Introduction to galactic dynamos

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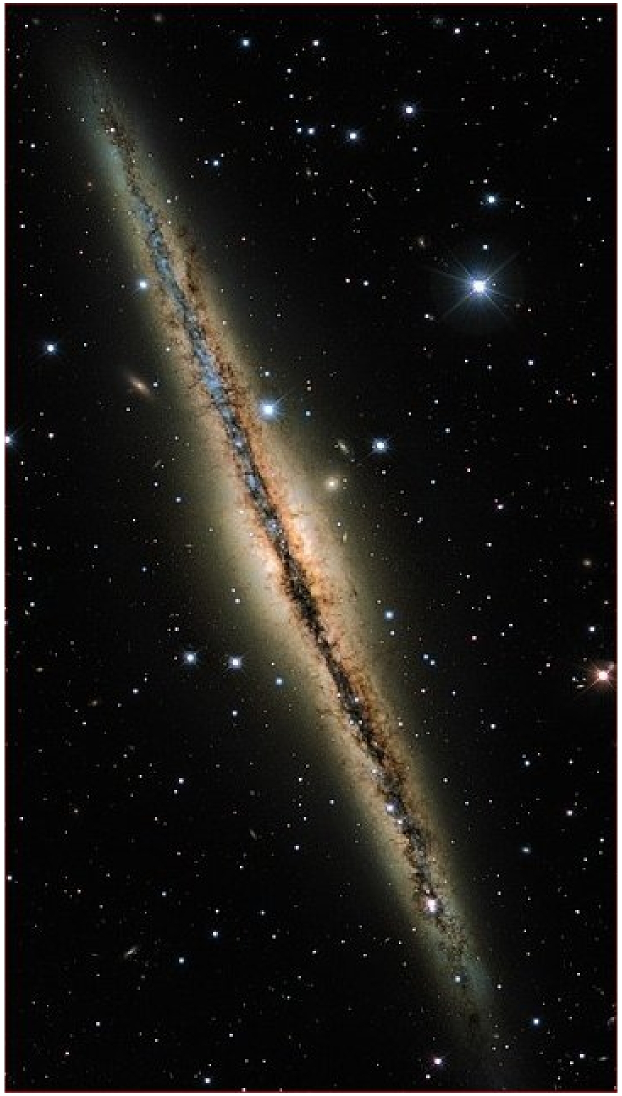
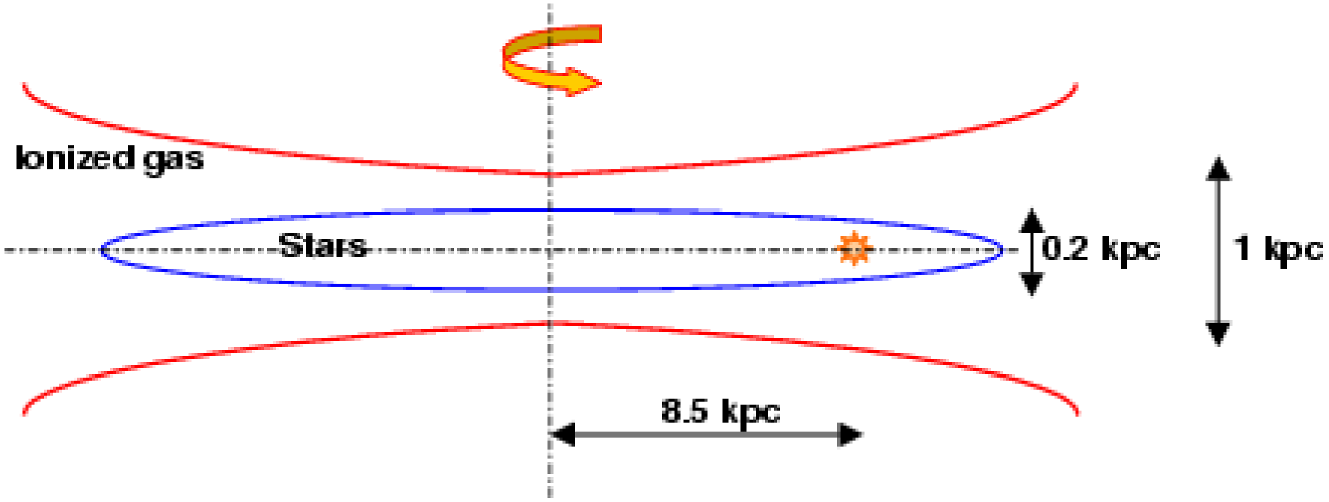
Spiral galaxies: thin rotating discs of 10^{10} stars and interstellar gas,
$\langle n \rangle \simeq 1\,\mathrm{cm}^{-3}$, $\quad 10^3 \lesssim n \lesssim 10^{-3}\,\mathrm{cm}^{-3}$, $\quad 10 \lesssim T \lesssim 10^6\,\mathrm{K}$

M51

NGC 891





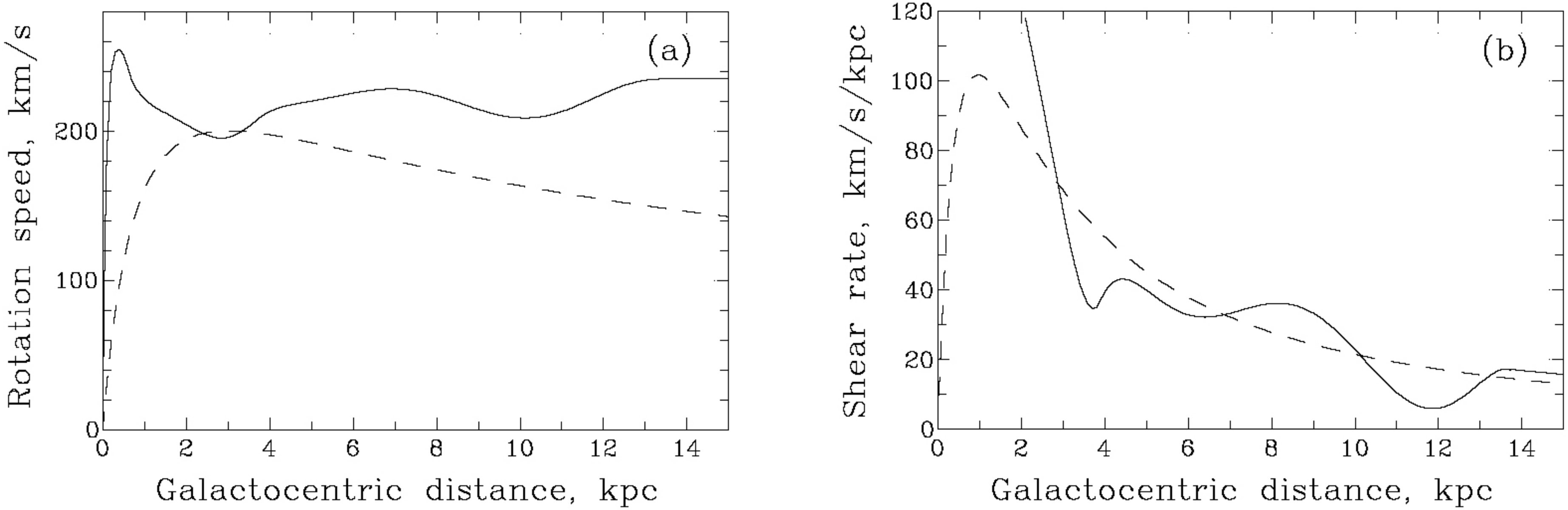
$1\,\mathrm{kpc} \approx 3 \times 10^{21}\,\mathrm{cm}$
$\approx 3,260\,\mathrm{light\ yr}$

$v_0 \simeq 10\,\mathrm{km\,s^{-1}}$,
turbulent speed

$l_0 \simeq 0.1\,\mathrm{kpc}$,
turbulent scale

Rotation: $V = r\Omega \simeq 200\,\mathrm{km\,s^{-1}}$, $\dfrac{v_0}{l_0\Omega} \simeq 5$.

Shear rate $|G| = \left| r\dfrac{d\Omega}{dr} \right|$



Rotation curves and shear in the Milky Way (solid) and in a generic galaxy (dashed)

Elliptical galaxies

Triaxial ellipsoids of 10^{11} stars and hot interstellar gas, $\langle n\rangle \simeq 10^{-3}\,\mathrm{cm}^{-3}$, $T \simeq 10^7\,\mathrm{K}$

M86

M87

Rotation: **insignificant** $(V \lesssim 100\,\mathrm{km\,s^{-1}})$

Plausibly host fluctuation dynamos (Moss & Shukurov, MNRAS, 279, 229, 1996)

The multi-phase interstellar medium (ISM) in spiral galaxies

Supernova explosions $\Rightarrow$ hot, tenuous gas $\Rightarrow$ slow cooling $\Rightarrow$ pervasive hot regions

Supernovae $\Rightarrow$ transonic turbulence $\Rightarrow$ compression $\Rightarrow$ cooling $\Rightarrow$ cool clouds

