# COSMIC-RAY DRIVEN DYNAMO IN GALACTIC DISKS

Michał Hanasz, CA UMK, Toruń

# COLLABORATION:

**Toruń:**

- Michał Hanasz
- Dominik Wóltański
- Kacper Kowalik

**Munich:**

- Harald Lesch
- Hanna Kotarba

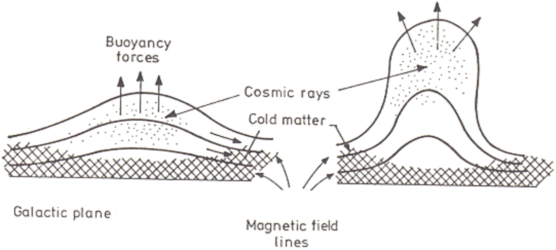
**Kraków:**

- Katarzyna Otmianowska-Mazur
- Grzegorz Kowal
- Marian Soida
- Barbara Kulesza
- Hubert Siejkowski
- Katarzyna Kulpa-Dybeł

**Bochum:**

- Dominik Bomans

Parker instability in the ISM (Parker 1966, 1967 )

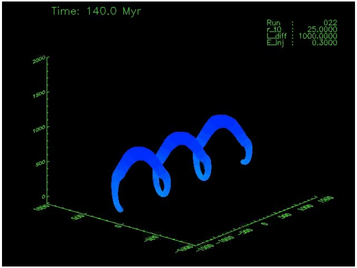



(from Longair 1994, *High Energy Astrophysics)*

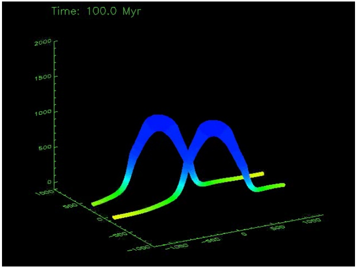
- Cosmic ray gas: an important ingredient - continuously supplied by SN remnants (diffusive shock acceleration), lead to strong buoyancy effects.
- Kinetic energy of SN II explosion $\sim 10^{51}$erg $\Rightarrow$ 10 % of $E_{\rm SN} \rightarrow$ acceleration of cosmic rays - charged particles (protons, electrons) accelerated in shocks to relativistic energies

## TOY MODEL: THIN FLUX-TUBE APPROXIMATION

(Hanasz & Lesch 2000, ApJ, 543, 235)




⇒ helical magnetic loops form on initially azimuthal magnetic field due to buoyancy of cosmic rays and the Coriolis force




⇒ small scale loops reconnect to form larger loops

⇒ generation of the large-scale radial m.f.

⇒ differential rotation: generation of the azimuthal m.f.

## SYSTEM OF RESISTIVE MHD EQUATIONS

$$\frac{\partial \boldsymbol{V}}{\partial t}+(\boldsymbol{V}\cdot\nabla)\boldsymbol{V} = -\frac{1}{\rho}\nabla(p+p_{CR})+\boldsymbol{g} -2\boldsymbol{\Omega}\times\boldsymbol{V}+\boldsymbol{\Omega}^2\boldsymbol{r}+\frac{1}{\rho}\nabla\left(\frac{B^2}{8\pi}\right)+\frac{\boldsymbol{B}\cdot\nabla\boldsymbol{B}}{4\pi\rho}$$

$$\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\boldsymbol{V})=0$$

$$\frac{\partial e}{\partial t}+\nabla(e\boldsymbol{V})=-p\nabla\boldsymbol{V}$$

$$p=(\gamma-1)e$$

$$\frac{\partial\boldsymbol{B}}{\partial t}=\nabla\times(\boldsymbol{V}\times\boldsymbol{B})+\eta\nabla^2 B$$

Diffusion - advection approximation
(eg. Schlickeiser & Lerche 1985, A&A, 151, 151)

$$\frac{\partial e_{cr}}{\partial t} + \nabla(e_{cr}\boldsymbol{V}) = -p_{cr}\nabla\boldsymbol{V} + \nabla(\hat{K}\nabla e_{cr}) \tag{1}$$
$$+ \text{ CR sources (SN remnants)}$$

$$p_{cr} = (\gamma_{cr} - 1)e_{cr} \tag{2}$$

Anisotropic diffusion of CRs
(Giaccalone & Jokipii 1998 , Jokipii 1999, Ryu et al. 2003)

$$K_{ij} = K_\perp \delta_{ij} + (K_\parallel - K_\perp)n_i n_j, \quad n_i = B_i/B, \tag{3}$$

