Galactic Dynamo

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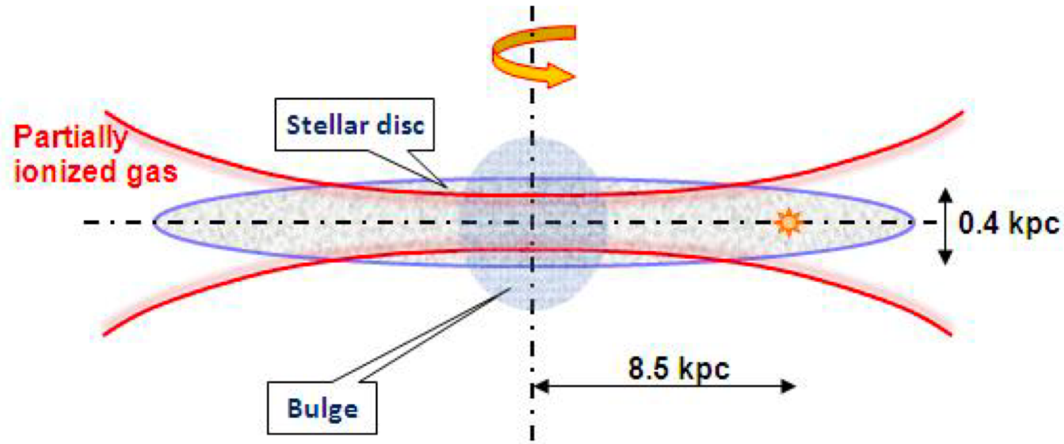
Outline

- An Introduction to Spiral Galaxies
- Necessity of dynamo action
  - Primordial-field hypothesis
- Mean-field dynamo theory
- Criticisms of mean-field dynamo theory
- Reference
- Summary

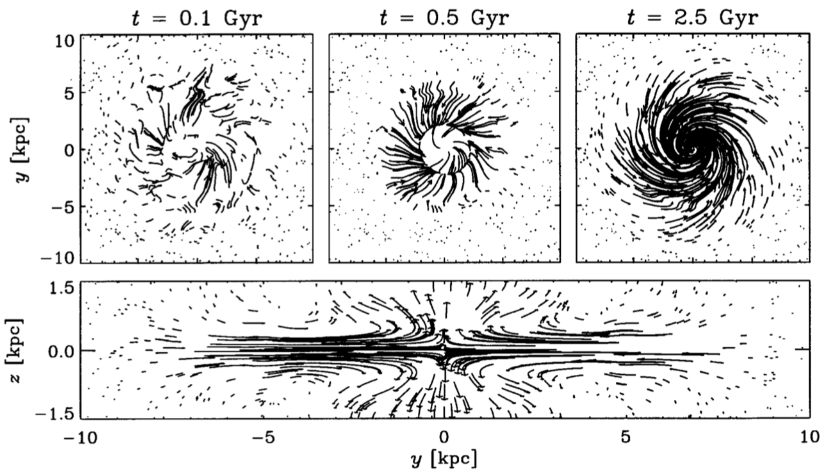
Introduction:Spiral Galaxies

thin rotating discs of $\cong 10^{11}$ stars (90% of visible mass)
and interstellar gas(10%)
+dark matter



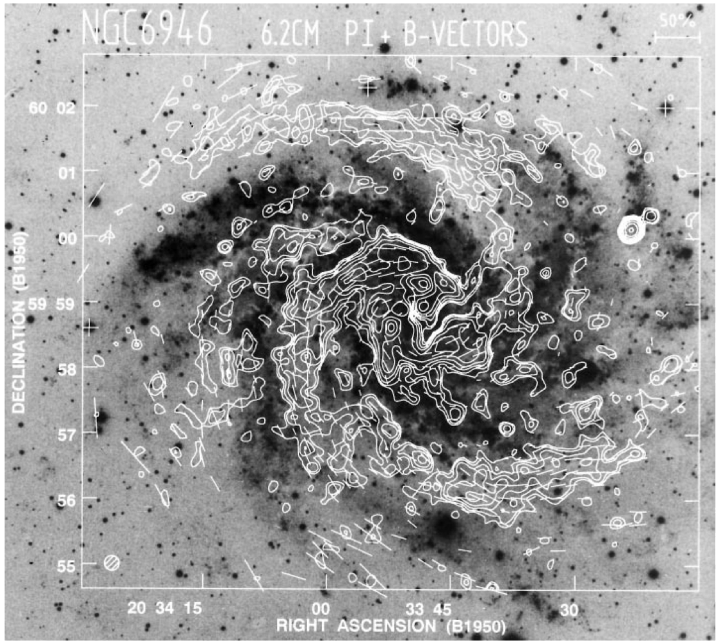
The structure of Milky Way(Shukurov,2004)

Introduction:Spiral Galaxies



the evolution of the magnetic field in a model of M83(Beck,et al,1996)

