Galactic magnetic fields simulations based on the cosmic-ray driven dynamo

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Introduction

Magnetic fields are ubiquitous in the Galaxy. They permeate the interstellar medium and extend beyond the Galactic disk, and they are present in stars, supernova remnants, pulsars and interstellar clouds. The magnetic fields play a important role in the evolution of galaxies. To better understand the role of galactic magnetic fields, theoretical predictions and simulations are compared to observations.
First of all to study the magnetic fields in our own Galaxy. It is important to better understand the strength, direction and structure of magnetic fields in the Milky Way. The Galactic magnetic field (GMF) has received considerable attention yet it remains poorly understood,even though the first detection of Galactic polarization was several decades ago (Wielebinski et al. 1962; Westerhout et al. 1962). As most observables are integrated quantities along the line of sight, our position at Galactocentric radius of about 8.5 kpc requires modeling of the field to interpret the observed data. A much used and very productive observational method to study of the GMF is the Faraday rotation measure (RM). When a linearly polarized electromagnetic wave passes a magnetized thermal medium its polarization angle experiences rotation, called Faraday rotation. The rotation is proportional to the square of the wavelength and the coefficient is the RM, which can be written as

$$RM \propto \int_0^L n_e B_{||} dl,$$

where the integral range is along the line of sight from the observer to the source at a distance D, n_e is the thermal electron density and $B_{||}$ is the magnetic field component along the line of sight. RM is positive when the magnetic field points towards us.

Background

Nowadays modelling of Galactic magnetic fields can be done with a high level of details (see. e.g. Jaffe et al. (2011, 2010), Van Eck et al (2011), Jansson & Farrar (2012) and more).
This all is possible with the availability of all-sky data of Faraday rotation measures (Oppermann et al. 2012) and polarised synchrotron emission obtained by space missions like WMAP or Planck (Fauvet et al. 2012). The typical approach utilises χ^2 minimisation for fitting a large number of free parameters.
To better understand the Galactic magnetic fields we present model of the Milky Way using 3D MHD numerical simulations based on cosmic-ray driven dynamo. For our calculations we use information from observations (see Model Section) and create model of magnetic fields in the Milky Way. After this we compare synthetic rotation measure maps with existing RM data.
We aim to find out whether it is possible to reproduce the observed RM distribution in the sky with a modeled Milky Way galaxy as evolved from MHD simulations.

Model

The computations of the evolution of Galactic magnetic fields in our Galaxy are done by solving the isothermal non-ideal MHD equations of the form

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0, \tag{1}$$

$$\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} = -\frac{1}{\rho}\nabla\left(p + p_{cr} + \frac{B^2}{8\pi}\right) + \frac{\vec{B} \cdot \nabla \vec{B}}{4\pi\rho} - \nabla\Phi, \tag{2}$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times (\vec{v} \times \vec{B} - \eta \nabla \times \vec{B}), \tag{3}$$

$$\nabla \cdot \vec{B} = 0, \tag{4}$$

where $\vec{v}$ is the large-scale velocity of gas, ρ is the gas density distribution, p is the gas pressure, p_{cr} is the cosmic-ray pressure, Φ is the gravitational potential, $\vec{B}$ is the magnetic induction, e is the thermal energy density and η is the turbulent magnetic diffusivity. An isothermal equation of state was assumed, that is $p = \rho c_s^2$, where c_s is the isothermal speed of sound.
Our model of the Milky Way galaxy consists of four components: the large massive halo, the central bulge, the rotating disk of stars, and the bar. They are represented by different analytical gravitational potentials.
The isochrone gravitational potential of the form:

$$\Phi_{IGP} = -\frac{GM_{IGP}}{a_{IGP} + \sqrt{a_{IGP}^2 + r^2}}, \tag{5}$$

where M_{IGP} is the total mass, a_{IGP} is its characteristic scale length, and r is the distance to the galactic center in cylindrical coordinates (r, ϕ, z)
The Plummer potential of the form:

$$\Phi_P = -\frac{GM_P}{\sqrt{z^2 + a_P^2 + r^2}} \tag{6}$$

The Miamoto-Nagai potential of the form:

$$\Phi_{MN} = -\frac{GM_{MN}}{\sqrt{r^2 + (a_{MN} + \sqrt{z^2 + b_{MN}^2})^2}}, \tag{7}$$

a_d is the disk scalelength, b_d is the disk scaleheight.

