Galactic dynamos and magnetic helicity fluxes

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Outline

- Galactic Mean field dynamos
  - Essential points
- Magnetic helicity conservation
  - Consequences on large-scale dynamo action
- Effect of magnetic helicity fluxes on the galactic dynamo
  - Advective flux
  - Anisotropy of interstellar turbulence
- Conclusions

Galactic dynamos : Essential points

- Galactic shear generates $\overline{B}_\phi$ from $\overline{B}_r$ front
- Supernovae drive helical turbulence in the disk
- Helical motions regenerate $\overline{B}_r$ from $\overline{B}_\phi$ through the α-effect

  Ruzmaikin, Sokoloff & Shukurov, 1988
- The mean-field satisfies the dynamo equation

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \nabla \times (\overline{\mathbf{U}} \times \overline{\mathbf{B}} + \alpha \overline{\mathbf{B}}) + \eta_t \nabla^2 \overline{\mathbf{B}}$$

  - $\alpha = (-\tau/3)\langle \mathbf{u} \cdot \omega \rangle$ and $\eta_t = (\tau/3)\langle \mathbf{u^2} \rangle$
- Magnetic helicity conservation : Poses a significant challenge

Constraints on mean-field evolution

- Evolution of the magnetic helicity $H_M = \int_V \mathbf{A} \cdot \mathbf{B} \; dV$

$$\frac{dH_M}{dt} = -2\eta \int_V \boldsymbol{J} \cdot \mathbf{B} \, \mathbf{dV}$$

  - For $R_{\rm m} \gg 1$, H_M is conserved

- Evolution of large and small-scale magnetic helicities

$$\frac{d}{dt} \langle \overline{\mathbf{A}} \cdot \overline{\mathbf{B}} \rangle = 2 \langle \overline{\boldsymbol{\mathcal{E}}} \cdot \overline{\mathbf{B}} \rangle - 2\eta \langle \overline{\mathbf{J}} \cdot \overline{\mathbf{B}} \rangle$$

$$\frac{d}{dt} \langle \boldsymbol{a} \cdot \mathbf{b} \rangle = -2 \langle \overline{\boldsymbol{\mathcal{E}}} \cdot \overline{\mathbf{B}} \rangle - 2\eta \langle \mathbf{j} \cdot \mathbf{b} \rangle$$

  - Produces equal and opposite amounts of large and small-scale helicity

Constraints on mean-field evolution

- Small-scale helicity contributes to the α-effect $\langle \mathbf{j} \cdot \mathbf{b} \rangle \approx k_\mathrm{f}^2 \langle \boldsymbol{a} \cdot \mathbf{b} \rangle$

  $\alpha = \alpha_\mathrm{k} + \alpha_\mathrm{m}$, with $\alpha_\mathrm{m} = (\tau/3)\langle \mathbf{j} \cdot \mathbf{b} \rangle$

- The growing α_m cancels the total α-effect
  - Leads to catastrophic quenching of the dynamo
- Helicity fluxes could help alleviate the problem

$$\frac{d}{dt} \langle \boldsymbol{a} \cdot \mathbf{b} \rangle = -2 \left\langle \overline{\boldsymbol{\mathcal{E}}} \cdot \overline{\mathbf{B}} \right\rangle - 2\eta \langle \mathbf{j} \cdot \mathbf{b} \rangle + \nabla \cdot \mathbf{F}$$

Subramanian & Brandenburg, ApJ, 2006

  - For $\mathbf{F} \neq 0$ as $\eta \to 0$, $\left\langle \overline{\boldsymbol{\mathcal{E}}} \cdot \overline{\mathbf{B}} \right\rangle \neq 0$
- Examine the effect of various helicity fluxes in galactic dynamos

