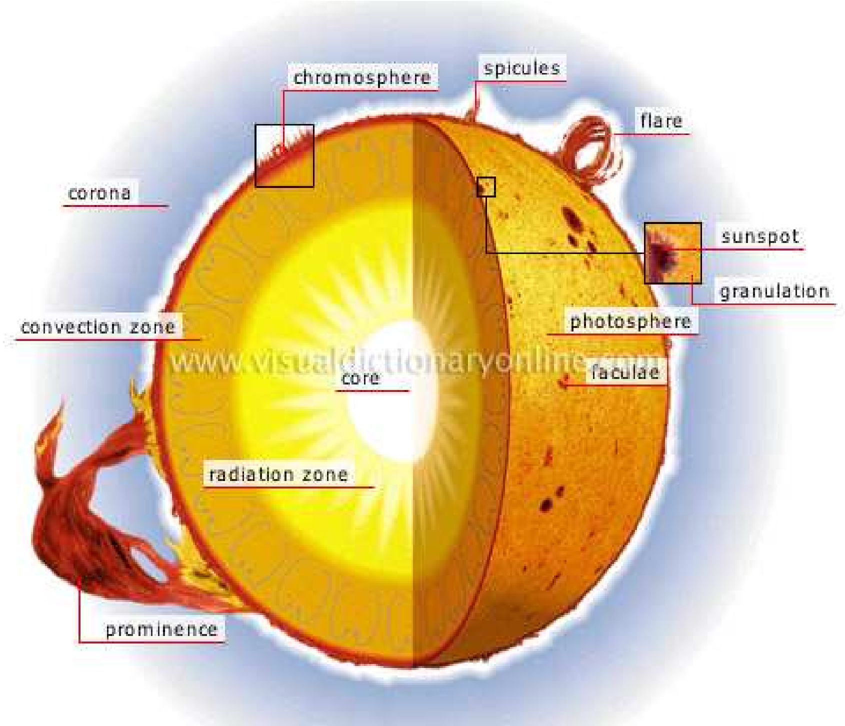
Effects of rotation and stratification on magnetic flux concentrations

[turbulence] [stratification] [magnetic field]

Illa R. Losada

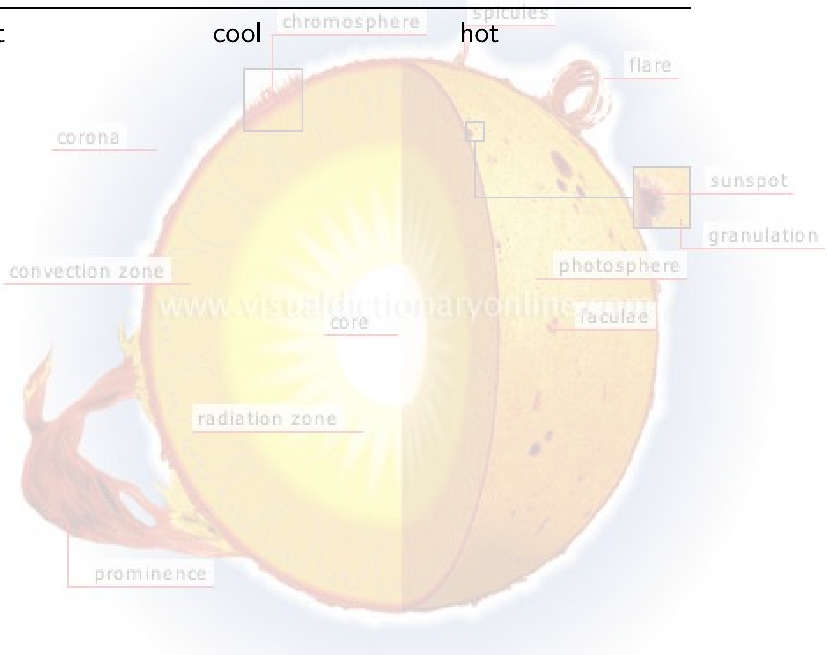
Nordita and Stockholm University

Sunspot formation
11 Mar 2015

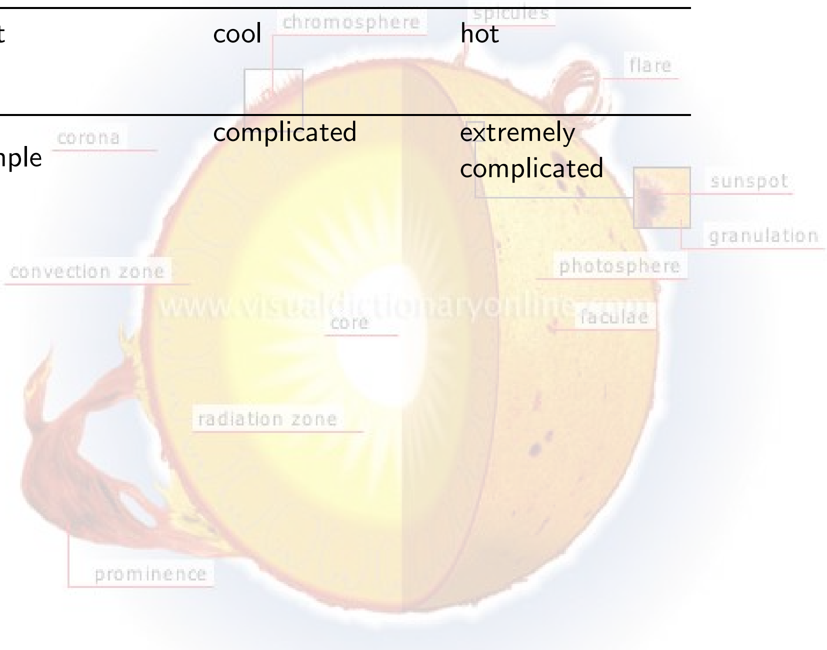

chromosphere
spicules
flare
corona
sunspot
granulation
convection zone
photosphere
www.visualdictionaryonline.com
core
faculae
radiation zone
prominence