Gravitational & thermal instabilities $\Rightarrow$ cold, dense clouds

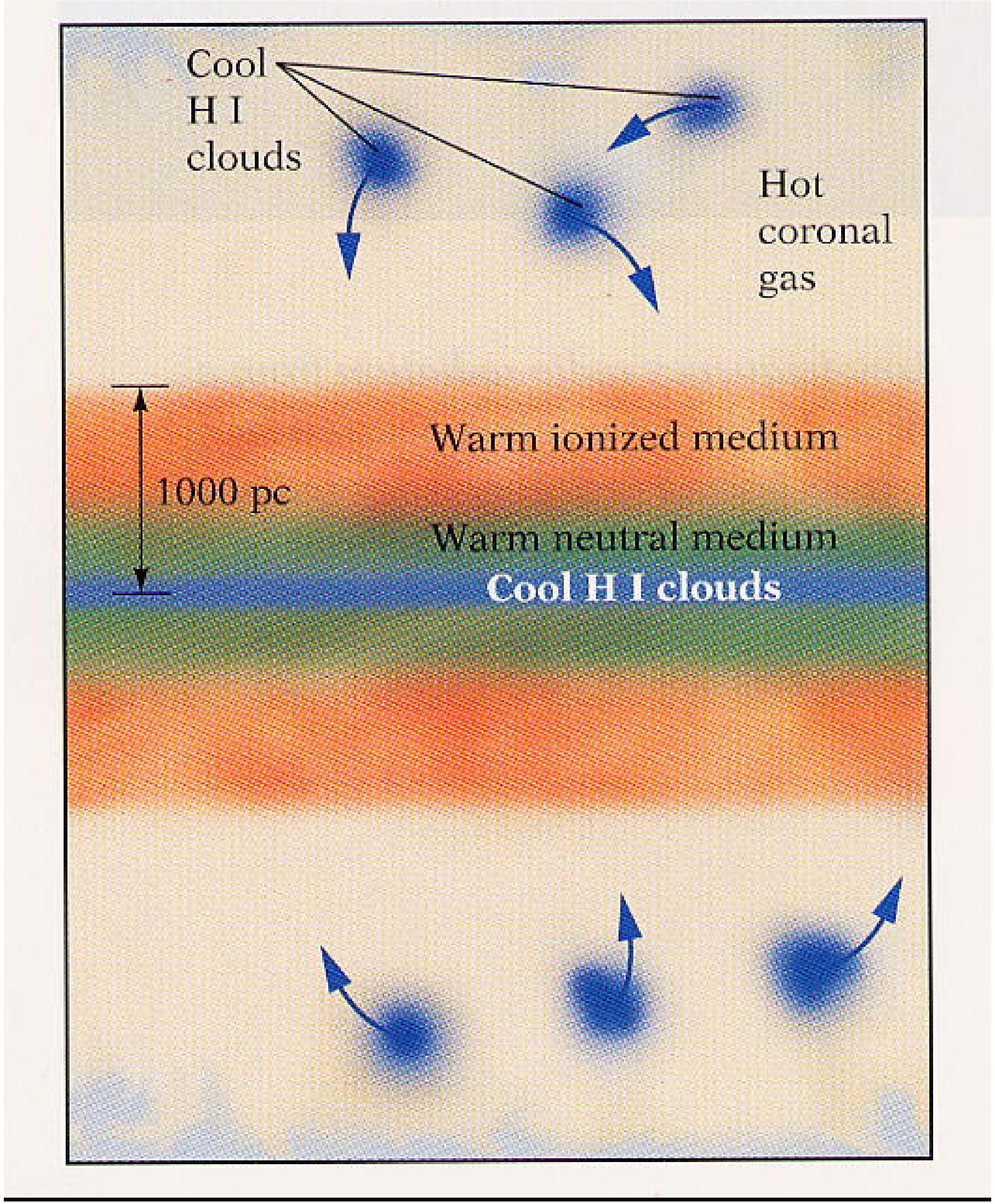
Phase	Origin	Density $[\mathrm{cm}^{-3}]$	Temperature $[\mathrm{K}]$	Size $[\mathrm{pc}]$	Volume fraction, %
Molecular clouds	Gravity, thermal instability	10^3	10	10	0.1
Hydrogen clouds	Compression	20	100	100	2
Diffuse warm gas		0.1	10^4	—	60
Hot gas	Supernovae	10^{-3}	10^6	100–1000	38

The multi-layered ISM

The warmer is the component of the ISM, the more it expands away from the Galactic midplane.

Galactic fountain:

hot gas rises to the halo, cools, and returns to the disc in $\simeq 10^9\,\mathrm{yr}$



Galactic gaseous halos:

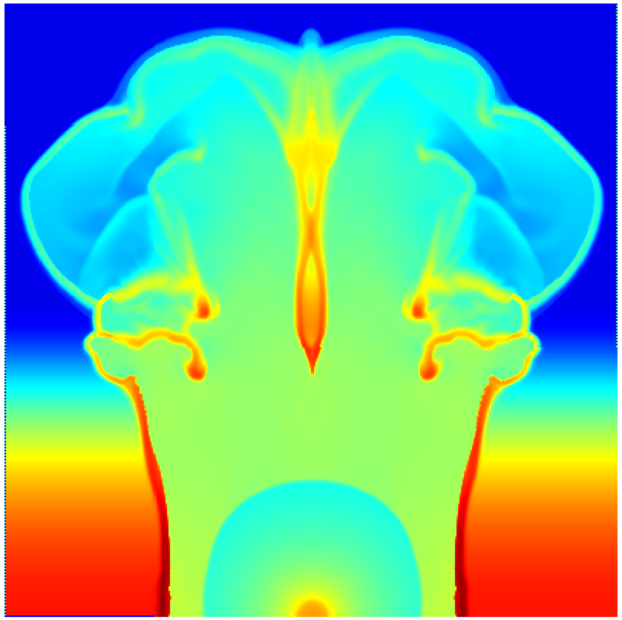
turbulent, rotating, hot, ionized, quasi-spherical gaseous envelopes of galactic discs

Multiple supernovae break through the gas layer
to fill the space above with buoyant hot gas

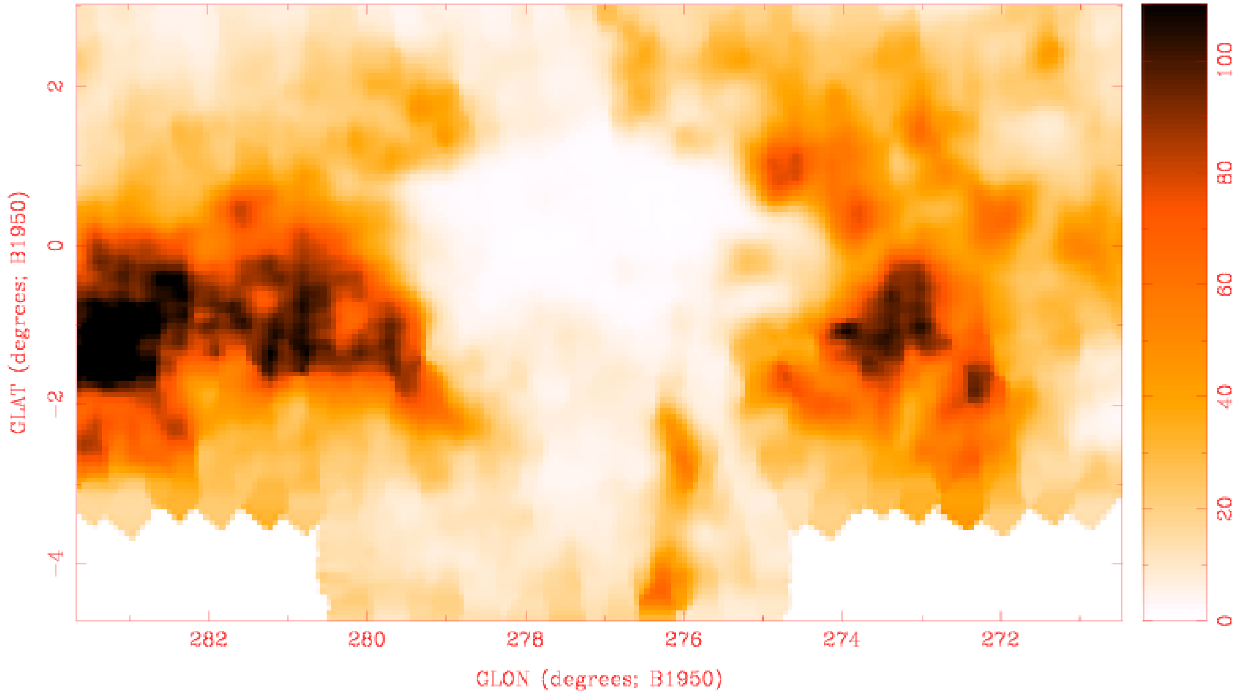
$\Rightarrow$ galactic halo, $n \simeq 10^{-3}\,\mathrm{cm^{-3}}$, $T \simeq 10^{6}\,\mathrm{K}$, $c_\mathrm{s} \simeq 100\,\mathrm{km\,s^{-1}}$, $L \simeq 15\,\mathrm{kpc}$

Simulation of the superbubble breakout to the halo (M-M. MacLow)

gas density in a vertical cross-section $800\,\mathrm{pc} \times 800\,\mathrm{pc}$

