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# Construction of Global Magnetic Field Structure Model in Disk Galaxies with Three-dimensional MHD simulations: Effects of Steady Spiral Arms

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## Abstract

We study numerically the large-scale gas and magnetic field evolution of spiral galaxies in the gravitational potential of a disk, bulge, halo, and spiral arms. We adopt a steady axisymmetric gravitational potential given by Miyamoto et al. and rigid rotating spiral potential. In order to understand the physical processes that the galactic magnetic fields are amplified and maintained, we assume initial condition is a magneto-hydro dynamically equilibrium thin disk gas component (T~$10^4$K) centered at r=10kpc threaded by weak azimuthal magnetic fields. We carried out three-dimensional magneto-hydrodynamic simulation taken into account radiative cooling energy loss. **Our models demonstrate that the magnetic fields strength are dramatically amplified by disturbance due to gravitational potential of spiral arms and Magnetic arms are generated.** Numerical results indicate that the isothermal shocks generated by gravitational potential of spiral Magnetic fields around the spiral arms are amplified up to a few μG at 200Myr. The azimuthal direction of mean magnetic fields in the disk changes with radius due to magneto-rotational instabilities. **The resultant structure of azimuthal magnetic fields distribution is also qualitatively consistent with the observed distribution of the Faraday rotation measure(RM).**

## 1. Introduction & Motivation

Previous activities on construction Galactic Magnetic Field(GMF) model with 3D MHD simulations:

①Kulpa-Dybel etal., ApJL, 733, L18 (2011):
Global 3D simulations with Cosmic-Ray(CR) pressure, bar potential, isothermal, turbulent resistivity, CRs and magnetic fields input from SNe. Since the initial state is far from magneto-hydrostatic state, it is difficult to see the physics for controlling the evolution of the GMF.

②Machida et al., ApJ, 2013, 764, 81 (2013):
GMF is amplified due to Magneto Rotational Instability (MRI) up to 1μG and bouyant escape of magnetic flux by Parker Instability. Gas disk reaches Quasi-steady state. Inversion of direction of azimuthal magnetic field components is found in the vertical direction.
Disk gas temperature = $10^5$K ($10\times T_{\rm thin\ disk}$), adiabatic, axis symmetric gravitational potential.

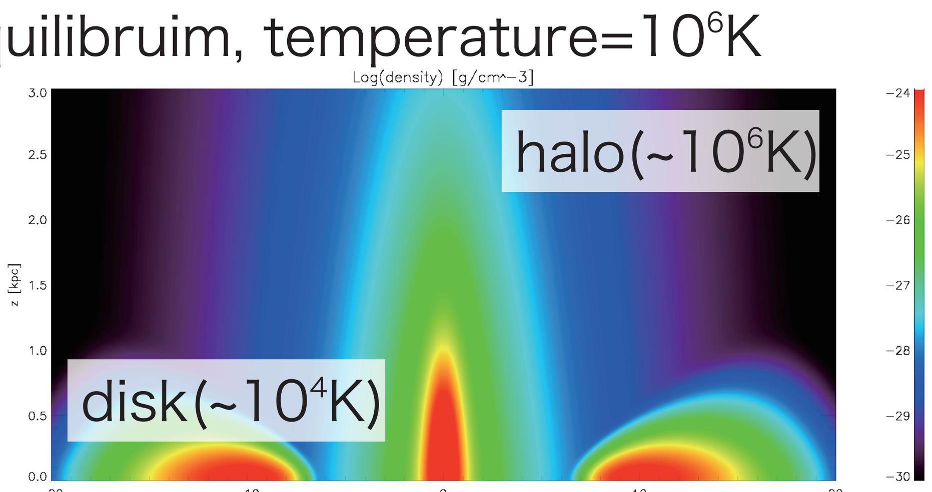
**We studied nonlinear evolution of the Galactic thin gas disk initially in magneto-hydrostatic state when the small amplitude spiral gravitational potential is inserted by global 3D MHD simulation. The temperature of the gas disk must be set to the realistic temperature of thin gas disk, that is around $10^4$ K, to reproduce an isothermal spiral shock originated by an insert of small amplitude spiral potential.**
**Therefore, we set initial temperature of the Galactic thin gas disk to be $10^4$K. Radiative cooling was also taken into account.**

## 2. Simulation model

①Method
- cylindrical coordinate, number of meshes($N_r$, $N_\phi$, $N_z$)=(280, 64, 250) for $0<r<42$kpc, $0<\phi<2\pi$, $0<z<4$kpc with logarithmic scaling
- finite volume scheme
- time step : 3rd order TVD Runge-Kutta
- space : 2nd order accuracy
- flux type : HLLD flux
- divergence constraint : GLM-MHD hyperbolic divergence cleaning