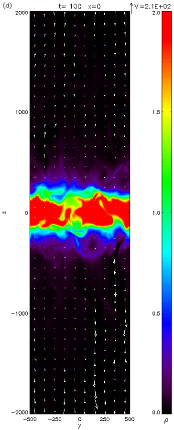
$$K_\parallel = 3 \cdot 10^{28}\text{cm}^{2}\text{s}^{-1}, \qquad K_\perp = (1-10)\%\,(K_\parallel)$$

**Original idea:** Parker (1992)

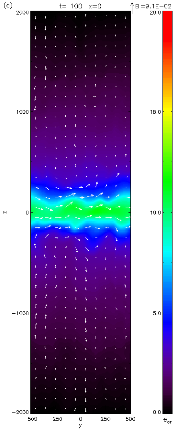
**Numerical model:** Hanasz, Kowal, Otmianowska-Mazur & Lesch, 2004)

- the cosmic ray component: diffusion-advection transport equation (Hanasz and Lesch 2003 - numerical algorithm).
- localized sources of cosmic rays: supernova remnants, exploding randomly in the disk volume, SN shocks & thermal effects neglected
- resistivity of the ISM (see Hanasz, Otmianowska-Mazur and Lesch 2002, and Hanasz and Lesch 2003, Kowal, Hanasz & Otmianowska-Mazur 2003) $\Rightarrow$ magnetic reconnection.
- sheared rotation (+ Coriolis and tidal forces in local simulations)
- realistic vertical disk gravity following the model of ISM in the Milky Way by Ferriere (1998)

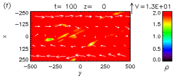
## MAGNETIC FIELD AMPLIFICATION



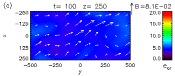

$\rho(y,z), \vec{V}(y,z)$



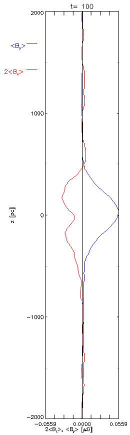

$e_{cr}(y,z), \vec{B}(y,z)$




$\rho(x,y), \vec{V}(x,y)$




$e_{cr}(x,y), \vec{B}(x,y)$




$\langle B_r\rangle(z), \langle B_\varphi\rangle(z)$

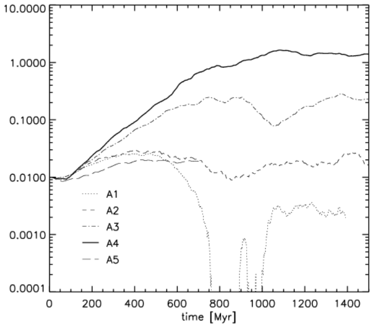
Slices through the computational box at $R_G = 5$kpc

& horizontally averaged magnetic field components.

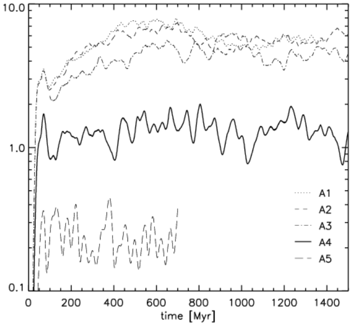
Hanasz, et al 2004 ApJ, 543, 235; 2006 AN 327, 469; 2009 A&A 498, 335)

Similar results for SN–thermally driven dynamo by Gressel et al 2008

Azimuthal magnetic flux




$B^2_{vert}/B^2_{azim}$




Runs: A1: $\eta = 0$, A2: $\eta = 1$, A3: $\eta = 10$, A4: $\eta = 100$, A5: $\eta = 1000$
Units: $1\text{pc}^2\text{Myr}^{-1} = 3 \cdot 10^{23}\text{cm}^2\text{s}^{-1}$