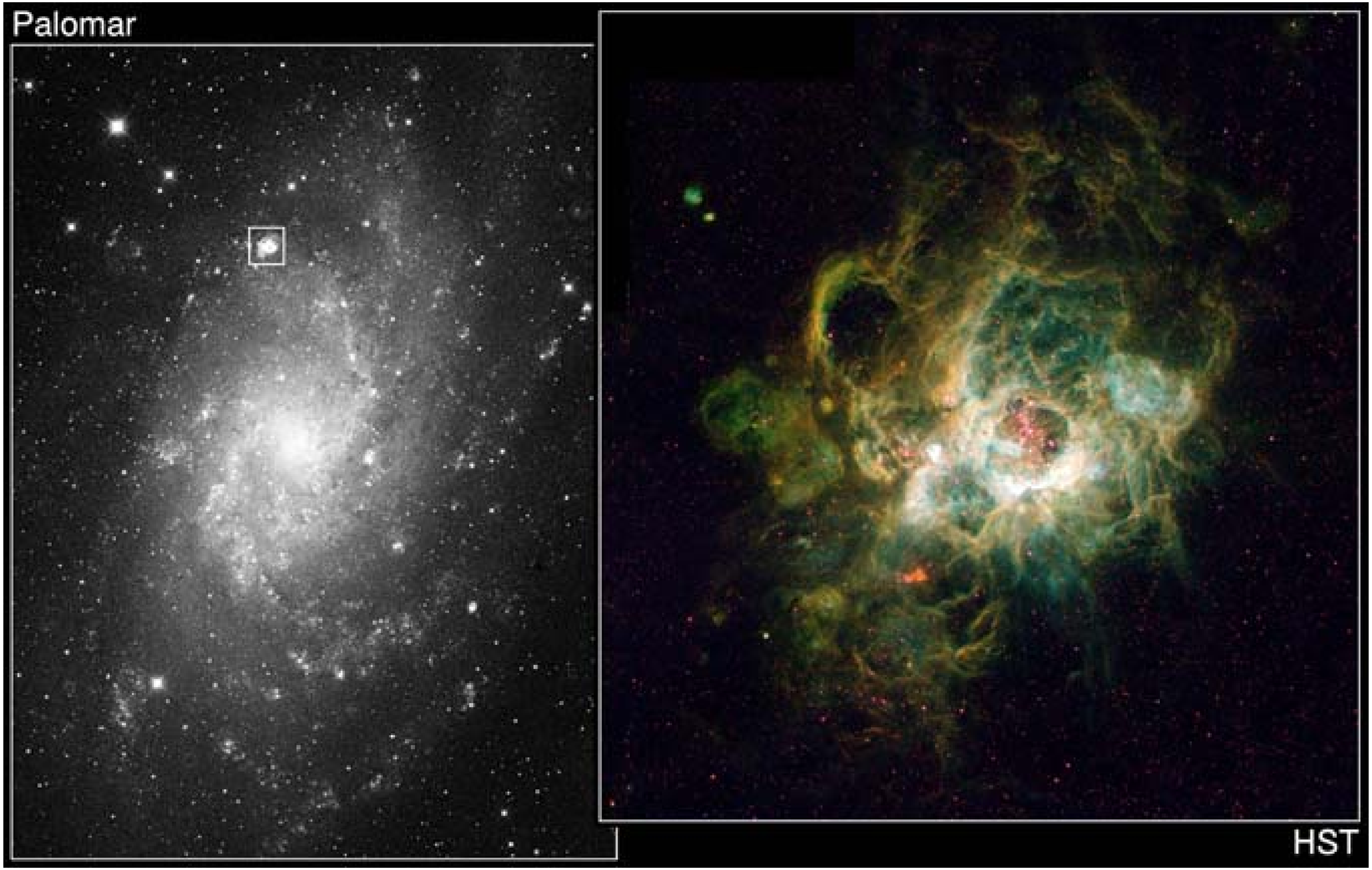


Neutral hydrogen supershell
distance $6.5\,\mathrm{kpc}$, diameter $600\,\mathrm{pc}$,
vertical size $1.1\,\mathrm{kpc}$ (N. M. McLure-Griffits & J. R. Dickey)



Interstellar turbulence: driven by explosions of supernova stars

STARBURST REGION NGC 604 in M33:
200 young massive stars (15–60 solar masses) in a region 1,500 light years across.



Expanding supernova shells drive motions in the ambient gas

$\Rightarrow$ **turbulence** in the ISM

Turbulent scale:

l_0 = shell size at pressure balance

$l_0 \simeq 0.1\,\mathrm{kpc} \approx 300\,\mathrm{light\ yr}$

Turbulent speed:

v_0 = expansion velocity at pressure balance

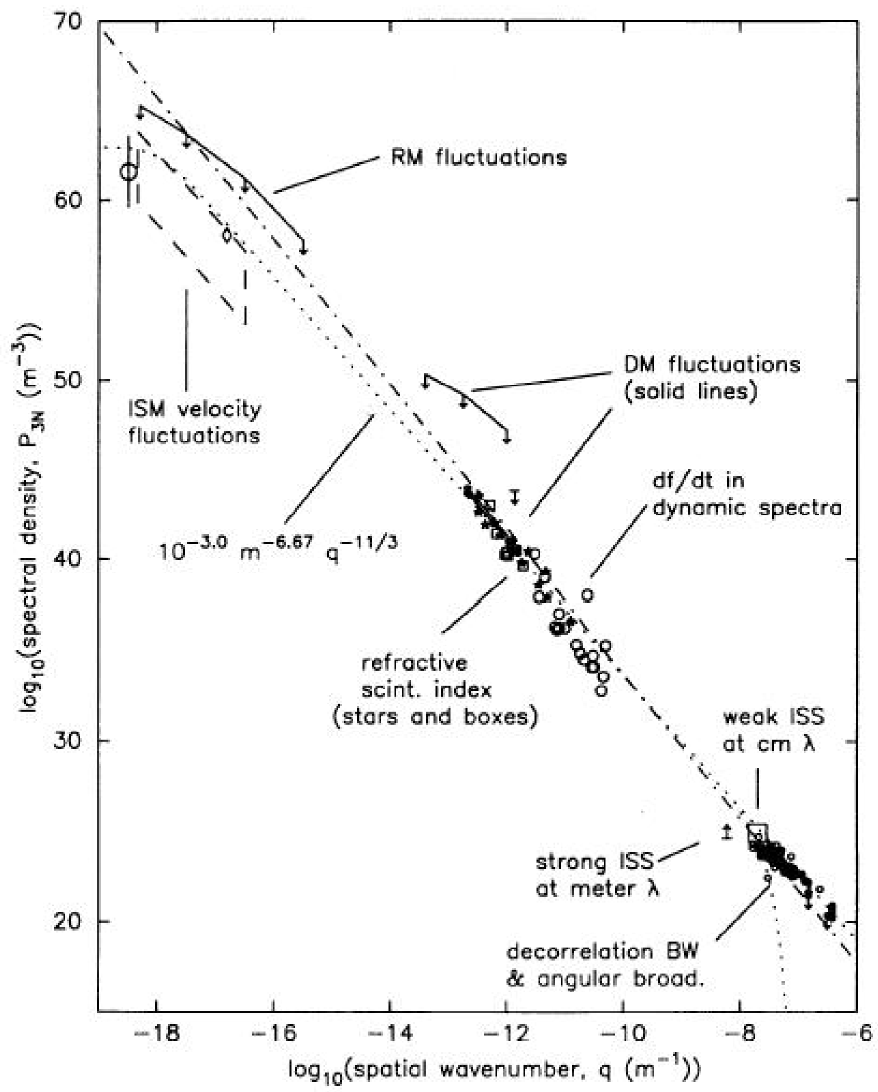
$v_0 \simeq 10\,\mathrm{km\,s^{-1}} \approx c_{\mathrm{sound}}$

A nearly Kolmogorov spectrum:

$v_l \propto l^{1/3}$,

over a wide range of scales

$10^{10}\,\mathrm{cm} \lesssim l \lesssim 10^{20}\,\mathrm{cm}$



(Armstrong et al., ApJ, 443, 209, 1995)

Interstellar medium in spiral galaxies:

- rotating,
- stratified,
- turbulent,
- electrically conducting

fluid (plasma) — perfect environment for **various types of dynamo action**.

Magnetic fields observed in spiral galaxies $(\vec{\mathcal{B}} = \vec{B} + \vec{b}\,,\ \langle\vec{\mathcal{B}}\rangle = \vec{B})$

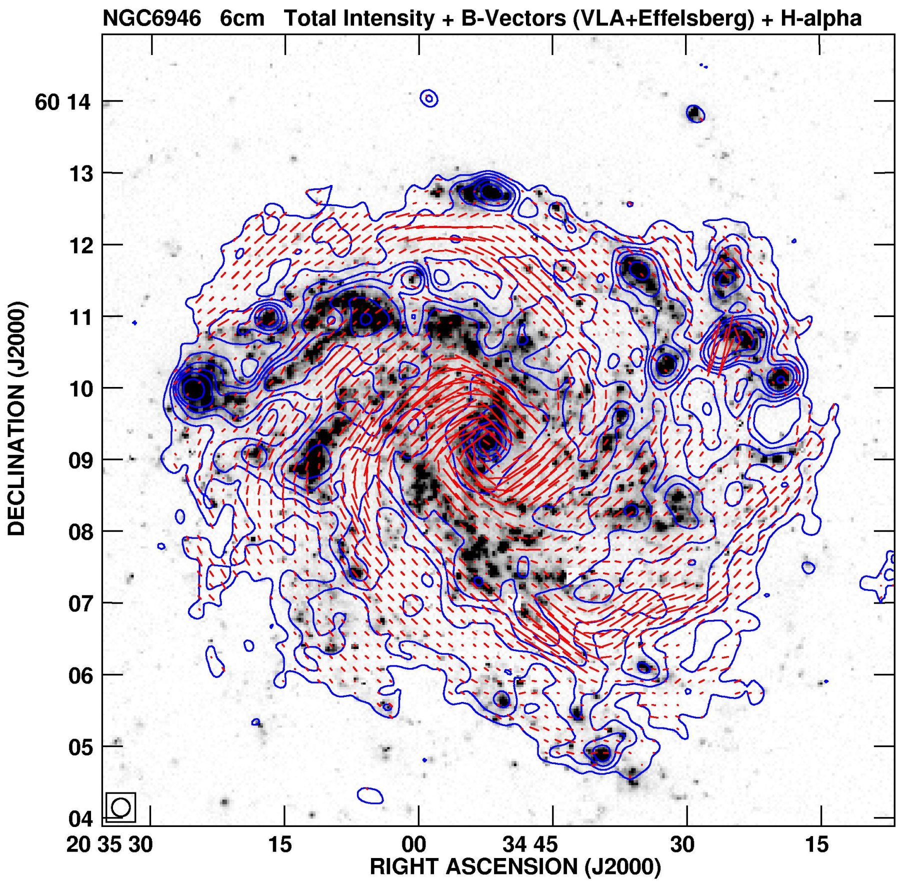
Synchrotron (radio) emission of relativistic electrons, $I \propto \int_0^L n_{\rm rel}\mathcal{B}_\perp^2\,ds$.

