MAGNETIC FIELD STRUCTURES FROM THE COSMIC-RAY-DRIVEN DYNAMO

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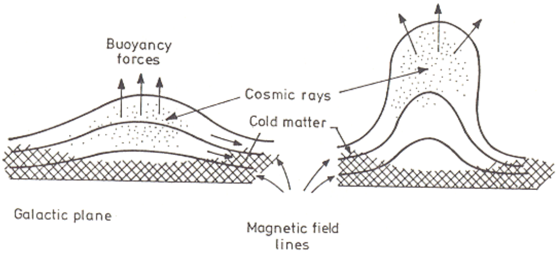
Parker instability in the ISM (Parker 1966, 1967)

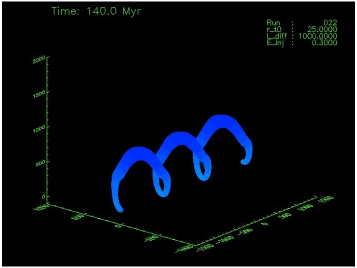


(from Longair 2007, *High Energy Astrophysics)*

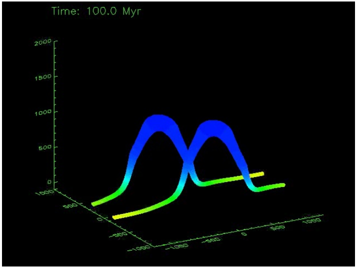
- Cosmic ray gas: an important ingredient - accellerated in SN remnants (see e.g. Hillas 2005, Ackermann et al. 2013), lead to strong buoyancy effects.
- Kinetic energy of SN II explosion $\sim 10^{51}$erg $\Rightarrow$ 10 % of $E_{\rm SN} \rightarrow$ acceleration of cosmic rays - charged particles (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



- ⇒ magnetic loops reconnect – changing magnetic topology
- ⇒ generation of the large-scale radial m.f.
- ⇒ differential rotation: generation of the azimuthal m.f.

MHD EQUATIONS

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

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

$$p = c_s^2 \rho \qquad \text{(isoth.approx)}$$

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

CR TRANSPORT EQUATION

Diffusion - advection approximation

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

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

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

Anisotropic diffusion of CRs

(Giaccalone & Jokipii 1998 , Jokipii 1999, Ryu et al. 2003)

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

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

Original idea: Parker (1992)

Shearing box model:

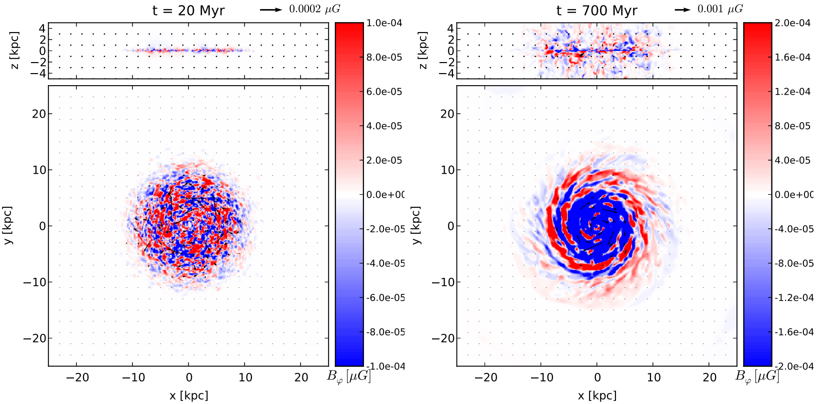
Hanasz, Kowal, Otmianowska-Mazur & Lesch, 2004, ApJL, 605, 33
Hanasz, Otmianowska-Mazur, Kowal & Lesch, 2009, A&A, 498, 335
Siejkowski et al., 2010, A&A, 510, 97

- differential rotating, gravitationally stratified galactic disk
- localized sources of cosmic rays: supernova remnants, exploding randomly in the disk volume, SN shocks & thermal effects neglected (see Gressel 2008a,b for complementary dynamo models directly powered by SN energy output)
- field-aligned, anisotropic diffusive transport of CRs (Hanasz and Lesch 2003 - numerical algorithm).
- resistivity of the ISM (see Hanasz, Otmianowska-Mazur and Lesch 2002) $\Rightarrow$ changing magnetic field topology and routes for CR propagation.