We investigated the problem of propagation of cosmic ray (CR) transport (Schlickeiser & Lerche 1985) in the ISM by solving the following diffusion-advection equation:

$$\frac{\partial e_{cr}}{\partial t} + \nabla(e_{cr}\vec{v}) = \nabla(\hat{K}\nabla e_{cr}) - p_{cr}(\nabla \cdot \vec{v}) + CR_{source}, \tag{8}$$

where e_{cr} is the cosmic ray energy density, $p_{cr} = (\gamma_{cr} - 1)e_{cr}$ is the cosmic ray pressure, $\hat{K}$ is the diffusion tensor, $\vec{v}$ is the gas velocity and CR_{source} is the source term for the cosmic-ray energy. Moreover, we assume that 10% of 10^{51} erg of the SNe kinetic energy from their outburst is transformed into the CR energy and leave out the thermal energy, applying the value of adiabatic index for the CR gas as $\gamma_{cr} = 14/9$ and adding the CRs pressure to the total pressure in the ISM gas motion equation as ∇p_{cr} (Berezinski et al. 1990). It is also assumed that the CR gas diffuses anisotropically (Ryu et al. 2003). The CR diffusion tensor K is defined as:

$$K_{ij} = K_\perp \delta_{ij} + (K_\| - K_\perp) n_i n_j, \tag{9}$$

where $K_\perp$ and $K_\|$ are the parallel and perpendicular (with respect to the local magnetic field direction) cosmic-ray diffusion coefficients and $n_i = B_i/B$ are components of unit vectors tangent to the magnetic field lines.

Discussion and Future Work

Due to the unpredictability of magnetic field structure in MHD simulations and the fact that the real Milky Way is only one realization of many possibilities, it is inherently difficult to compare rotation measure maps from MHD simulations of the Milky Way to the observed map. However, in some of the models, we do find significant correspondances between models and observations, most notably the presence of a magnetic field reversal in the Galactic disk, the quadrupolar (butterfly, odd parity) pattern of RMs in the inner Galaxy and a dipolar (even parity) structure in the outer Galaxy. Uncertainties in estimates of the input parameters make predictions difficult.
Some features of the models are still distinctly different from the observations, to be studied in the near future. E.g. the RM values in the models are still too low, especially at large Galactocentric radii (> 8 kpc), and the quadrupolar pattern is very asymmetric with respect to the plane.

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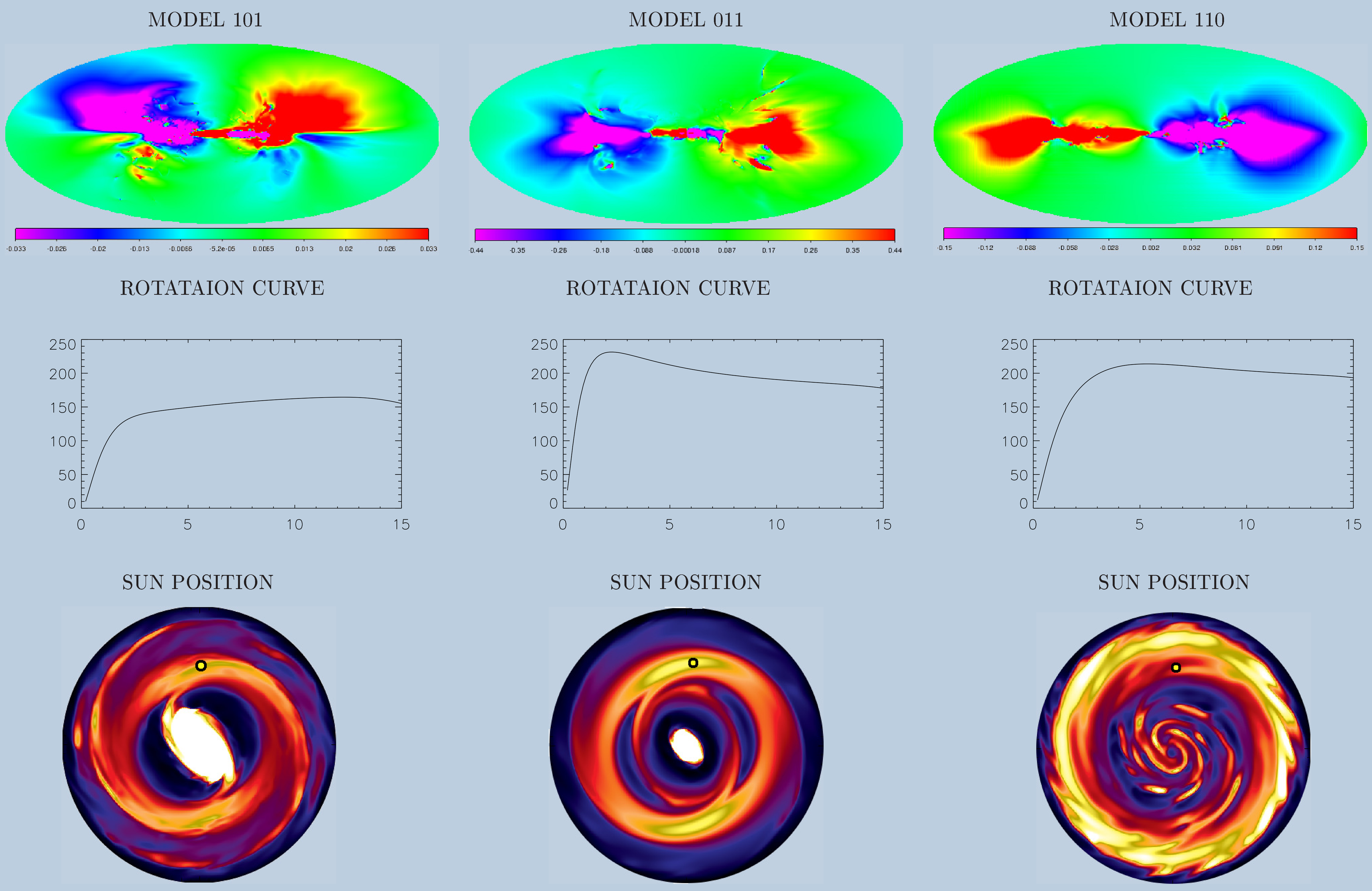
Acknowledgements