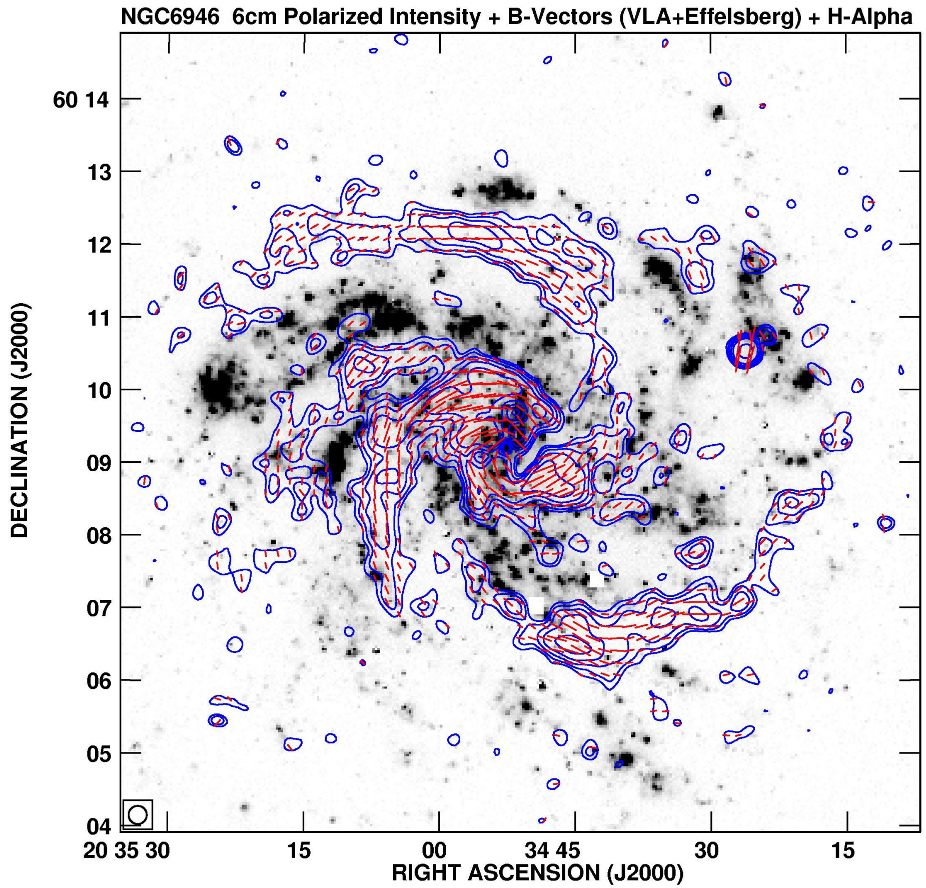
Large-scale magnetic field B:

traced by the polarized emission, $P \propto \int_0^L n_{\rm rel}B_\perp^2\,ds$,

and Faraday rotation in thermal gas, $\mathrm{RM} = K\int_0^L n_{\rm e}\vec{B}\cdot d\vec{s}$

Turbulent magnetic field b: traced by the unpolarized emission, $I - P$





M51, I contours & B-vectors at $\lambda 3\,\mathrm{cm}$, resolution $700\,\mathrm{pc}$

(A. Fletcher & R. Beck)

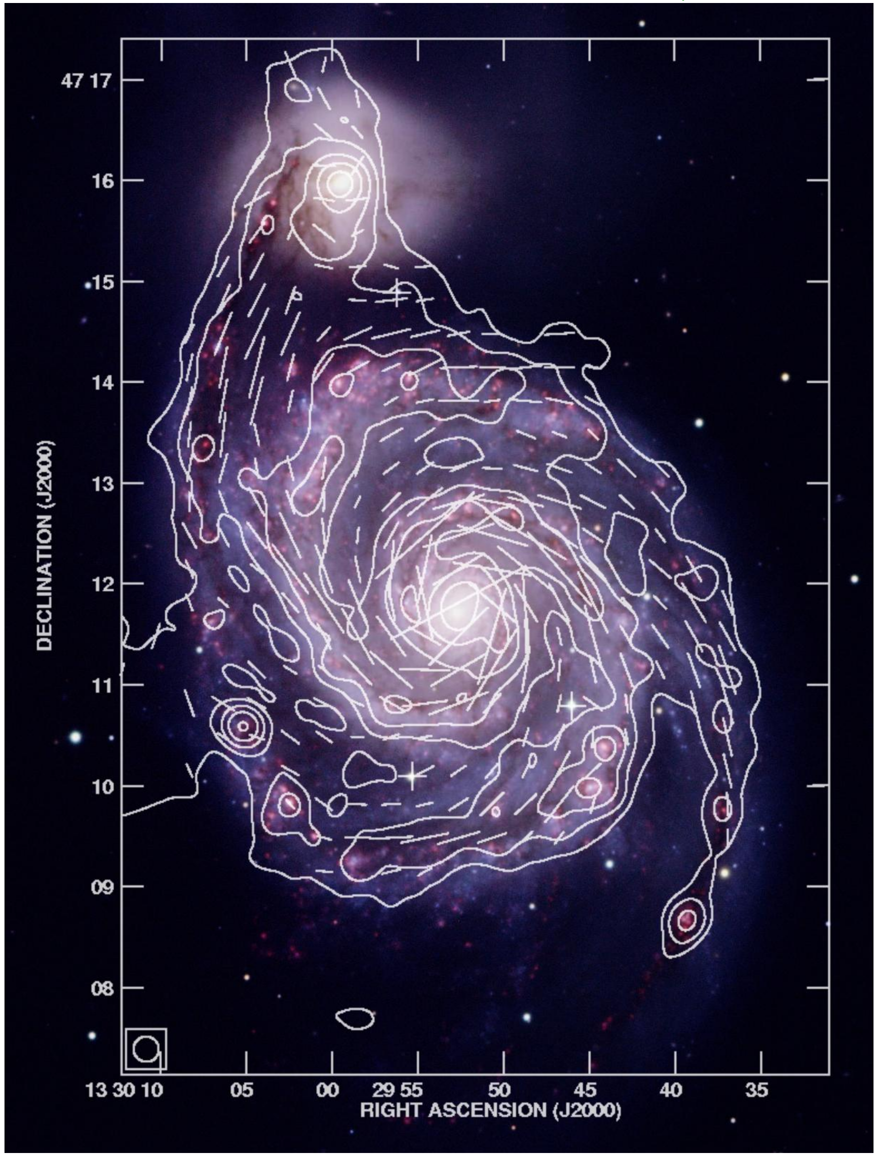
Approximate equipartition between magnetic and turbulent energy:

$b \simeq \sqrt{4\pi\rho v^2} \simeq 5\,\mu\mathrm{G}$,

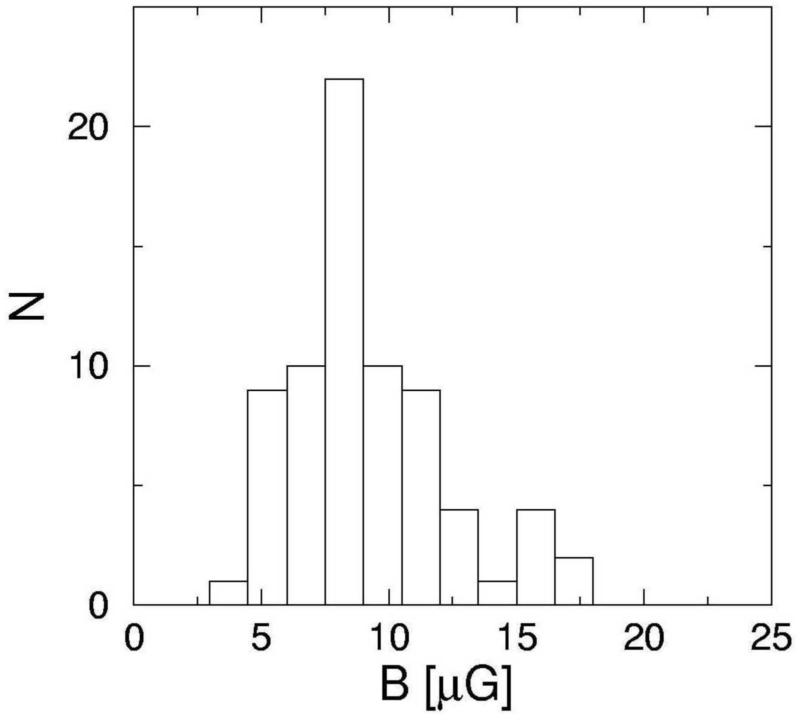
$\frac{b^2}{B^2} \simeq 3.$

The B-vector of polarized synchrotron emission is parallel to $\vec{B}_\perp$.