GALACTIC DISK MODEL - MW (Hanasz et al 2009, ApJ 706L, 155)

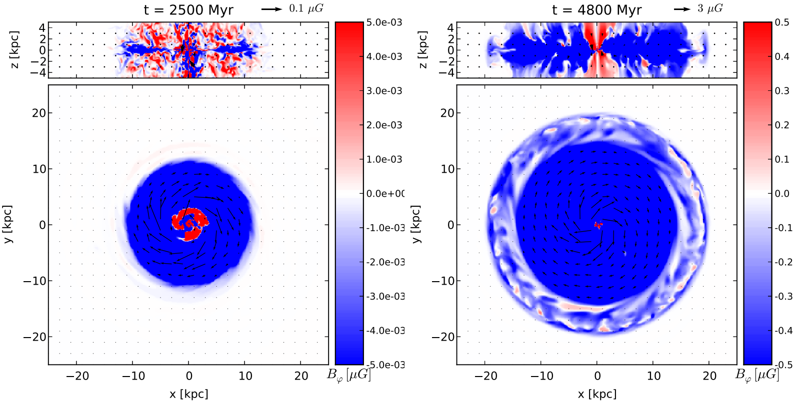
(see also dwarf galaxy models by Siejkowski et al. A&A 2014, 562, 136

- Galactic gravitational potential: halo+bulge+disk: analytical model (Allen & Santillan 1991), N-body model (Hernquist 1993)
- Interstellar gas: Global model of ISM for the Milky Way (Ferriere 1998)
- **Schmidt-Kennicutt law:** SFR $\propto$ (gas density)$^{1.4}$
- SNR $\propto$ SFR
- 10% of of SN energy output is converted to CR energy.
- **No magnetic field at** $t = 0$
- **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**



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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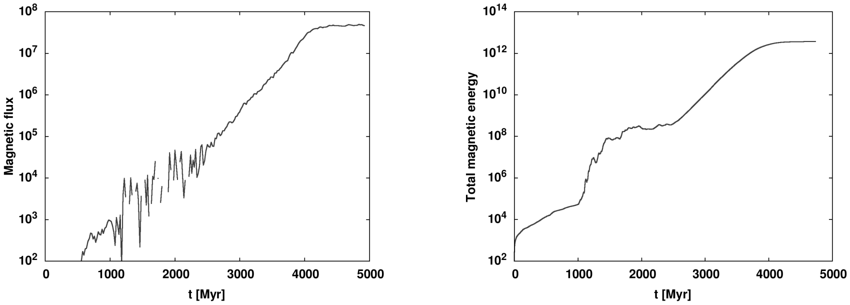
Cosmic-ray driven buoyancy, and disk rotation cause amplification and ordering of magnetic field in the interstellar medium

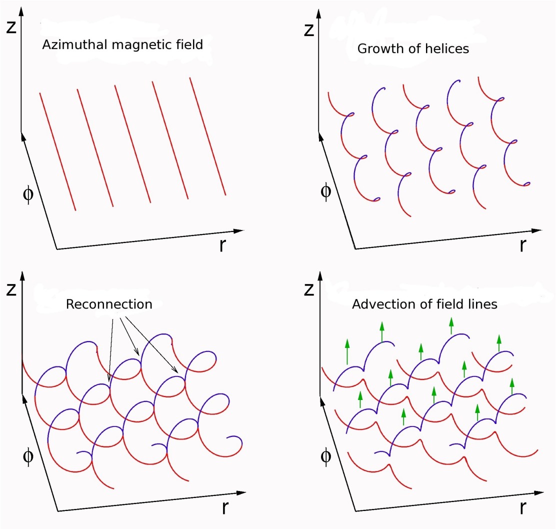
GROWTH OF MAGNETIC FLUX AND ENERGY IN THE GLOBAL DISK



