Quasi-Periodic Galactic Dynamo obtained from 3D MHD Simulations

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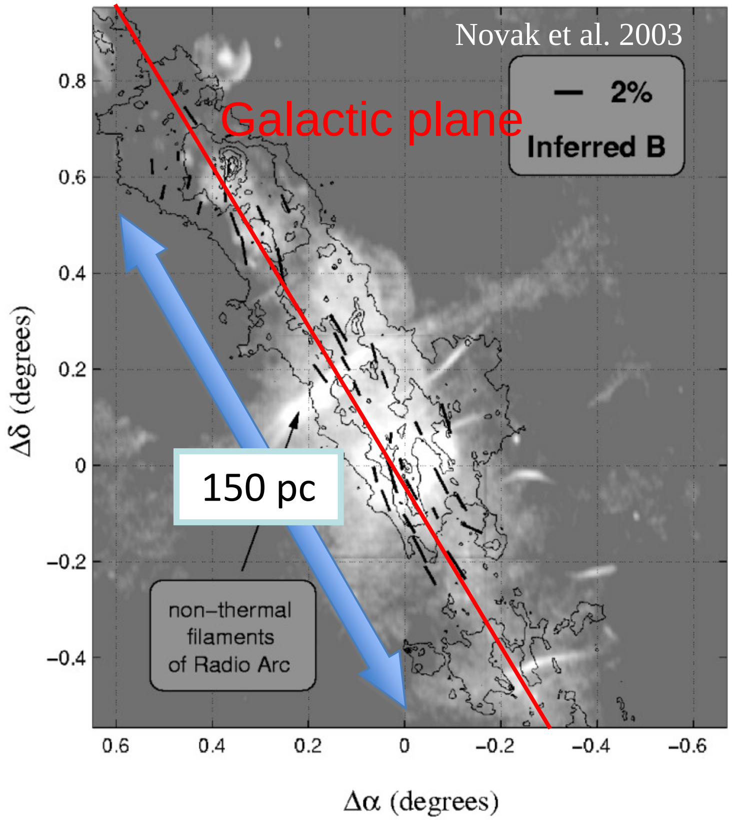
Outline

1. Introduction
    1. Magnetic fields in our galaxy
    2. Kinematic Dynamo mechanism
    3. Previous Results about Dynamical Dynamo
2. Initial Model
3. Numerical Results
    1. Magnetic field structure
    2. Time evolution of the azimuthal magnetic fields
    3. Butterfly Diagram of the Galactic Gaseous Disk
4. Conclusion

Magnetic fields: Central region

Horizontal fields
(Novak+00; 03; Nishiyama+09)
vs
Vertical fields
(Yusef-Zadeh+84; Morris90)



Straight vertical fields are observed in the central region of our galaxy.

Horizontal fields are dominant in the disk region.

←Galactic rotation stretches the magnetic fields horizontally. (Davidson96)

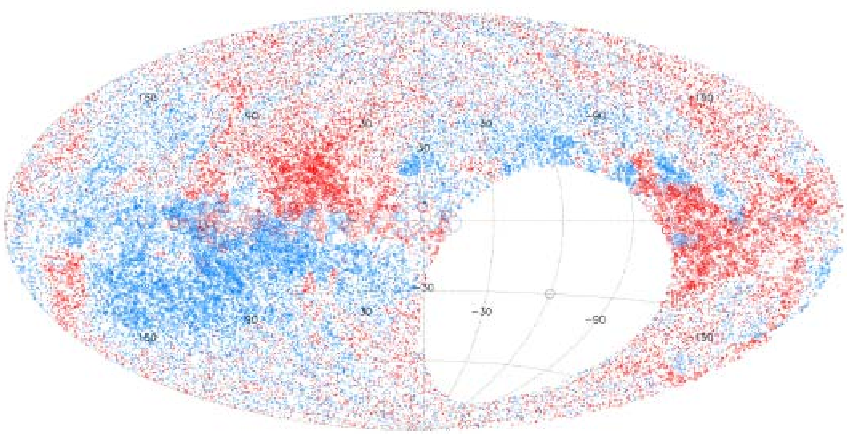
From Zeeman effect :
$B_{\parallel} <$ 0.1 - 1.0 mG

(Killee+92; Uchida & Guesten 95)