②Initial condition & Model
- disk : magneto-hydrodyanmic equilibrium torus
  temperature ~$10^4$K, total mass~$10^9 M_\odot$
  threaded by weak toroidal B fields($P_{mag}/P_{gas}$~$10^{-4}$, $B_\phi$~50nG)
  constant rotation velocity ~ 220kms$^{-1}$
- halo : isothermal hydrostatic equilibruim, temperature=$10^6$K

Fig1. initial gas density distribution




- gravitational potential : Miyamoto-Nagai potential (including DM) + spiral potential

$$\Phi_{\rm sp}(r,\varphi,z) = \Phi_{\rm disk}(r,z)\epsilon_{\rm sp}\frac{r/r_a}{\{1+(r/r_a)^2\}^{3/2}}\frac{z_0}{\sqrt{z^2+z_0^2}}\cos\left[m\{(-\varphi-\Omega_{\rm sp}+\cot i_{\rm sp}\ln(r/r_0)\}\right]$$

where $\varepsilon_{sp}$=0.05, $r_a$=7.0kpc, $z_0$=0.3kpc, m=2, $\Omega_{sp}$=12.2kms$^{-1}$kpc$^{-1}$, $i_{sp}$=15°, $r_0$=1kpc
- radiative cooling : Raymond-Smith type($10^4$K<T<$10^6$K)
- boundary conditions : mirror symmetric boundary @ z=0 plane
  absorbing boundary in inner R=√($r^2$+$z^2$) < 0.8kpc and outer boundary regions

## 3. Results

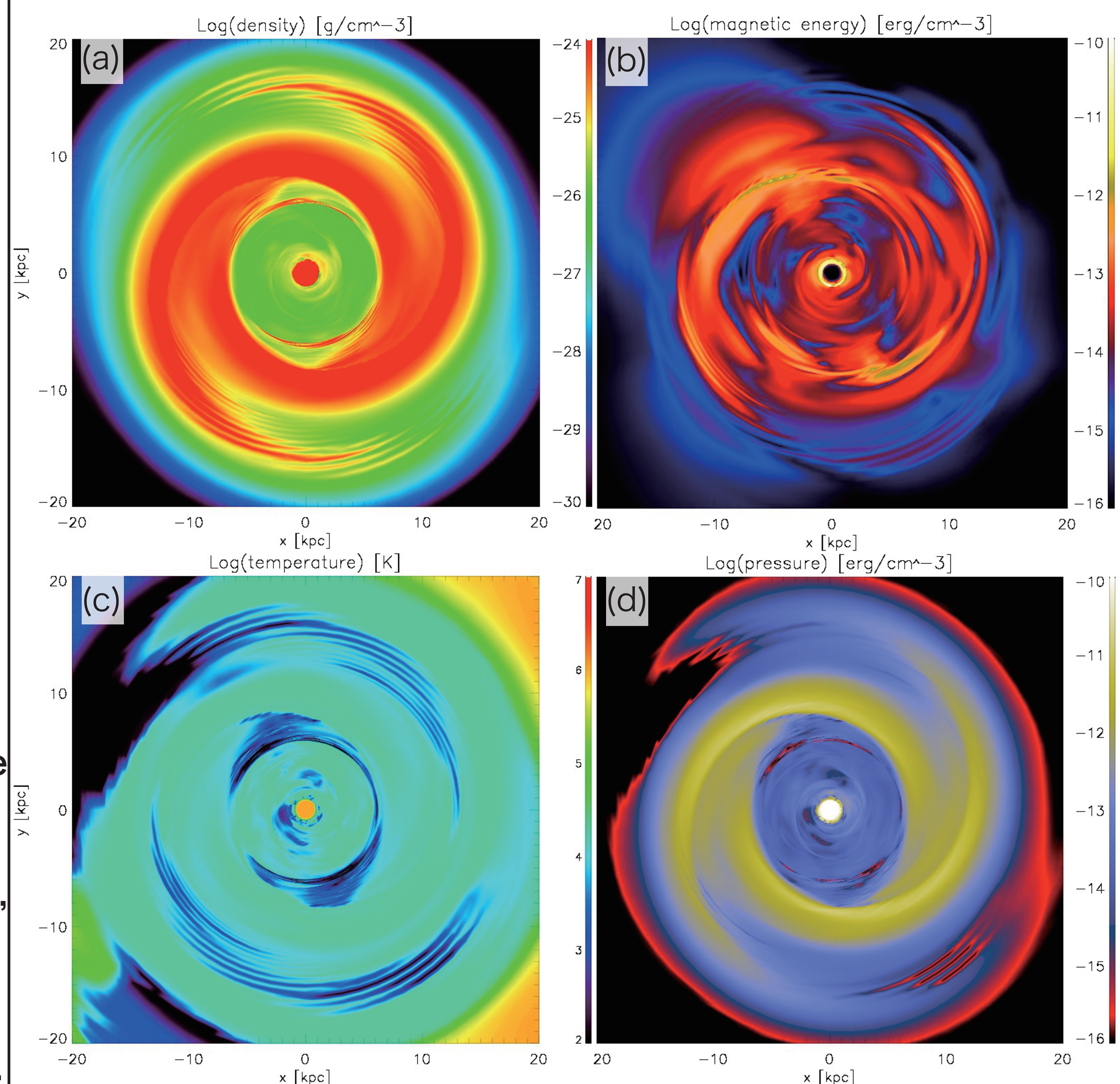



Fig2. Cross sections (a) gas density, (b) magnetic energy, (c) temperature and (d) pressure on z=0 plane @ t=260Myr

The horizontal slice demonstrates formation of isothermal spiral shocks and magnetic arms.