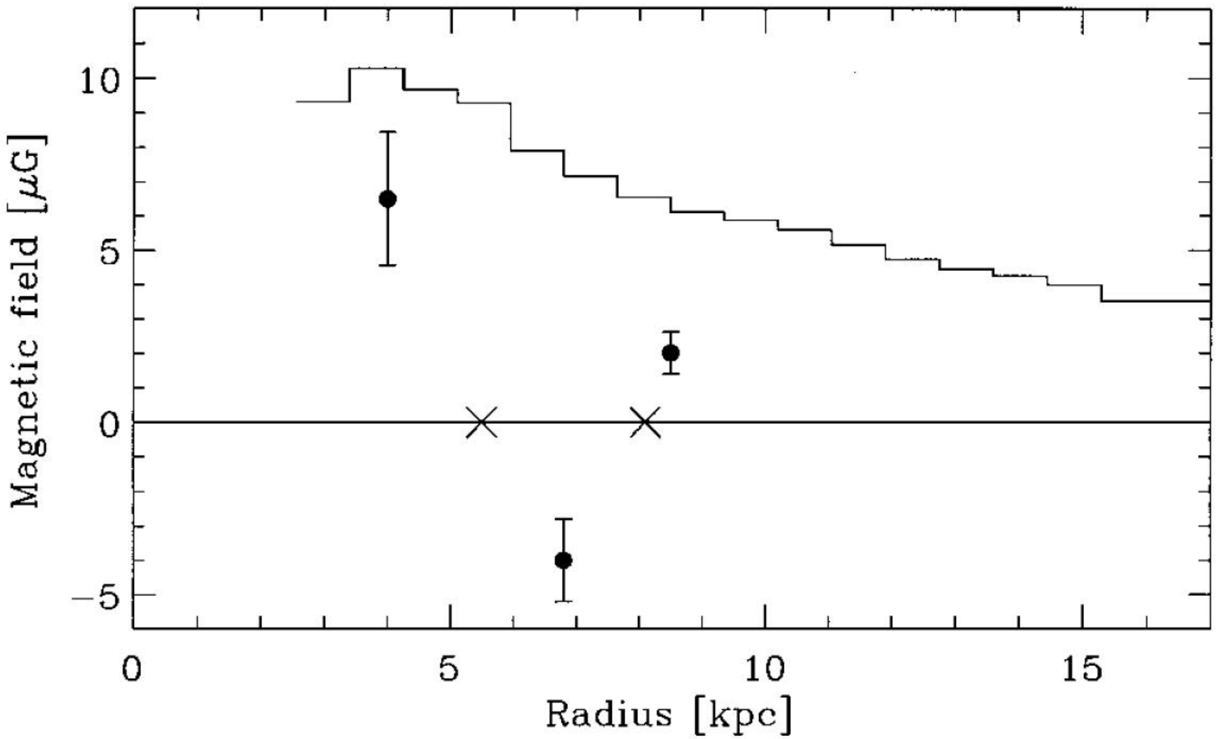
Large-scale magnetic field:
trailing spiral, moderate pitch angle
$p = -(10°–30°)$



Total magnetic field
in a sample of spiral galaxies (R. Beck)



$\mathcal{B}$ and B in the Milky Way (E. M. Berkhuijsen)

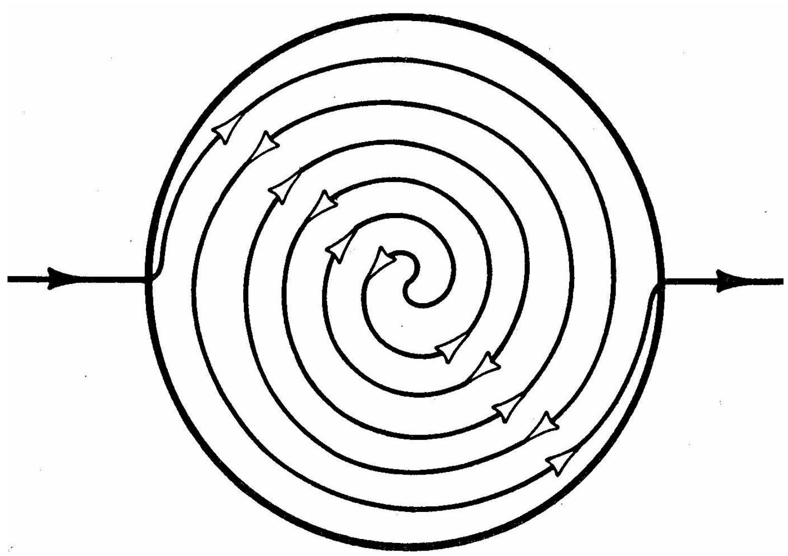


Theories of galactic magnetic fields

Primordial magnetic fields

are rapidly twisted by differential rotation
and removed from the disc
by reconnection, turbulent diffusion
and magnetic buoyancy;

produce magnetic structures incompatible with observations
(wrong symmetry, pitch angle, strength)



Mean-field dynamo

- A natural product of turbulence in a rotating, stratified object

  (Parker 1955; Steenbeck, Krause & Rädler 1966; Moffatt 1978; Krause & Rädler 1980).

- Compatible with our knowledge of spiral galaxies.
- Reliable kinematic (fixed velocity field) theory.
- Nonlinear behaviour is still controversial:
  - numerical experiments with idealized models indicate saturation at a low level $B \simeq R_{\rm m}^{-1/2} B_{\rm eq}$ (Vainshtein & Cattaneo 1992,...)
  - magnetic helicity flux through the boundaries is vital for the dynamo (?)

    (Blackman & Field 2000, Kleeorin et al. 2000, Brandenburg & Subramanian 2000)
  - progress towards more realistic models is hard and slow

    (accretion discs—Brandenburg et al. 1995; galactic discs—Korpi et al. 1999)

What's unusual about galaxies as dynamo systems?

- The ISM has a complicated, **multi-phase structure,** with strong interactions between the phases
- Galactic discs are **open** systems with strong mass/magnetic field interchange with the halo

Mean-field dynamo in a thin disc

Induction equation:

$$\frac{\partial \vec{\mathcal{B}}}{\partial t} = \nabla \times (\vec{U} \times \vec{\mathcal{B}} - \eta \nabla \times \vec{\mathcal{B}})$$

$$\vec{\mathcal{B}} = \vec{B} + \vec{b}\,, \qquad \langle \vec{\mathcal{B}} \rangle = \vec{B}\,, \qquad \langle \vec{b} \rangle = 0\,.$$

$$\vec{U} = \vec{V} + \vec{v}\,, \qquad \langle \vec{U} \rangle = \vec{V}\,, \qquad \langle \vec{v} \rangle = 0\,.$$

Turbulent e.m.f.:

$$\vec{\mathcal{E}} = \langle \vec{v} \times \vec{b} \rangle \approx \alpha \vec{B} - \beta \nabla \times \vec{B}$$

$$\frac{\partial \vec{B}}{\partial t} = \nabla \times \left[\alpha \vec{B} + \vec{V} \times \vec{B} - (\beta + \eta) \nabla \times \vec{B}\right]$$

(+ Navier–Stokes eqn. + energy equation + $\cdots$)

Thin discs (spiral galaxies, accretion discs):

$$\frac{\partial}{\partial z} \gg \frac{\partial}{\partial r}, \frac{\partial}{r \partial \phi}\,, \qquad \lambda = \frac{h}{R} \ll 1\,.$$

Axisymmetric kinematic solutions:

$$\begin{pmatrix} B \\ A \end{pmatrix} = \exp(\Gamma t) \left[Q(r/\lambda^s) \begin{pmatrix} b(z;r) \\ a(z;r) \end{pmatrix} + \ldots \right]$$

Lowest order in λ:

$$\gamma b_r = -\frac{\partial}{\partial z}(\alpha b_\phi) + \beta \frac{\partial^2}{\partial z^2} b_r \, ,$$

$$\gamma b_\phi = G b_r + \beta \frac{\partial^2}{\partial z^2} b_\phi \, , \qquad G = r d\Omega/dr$$

First order in λ (disc surrounded by vacuum):

$$\Gamma q(r) = \gamma(r) q(r) + \lambda \eta(r) \mathcal{L}\{q(r)\} \, ,$$

$$q(r) = Q(r) a(1;r) \, ,$$

$$\mathcal{L}\{q\} = \frac{1}{r} \int_0^\infty W(r,r') \frac{\partial}{\partial r'} \left[\frac{1}{r'} \frac{\partial}{\partial r'} (r'q) \right] dr' \, ,$$

$W(r,r') = rr' \int_0^\infty J_1(kr) J_1(kr') \, dk$, a singular kernel.

Non-local magnetic connection through the vacuum (halo),
+ local, diffusive coupling of regions at different radii:
$B_r(h) = O(\lambda)$.

