POLARIZED EMISSION OF EDGE-ON GALAXIES IN COMPARISON WITH THE COSMIC-RAY DRIVEN DYNAMO MODEL

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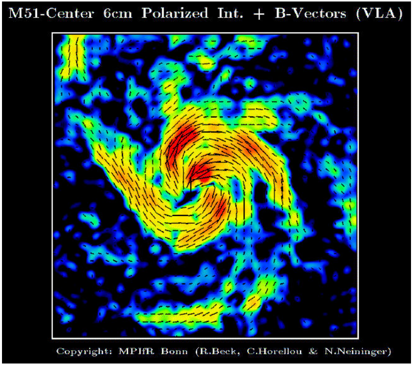
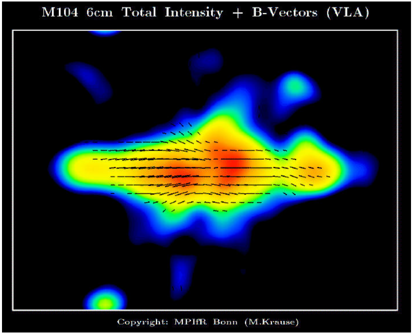


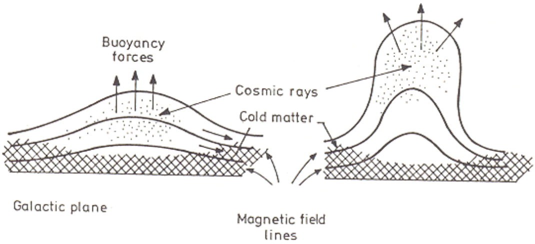


review papers: Beck et al. (1996); Kulsrud (1999); Widrow (2002)

- Externally forced numerical simulations of a local cube taking into account the back-reaction of magnetic field on turbulent motions (Cattaneo & Hughes 1996) showed that the Lorentz force strongly suppresses the turbulent dynamo action.
- One of the aspects of the back reaction problems is related to the conservation of the total magnetic field helicity in media with the high magnetic Reynolds numbers $R_m \gg 1$ (e.g. Berger & Field 1984, Brandenburg & Subramanian 2005).
  There are two ways to solve this problem:
- constant ejection of the magnetic helicity flux through boundaries (Blackman & Field 2000 and Kleeorin et al. 2000)
- creation of helicity with the opposite signs at large and small scales (see Brandenburg et al. 2002, Kleeorin et al. 2002)

- In their paper Blackman & Field 2000 found that the strong suppression of α obtained by Cattaneo & Hughes 1996 in their numerical simulations was caused by the periodic boundary conditions assumption.
- But the calculations concerning a local cube with external forcing and the open boundaries did not solve the quenching problem, as well (e.g. Brandenburg & Dobler 2001, Brandenburg & Sokoloff 2002).

Parker instability in the ISM (Parker 1966, 1967)



from Longair 1994, *High Energy Astrophysics)*

Mouschovias, Shu & Woodward (1974), Blitz & Shu (1980), Franco et al. (2002):

large cloud complexes, OB associations form as a result of Parker instability

spatial separation of superclouds $\sim$ kpc & cloud masses $10^6 \div 10^7 M_\odot$ consistent with predictions of the Parker instability model.

Cosmic ray gas: an important ingredient - continuously supplied by SN remnants (diffusive shock acceleration), provide buoyancy without any restoring force.

- The major source of ISM disturbances: SN type II explosions (Mac Low & Klessen, 2004, RvMP 76, 125)
- Kinetic energy of SN II explosion $\sim 10^{51}$erg $\Rightarrow$ 10 % of $E_{\rm SN} \rightarrow$ accelleration of cosmic rays - charged particles (protons, electrons, ...) accelerated in shocks to relativistic energies
  Ellison, Decrouchelle, Ballet, 2004, A&A 413, 189: 50 % conv. rate possible
- instabilities due to CR streaming $\Rightarrow$ turbulence $\Rightarrow$ scattering of CR particles (Kulsrud & Pearce 1969) $\Rightarrow$ diffusive propagation of CRs
- Particle diffusion numerical experiments (Giaccalone & Jokipii 1998 , Jokipii 1999) $\boldsymbol{B}_{\rm turb} \sim \boldsymbol{B}_{\rm uniform} \Rightarrow K_\perp / K_{||} \sim 0.05$, $K_{||} \sim 10^{28} \div 10^{29}$cm ^{2}s^{-1}
- In the fluid approximation: diffusion-advection equation with the diffusion tensor adopted for the anisotropic diffusion and source terms from SN shocks

