Magnetic field saturation
in simulations of the supernova-driven ISM

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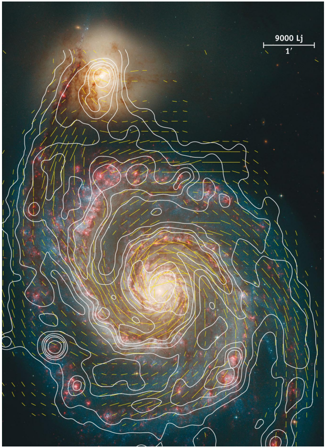
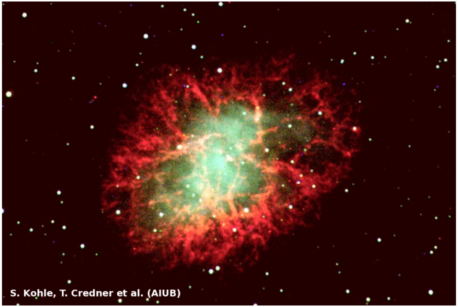
observations



Andrew Fletcher/Rainer Beck,
SuW and Hubble Heritage Team, STScI/AURA

- What is the origin of regular galactic magnetic fields?
  - primoridial field, (i.e. frozen-in fossil record of galaxy formation)
  - dynamo-generated field, (i.e. dynamically replenished)
- Beck of the envelope
  - turbulent diffusion
    $\tau_{\rm d} \simeq (0.5\,{\rm kpc})^2/0.5\,{\rm kpc\,km\,s^{-1}} \simeq 500\,{\rm Myr}$
  - B_ϕ wound-up
    $\tau_\Omega \simeq 2\pi/25\,{\rm kpc^{-1}\,km\,s^{-1}} \simeq 250\,{\rm Myr}$
  - large observed pitch angle strongly favours dynamo

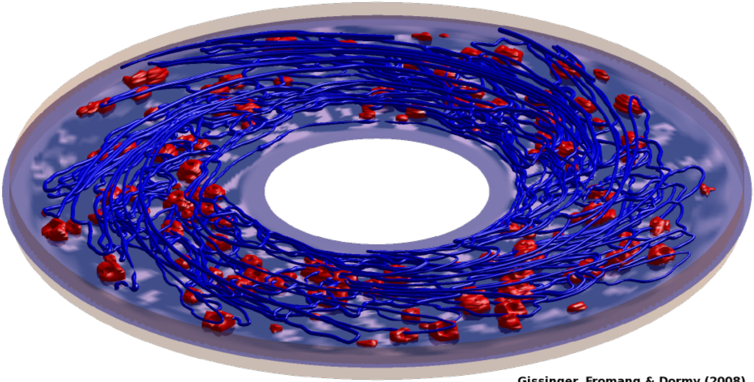
supernova-driven turbulence



- interstellar medium strongly turbulent
- energy deposited by supernovae, CRs, MRI, stellar winds, protostellar jets, . . .
- 2-3 SNe per century in our own Milky Way

- how do you amplify fields in a turbulent environment?
  rotation + stratification → turbulent dynamo
- vertical disk structure important for flux transfer
  disk wind ↔ turbulent transport

the big picture



Gissinger, Fromang & Dormy (2008)

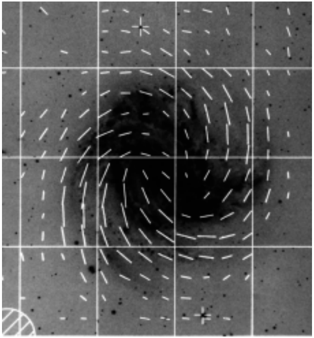
- encapsulate the effect of the supernovae
- model the evolution of the large-scale field

modelling the dynamo process

- Dynamo models (MF-MHD):
  - successfully reproduce field amplification and topology
  - but: predictive power relies on derivation of closure parameters
- Mean-field approach:
  - split into mean + fluctuation
    $\mathbf{u} = \bar{\mathbf{u}} + \mathbf{u}'$ and $\mathbf{B} = \bar{\mathbf{B}} + \mathbf{B}'$
  - derive mean-field equation

$$\partial_t \bar{\mathbf{B}} = \nabla\times(\bar{\mathbf{u}}\times\bar{\mathbf{B}}) + \nabla\times\bar{\mathcal{E}} + \eta\,\nabla^2\,\bar{\mathbf{B}}$$