'Simplified' version: $B_r(h) = 0$,

$$\Gamma Q = \gamma(r) Q + \lambda^2 \frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(rQ(r))\right],$$

Schrödinger-type equation, with potential $-\gamma(r)$.

With α-quenching, $\alpha = \frac{\alpha_0}{1 + B^2/Q_0^2}$:

$$\frac{\partial Q}{\partial t} = \gamma(r)\left(1 - \frac{Q^2}{Q_0^2}\right) Q + \lambda^2 \frac{\partial}{\partial r}\left[\frac{1}{r}\frac{\partial}{\partial r}(rQ(r))\right]$$

Dynamo control parameters

$$R_\omega = \frac{Gh^2}{\beta} \qquad \text{differential rotation,} \qquad G = r\frac{d\Omega}{dr}$$

$$R_\alpha = \frac{\alpha h}{\beta} \qquad \alpha\text{-effect,} \qquad \alpha \simeq \frac{l^2\Omega}{h}$$

Dynamo number $D = R_\alpha R_\omega \simeq 10\frac{h^2}{v^2} r\Omega \frac{d\Omega}{dr} \simeq -10\left(\frac{h\Omega}{v}\right)^2 \gtrsim 10$

Dynamo action occurs ($\gamma > 0$) for $|D| \geq |D_{\rm cr}| \approx 10$

Regeneration rate of the regular magnetic field: $\gamma \simeq \frac{\beta}{h^2}\left(\left|\frac{D}{D_{\rm cr}}\right|^{1/2} - 1\right) \simeq (1–10)\,\mathrm{Gyr}^{-1}$.

Steady-state strength of the regular magnetic field: $B \simeq B_0\sqrt{\frac{D}{D_{\rm cr}} - 1}$.

$$B_0 \propto \sqrt{4\pi\rho v^2}$$

Galactic dynamo parameters are reasonably well known from observations

$\Omega \simeq 20\,\mathrm{km\,s^{-1}\,kpc^{-1}}$	angular velocity of rotation,
$r \simeq 10\,\mathrm{kpc}$	galactocentric radius,
$h \simeq 500\,\mathrm{pc}$	scale height of the stratified, ionized disc,
$\beta \simeq \frac{1}{3}lv \simeq 0.3\,\mathrm{kpc\,km\,s^{-1}}$	turbulent magnetic diffusivity,
$\alpha \simeq \dfrac{l^2\Omega}{h} \simeq 1\,\mathrm{km\,s^{-1}}$	helical part of the turbulent velocity,
$v \simeq 10\,\mathrm{km\,s^{-1}}$	turbulent velocity,
$l \simeq 100\,\mathrm{pc}$	turbulent scale,
$\rho \simeq 1\,m_{\mathrm{H}}\,\mathrm{cm^{-3}}$	gas density.

$R_\omega \simeq -15, \qquad R_\alpha \simeq 1, \qquad D \simeq -15$ at the Solar orbit

Local kinematic dynamo

Lowest-order in $\lambda = h/r$, slab surrounded by vacuum:

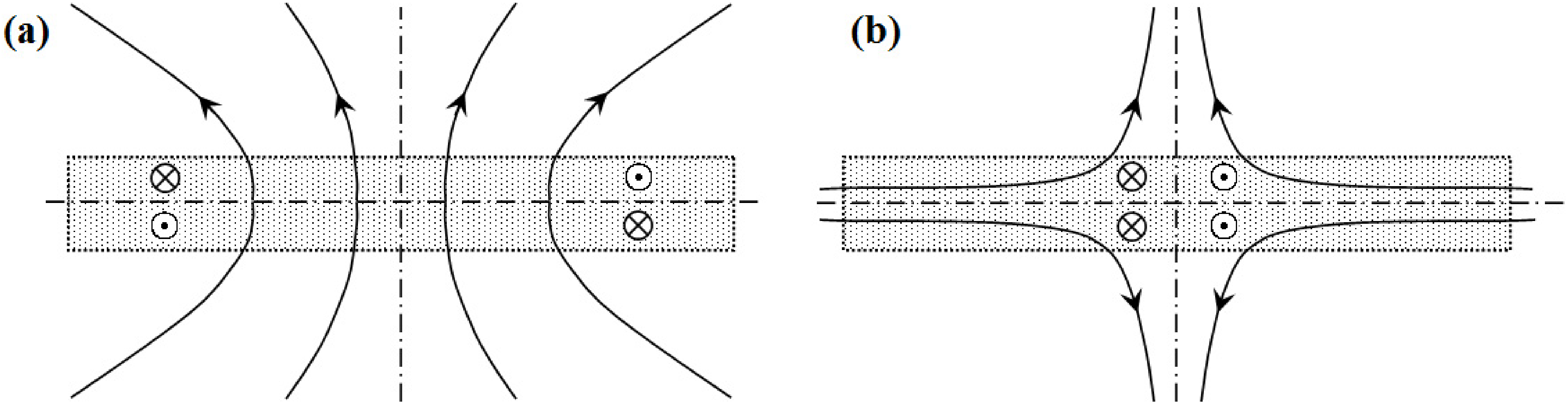
$$
\begin{aligned}
\gamma b_r &= -\frac{\partial}{\partial z}(\alpha b_\phi) + \frac{\partial^2 b_r}{\partial z^2} \ , \\
\gamma b_\phi &= D b_r + \frac{\partial^2 b_\phi}{\partial z^2} \ , \\
b_r(\pm 1) &= b_\phi(\pm 1) = 0 \ .
\end{aligned}
$$

Symmetry:

$\alpha(z) = -\alpha(-z) \Rightarrow$

$B_r(-z) = -B_r(z), \quad B_\phi(-z) = -B_\phi(z)$ $\qquad$ $B_r(-z) = B_r(z), \quad B_\phi(-z) = B_\phi(z)$

dipolar, odd $\qquad$ quadrupolar, even



$B_r = B_\phi = \dfrac{\partial B_z}{\partial z} = 0,$ at $z = 0$ $\qquad$ $\dfrac{\partial B_r}{\partial z} = \dfrac{\partial B_\phi}{\partial z} = B_z = 0,$ at $z = 0$

Dominant symmetry in a thin disc

$\alpha = z$, $|D| \ll 1$:

$$\gamma^{(\text{dipole})} \approx -\pi^2 + \sqrt{-\tfrac{1}{2}D} \,,$$
$$\gamma^{(\text{quadrupole})} \approx -\tfrac{1}{4}\pi^2 + \sqrt{-\tfrac{1}{2}D}$$

- Lower dynamo modes are non-oscillatory, $\operatorname{Im}\gamma = 0$.
- Magnetic field grows for $|D| > |D_{\text{cr}}|$, with

$$D_{\text{cr}}^{(\text{dipole})} \approx -2\pi^4 \approx -200 \,, \qquad D_{\text{cr}}^{(\text{quadrupole})} \approx -\tfrac{1}{8}\pi^4 \approx -10 \,,$$

- Quadrupolar modes are dominant in a thin disc,

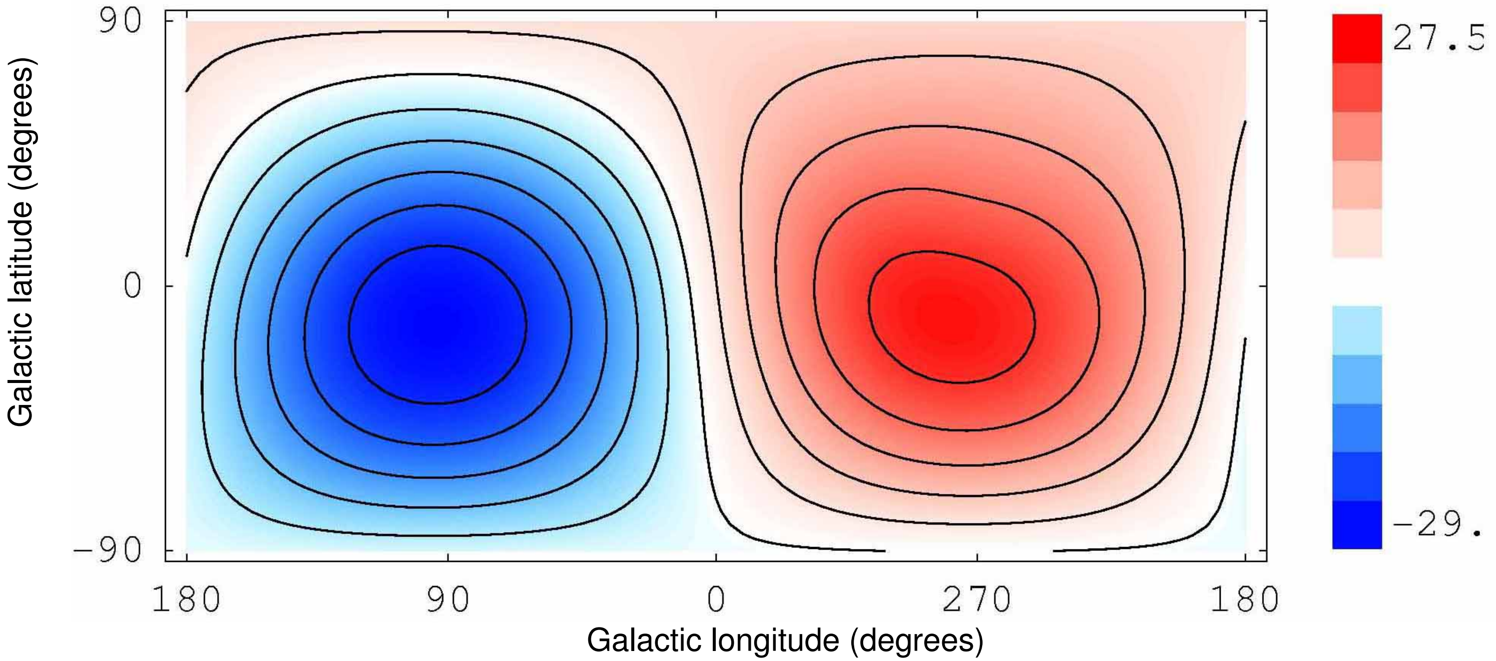
$\gamma^{(\text{quadrupole})} > \gamma^{(\text{dipole})}$ for a given D.