Galactic dynamos and helicity fluxes

- Galactic dynamo model
  - Galactic disc's are thin; retain only the z-derivatives
  - $\alpha\omega$-dynamo approximation
    - $\overline{B}_\phi \rightarrow \overline{B}_r$ via α-effect
    - $\overline{B}_r \rightarrow \overline{B}_\phi$ via differential rotation
  - Differential rotation and vertical advection : $\overline{\mathbf{U}} = (0, \overline{U}_\phi, \overline{U}_z)$
- Galactic dynamo models using the No-z approximation :
  - z derivatives replaced by the disk semi-thickness
  - $\partial/\partial z \rightarrow 1/h$ and $\partial^2/\partial z^2 \rightarrow -1/h^2$

    Subramanian & Mestel, MNRAS, 1993, Moss, MNRAS, 1995
    Phillips, GAFD, 2001, Sur, Shukurov & Subramanian, MNRAS, 2007
- Results hold true for z-dependent models

Helicity fluxes

- Implications and interplay of two types of helicity flux
  - Advective flux - Galactic fountain flow

    Shukurov et al. A&A, 2006

$$\frac{\partial \alpha_{\rm m}}{\partial t} = ... - \frac{\partial F_z}{\partial z},$$

$$F_z \approx \alpha_{\rm m} \overline{U}_z$$

  - Vishniac-Cho flux - anisotropy of turbulence and shear

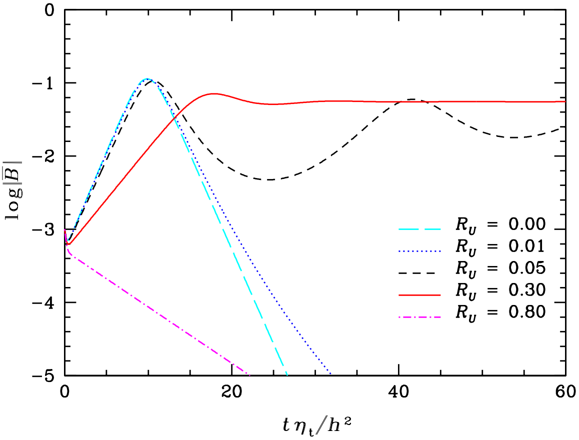
$$F_z \approx \frac{1}{2}(u\tau)^2\, G\, \left(\overline{B}_r^2 - \overline{B}_\phi^2\right)$$

Brandenburg & Subramanian, AN, 2005

Helicity fluxes

- Parameter values in the solar neighbourhood
  - Scaleheight of ionized gas layer $h \simeq 500\, pc$
  - Interstellar turbulence : $l_0 \simeq 100\, pc$
  - $\eta_{\rm t} \simeq 10^{26}\, cm^2 s^{-1}$ and $U_0 = (0.1 - 2)\, km\, s^{-1}$
  - $\alpha_0 = 0.5\, km\, s^{-1}, \quad \Omega_0 = 25\, km\, s^{-1}\, kpc^{-1}$
- Dynamo control parameters :
  - $R_\alpha = \alpha_0 h/\eta_t, R_\omega = Gh^2/\eta_t$ and $R_U = U_0 h/\eta_t$
- Time scales :
  - Small-scale field removal time scale : $h/U_0 = 5 \times 10^8\, yr$
  - Growth time scale of the large-scale field : $h^2/\eta_{\rm t} = 8 \times 10^8\, yr$
- Magnetic helicity fluxes can significantly affect the galactic dynamo