Inside	Surface	Outside

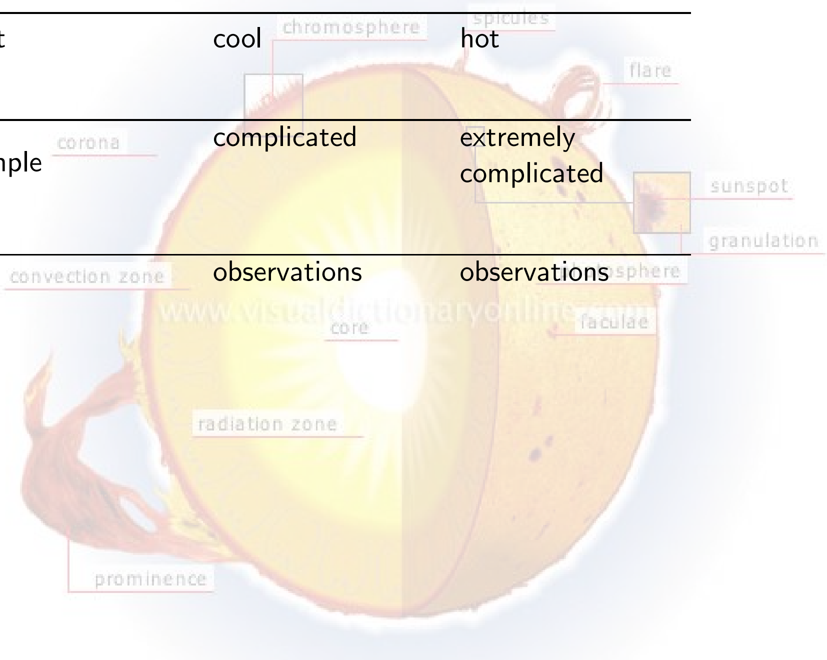
Inside	Surface	Outside
hot	cool	hot



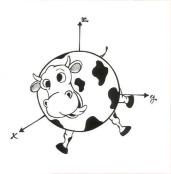
Inside	Surface	Outside
hot	cool	hot
simple	complicated	extremely complicated



Inside	Surface	Outside
hot	cool	hot
simple	complicated	extremely complicated
	observations	observations



Inside	Surface	Outside
hot	cool	hot
simple	complicated	extremely complicated
model	observations	observations



"It is also a good rule not to put overmuch confidence in the observational results that are put forward until they are confirmed by theory." Arthur Eddington

Flux tubes

Parker instability (1955)

Flux tubes

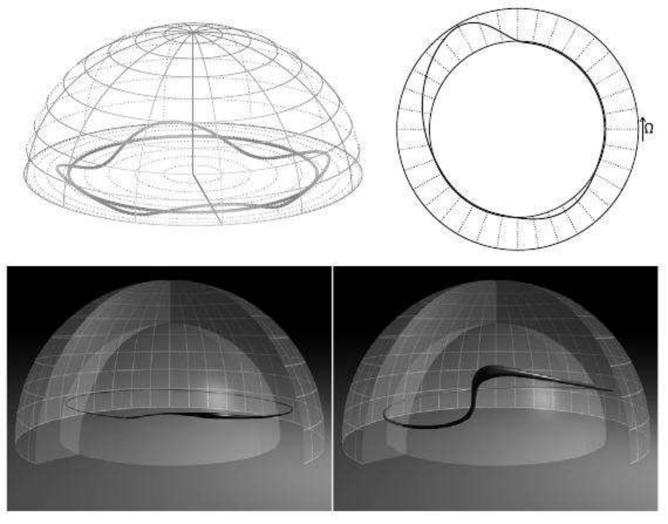


Figure 1 : Caligari et al. (1995)

Flux tubes

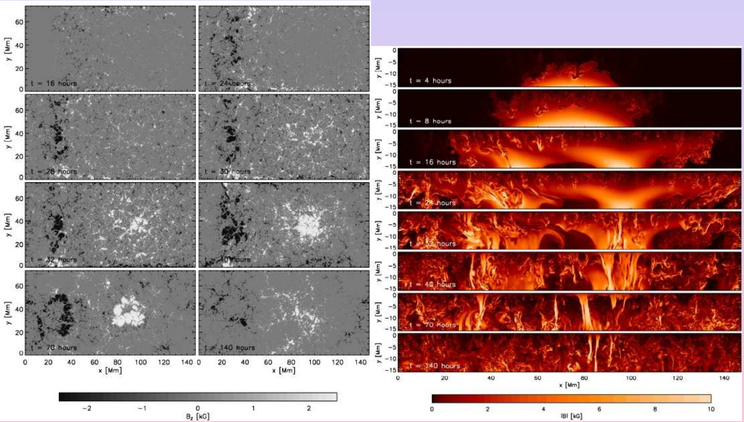


Figure 2 : Time evolution of $|B|$ at the surface and along a vertical cut. Rempel et al. (2014)

Negative Effective Magnetic Pressure Instability

Vertical field. Sunspot-like structure

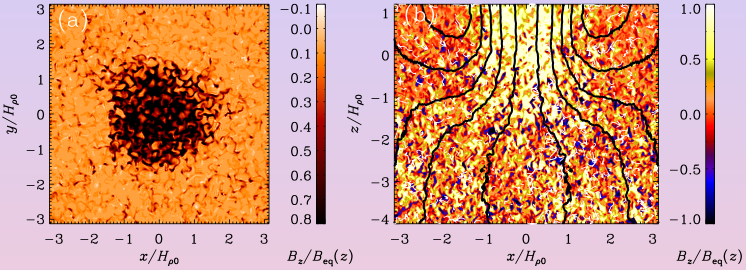


Figure 3 : Cuts of $B_z/B_{\rm eq}(z)$ in the xy plane at the top boundary ($z/H_{\rho 0} = 1.2$) and the xz plane through the middle of the spot at $y = 0$ for $\gamma = 5/3$ and $\beta_0 = 0.05$. In the xz cut, we also show magnetic field lines and flow vectors obtained by numerically averaging in azimuth around the spot axis.