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

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

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

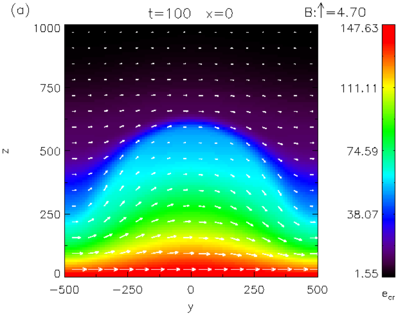
Anisotropic diffusion of CRs
(eg. Ryu et al. 2003, ApJ, 581, 338):

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

and

$$\gamma_{\rm cr} = 14/9 \quad (4)$$

Dynamics of magnetized ISM with CRs:
MHD equations + CR diffusion-advection equation (CR MHD)
In presence of cosmic rays additional source term: $-\nabla P_{\rm CR}$
on the r.h.s. of the gas equation of motion.
(eg. Berezinski et al. 1990, *Astrophysics of Cosmic Rays*)

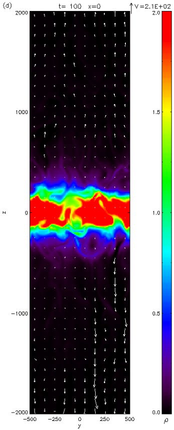


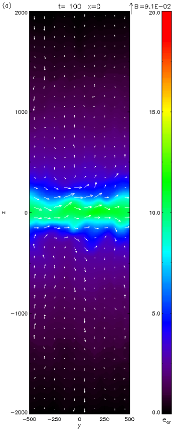
Parker loop due to CR buoyancy
Hanasz & Lesch 2003, A&A 412, 331

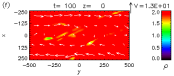
Other implementations of CRs in MHD codes:
Kuwabara, Nakamura, & Ko (2004),
Snodin, Brandenburg, Mee & Shukurov (2006) – a more accurate description of CR diffusion & confinement

(Hanasz, Kowal, Otmianowska-Mazur & Lesch, 2004)

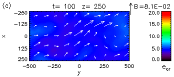
- the cosmic ray component: diffusion-advection transport equation (Hanasz and Lesch 2003 - numerical algorithm).
- localized sources of cosmic rays: supernova remnants, exploding randomly in the disk volume, SN shocks & thermal effects neglected
- resistivity of the ISM (see Hanasz, Otmianowska-Mazur and Lesch 2002, and Hanasz and Lesch 2003) $\Rightarrow$ magnetic reconnection.
- shearing boundary conditions, a modification of periodic boundary conditions (Hawley, Gammie and Balbus 1995) + Coriolis and tidal forces, aimed for modeling of differentially rotating disks in the local approximation,
- realistic vertical disk gravity and rotation following the model of ISM in the Milky Way by Ferriere (1998)



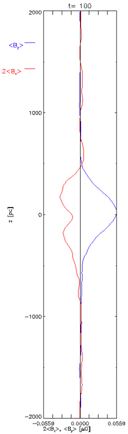




$\rho(x,y), \vec{V}(x,y)$



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

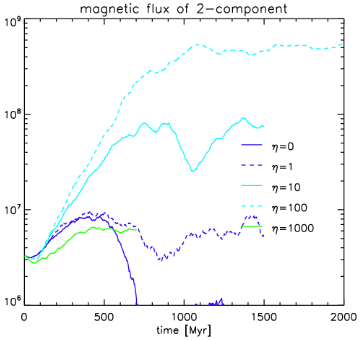


$\rho(y,z), \vec{V}(y,z)$ $e_{cr}(y,z), \vec{B}(y,z)$ $\langle B_r\rangle(z), \langle B_\varphi\rangle(z)$

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)

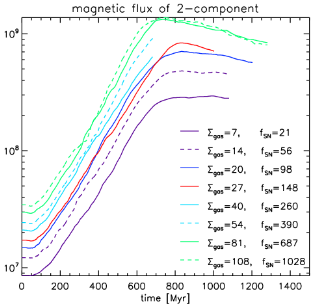


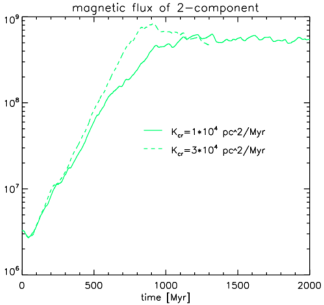
Magnetic diffusivity η – a free parameter
Units: $1\mathrm{pc}^2\mathrm{Myr}^{-1} = 3 \cdot 10^{23}\mathrm{cm}^2\mathrm{s}^{-1}$

while the commonly accepted value for turbulent diffusivity in ISM is:

$$\eta_{turb} \simeq 1/3 v_{turb} L_{turb} \sim 10^{26}\mathrm{cm}^2\mathrm{s}^{-1}$$

