COSMIC-RAY DRIVEN DYNAMO IN GALACTIC DISKS

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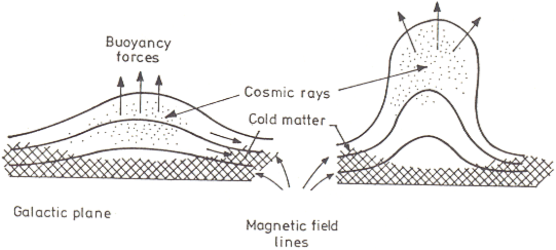
Parker instability in the ISM (Parker 1966, 1967)

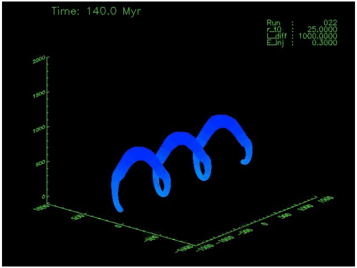


(from Longair 1994, *High Energy Astrophysics)*

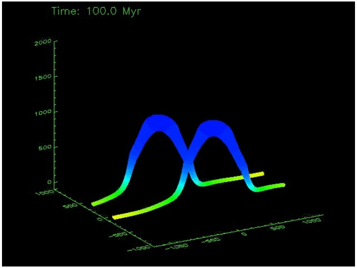
- Cosmic ray gas: an important ingredient - continuously supplied by SN remnants (diffusive shock acceleration), lead to strong buoyancy effects.
- Kinetic energy of SN II explosion $\sim 10^{51}$erg $\Rightarrow$ 10 % of $E_{\rm SN} \rightarrow$ acceleration of cosmic rays - charged particles (protons,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

RESISTIVE MHD EQUATIONS

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

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

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

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

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

CR TRANSPORT EQUATION

Diffusion - advection approximation

(eg. Schlickeiser & Lerche 1985, A&A, 151, 151)

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

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

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)

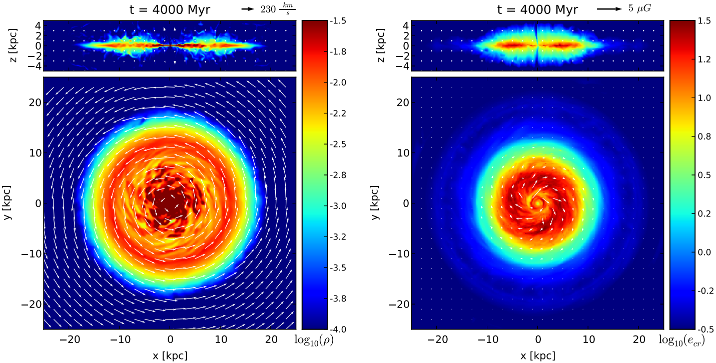
Shearing box model:
Hanasz, Kowal, Otmianowska-Mazur & Lesch, 2004, ApJL, 605, 33
Hanasz, Otmianowska-Mazur, Kowal & Lesch, 2009, A&A, 498, 335

- the cosmic ray component: anisotropic diffusion-advection transport (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.
- differential rotation (+ Coriolis and tidal forces in local simulations)
- realistic vertical disk gravity following the model of ISM in the Milky Way by Ferriere (1998)

GALACTIC DISK MODEL

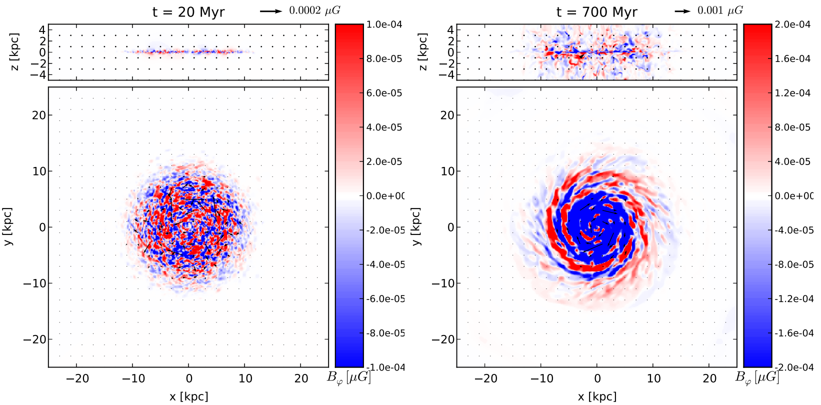
- Galactic gravitational potential: halo+bulge+disk (Allen & Santillan 1991)
- Interstellar gas: Global model of ISM for the Milky Way (Ferriere 1998), molecular ring at $R_G = 4.5$kpc
- **No magnetic field at** $t = 0$
- SN rate $\propto$ star formation rate $\propto$ to gas column density: maximum 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.