Vertical field. Sunspot-like structure

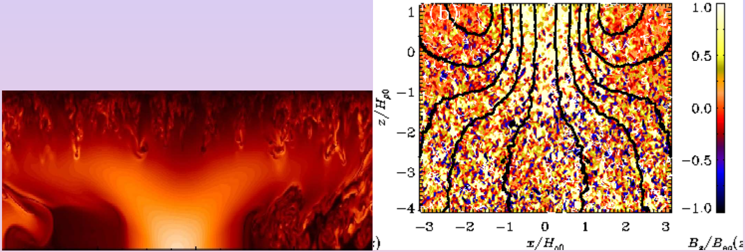


Figure 4 : Rempel et al. (2014) and Losada et al. (2014)

Velocity field and NEMPI

Forced Velocity field

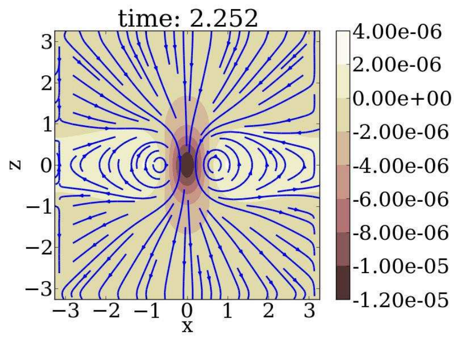


Figure 5 : hydro simulation with imposed velocity

NEMPI.

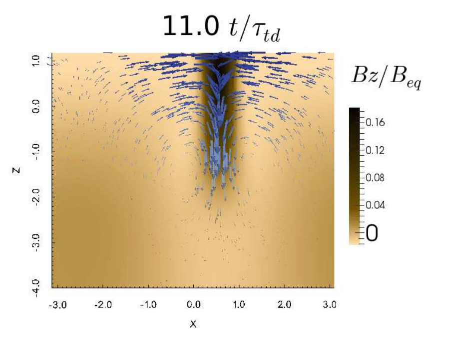


Figure 6 : MHD simulation. $P = P_{gas} + P_{eff}$

Let's go back to the equations!

MHD equations

Magnetohydrodynamics (MHD): equations for the dynamics of the plasma.

- Maxwell equation: $\frac{\partial \mathbf{B}}{\partial t} = \nabla \times \mathbf{E}$
- Mass conservation: $\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{U}) = 0$
- Momentum conservation: $\rho \frac{\mathrm{D}\mathbf{U}}{\mathrm{D}t} = -\nabla p + \mathbf{J} \times \mathbf{B}$
- Low frequency Maxwell eq. : $\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$
- Energy conservation: $\frac{d}{dt}\left(\frac{p}{\rho^\gamma}\right) = 0$
- Ohm's law: $\mathbf{E} + \mathbf{U} \times \mathbf{B} = \eta \mu_0 \mathbf{J}$

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Missing: viscosity, heating, condution, radiation, gravity, rotation, ionisation, etc

Solve MHD equations

MHD simulations

- Goal of simulations: solve MHD equations.
- Not possible to use solar parameters:
  $\mathrm{Re} \approx \frac{UL}{\nu} \approx 10^{10} - 10^{15}$

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Simulations

- Direct Numerical Simulations (DNS)
- Mean-field Simulations (MFS)
- Large Eddy Simulations (LES)

MFS and DNS: How to cook paella!

Mean Field Simulations (MFS)

- Quantities = averaged + fluctuations: $F = \overline{F} + f$
- Approximations: add or subtract terms in the equations.
- Control the physics.

Direct Numerical Simulations (DNS)

- Solve full equations.
- Approximations: only in resolution.
- No control.

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Simulations done with Pencil Code (`http://pencil-code.googlecode.com`)

Full MHD equations.

Direct Numerical simulations (DNS):

- Continuity equation: $\frac{\partial \rho}{\partial t} = -\nabla \cdot (\rho \mathbf{U})$
- Momentum equation:
  $\rho \frac{\mathrm{D}\mathbf{U}}{\mathrm{D}t} = -\nabla p + \mathbf{J} \times \mathbf{B} + \rho \mathbf{g} + \rho \mathbf{F}_\nu + \rho \mathbf{f}$
- Induction equation: $\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \mu_0 \mathbf{J})$

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Setup:

- Forcing, $k_f/k_1 = 15$ (control scale separation)
- Strong stratification: density contrast ≈ 535
- $B_0/B_{\rm eq0} = 0.05$ (in range)
- 64^3x128 mesh-points
- $\mathrm{Re}_M \approx \frac{UL}{\eta} = 6$

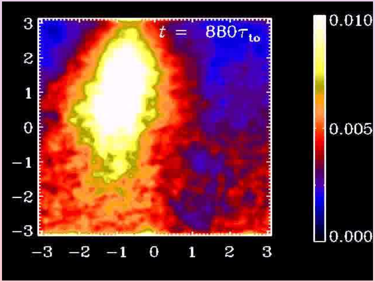

Figure 7: $\Delta\overline{\mathbf{B}}/B_{\rm eq0}$ (Brandenburg et al. 2011)

Mean-Field MHD equations.

Quantities = averaged+ fluctuations: $F = \overline{F} + f$

Mean field simulations (MFS):

- Continuity equation: $\frac{\mathrm{D}\overline{\rho}}{\mathrm{D}t} = -\overline{\rho}\boldsymbol{\nabla}\cdot\overline{\mathbf{U}}$
- Momentum equation:
  $\frac{\mathrm{D}\overline{\mathbf{U}}}{\mathrm{D}t} = -c_{\mathrm{s}}^2\boldsymbol{\nabla}\ln\overline{\rho} + \mathbf{g} + \overline{\boldsymbol{\mathcal{F}}}_{\mathrm{M}} + \overline{\boldsymbol{\mathcal{F}}}_{\mathrm{K}}$
- Induction equation:
  $\frac{\partial\overline{\mathbf{B}}}{\partial t} = \boldsymbol{\nabla}\times(\overline{\mathbf{U}}\times\overline{\mathbf{B}} + \overline{\mathbf{u}\times\mathbf{b}}) + \eta\boldsymbol{\nabla}^2\overline{\mathbf{B}}$

From induction equation: dynamo instability

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \boldsymbol{\nabla} \times (\overline{\mathbf{U}} \times \overline{\mathbf{B}} + \overline{\mathbf{u} \times \mathbf{b}}) + \eta \boldsymbol{\nabla}^2 \overline{\mathbf{B}} \qquad (1)$$

α-effect (Steenbeck et al. 1966; Moffat 1978; Krause & Rädler 1980)

- Isotropic case: $\overline{\mathbf{u} \times \mathbf{b}} = \alpha \overline{\mathbf{B}} - \eta_t \overline{\mathbf{J}}$
- If $\alpha \neq 0 \rightarrow$ generate a $\overline{\mathbf{B}}$
- $\alpha \propto$ helicity
- η_t: turbulent diffusivity.