This research was supported by Polish grant NCN UMO-2012/07/B/ST9/04404. The supports are gratefully acknowledged.

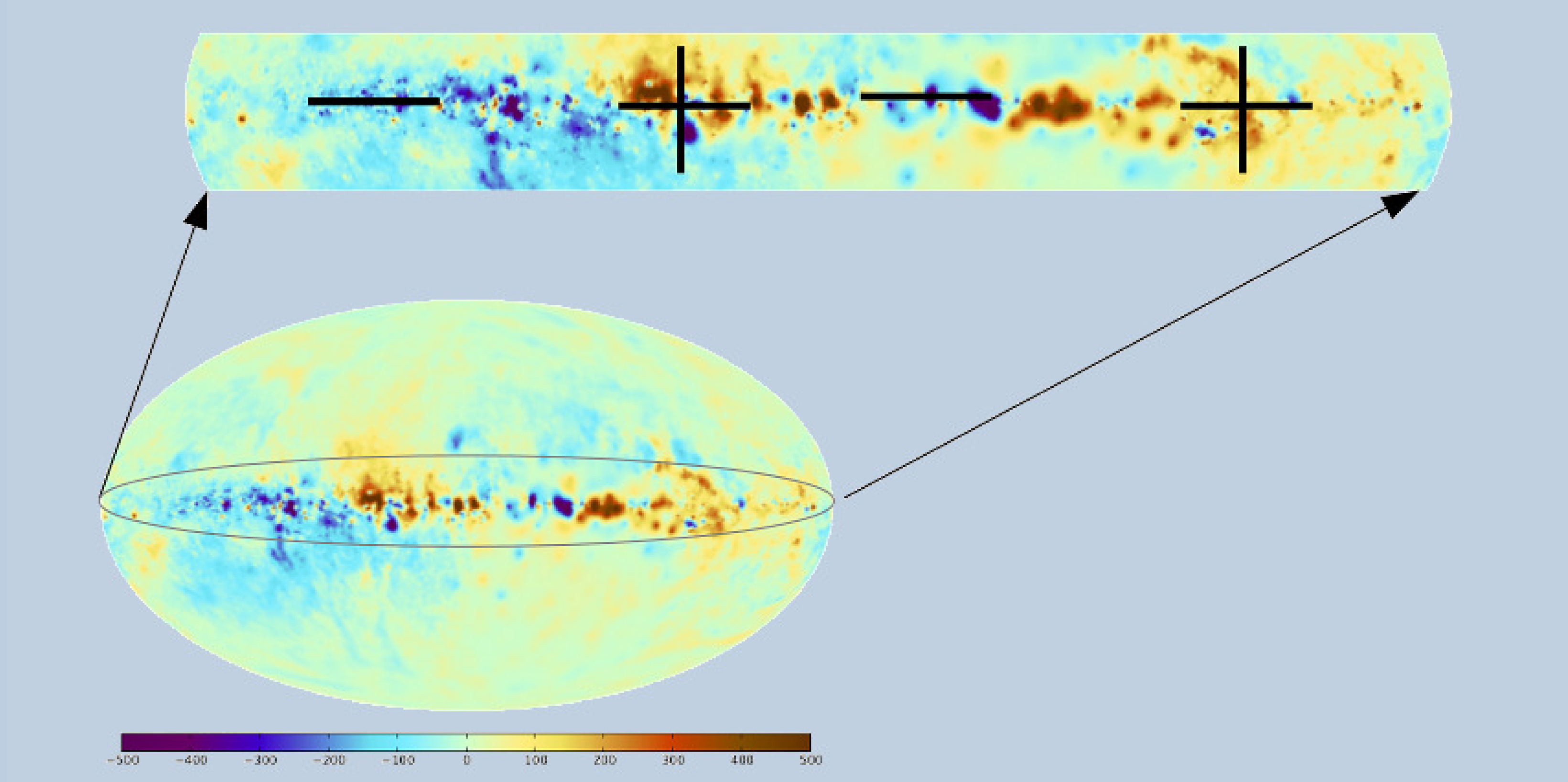
Results

Using MHD numerical simulations based on cosmic-ray driven dynamo, we prepared models of our Galaxy. Precise reconstruction of a Milky Way-like galaxy proved difficult, since correct input parameters often failed to produce spiral arms and/or a correct rotation curve. Therefore, we selected relevant models with the following method. We focus on three parameters: first if our input parameters (table above) fit with the observational data, second if the synthetic rotation curve matches with the data and the last one if spiral arms appear in our simulations. Unfortunatelly we didn't get the model with all three parameters, but still models with two of them give interesting results. We present three reference models M101, where the synthetic rotation curve does not match, M011 where one of input parameters does not match with observational values and the last one M110, where the spiral arms not appear.
In the table we present input parameters for this three models of Galactic magnetic fields, calculated using MHD simulations based on cosmic-ray driven dynamo.

parameter	meaning	M101	M011	M110	units
M_d	disk mass	$7.0 \cdot 10^{10}$	$6.0 \cdot 10^{10}$	$7 \cdot 10^{10}$	$M_\odot$
a_d	length scale of the disk	5.0	0.9	3.5	kpc
b_d	height scale of the disk	-	-	0.5	kpc
M_b	bulge mass	$1.5 \cdot 10^{10}$	$1.5 \cdot 10^{10}$	$1.7 \cdot 10^{10}$	$M_\odot$
a_b	length scale of the bulge	1.75	5.0	1.75	kpc
b_d	height scale of the bulge	-	0.5	-	kpc
M_h	halo mass	$1.2 \cdot 10^{10}$	$1.2 \cdot 10^{10}$	$2.2 \cdot 10^{10}$	$M_\odot$
a_h	length scale of the halo	15.0	15.0	20.0	kpc
M_{bar}	bar mass	$1.5 \cdot 10^{10}$	$1.5 \cdot 10^{10}$	$1.5 \cdot 10^{10}$	$M_\odot$
a_{bar}	length scale of bar major axis	6.0	6.0	6.0	kpc