Effect of helicity fluxes



Sur, Shukurov & Subramanian, MNRAS, 2007

Effect of helicity fluxes

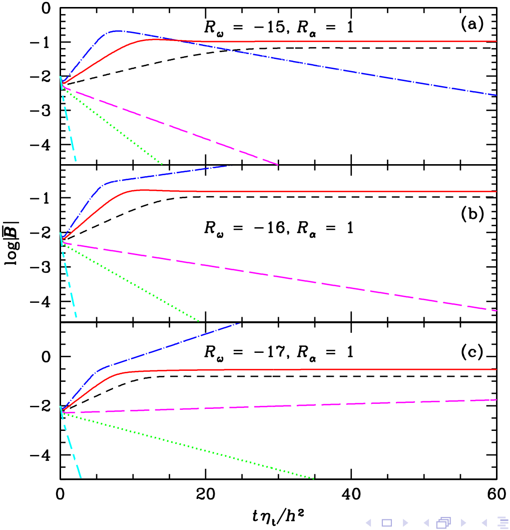
- Advective fluxes in galactic dynamos
  - Moderate advection resolves quenching problem
  - Strong advection hinders dynamo action
- Steady state field strength :

$$\overline{B}^2 \simeq \rho v_0^2 R_U \left(\frac{l_0}{h}\right)^2 \left(\frac{D}{D_{\rm crit}} - 1\right)$$

  - $D \simeq (\Omega h_0/v_0)^2 \approx 10$ in the Solar neighbourhood
  - Critical dynamo number : $D_{\rm crit} \approx 8$
  - $\overline{B} \approx R_U^{1/2}$ for small R_U

Effect of helicity fluxes

- Advective flux combined with the Vishniac-Cho flux



Conclusions

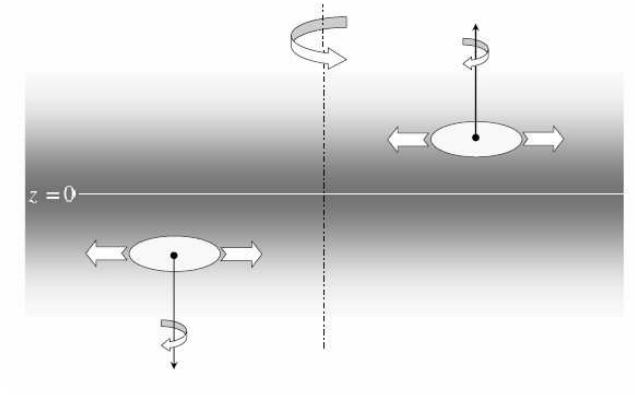
- Magnetic helicity conservation constrains the growth of the large-scale magnetic field
- Possible mechanism : Magnetic helicity fluxes
- Advective flux due to galactic fountains
  - Facilitates the galactic dynamo for moderate advection velocities
  - Strong advection $\sim R_U \geq 0.8$, leads to quenching of the dynamo
- Combined action of the Advective flux and Vishniac-Cho flux
  - Vishniac-Cho flux contributes effectively at large R_U as $|R_\omega|$ increases
- For $R_U = 0$, the Vishniac-Cho flux can alone drive a dynamo for higher $|R_\omega|$

Extra slides

Physical picture

- Magnetic field generation in disk galaxies back

  Ruzmaikin, Sokoloff & Shukurov, 1988



Physical picture

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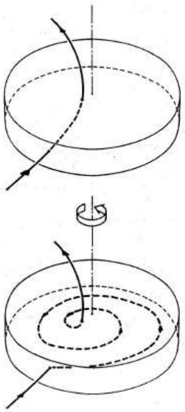

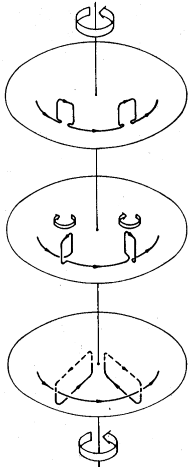

Helicity evolution

- The evolution equation for $\alpha_{\rm m}$ is given by

$$\frac{\partial \alpha_{\rm m}}{\partial t} = -\frac{2\eta_{\rm t}}{l_0^2}\left(\frac{\overline{\boldsymbol{\mathcal{E}}}\cdot\overline{\mathbf{B}}}{B_{\rm eq}^2} + \frac{\alpha_{\rm m}}{R_{\rm m}}\right) - \nabla\cdot\left(\alpha_{\rm m}\overline{\mathbf{U}}\right)$$