Responsible for the Sun's large-scale field.

From momentum equation: NEMPI

$$\frac{D\overline{\mathbf{U}}}{Dt} = -c_s^2 \boldsymbol{\nabla} \ln \overline{\rho} + \mathbf{g} + \overline{\boldsymbol{\mathcal{F}}}_M + \overline{\boldsymbol{\mathcal{F}}}_K \tag{2}$$

$\overline{\boldsymbol{\mathcal{F}}}_M$: Lorentz Force $\rightarrow$ magnetic stress tensor
$\overline{\boldsymbol{\mathcal{F}}}_K$: Reynolds stresses $\rightarrow$ kinetic stress tensor

(3)

From momentum equation: NEMPI

$$\frac{\mathrm{D}\overline{\mathbf{U}}}{\mathrm{D}t} = -c_\mathrm{s}^2 \boldsymbol{\nabla} \ln \overline{\rho} + \mathbf{g} + \overline{\boldsymbol{\mathcal{F}}}_\mathrm{M} + \overline{\boldsymbol{\mathcal{F}}}_\mathrm{K} \qquad (2)$$

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Total pressure:

$$P_T = P_{gas} + \frac{\overline{\mathbf{B}}^2}{2\mu_0} + p_t \qquad (3)$$

From momentum equation: NEMPI

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Total pressure:

$$P_T = P_{gas} + \underbrace{\frac{\overline{\mathbf{B}}^2}{2\mu_0} + p_t}_{\text{Effective magnetic pressure}} \quad (3)$$

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Effective magnetic pressure = turbulent pressure = hydrodynamic + magnetic

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Total pressure:

$$P_T = P_{gas} + P_{eff} \quad (3)$$

Effective magnetic pressure = turbulent pressure = hydrodynamic + magnetic

$$P_{eff} = \left(1 - q_p(\overline{\mathbf{B}})\right) \frac{\overline{\mathbf{B}}^2}{2\mu_0} \quad (4)$$

$$< b^2 >= f(\overline{\mathbf{B}})\overline{\mathbf{B}}^2 = q_p \, 3 \, \overline{\mathbf{B}}^2 \quad (5)$$

From momentum equation: NEMPI

$$\frac{\mathrm{D}\overline{\mathbf{U}}}{\mathrm{D}t} = -c_\mathrm{s}^2 \boldsymbol{\nabla} \ln \overline{\rho} + \mathbf{g} + \overline{\boldsymbol{\mathcal{F}}}_\mathrm{M} + \overline{\boldsymbol{\mathcal{F}}}_\mathrm{K} \tag{2}$$

$\overline{\boldsymbol{\mathcal{F}}}_\mathrm{M}$: Lorentz Force $\rightarrow$ magnetic stress tensor
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Total pressure:

$$P_T = P_{gas} + P_{eff} = P_{gas} + (1 - q_p(\overline{\mathbf{B}}))\frac{\overline{\mathbf{B}}^2}{2\mu_0} \tag{3}$$

Effective magnetic pressure = turbulent pressure = hydrodynamic + magnetic

$$P_{eff} = \left(1 - q_p(\overline{\mathbf{B}})\right) \frac{\overline{\mathbf{B}}^2}{2\mu_0} \tag{4}$$

$$< b^2 >= f(\overline{\mathbf{B}})\overline{\mathbf{B}}^2 = q_p \, 3 \, \overline{\mathbf{B}}^2 \tag{5}$$

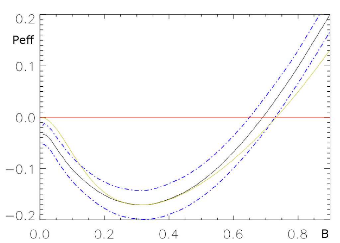
Pressure. NEMPI.

Effective magnetic pressure

(Kemel et. al 2012):

(effects of turbulence on the mean Lorentz force)

$$P_{eff} = \frac{1}{2}(1 - q_p)\overline{\mathbf{B}}^2/\overline{B}_{eq}^2 \quad (6)$$



Negative Effective Magnetic Pressure Instability (NEMPI)

- Regions below the minimum value of P_{eff} $\rightarrow$ NEMP
- NEMP + strong stratification ($|\nabla \ln \rho| > |\nabla \overline{\mathbf{B}}|$) $\rightarrow$ NEMPI [1]
- Magnetic field suppress turbulence $\rightarrow$ structures sink!

[1] Predicted: Kleeorin et al. 1989, 1990; Kleeorin & Rogachevskii 1994; Kleeorin et al. 1996; Rogachevskii & Kleeorin 2007. Confirmed: Brandenburg et al. 2011

MFS Parametrization

Normalized effective magnetic pressure:

$$\mathcal{P}_{\rm eff} = \tfrac{1}{2}(1 - q_{\rm p})\beta^2, \qquad (7)$$

$q_{\rm p}(\beta)$ approximated by (Kemel et al. 2012a):

(empirical, fits to DNS results)

$$q_{\rm p}(\beta) = \frac{q_{\rm p0}}{1 + \beta^2/\beta_{\rm p}^2} = \frac{\beta_\star^2}{\beta_{\rm p}^2 + \beta^2}, \qquad (8)$$

$q_{\rm p0}$, $\beta_{\rm p}$, and $\beta_\star = \beta_{\rm p} q_{\rm p0}^{1/2}$: constants.
$\mathcal{P}_{\rm eff}$ has a minimum value $\mathcal{P}_{\rm min}$ at $\beta_{\rm min}$, related with the parameters:

$$\beta_{\rm p} = \beta_{\rm min}^2 \Big/ \sqrt{-2\mathcal{P}_{\rm min}}, \quad \beta_\star = \beta_{\rm p} + \sqrt{-2\mathcal{P}_{\rm min}}. \qquad (9)$$

Growth rate:

$$\frac{\lambda}{\eta_t k^2} \approx 3\beta_\star \frac{k_f/k}{kH_\rho - 1} \qquad (10)$$

Previous results.