b_{bar}	length scale of bar minor axis	3.0	3.0	3.0	kpc
c_{bar}	length scale of bar vertical axis	2.	2.5	2.5	kpc



Top panels present synthetic Faraday rotation maps in the plane of Galaxy for three reference models for time step 14 Gyr. The red area denotes the positive RM and purple area denotes the negative RM. The maps that are centered on the Galactic center with positive Galactic latitudes at the top and positive Galactic longitudes plotted to the left. **Middle panels:** the rotation curve with rotation velocity in $\frac{km}{s}$ and radial distance in kpc. **Bottom panels:** image of gas density, where the sun is denoted as the yellow circle, at Galactocentric radius 8.5 kpc. In models M101 and M011, we observe a dipolar structure in RM at Galactic longitude $\ell < 100°$; at $\ell > 100°$, the dipolar structure has reversed, where negative values at the left edge of the map and positive ones on the very right, reflecting the observed reversal in the inner Milky Way. In the third model M110, the structure of Galactic magnetic fields have only dipolar structure.
In the physical Galactic Faraday map below from Oppermann et al. (2012), we can observe the quadrupole-like structure on large scales that favors positive Faraday depths in the upper left and lower right quadrant and negative Faraday depths in the upper right and lower left quadrant. At the Galactic longitude beyound $\pm 100°$ we can notice the dipolar structure of magnetic fields, with negative values at the left edge and positive at the right edge of the map.



Compare our results with numerical simulatons, we can find three similarities:
1. The structure of Galactic magnetic fileds in the Galaxy plane are similar and have structure - + - +,
2. At high longitudes in both cases we can observed dipolar structure of magnetic fields,
3. In some models we can find a quadrupole at longitudes $|\ell| < 100°$.