Amplification timescale of the large-scale magnetic field:

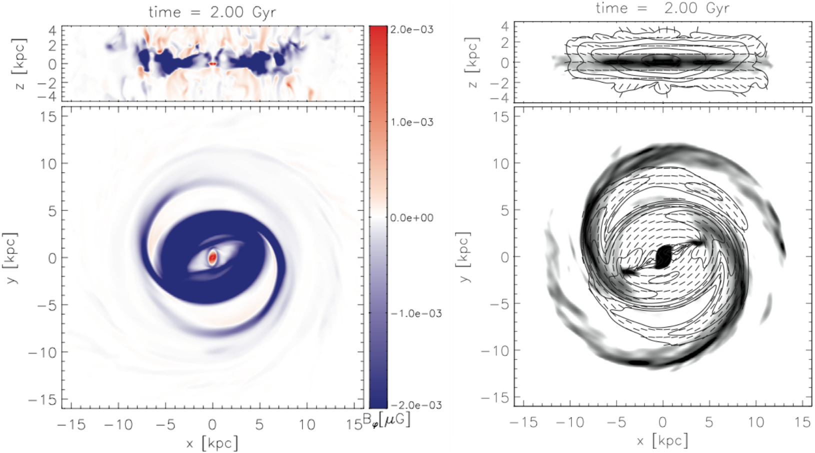
$$T_{\langle B \rangle} = 270\mathrm{Myr} \ \simeq \ T_{rot}$$

Parker instability + magnetic reconnection



Hanasz & Lesch (1998)

Axisymmetric gravitational potential + elliptical bar



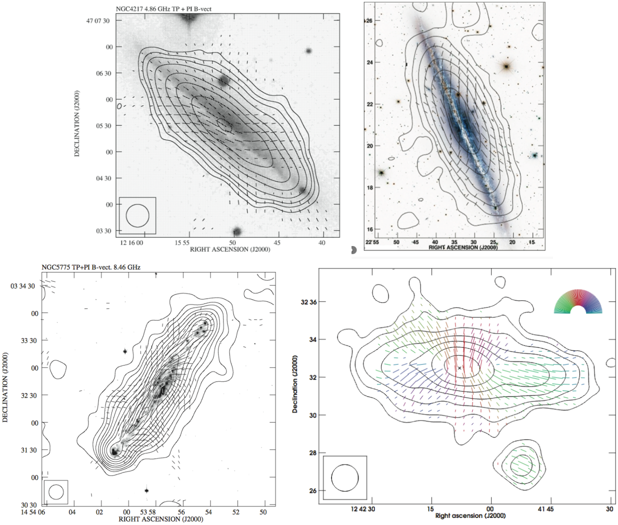
Colours: – azimuthal magnetic field component blue: $B_\varphi < 0$, red: $B_\varphi > 0$

– magnetic arms form in between gaseous arms

– 'X'-shaped structures in the edge-on view

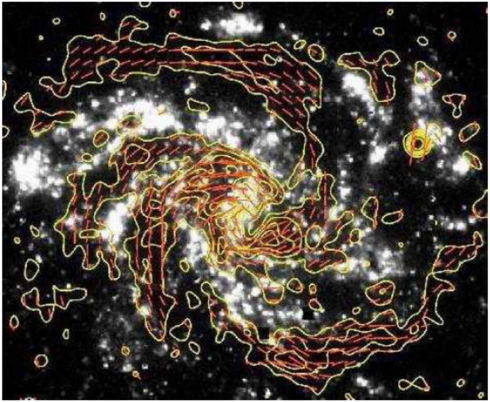
Kulpa-Dybel et al. 2011, ApJL, 733,L18

X-SHAPED STRUCTURES IN EDGE-ON GALAXIES – EXAMPLES



Soida (2005), Krause (2009), Soida (2011), Mora&Krause(2013)