- NEMP and NEMPI described in DNS and MFS [2].
- NEMPI observed in DNS and MFS [3]
- Parameters values studied for maximize the growth strength and time:
  - $k_{\mathrm{f}}/k_1 = 30$ (scale separation ratio)
  - $\mathrm{Re} \equiv u_{\mathrm{rms}}/\nu k_{\mathrm{f}} = 36$
  - $P_{\mathrm{m}} = \nu/\eta = 0.5$.
  - $\mathrm{Re}_M = P_{\mathrm{m}}\mathrm{Re} = 18$

My contribution:

- Effects of rotation
- Effects of stratification

[2] Kleeorin et al. 1989, 1989, 1996; Kleeorin & Rogachevskii 1994; Rogachevskii & Kleeorin 2007; Brandenburg et al. 2010

[3] Brandenburg et al. 2011, 2012; Kemel et al. 2012

Units

Magnetic field

Equipartition field strength: $B_{\mathrm{eq}} = \sqrt{\mu_0 \rho}\, u_{\mathrm{rms}}$
Sun (top-bottom): 300 G - 3 kG
Sunspots: 1 kG

Time

Turnover time: $\tau_c = \frac{1}{u_{\mathrm{rms}} k_{\mathrm{f}}}$
Sun: $10^3 - -10^{-1}$ hours

Length

Density scale height: $H_\rho = \frac{c_{\mathrm{s}}^2}{g}$

Some results

Rotation. Structures evolution

Co = 0.03

DNS | MFS

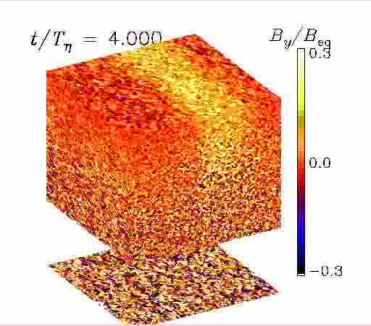


Figure 8 : DNS

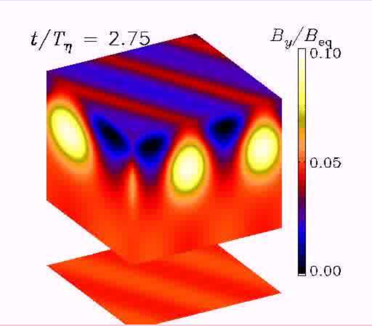


Figure 9 : MFS

Rotation. MFS and DNS growth rates.

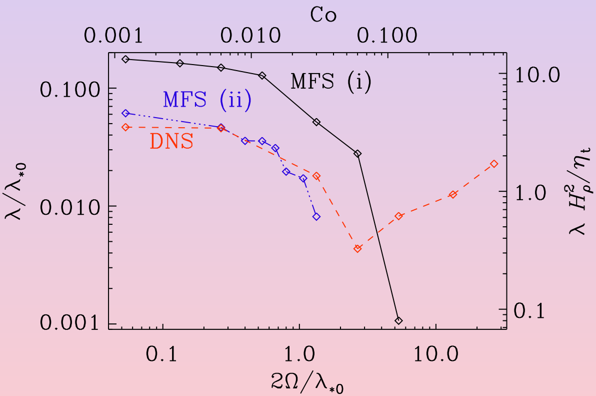
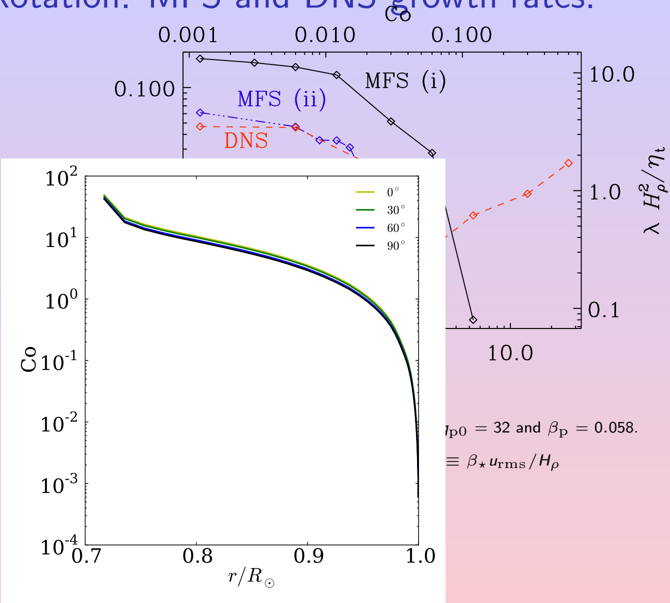


Figure 10 : MFS (i): $q_{\rm p0} = 20$ and $\beta_{\rm p} = 0.167$; MFS (ii): $q_{\rm p0} = 32$ and $\beta_{\rm p} = 0.058$.

$B_0/B_{\rm eq0} = 0.05$. $q_p = \frac{\beta_\star^2}{(\beta_{\rm p}^2+\beta^2)}$ $\beta = \frac{\overline{\mathbf{B}}}{B_{\rm eq0}}$ $\lambda_{*0} \equiv \beta_\star u_{\rm rms}/H_\rho$

Rotation. MFS and DNS growth rates.



$\ldots_{p0} = 32$ and $\beta_p = 0.058$.

$\equiv \beta_\star u_{rms}/H_\rho$

Polytropic EoS: q-exponential

Isentropic

$$\frac{\rho}{\rho_0} = \left[1 + (\gamma - 1)\left(-\Phi/c_{s0}^2\right)\right]^{1/(\gamma-1)}$$

Density and Scale Height dependence.