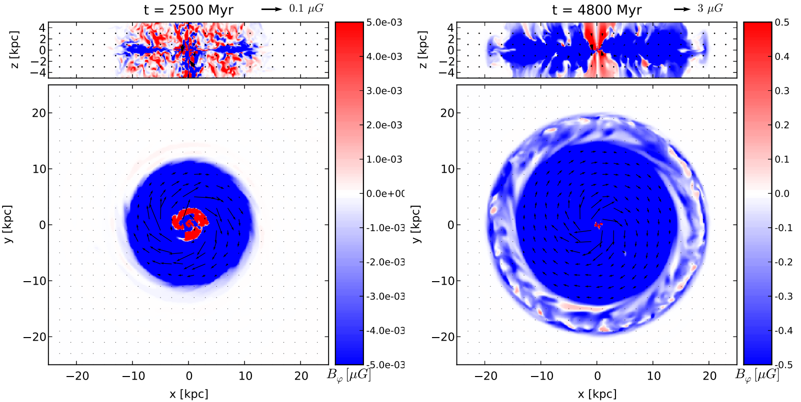
Gas density + wectors of gas velocity (left), a and cosmic ray energy density + vectors of magnetic field at $t = 4$Gyr .

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



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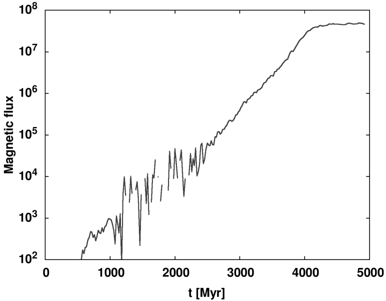
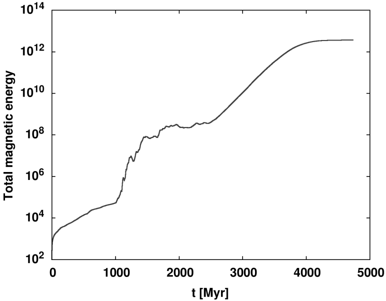
Cosmic rays resulting from Supernova Explosions, and disk rotation cause amplification and ordering of magnetic field in the interstellar medium

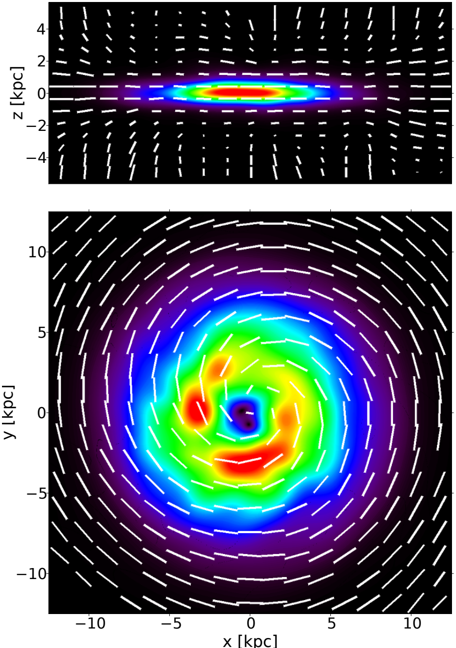
GROWTH OF MAGNETIC FLUX AND ENERGY IN THE GLOBAL DISK





Amplification timescale of the large-scale magnetic field component:

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



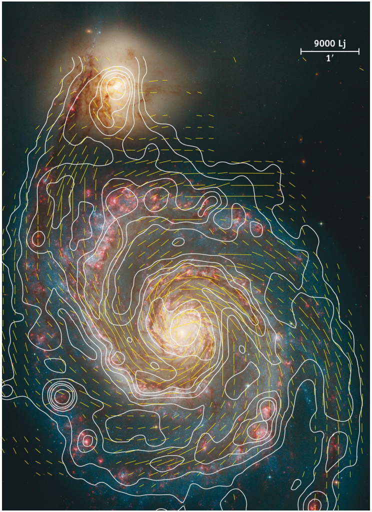
X-type structure in edge-on view

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

Spiral structure of magnetic field in the disk plain

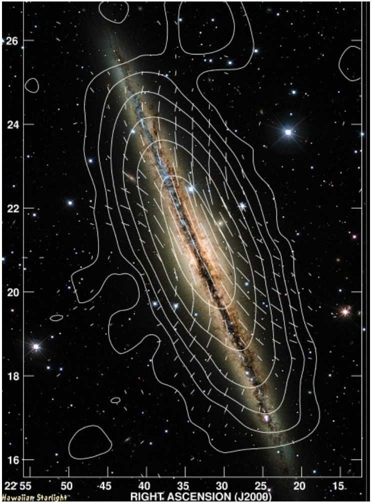
MAGNETIC FIELDS IN SPIRAL GALAXIES - RADIO OBSERVATIONS