Magnetic fields structures

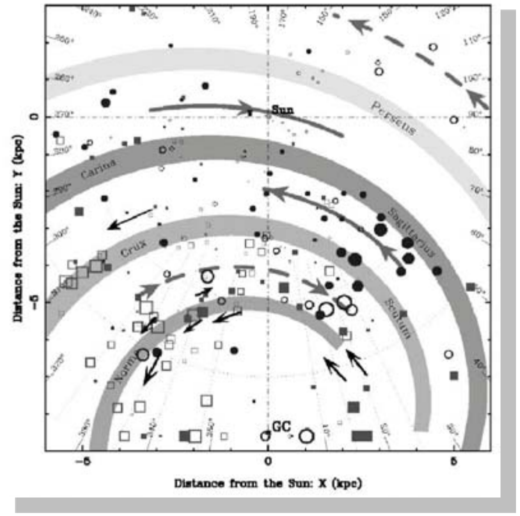
Rotation Measure (RM): $RM = 0.81\int_0^{L(\mathrm{pc})} n \cdot B_{//}\,dl,\ \ n[\mathrm{cm}^{-3}],\ \ B_{//}[\mu\mathrm{G}]$

All sky distribution of the RMs
in Galactic coordinate



Taylor + ApJ, 702, (2009)

Reversal of magnetic fields



Han + ApjL 570 (2002)

Complex distribution of RM

Mean line of sight magnetic fields: north-positive, south-negative

Direction of the fields change between stellar arms.

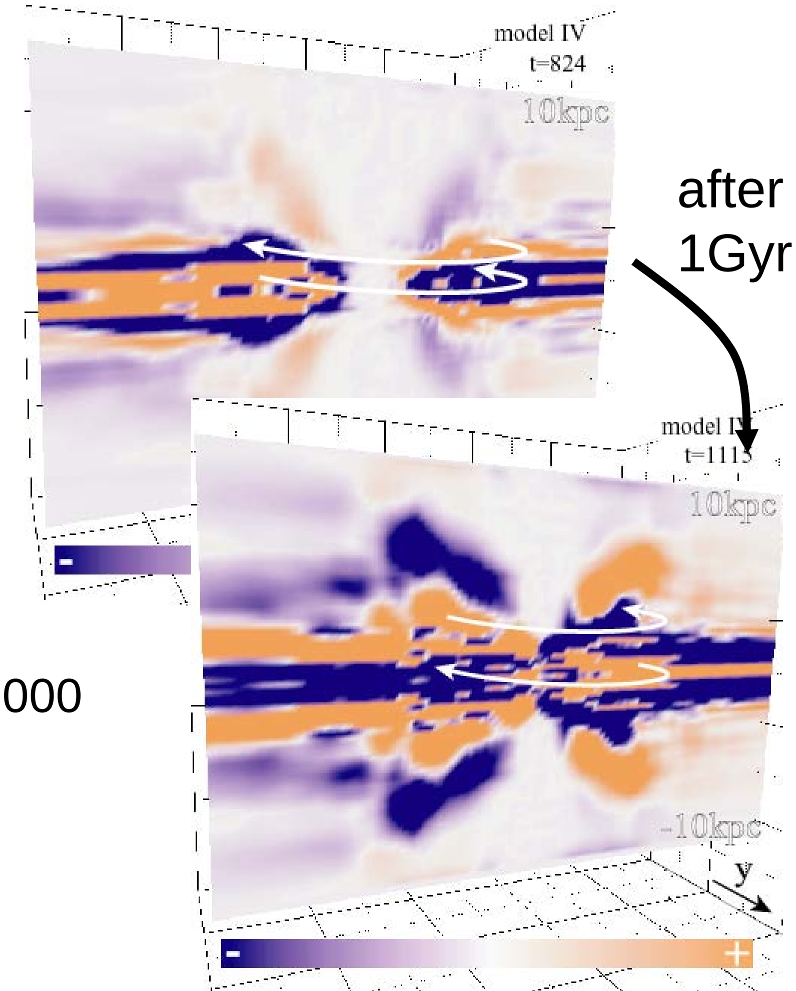
Kinematic Dynamo Mechanism

- Galactic magnetic fields have been explained by the dynamo action operating in the galactic gaseous disk (Parker 1971).
- Dynamo = self-sustaining mechanism of magnetic fields.
- Kinematic Dynamo
  - Velocity fields are given.
  - Magnetic field structures are obtained from time evolution of the induction equation.(e.g. Brandenburg + 1989 etc.)