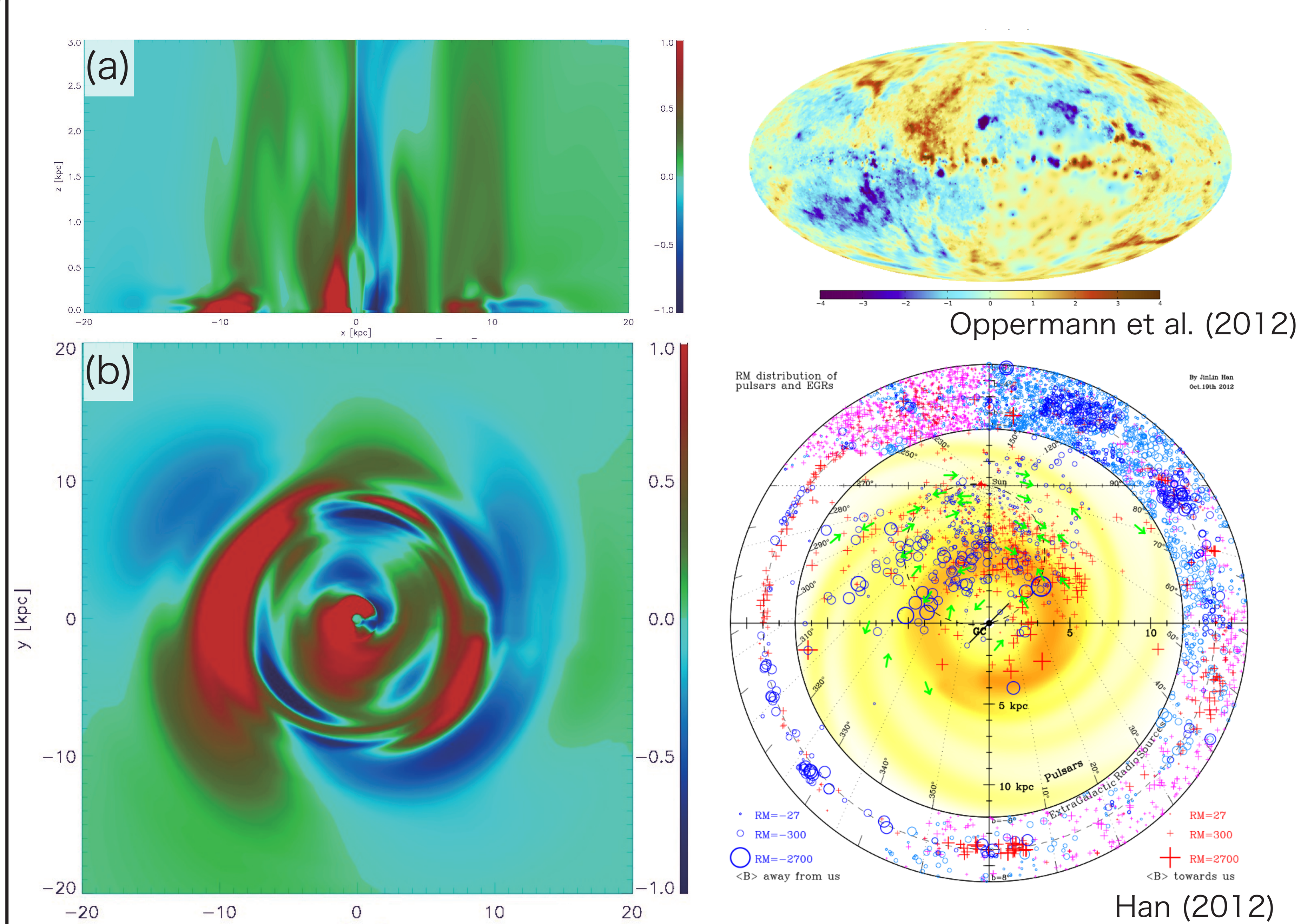



Fig3. mean toroidal magnetic fields on (a) x-z and (b) x-y planes @ t=260Myr. Positive and negative toroidal magnetic fields are marked with red and blue colours respectively.

Our results are qaulitatively consistent with observed distribution of RMs(Oppermann et al. (2012), Han (2012)).

## 4. Conclusions

①We have shown that spiral arms rapidly amplify magnetic fields.
②Our numerical models are consistent with RM maps.