M51



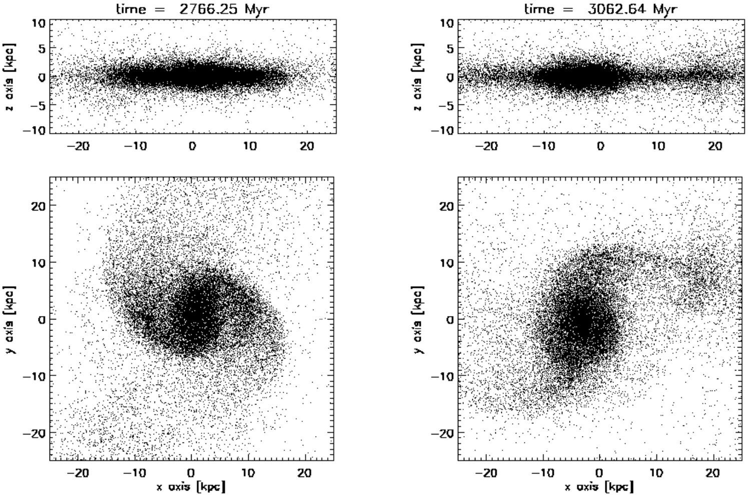
A. Fletcher et al. 2008

NGC891



M. Krause et al. 2008

N-body simulations: VINE code (Wetzstein et al 2008)
Simulations by Domink Woltanski, PhD thesis (in prep)



Evolution of gas density and toroidal magnetic field in the gravitational field of N-body system (PIERNIK code)
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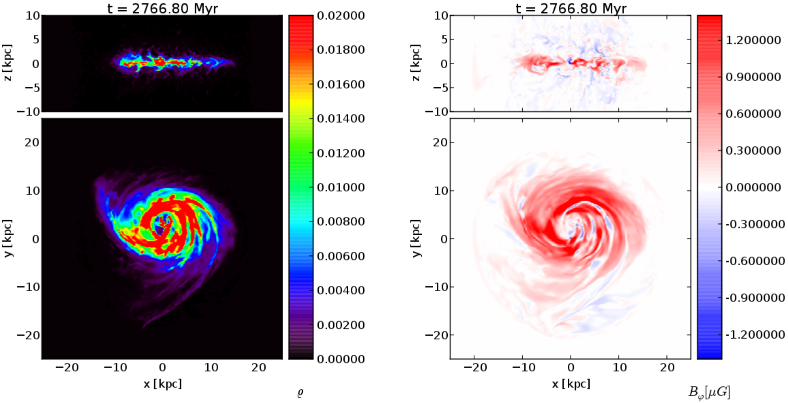

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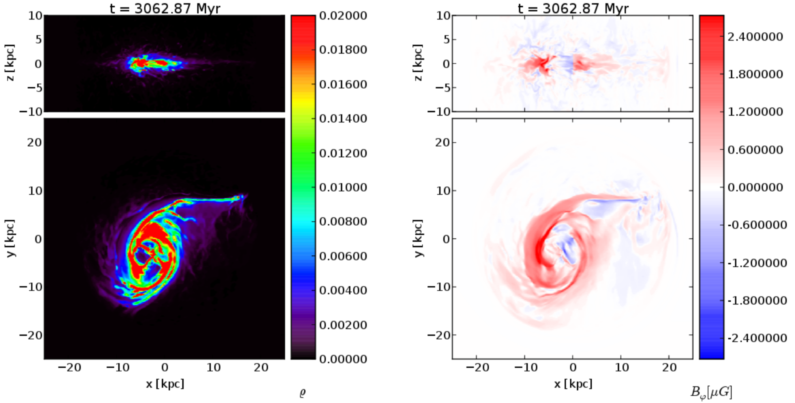

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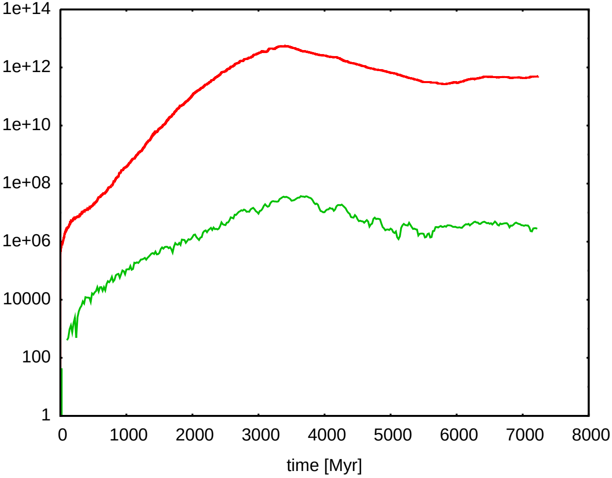

Amplification of magnetic energy (red) and azim. magnetic flux (green)

- First selfconsistent model of magnetic filed amplification and CR propagation
- 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 formation region.
- Synthetic radio-maps resemble magnetic field structures in real galaxies.
- Magnetic field in models based on N-body simulations tend to reproduce real galaxies.

IN PROGRESS:

- Multicomponent, energy dependent transport of CR nuclei, radioactive decay & nuclear reactions with ISM nuclei $\Rightarrow$ towards GALPROP functionality in dynamically evolving galactic magnetic fields.
- Synchrotron cooling of CR electrons $\Rightarrow$ selfconsistent global galactic models of synchrotron radioemission