→ **Ignore the back reaction from the magnetic fields.**

Since galactic gaseous disk is the differentially rotating disk, magneto-rotational instability also becomes important. Therefore, **we have to include the gas dynamics and back reaction from magnetic fields.**

Amplification and Reversal of Galactic Magnetic Fields

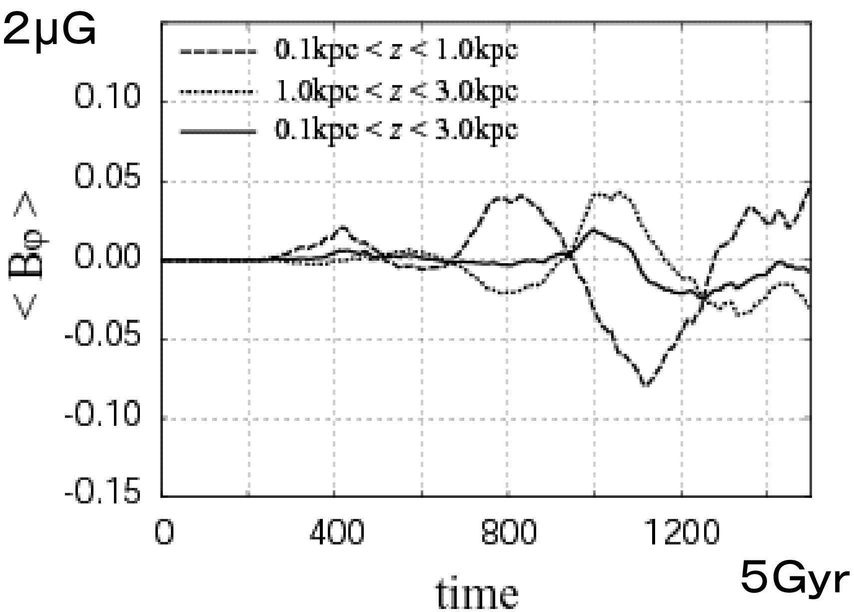


after 1Gyr…

β_0=1000

Nishikori , MM, + , ApJ (2006)

Time evolution of the averaged azimuthal magnetic fields (5kpc < r < 6kpc)



Mean azimuthal magnetic fields reverse their direction with period about 1billion years.

Purpose of this talk

- Which components is dominant in our galactic center?
- What is the origin of the galactic dynamo?

We present the numerical result of the galactic gaseous disk which does not impose symmetric boundary condition at the equatorial plane.

Basic Equations

Ideal MHD equations

Mass conservation $$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho v) = 0$$

Eq. of Motion $$\frac{\partial v}{\partial t} + v \cdot \nabla v = -\frac{1}{\rho} \nabla p + \frac{1}{4\pi\rho} (\nabla \times B) \times B - \nabla \phi$$

Induction eq. $$\frac{\partial B}{\partial t} = \nabla \times (v \times B)$$

Energy eq. $$\frac{\partial \rho \varepsilon}{\partial t} + \nabla \cdot (\rho \varepsilon v) + p \nabla v = 0$$

Model Half: $0 < r < 57$kpc , $0 < \varphi < 2\pi$、 $0 < z < 12$ kpc
Model Full: $0 < r < 57$kpc , $0 < \varphi < 2\pi$、 $-12\text{kpc} < z < 12$ kpc

Initial Model

- We solved ideal MHD equations.
- Equilibrium gas disk threaded by toroidal magnetic fields (Okada + 1989)

・Specific angular momentum	$L \propto r^{0.46}$
・sound speed (disk)	$c_{s0}=0.14\ v_0$
・Specific heat ratio	$\gamma=5/3$
・plasma β	$\beta=100$

Units

length	r_0 =	1kpc
velocity	v_0 =	207 km/s
Central Mass	M_0 =	$10^{10} M_{solar}$
Temperature	T_0 =	5.2×10^6 K

◇ We simulated only ionized component.

◇ We ignore self-gravity of gas and radiative cooling.