The fastest magnetic field amplification for magn. diffusivity

$$\eta \simeq 3 \cdot 10^{25}\text{cm}^2\text{s}^{-1}$$

- Weak influence of SN rate on magnetic field amplification in the range of 10% - 100% of the realistic value ($f_{SN} = 130/\mathrm{Myr}\ /\mathrm{kpc}^{\ 2}$ at $R \simeq 5\mathrm{kpc}$ ).
- The efficiency of m.f. amplification increases with rising $K_{\parallel}$ (up to $3 \times 10^{28}\mathrm{cm}^{\ 2}\mathrm{s}^{-1}$) and decreases with rising $K_{\perp}$ $\Rightarrow$ anisotropic diffusion $K_{\perp}/K_{\parallel} \leq 10\%$ necessary for efficient action of CR-driven dynamo.
- Final saturated magnetic fields reach energetic equipartition with gas kinetic energy
- CR energy density remains an order of magnitude larger than gas and magnetic energy densities in local CR-driven dynamo models.

- Dynamo coefficients in Parker unstable disks with cosmic rays and shear (Kowal et al. 2006, A&A 445, 915)
- Computation of $\alpha$ and $\eta$ tensors in the framework of Kleeorin et al. (2003) and Blackman & Field (2003) nonlinear $\alpha - \omega$ dynamo theories (Otmianowska-Mazur et al. 2007, ApJ, 668, 110)
- Synthetic radio-maps of a global galactic disk based on local CR-driven dynamo models exhibit X-type structures (Otmianowska-Mazur et al 2009, ApJ, 693,1)
- Demonstration that CR-driven dynamo can work in physical conditions (rotation, shearing rate) of irregular galaxies (Siejkowski et al 2010, A&A, 510, 97)

- CR-driven dynamo works in a wide range of parameter space!
- but ... CR excess is worrying.

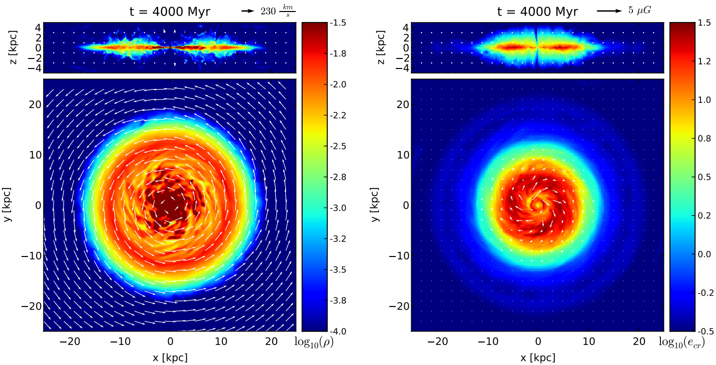
Improvements necessary:

- Global galactic disk simulations → escape of CR along horizontal magnetic filed in galactic plane, to avoid the CR excess.

## GALACTIC DISK MODEL

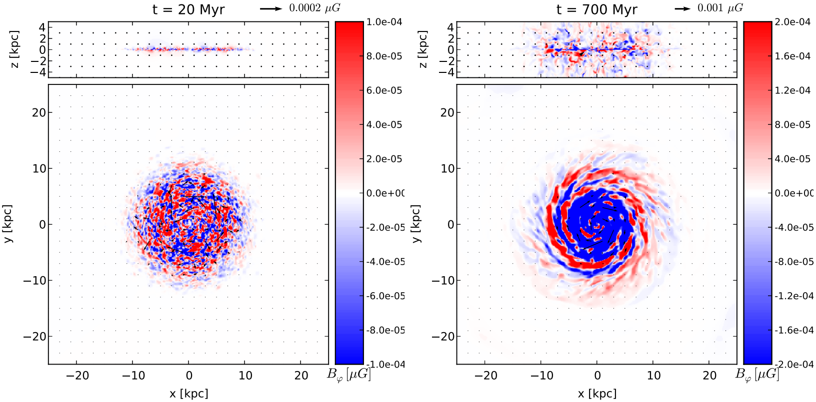
- Galactic gravitational potential: halo+bulge+disk (Allen & Santillan 1991)
- Flat rotation curve for $R_G \geq 3$kpc
- Interstellar gas: Global model of ISM for the Milky Way (Ferriere 1998), molecular ring at $R_G = 4.5$kpc
- **No magnetic field and no CRs at $t = 0$**
- SN rate $\propto$ star formation rate $\propto$ to gas column density: maximum of SN activity at $R_G = 4.5$kpc , Gaussian distribution of SNe in $z$-coordinate ($H = 200$pc )
- 10% of of SN energy output is converted to CR energy.
- **weak ($10^{-4}\mu$G) dipolar, small scale ($r \sim 50$pc ) randomly oriented magnetic field is supplied locally with every SN explosion for $t \leq 1$Gyr**
- resistive dissipation of small-scale magnetic fields.