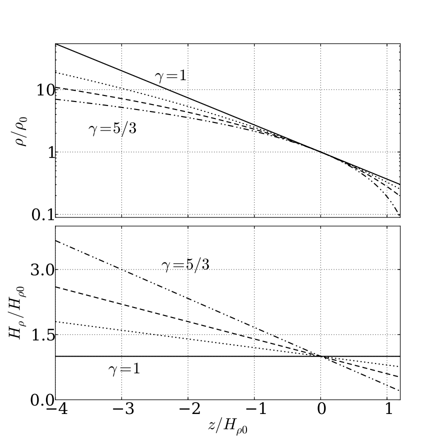


Figure 11 : Polytropes with $\gamma = 1$ (solid line), 1.2 (dash-dotted), 1.4 (dotted), and 5/3 (dashed) for

Stratification. Horizontal imposed field (MFS).

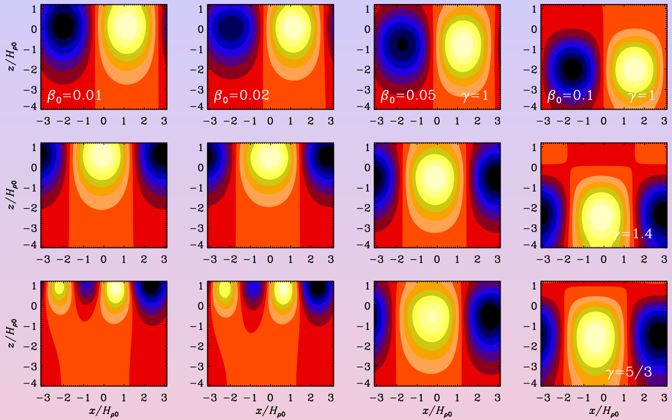


Figure 12 : $\overline{B}_y$ in the kinematic growth phase for $\gamma = 1$ (top row), 1.4 (middle row), and 5/3 (bottom row) and $\beta_0 = 0.01$ (left column), 0.02, (middle column), and 0.05 (right column) in the presence of a horizontal field using the perfect conductor boundary condition.

Horizontal: $k_\perp H_\rho \sim 0.8 \ldots 1$
Vertical: $k_\perp H_\rho \sim 0.7 \ldots 1$

Vertical imposed field (DNS vs MFS). Evolution.

DNS

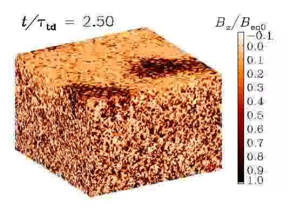


Figure 13 : DNS

MFS

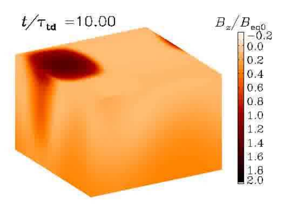


Figure 14 : MFS

$\beta_0 = 0.05$

Parameters dependence study in polytropic stratification

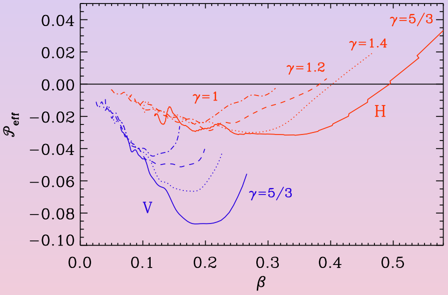


Figure 15 : Effective magnetic pressure obtained from DNS in a polytropic layer with different γ for horizontal (H, red curves) and vertical (V, blue curves) mean magnetic fields.

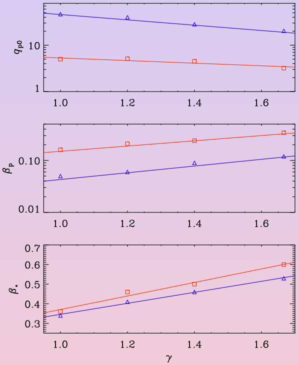
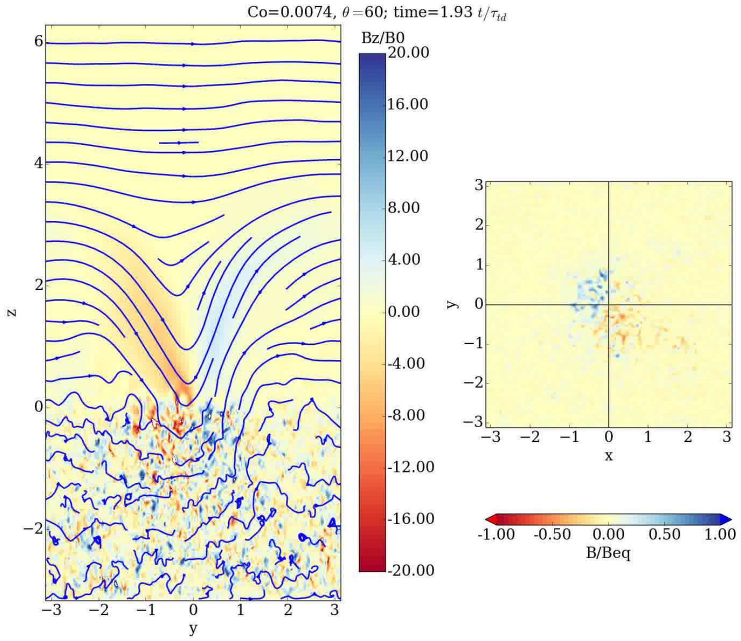


Figure 16 : Parameters $q_{\rm p0}$, $\beta_{\rm p}$, and $\beta_\star$ for the function $q_{\rm p}(\beta)$ versus γ for horizontal (red line) and vertical (blue line) mean magnetic fields.