REGULAR MAGNETIC FIELD IN INTERARM REGIONS – NGC6946

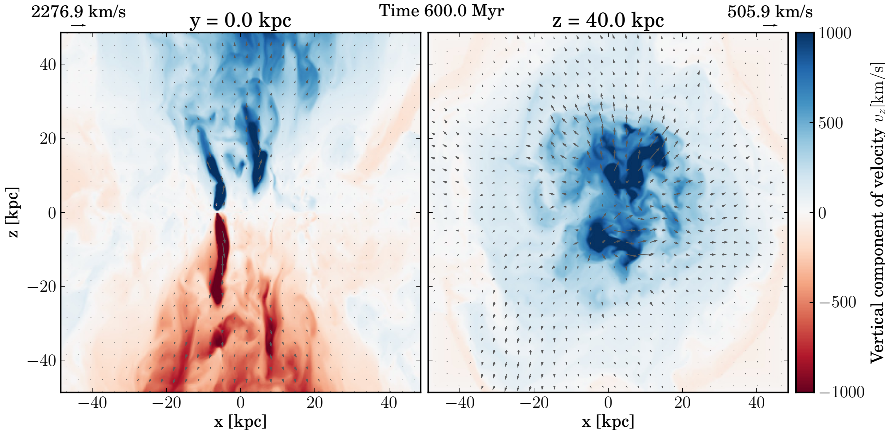


NGC 6946, Beck & Hoernes 1996, Beck 2011

Interpreted by varying dynamo parameters between arms and interarm regions. (Moss et al 2013, Chamandy et al 2013a,b) and stronger outflows in arm regions (Chamandy et al. 2014)

CR-DRIVEN WINDS

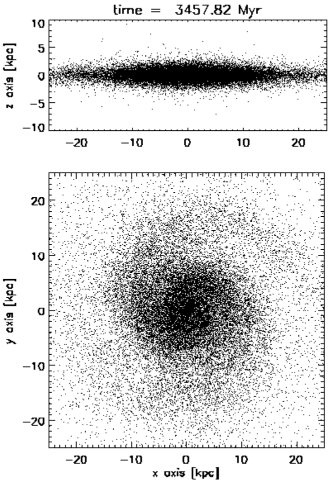
- Breitschwerdt, McKenzie & Voelk (1991), Zirakashwilli et al (1996), Ptuskin et al 1997, Dorfi & Breitschwerdt (2012), Heesen et al (2009), Everett et al (2008)
- **3D time-dependent CR-driven wind models:**
  Uhlig et al 2012, MNRAS, 423, 2374
  Booth, et al 2013, ApJ 777, L16
  Hanasz et al. 2013 , ApJ 777, L38
  Salem & Bryan 2013, MNRAS, 437, 3312

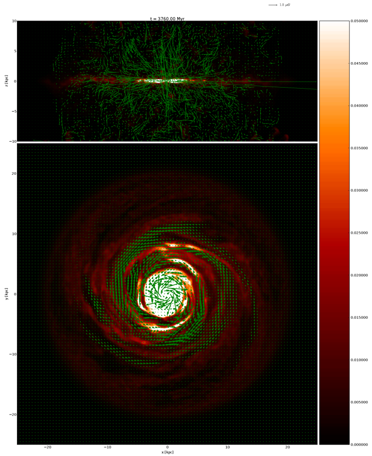


Vertical component of velocity. Collimated streams of high velocity gas extend several 10 kpc above and below the disk in a gas-reach, high star formation galaxy (Hanasz et al 2013)

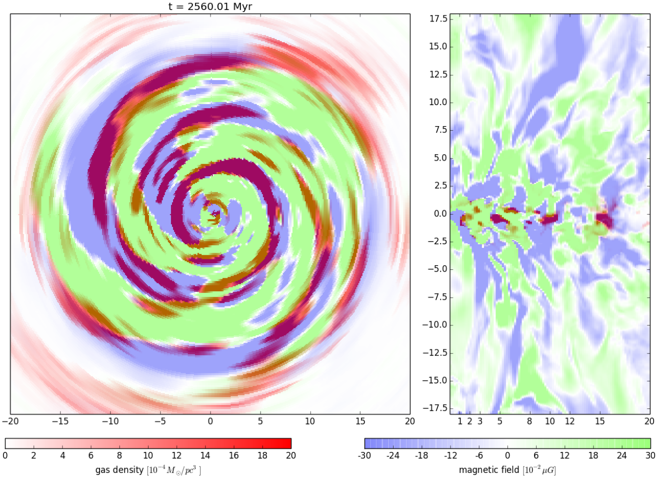
Gravitational potential from N-body simulations – VINE (Wetzstein et al 2008), MHD+CR – PIERNIK