◇ Simulation box: $0 < r < 57$kpc, $|z| < 12$kpc, $0 < \phi < 2\pi$

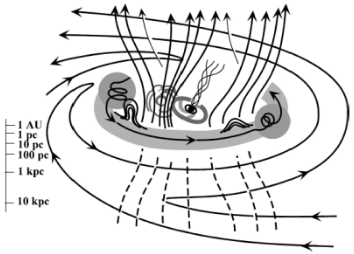
・**Gravitational potential of the Galactic gaseous disk**: Miyamoto・Nagai(1975)

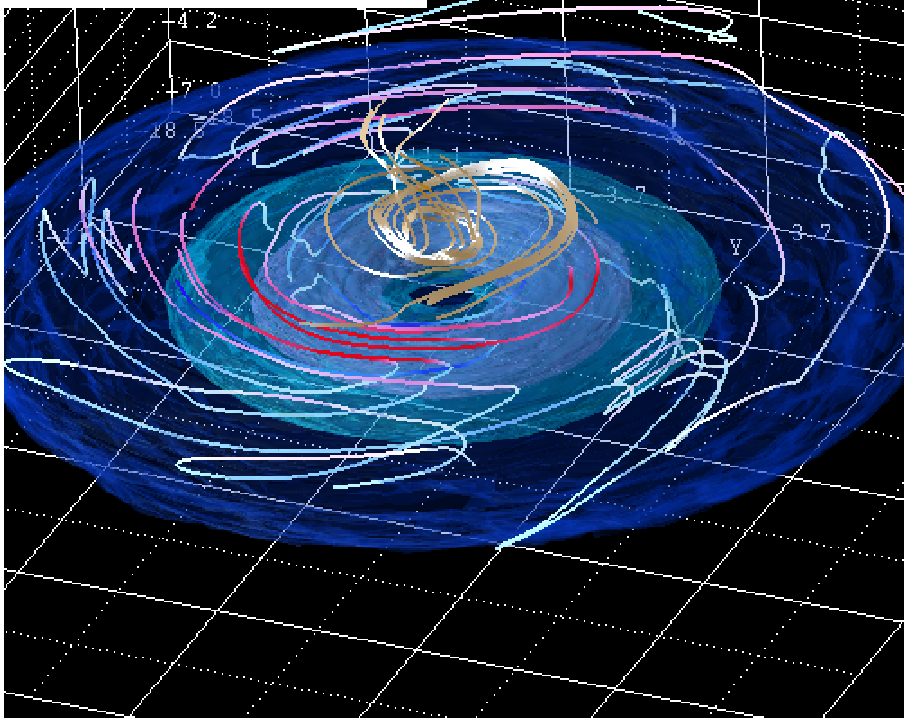
Potential combined with the galactic stellar disk and bulge stars.

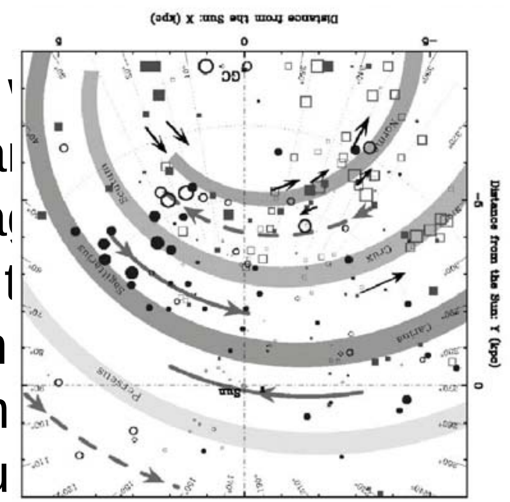
$$\phi(\varpi, z) = \frac{GM_1}{\left[\varpi^2 + \left(z^2 + b_1^2\right)\right]^{1/2}} + \frac{GM_2}{\left[\varpi^2 + \left\{a_2 + \left(z^2 + b_2^2\right)^{1/2}\right\}^2\right]^{1/2}}$$

	a	b	M
1.Bulge	0	7.258	2.05
2.Disk	0.495	0.520	25.47

General Properties of Magnetized Disk







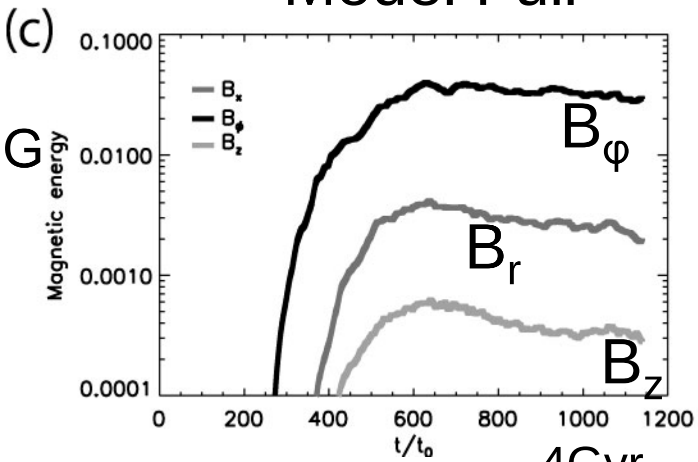
•Initial … fied by MRI, a… turbulent.
•Avera… t 10 inside t…
•When … becom… gas pressu… driven ou… re… - sc… in…

We can explain the direction change in radial direction.