Multifluid, parallel (MPI) magnetohydrodynamical code PIERNIK (Hanasz et al. 2008): http://piernik.astri.uni.torun.pl, GALERA, TASK Gdańsk, resol. 500x500x200 up to 1000x1000x200 grid cells, $\simeq$ 100k-250k CPU h per experiment, 400-1600 CPU cores.



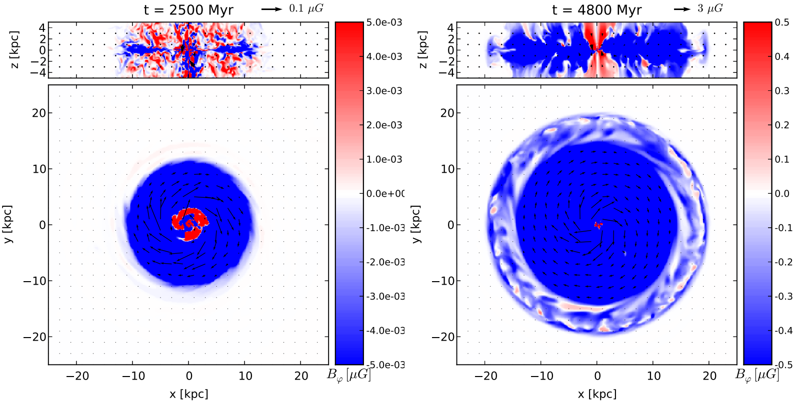

Gas density + wectors of gas velocity (left), a and cosmic ray energy density + vectors of magnetic field at $t = 4$Gyr .

Hanasz, Woltański, Kowalik 2009, ApJ Letter 706L, 155




Colours: – azimuthal (toroidal) magnetic field component blue: $B_\varphi < 0$, red: $B_\varphi > 0$

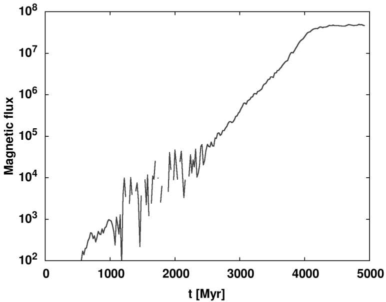
Exploding magnetized stars spread weak irregular magnetic fields in the interstellar medium

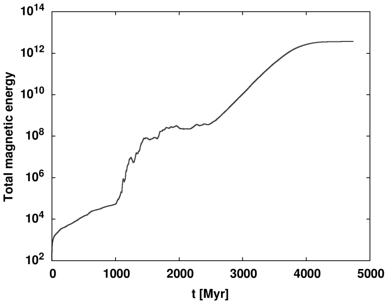



Colours: – azimuthal (toroidal) magnetic field component blue: $B_\varphi < 0$, red: $B_\varphi > 0$

Cosmic rays resulting from Supernova Explosions, and disk rotation cause amplification and ordering of magnetic field in the interstellar medium

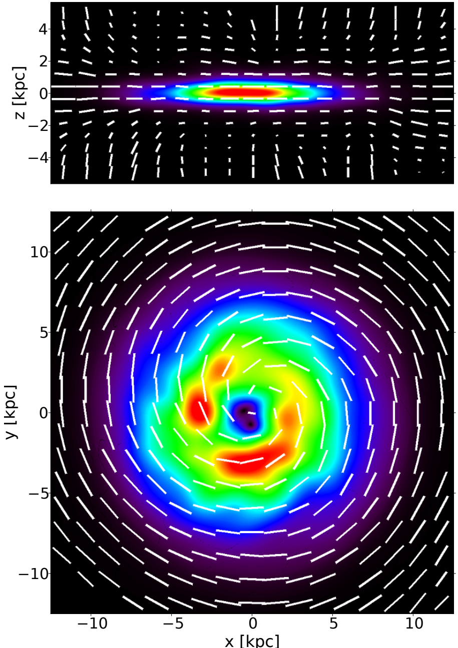
## GROWTH OF MAGNETIC FLUX AND ENERGY IN THE GLOBAL DISK