From now on – results of Dominik Wółtański PhD thesis (in prep)

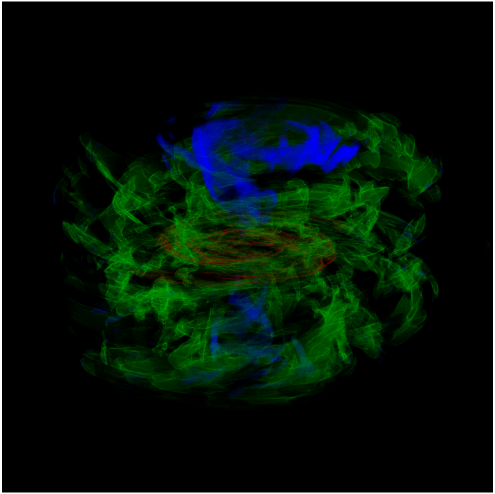




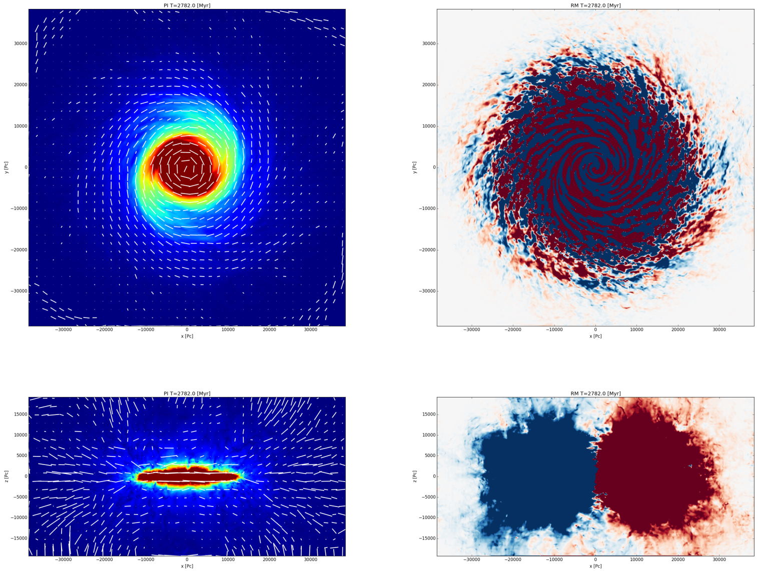
Toroidal magnetic field filtered by FFT – only modes $m = 1 \div 12$ in radial-vertical and horizontal slices (axisymmetric mode subtracted) (green: excess of B_φ, blue: deficit of B_φ, red: excess of gas density in arms.) – see also poster by Dominik.



3D volume rendering of azimuthal magnetic field component, rotation of the viewpoint, time fixed.



PI + polarization vectors and RM.



- Galactic winds associated to CR-driven dynamo lead to large-scale helical magnetic fields in galactic halos.
- Non-uniform magnetic helices are based in the underlying disk.
- Visual inspection indicates that the large-scale magnetic helices originate from magnetic arms.
- Due to enhanced SN rate in arms (Schmidt-Kennicutt law) winds advect magnetic field structures produced in the interarm regions – consistent with Chamandy (2014) interpretation.
- Synchrotron polarization radiomaps indicate that the magnetic helices are visible as X-shaped structures.
- Faraday rotation maps: the helices are formed by regular magnetic field, but depolarization effects cancell polarized emission near the rotation axis.
- Magnetic arms and X-shaped magnetic structures in galactic halos appear as closely related phenomena.