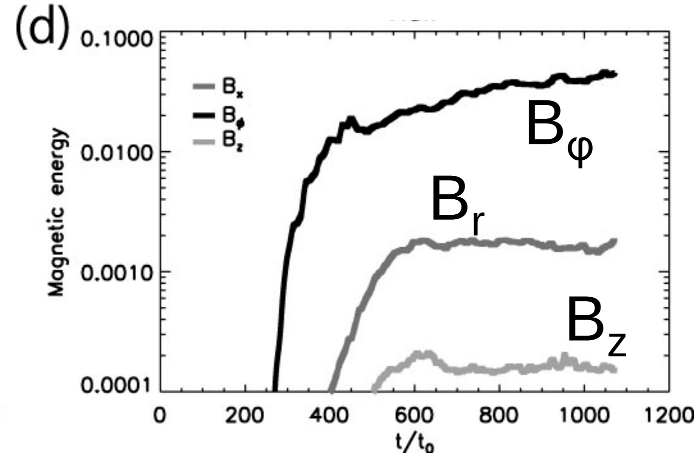
Vertical fields in the Galactic center and toroidal disk fields are natural structure.

Time evolution of the magnetic energy

Model Full



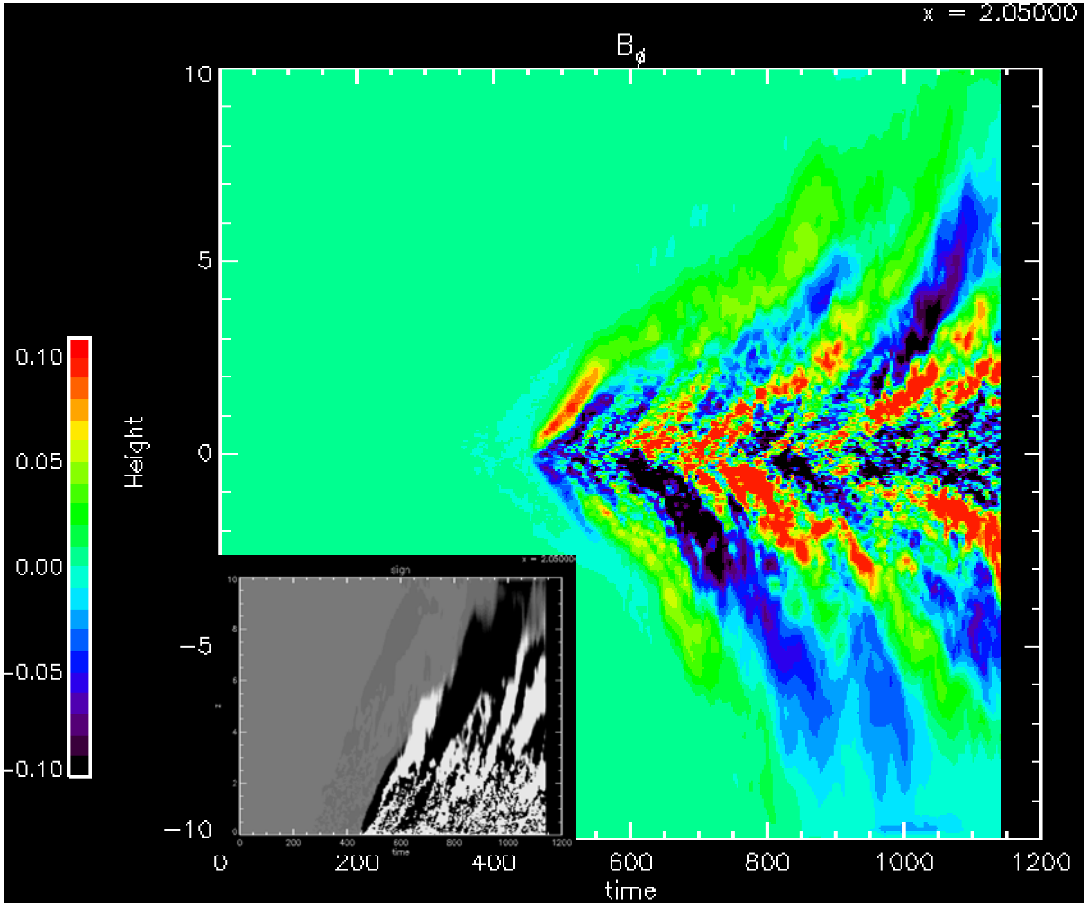
Model Half



Time evolution of the magnetic energy averaged in the region where $-1 < z < 1$, $2 < r < 5$.
Black: Azimuthal component, Dark gray: Radial component, Gray: Vertical component