2-layers model + rotation



Energy transfer

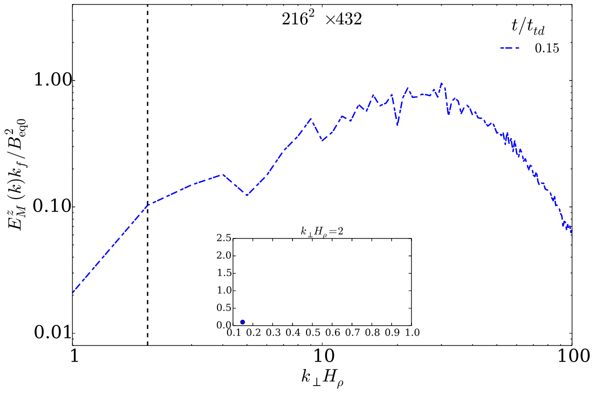


Figure 18 : Magnetic power spectra

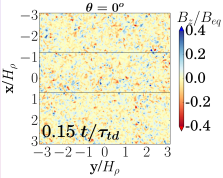
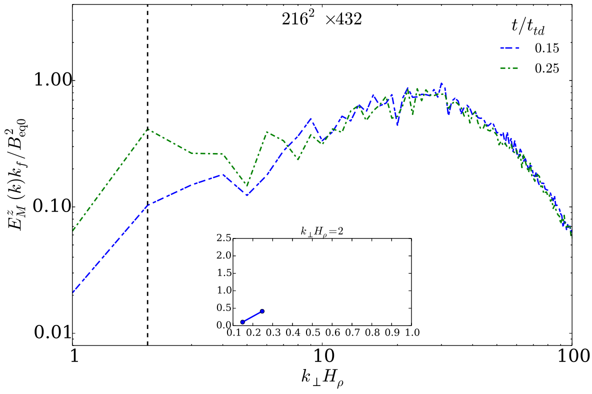


Figure 19 : xy visualization at the surface

Energy transfer



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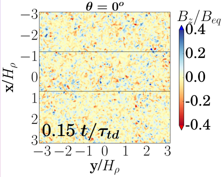

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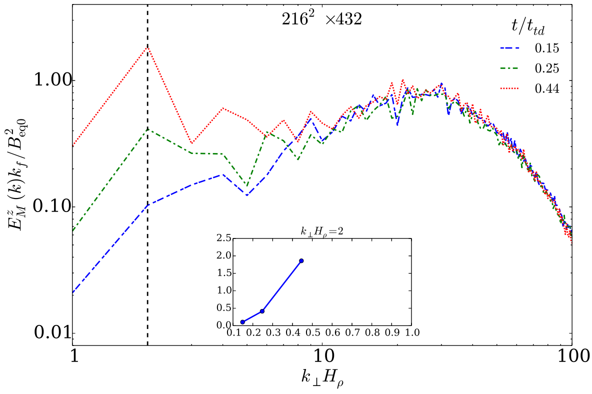

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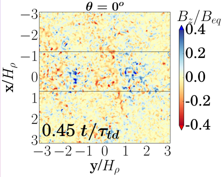

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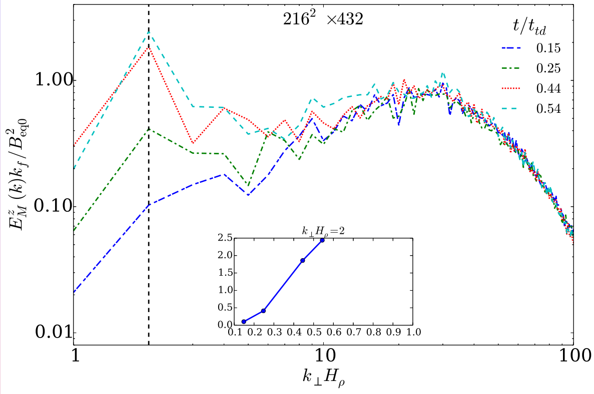

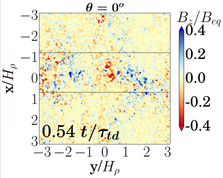

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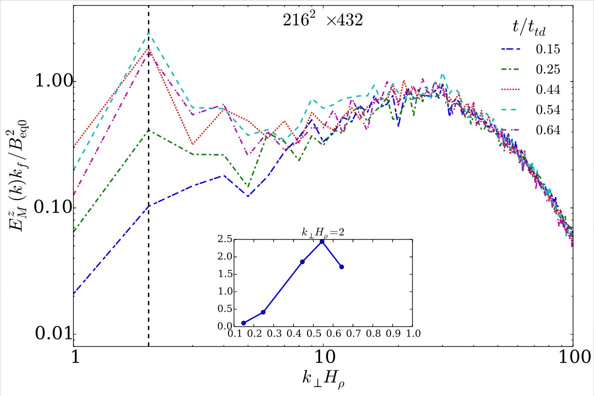

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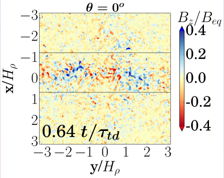

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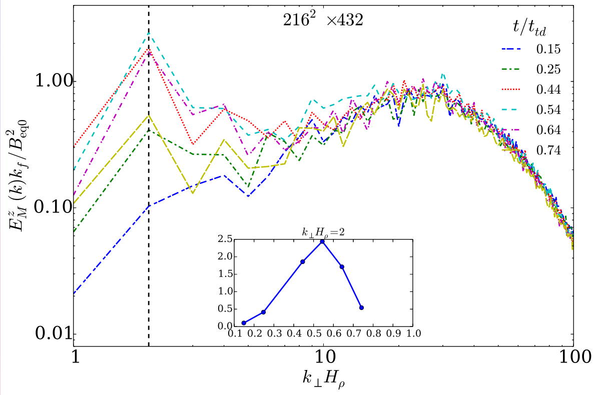

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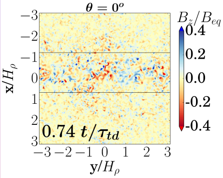

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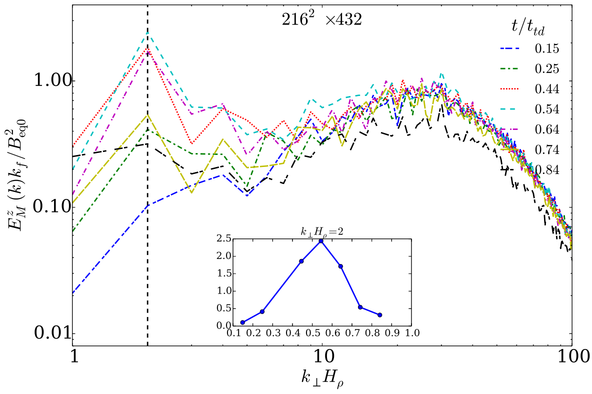