turbulent EMF $\bar{\mathcal{E}} = \overline{\mathbf{u}'\times\mathbf{B}'}$



closure ansatz for MF-MHD

- parametrise turbulent EMF as a functional of $\bar{\mathbf{u}}$, $\bar{\mathbf{B}}$, $\overline{f(\mathbf{u}')}$
  - $\bar{\mathcal{E}}_i = \alpha_{ij}\bar{B}_j + \eta_{ijk}\partial_k\bar{B}_j \quad = \alpha_{ij}\bar{B}_j - \tilde{\eta}_{ij}\,\varepsilon_{jkl}\partial_k\bar{B}_l$
- Interpretation of parameters for $\bar{\mathbf{B}} = \bar{\mathbf{B}}(z)$:

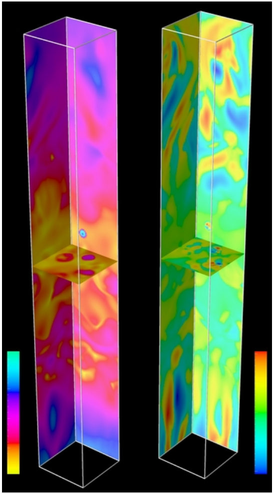
$$\bar{\mathcal{E}} = \begin{pmatrix} \alpha_R & -\gamma_z & 0 \\ \gamma_z & \alpha_\phi & 0 \\ 0 & 0 & \alpha_z \end{pmatrix} \bar{\mathbf{B}} - \begin{pmatrix} \tilde{\eta}_R & \delta_z & 0 \\ -\delta_z & \tilde{\eta}_\phi & 0 \\ 0 & 0 & \tilde{\eta}_z \end{pmatrix} \nabla\times\bar{\mathbf{B}}$$

  - diagonal elements of α give dynamo-effect
  - vertical turbulent pumping is contained in γ_z
  - diagonals of $\tilde{\eta}$ give turbulent diffusivity
  - off-diagonals $\rightarrow$ $\Omega \times J$ effect, Rädler (1969)

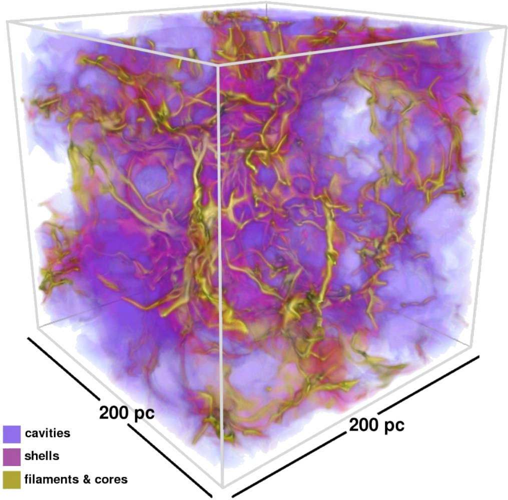
local box simulations

- Model geometry:
  - local patch of interstellar medium, up to 1.6 kpc on edge ($\Delta \simeq 10$ pc)
  - vertical stratification up to ± 6 kpc
  - sheared galactic rotation
- Physical ingredients:
  - non-ideal MHD (+ heat conduction)
  - optically thin radiative heating/cooling
  - localised thermal energy input modelling the supernovae

  Korpi, Brandenburg, Shukurov, Tuominen & Nordlund (1999)