- The vertical fields penetrating the equatorial plan are created in model full, which subjects to the axisymmetric MRI.
- The saturation level of the azimuthal component is approximately the same for model half and full.

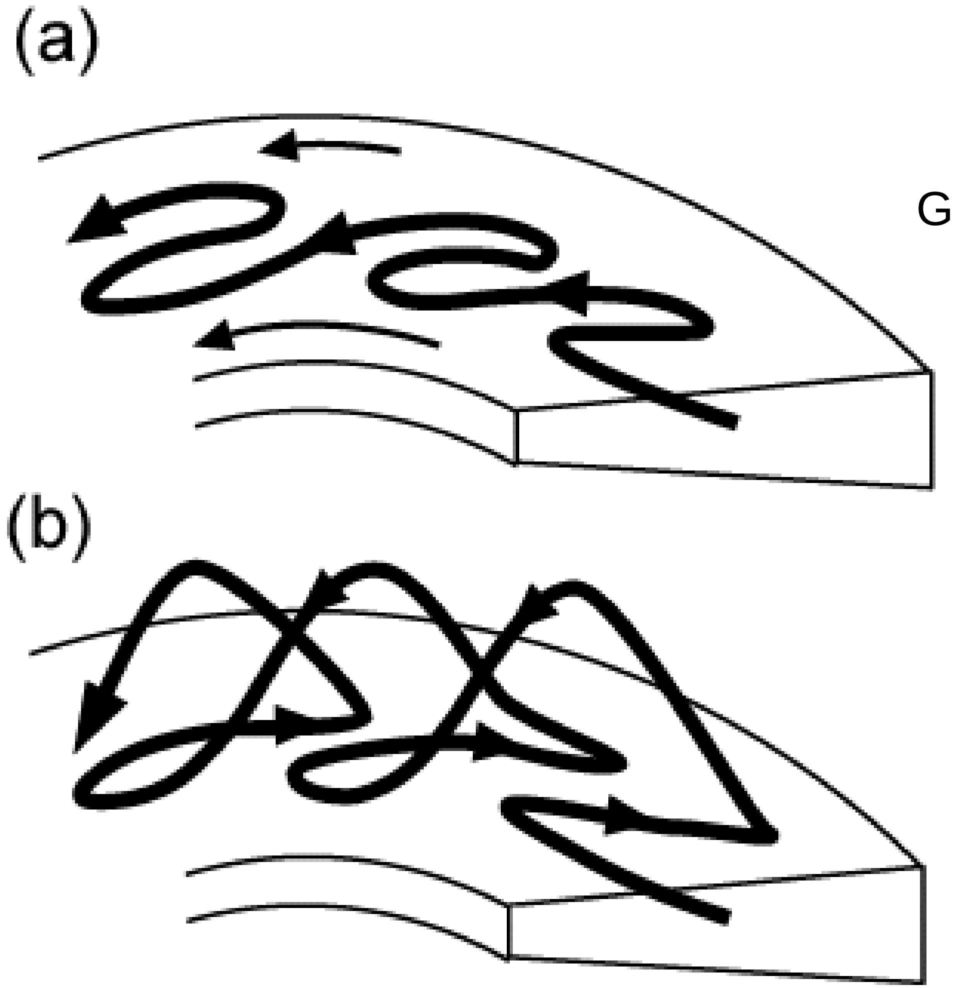
Butterfly diagram of the Galactic Gaseous Disk



Color denotes Bφ averaged in the azimuthal direction. Left corner: Correlation of B_φ below the equatorial plane and above it. White: positive, Black: negative.