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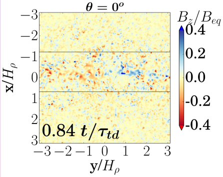

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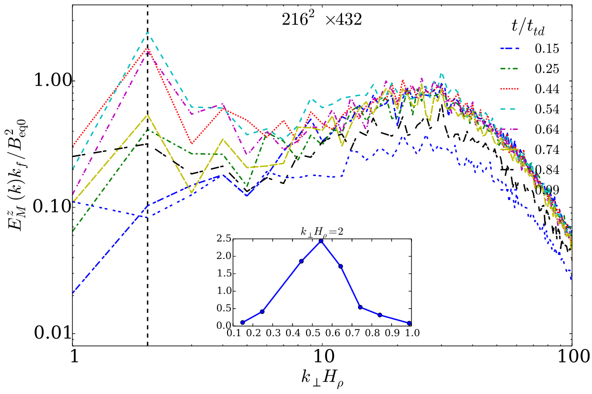

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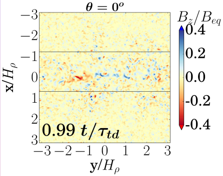

Figure 19 : xy visualization at the surface

Conclusions

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Rotation.

NEMPI depends on the ratio between rotation and turbulence.

- Turnover time: $\tau \approx 2$hours
- On the Sun: only upper-most layers (supergranulation layer $\tau \sim 1 day$)

Polytropic EoS:

- NEMPI develops in the uppermost layers.
- Isothermal models applicable locally.
- No "potato-sack" effect with vertical fields.

How sunspots/active regions are form?

Formation

Observations

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Formation

- Flux tube?

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- Other ?

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- Other ?

Observations

- Downflow/uppflow

How sunspots/active regions are form?

Formation

- Flux tube?
- NEMPI?
- Flux tube + NEMPI?
- Other ?

Observations

- Downflow/uppflow
- Structure depth

Thank you for your time

From momentum equation: NEMPI

Why the pressure is negative?

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Total Energy

$$E = E_k + E_m \approx \text{const} \tag{11}$$

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$< b^2 >$: magnetic fluctuations of the mean magnetic field

$$< b^2 >= f(\overline{\mathbf{B}})\overline{\mathbf{B}}^2 = q_p\, 3\, \overline{\mathbf{B}}^2 \tag{15}$$

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1st aproach:

Total stress tensor

(Isotropic turbulence)

$$\sigma = \delta_{ij} \left(\rho U_i U_j - B_i B_j + \frac{1}{2} \delta_{ij} B^2 \right) \tag{16}$$

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The magnetic field decrease the turbulent pressure!

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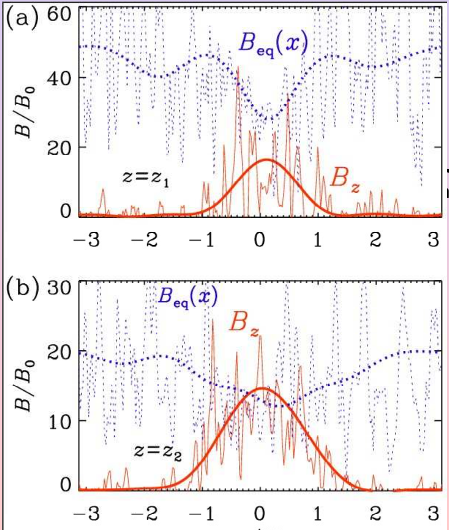

$$+ \frac{1}{2}\delta_{ij} B^2) \quad (16)$$

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Approx:

$$p_{turb} = \frac{1}{3}\rho v^2 \approx \frac{\frac{1}{3}\rho v_0^2}{1 + a_p \frac{B^2}{B_{\rm eq}^2}} \tag{18}$$

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2nd aproach: Total pressure + mean field considerations

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Stress tensor.

Momentum equation:

$$\frac{\mathrm{D}\overline{\mathbf{U}}}{\mathrm{D}t} = -c_s^2 \boldsymbol{\nabla} \ln \overline{\rho} + \mathbf{g} + \overline{\boldsymbol{\mathcal{F}}}_{\mathrm{M}} + \overline{\boldsymbol{\mathcal{F}}}_{\mathrm{K}} \tag{21}$$

Magnetic stress tensor: Lorentz Force, $\mathcal{F}_{\mathrm{M}}$:

$$\mathcal{F}_{\mathrm{M}} = \mathbf{J}\times\mathbf{B} = -\tfrac{1}{2}\nabla\mathbf{B}^2 + (\mathbf{B}\cdot\nabla)\mathbf{B} = -\nabla_j\left[\tfrac{1}{2}\mathbf{B}^2\delta_{ij} - B_iB_j\right] = \nabla_j\sigma_{ij} \tag{22}$$

Mean Lorentz Force, $\overline{\boldsymbol{\mathcal{F}}}_{\mathrm{M}}$:

$$\overline{\boldsymbol{\mathcal{F}}}_{\mathrm{M}} = -\nabla_j\left[\frac{< b^2 >}{2}\delta_{ij} - < b_ib_j >\right] = \nabla_j\sigma_{ij}^m \tag{23}$$

Isotropic turbulence:

$$\sigma_{ij}^m = -\frac{< b^2 >}{2}\delta_{ij} + < b_ib_j > = -\frac{< b^2 >}{2}\delta_{ij} + \frac{< b^2 >}{3}\delta_{ij} = -\frac{1}{3}\left(\frac{< b^2 >}{2}\right)\delta_{ij} = -\frac{W_m}{3} \tag{24}$$

Stress tensor.

Kinetic stress tensor: Reynolds stresses

$$< v_i v_j >= \frac{< v^2 >}{3}\delta_{ij} = \frac{2}{3}\frac{< v^2 >}{2}\delta_{ij} = \frac{2}{3}W_k\delta_{ij} \qquad (25)$$

(isotropic turbulence)