Amplification timescale of the large-scale magnetic field component:

$$T_{\langle B \rangle} = 270\mathrm{Myr} \simeq T_{rot}$$



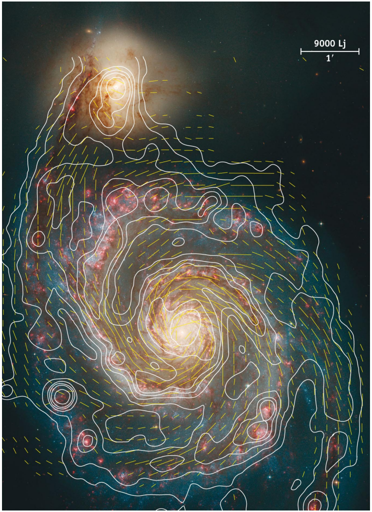

X-type structure in edge-on view

**Synthetic radio-maps of the simulated galaxy reproduce the main features observed in real galaxies**

Spiral structure of magnetic field in the disk plain

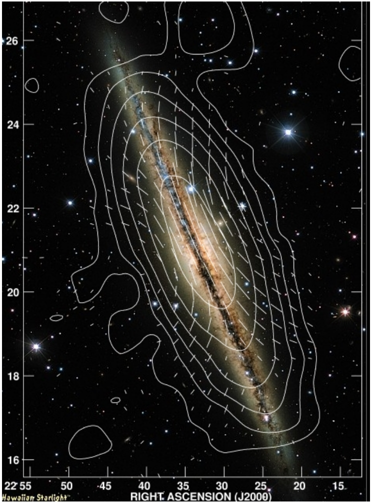
## MAGNETIC FIELDS IN SPIRAL GALAXIES - RADIO OBSERVATIONS

