rho_0}{1kpc}\right)^{-1} \left(\frac{\rho_1}{\rho_0}\right) \mu G \quad (5)$$

This model suggests that an instance magnetic field (few microgauss) can still exist at a large distance since:

- the free electron density decrease very fast (no Faraday rotation),
- large amplitude is confined near the Galactic center (decreases quickly as $1/\rho^2$ on small scales then as $1/\rho$ at larger distance)