Even (quadrupole) symmetry of magnetic field in the Milky Way

Magnetic structure of the Orion arm: wavelet transform of $\mathrm{RM} = K \int_0^L n_\mathrm{e} \vec{B} \cdot d\vec{s}$

at a scale 76° (Frick et al. 2000)

The sky map of the local line-of-sight magnetic field weighted with n_e



Red: magnetic field towards the observer,
Blue: magnetic field away from the observer

The local magnetic field is similarly directed above and below the Galactic equator indicating even overall symmetry

Properties of the even solution

$$\begin{aligned}\frac{\partial B_r}{\partial t} &= -\frac{\partial}{\partial z}(\alpha B_\phi) + \beta \frac{\partial^2}{\partial z^2} B_r \ , \\ \frac{\partial B_\phi}{\partial t} &= G B_r + \beta \frac{\partial^2}{\partial z^2} B_\phi \ , \\ \frac{\partial B_r}{\partial z}(0,t) &= \frac{\partial B_\phi}{\partial z}(0,t) = 0 \ .\end{aligned}$$

Integrate over $0 < z < h$, use quadrupolar 'b.c.' at $z = 0$, vacuum b.c. at $z = h$:

$$\begin{aligned}\frac{\partial}{\partial t} \int_0^h B_r \, dz &= \beta \frac{\partial B_r}{\partial z}(h) \ , \\ \frac{\partial}{\partial t} \int_0^h B_\phi \, dz &= G \int_0^h B_r \, dz + \beta \frac{\partial B_\phi}{\partial z}(h) \ ,\end{aligned}$$

$\beta = 0 \Rightarrow \int_0^h B_r \, dz =$ const $\Rightarrow$ dynamo needs diffusion

$$\frac{\partial}{\partial t}\int_0^h B_r\,dz = \beta\frac{\partial B_r}{\partial z}(h)\ ,$$

$$\frac{\partial}{\partial t}\int_0^h B_\phi\,dz = G\int_0^h B_r\,dz + \beta\frac{\partial B_\phi}{\partial z}(h)\ .$$

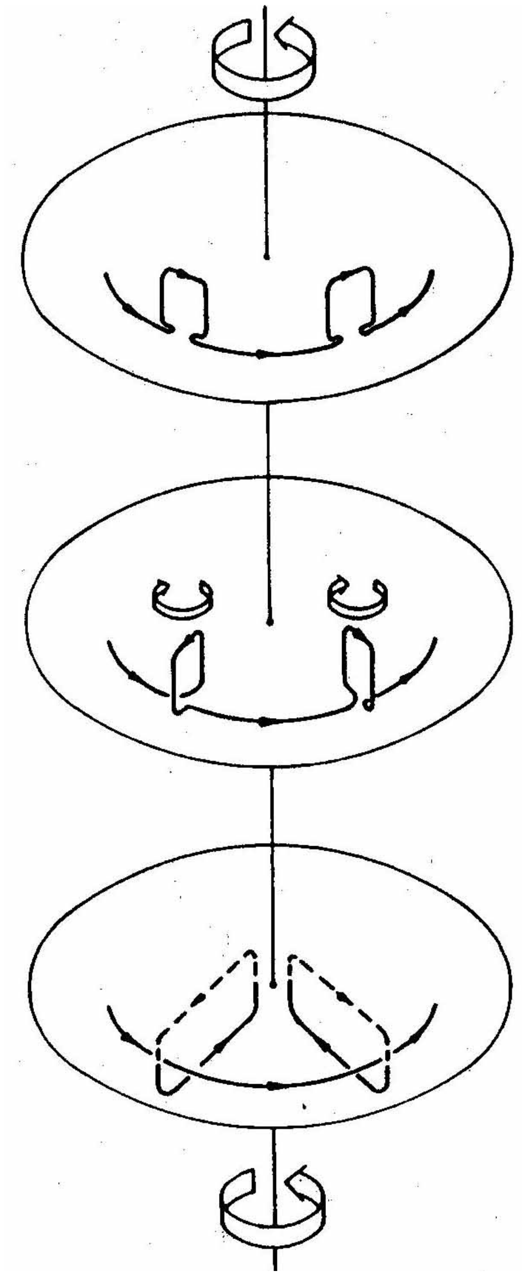
Suppose that $B_\phi > 0$ in $0 < z < h$.

$$B_\phi(h) = 0 \quad \Rightarrow \quad \frac{\partial B_\phi}{\partial z}(h) < 0.$$

Then, for $G < 0$,

$$\int_0^h B_r\,dz < 0\ , \qquad \beta\frac{\partial B_r}{\partial z}(h) < 0\ ,$$

i.e., the dynamo needs diffusive flux of B_r from the disc.



Magnetic pitch angle, $p = \arctan B_r/B_\phi$

Self-excited magnetic fields must have $B_r/B_\phi \neq 0$:

$$\gamma B_r = -\frac{\partial}{\partial z}\alpha B_\phi + \beta \frac{\partial^2}{\partial z^2} B_r \ ,$$
$$\gamma B_\phi = G B_r + \beta \frac{\partial^2}{\partial z^2} B_\phi \ ,$$

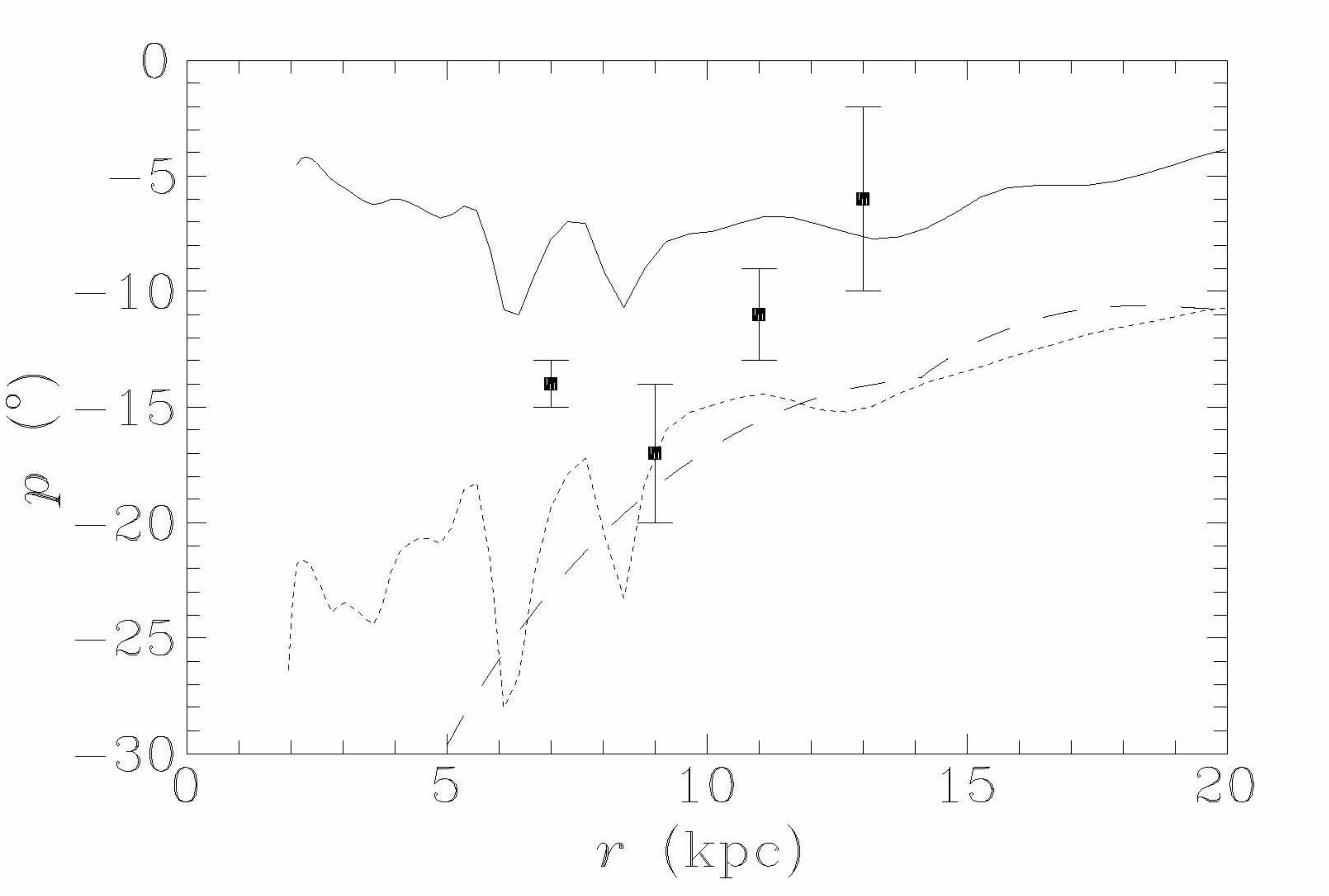
No-z approximation: $\partial/\partial z \to 1/h$,

$$\left(\gamma + \frac{\beta}{h^2}\right) B_r + \frac{\alpha}{h} B_\phi = 0 \ , \qquad \left(\gamma + \frac{\beta}{h^2}\right) B_\phi - G B_r = 0$$

$$\Rightarrow \qquad \tan p \equiv \frac{B_r}{B_\phi} \simeq \sqrt{\frac{\alpha}{-Gh}} = -\sqrt{\frac{R_\alpha}{|R_\omega|}} = -\sqrt{\frac{l}{h}\frac{\Omega/r}{|d\Omega/dr|}} \qquad (1)$$