M51



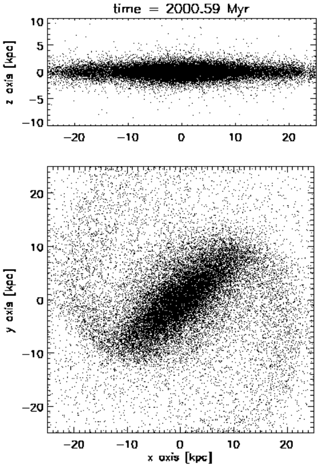

A. Fletcher et al. 2008

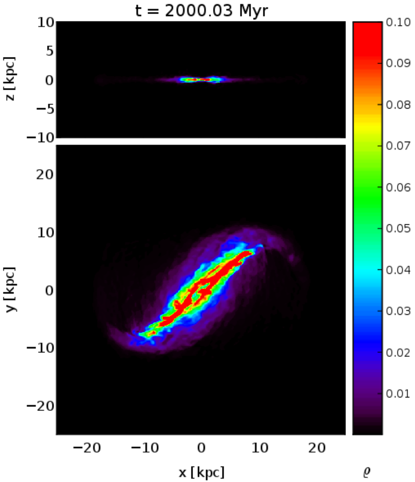
NGC891

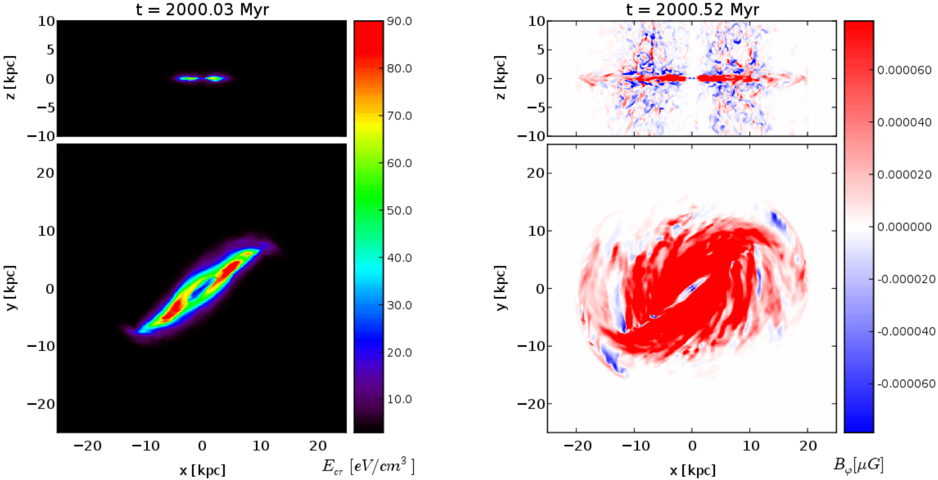



M. Krause et al. 2008

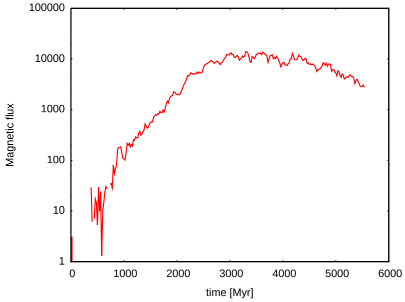
## LIVE DISKS: STARS + GAS

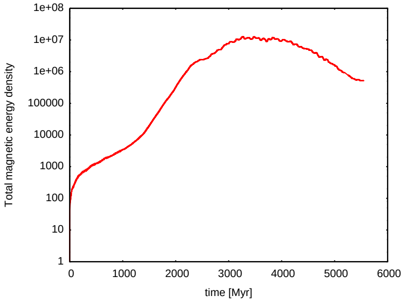



t = 2000.03 Myr
z [kpc]
y [kpc]
x [kpc]
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
$E_{cr}$ $[eV/cm^3]$
t = 2000.52 Myr
0.000060
0.000040
0.000020
0.000000
-0.000020
-0.000040
-0.000060
$B_\varphi [\mu G]$

## MAGNETIC FIELD AMPLIFICATION IN THE LIVE DISK



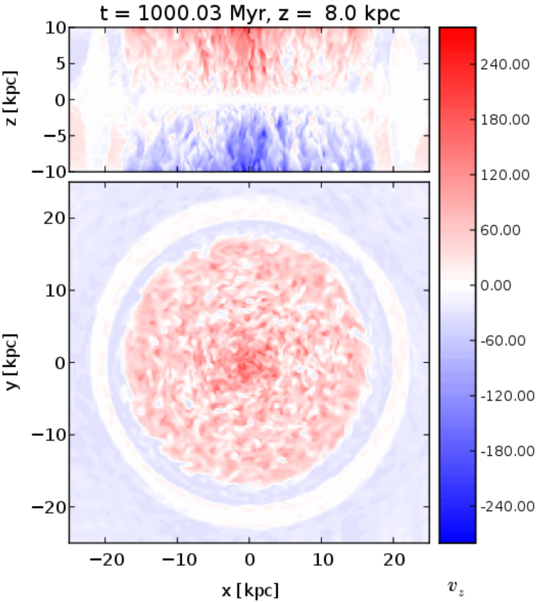




Magnetic field amplification stops too early

– due to the loss of angular momentum in the bar ?

WE NEED A BETTER N-BODY DISK

## CR-DRIVEN WIND



- COSMIC RAY DYNAMICS LEADS TO A VERY EFFICIENT MAGNETIC FIELD AMPLIFICATION IN GALACTIC DISKS
- Amplification timescale $\sim t_{rot} \Rightarrow$ growth of the large-scale magnetic field by several orders of magnitude, fast enough to expect $\sim 1\mu$G magnetic field in galaxies at $z \sim 1 \div 2$
- Dipolar small-scale magnetic fields supplied by exploding stars build up a large scale magnetic field $\Rightarrow$ no need for seed fields of cosmological origin.
- Efficient regularization of the random magnetic field component.
- Growth of magnetic field, driven by SNe, far outside the star forming ring.
- Synthetic radio-maps resemble magnetic field structures in real galaxies.
- Simulations of the live disk need improvments