- The azimuthal magnetic fields change direction quasi-periodically .
- When the plasma β decreases to around 5, the magnetic flux buoyantly escapes from the gaseous disk.
- The disk changes between symmetric state and anti-symmetric state.
- The timescale of the magnetic field flotation was about 10 rotation period at that radius, which corresponded to the growth timescale of MRI.

Mechanism of the MHD Dynamo



+1

Growth of the MRI

+2

−1

Magnetic flux escape by the Parker instability

+2

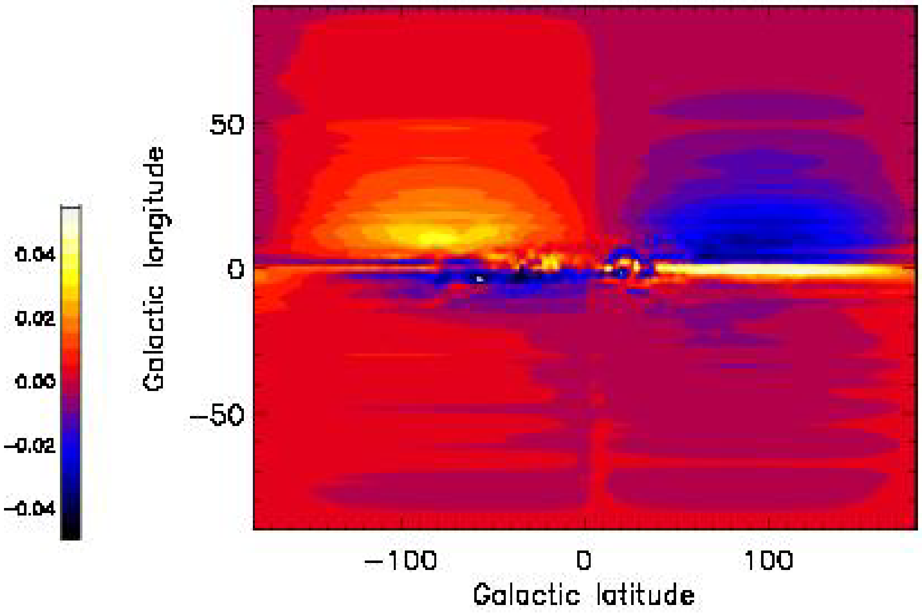
flotation

−1

Remain the anti-direction field

Rotation Measure Distribution

Numerical result



Observation

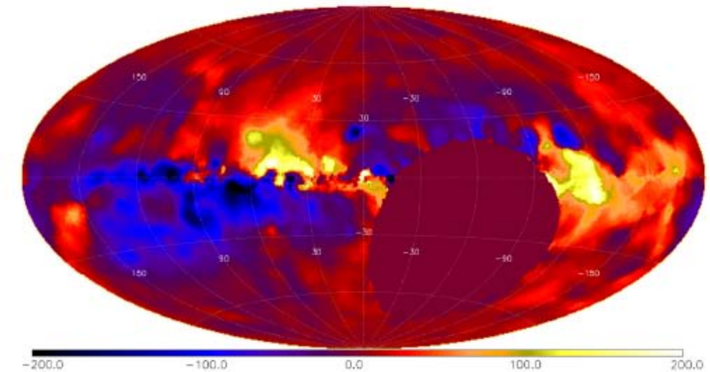


Figure 4. Image of the median value of rotation measure. Each pixel represents the median rotation measure of all sources within a circle of diameter of 8°. Typically about 60 sources contribute to each median calculation.

Taylor + (2009)

Left) RM distribution obtained by numerical results. The Sun is located at R=8kpc.
Right) The sky distribution of the RMs.

- The distribution of RM is point symmetric with respect to the galactic center, consistent with the observation.
- Reversals of the sign of RM in the longitudinal direction indicate that magnetic fields with opposite polarity emerge from the disk quasi-periodically.

Conclusion

- Saturation level of the magnetic field strength is almost independent of the presence of vertical magnetic fields threading the equatorial plane.
- The azimuthal magnetic fields change direction quasi-periodically. The disk changes between symmetric state and anti-symmetric state.
- The timescale of the magnetic field flotation was about 10 rotation period at that radius, which corresponded to the growth timescale of MRI.
- Numerical result roughly represents the results of the observed RM distribution.