ISM morphology



play
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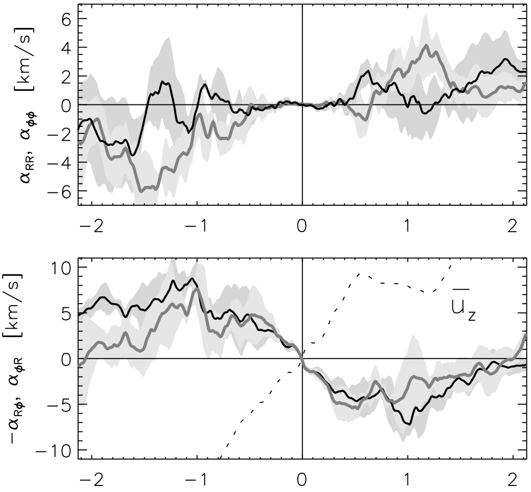
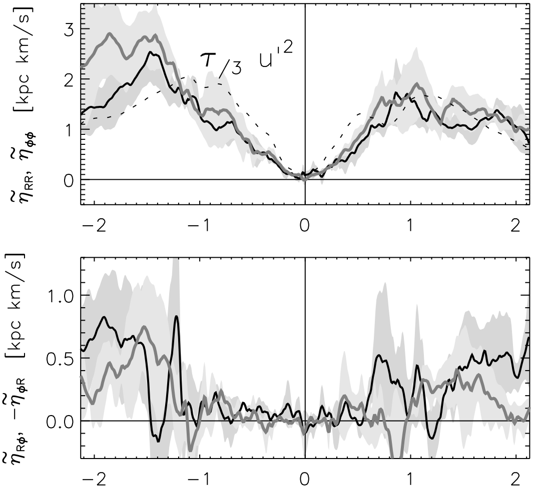
α-profiles



Gressel, Elstner, Ziegler & Rüdiger (2008), A&A 486, L35

- dynamo effect $|\alpha_R|,\ |\alpha_\phi| \simeq 3\,\mathrm{km\,s^{-1}}$
- diamagn. pumping $|\gamma_z| \simeq 7\,\mathrm{km\,s^{-1}}$ directed inward
- $|\alpha| : |\gamma|$ consistent w/ SOCA results
- effect of galactic wind $\bar{u}_z$ balanced by turb. pumping

$\tilde{\eta}$-profiles



- turb. diffusivity $\simeq 2\,\mathrm{kpc\,km\,s^{-1}}$
- coherence time $\tau \simeq 3\,\mathrm{Myr}$
- non-vanishing $\Omega \times J$ effect $\delta_z \simeq 0.5\,\mathrm{kpc\,km\,s^{-1}}$
- add shear $\rightarrow$ dynamo

it really works!

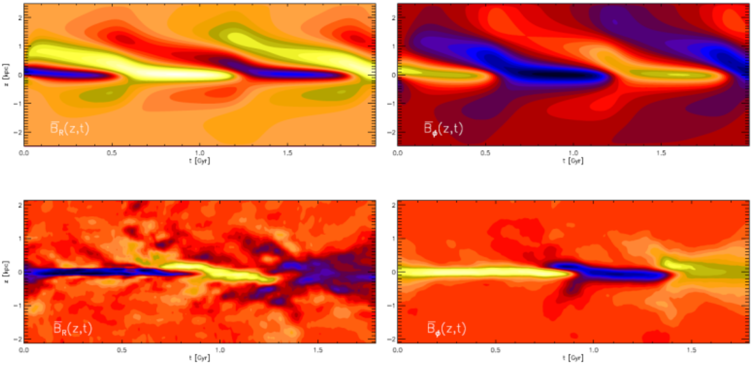
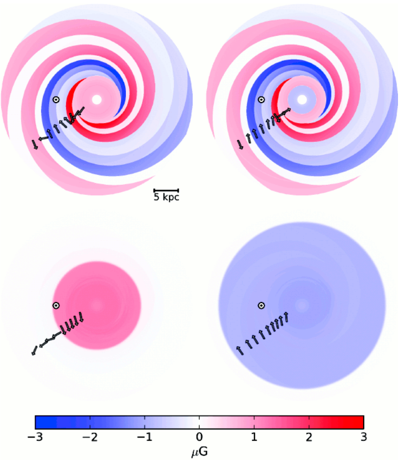
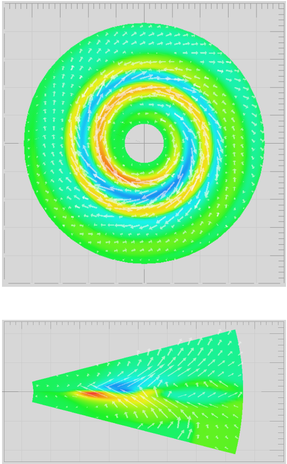


Figure 4.10: Same as Fig. 4.9, but additionally including a mixed (anti-)symmetric contribution in the off-diagonal elements of $\tilde{\eta}$ (upper panels). Now the lopsided dipolar symmetry in the field reversals persists and closely resembles the features seen in the *direct* simulation H4 (lower panels).