AMPLIFICATION OF B vs. SN RATE and CR DIFFUSION COEFFICIENT





$f_{SN} \propto f_{SF} \propto \Sigma_{gas}^{1.4}$ – Schmidt-Kennicutt law

f_{SN} : $\times 1\,\mathrm{kpc}^{-2}\,\mathrm{Myr}^{-1}$,
Σ_{gas} : $\times 10^{20} N_H\,\mathrm{cm}^{-2}$

$\tau_{\mathrm{dynamo}} \simeq 130\mathrm{Myr} \simeq T_{\mathrm{rot}}$ at $R_G = 5\mathrm{kpc}$

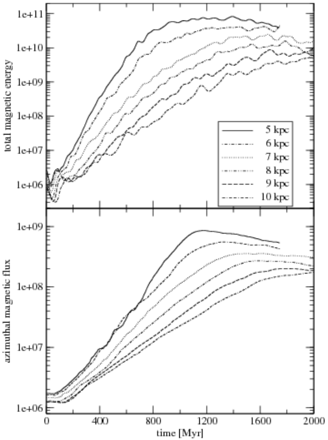
- Magnetic field amplification in a wide range of SN rates
- more efficient for larger $K_{\|}$

But ... CR energy larger by an order of magnitude than magnetic energy

Otmianowska-Mazur, Marian Soida, Kulesza-Żydzik, Hanasz & Kowal (submitted)

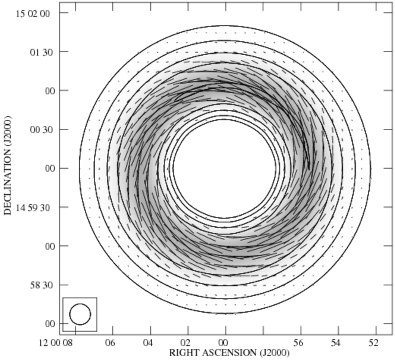
Assume parameters typical for the Milky Way at different galactocentric radii
5kpc $\leq R_G \leq$ 10kpc

– vertical gravity
– gas column density
– angular velocity (and shear)
– SN rate

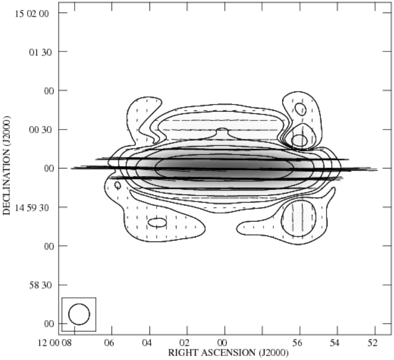


Growth of magnetic flux and magnetic energy at different R_G

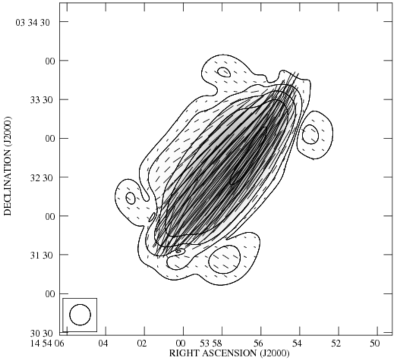
- Magnetic field from local cubes ($t = 700$Myr) at different radii replicated into subsequent rings and then combined together.
- Synchrotron-emitting electrons: Gaussian distrib. in z ($H_e = 2.5$kpc)
- standard synchrotron emissivity formulae (eg. Longair 1994)



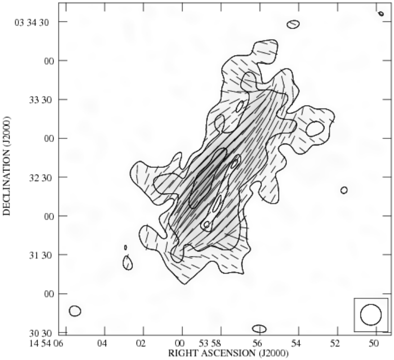
$i = 10^\circ$



$i = 89^\circ$



$i = 80^{\circ}$, model



Galaxy NGC 5775

CONCLUSIONS

- CR-driven dynamo amplifies the mean magnetic field on galactic rotation timescale.
- Synthetic radio maps constructed on the base of local shearing box simulations display morphological details (magnetic pitch angles, X-shaped structures) consistent with observed galactic images.
- In Otmianowska-Mazur et al. 2007 we also show that our modeled EMF is fully nonlinear and it is not possible to apply any of the considered nonlinear dynamo approximations due to the fact that the conditions for the scale separation are not fullfiled

Necessary improvements:

- Enlargement of CR diffusion coefficients $K_{\|}$, $K_{\perp}$ to realistic values, by an order of magnitude.
- Global galactic disk simulations $\rightarrow$ escape of CR along horizontal magnetic filed in galactic plane, to avoid the CR excess.