$R_\alpha \simeq 1 \ , \ R_\omega \simeq -10 \ \Rightarrow \ p \simeq -20^\circ$ as observed + correct radial trend

Magnetic pitch angle in M31



squares with error bars: observations (Fletcher et al. 2000),
solid: $\alpha^2\omega$-dynamo with α-quenching (Moss et al. 1998),
dashed: (1) with the rotation curve of Daharveng & Pellet (1975) & Haud (1981),
dotted: (1) with the rotation curve of Braun (1991)

Nonlinear state and magnetic helicity conservation

Magnetic helicity: $(\vec{\mathcal{B}} = \nabla \times \vec{\mathcal{A}})$

$$H = \langle \vec{\mathcal{A}} \cdot \vec{\mathcal{B}} \rangle \equiv H_B + H_b \;, \qquad (\vec{\mathcal{A}}, \vec{\mathcal{B}}) = (\vec{A}, \vec{B}) + (\vec{a}, \vec{b}) \;, \quad (\vec{A}, \vec{B}) = \langle (\vec{\mathcal{A}}, \vec{\mathcal{B}}) \rangle$$

$$H_B = \langle \vec{A} \cdot \vec{B} \rangle \simeq -L B_r B_\phi \simeq \tfrac{1}{4} L B^2 \;,$$ for $B_r/B_\phi = -\sin p \;, \quad p = 15^\circ; \quad L \gtrsim 1\,\mathrm{kpc}$

$$H_b = \langle \vec{a} \cdot \vec{b} \rangle \simeq -l_d b^2 \;,$$ with $l_d \lesssim l \simeq 100\,\mathrm{pc} \;, \qquad l_d =$ scale of H_b

$$t = 0 \quad \Rightarrow \quad \vec{\mathcal{B}} \approx 0 \quad \Rightarrow \quad H \approx 0$$

$$H = 0 \Rightarrow \frac{B^2}{b^2} \simeq \frac{4 l_d}{L} \simeq 0.4 \;,$$ consistent with observations for $l_d \simeq l$

However, $\dfrac{B^2}{b^2} \simeq R_\mathrm{m}^{-1}$ **if** $\dfrac{l_d}{L} \simeq R_\mathrm{m}^{-1}$

Galactic fountain removes magnetic field from the disc

Galactic fountain: hot gas outflow through the disc surface, $u_z = 140\text{–}200\,\mathrm{km\,s^{-1}}$

Surface filling factor of the hot gas: $f_S = 0.2\text{–}0.3$

Density ratio in the disc and halo: $\rho_\mathrm{h}/\rho_\mathrm{d} \simeq 10^{-2}\text{–}10^{-3}$

Effective advection speed: $U \simeq f_S \dfrac{\rho_\mathrm{h}}{\rho_\mathrm{d}} V_z \simeq 0.1\text{–}2\,\mathrm{km\,s^{-1}}$

Helicity balance

(Shukurov et al. A&A 448, L33, 2006)

Random field $\vec{b}$ has finite correlation length $\Rightarrow$ define volume density of linkages of $\vec{b}$:

$\chi \approx H_b$ for $\nabla \cdot \vec{a} = 0$

Evolution equation:

$$\frac{\partial \chi}{\partial t} + \nabla \cdot \vec{F} = -2\vec{\mathcal{E}} \cdot \vec{B} - 2\eta \overline{\vec{j} \cdot \vec{b}}$$

$\vec{j} = \nabla \times \vec{b}$, $\vec{J} = \nabla \times \vec{B}$, electric current densities

$\vec{\mathcal{E}} \approx \alpha \vec{B} - \beta \nabla \times \vec{B}$, mean electromotive force

$\vec{F} = \chi \vec{U}$, advective flux.

$\alpha = \alpha_{\text{kinetic}} + \alpha_{\text{m}}$, $\alpha_{\text{m}} \simeq \frac{1}{3}\tau k_0^2 \frac{\chi}{\rho}$

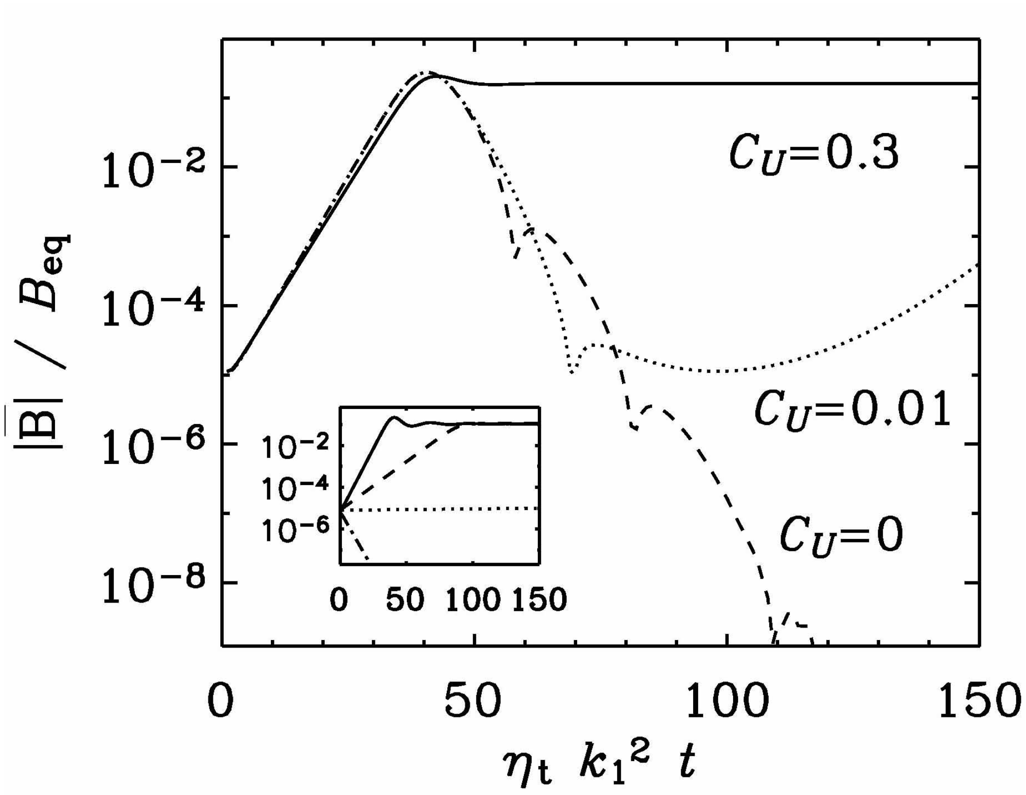
$$\frac{\partial \alpha_{\text{m}}}{\partial t} = -2\beta k_0^2 \left(\frac{\vec{\mathcal{E}} \cdot \vec{B}}{B_{\text{eq}}^2} + \frac{\alpha_{\text{m}}}{R_{\text{m}}} \right) - \nabla \cdot \left(\alpha_{\text{m}} \vec{U} \right)$$

+ mean-field dynamo equations for B_r and B_ϕ

Numerical solution:

$\alpha_{\text{kinetic}} = z, \qquad R_\omega = -20, \qquad R_\alpha = 3, \qquad R_{\text{m}} = 10^5,$

$U = U_0 z/h, \qquad 1/(\eta_{\text{t}} k_1^2) \simeq 8 \times 10^7\,\text{yr}, \qquad B_{\text{eq}} = \sqrt{4\pi\rho v_0^2} \simeq 5\,\mu\text{G},$



B at $z = 0$: $\quad R_U = U_0 h/\beta =$ 1 (solid), 0 (dashed), 0.03 (dotted)

$\Rightarrow$ moderate advection facilitates the dynamo

Inset: $R_U =$ 0.3 (solid), 4.5 (dashed), 6 (dotted), 9 (dash-dotted)

$\Rightarrow$ strong advection destroys the dynamo

Optimal advection: $R_U \simeq 0.3 \Rightarrow U \simeq 0.2\,\text{km}\,\text{s}^{-1}$, similar to the estimated value.

Conclusions

- The **mean-field dynamo theory** form provides a remarkably satisfactory description of virtually all gross features of galactic magnetic fields.
- Most parameters of galactic dynamos can be expressed in terms of observable quantities, leaving relatively little freedom for speculation.
- Magnetic field properties captured by the dynamo theory:
  - pitch angle of magnetic field and its variation with r;
  - quadrupolar symmetry;
  - predominantly axially-symmetric structure;
  - magnetic structures in specific galaxies
    (radial reversals in the Milky Way, vertical reversal in M51, synchrotron ring M31).

(details in AS, astro-ph/0411739)

Critical values: $R_\alpha = 0.8$ for $R_\omega = -6,\ R_U = 1$.