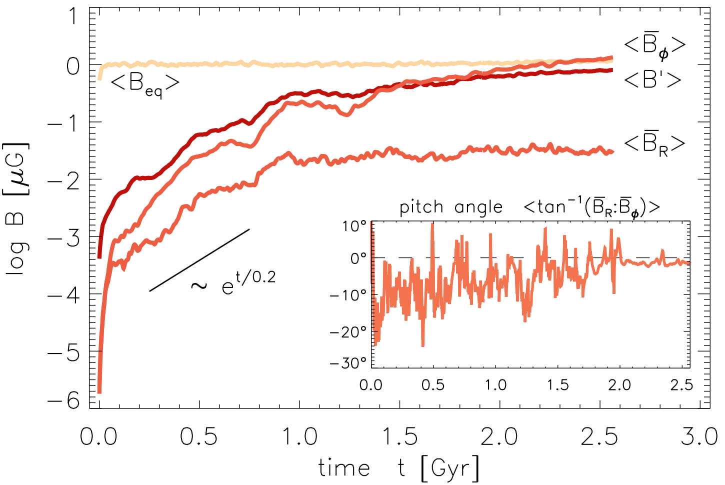
a new model of the galactic magnetic field



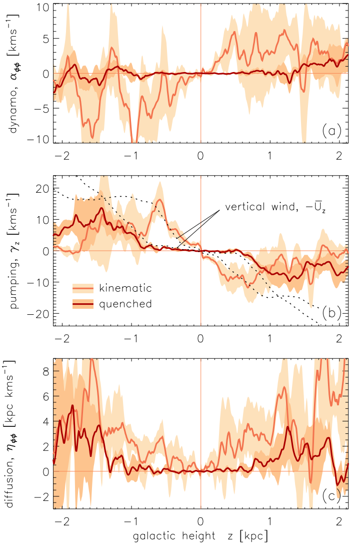
Jansson & Farrar (2012)



magnetic field saturation



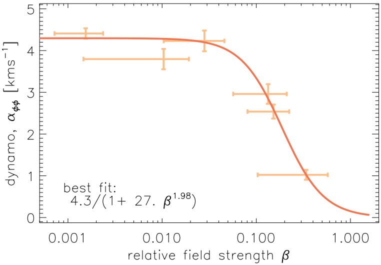
a lingering catastrophe

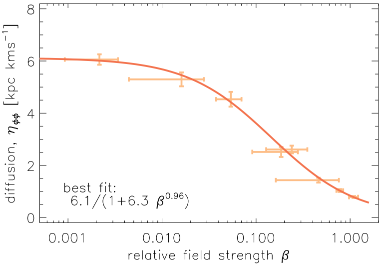


- Quenching scenarios:
  - (a) classic: flow quenching due to Lorentz force
  - (b) catastrophic: helicity conservation inhibits growth
  - (c) similar to scenario (b) but alleviated by small-scale helicity removal
- Test possible realisations:
  - quenching sets-in . . .
    (a) . . . at $B \simeq B_{\rm eq}$
    (b) . . . at $B \simeq B_{\rm eq}/{\rm Rm}$
    (c) . . . at $B \simeq B_{\rm eq}\, l_0/L_0$
- Suppression of wind: (c) $\rightarrow$ (b)

extracting quenching functions

- quenching quadratic in $\beta \equiv \bar{B}/B_{\rm eq}$
- magnetic Reynolds number, $\mathrm{Rm} \equiv u_{\rm rms}(k_{\rm f}\,\eta)^{-1} \simeq 75$–$125$
- scale separation ratio, $l_0/L_0 \simeq 0.1\,\mathrm{kpc}/1\,\mathrm{kpc} = 10$





Gressel, Bendre & Elstner (2012), MNRAS, (arXiv astro-ph : 1210.2928)

summary of results

- I. Measuring dynamo coefficients via TF
  - 1D mean-field model matches DNS
  - global models to predict field topology
- II. Non-linear saturation
  - quenching functions obtained
  - indications for the presence of helicity constraints
  - suppression of wind threatens saturation level
- III. Future prospects
  - fully quantitative global dynamo models
  - solve dynamic momentum equation $\rightarrow$ MRI on large scales
  - include Negative Effective Magnetic Pressure effects (NEMPI)