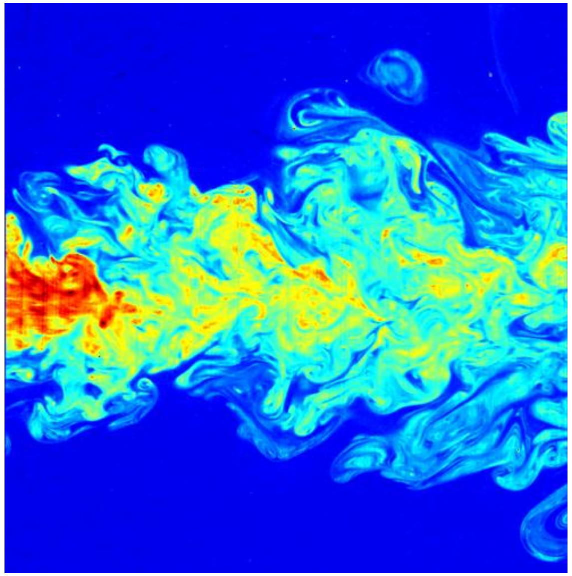
- $B_{spiral} \approx 5\mu G$, the magnetic fields in nonrotating or slowly rotating systems such as elliptical galaxies and clusters appear to have smaller B



Polarized synchrotron intensity (contours) and magnetic field orientation of M51(Beck and Hoernes, 1996)

Turbulence(α effect) [1]

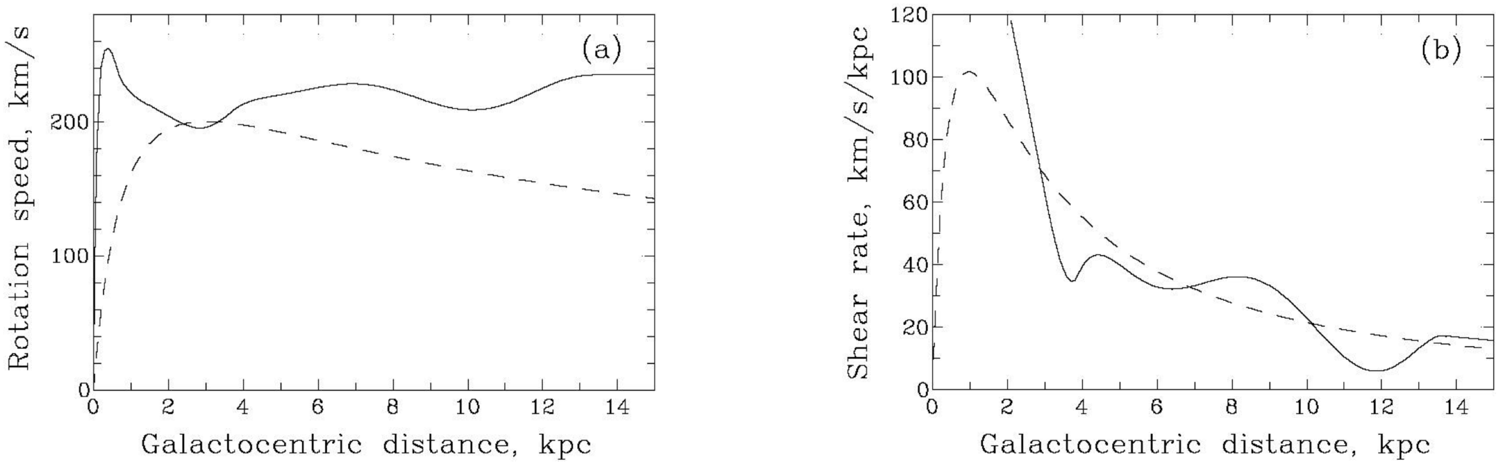
- Interstellar turbulence
  - In some models,driven by gravity and density gradients(supernovae, superbubble explosions⋯)
  - Correlation scale:$l_0 = 50 - 100\ \mathrm{pc}$
  - Turbulent velocity:$v_0 \approx 10\ \mathrm{km/s} \approx c_s$ at $z = 0$



Flow visualization of a turbulent jet

Differential rotation(ω effect) [1]

- Differential rotation: angular velocity varying with position
- Flat rotation curves at large radii:
  - $V = r\Omega \cong 200\, km/s \cong const$; $\Omega \cong V_0/r$, $V_0 \cong const$
  - Rotational shear rate: $G = r\, d\Omega/dr \cong -\Omega$



Rotation curve and shear: Milky Way (solid) and a generic galaxy (dashed)(Shukurov,2004)

Necessity of dynamo action

- Can the magnetic fields observed be primordial?

- Do they need to be maintained by ongoing dynamo action?

- Dynamo action: conversion of kinetic energy into magnetic energy

Can the magnetic fields observed be primordial?

- Primordial-field hypothesis
  - astrophysical battery : $V{\sim}3{\times}10^{13}$ V   so enormous!

  - magnetic fields are present ab initio in the material that collapses to form a galaxy:

$$\boldsymbol{B}(\mathbf{x},0) = \boldsymbol{B_0}\hat{\mathrm{x}}$$

$$\boldsymbol{B}(R,\phi,t) = B_0(\widehat{\boldsymbol{b}} + \mathrm{t}\frac{\mathrm{d}\ \omega}{\mathrm{d}\ \ln\mathrm{R}}[\cos(\omega+\phi t)]\widehat{\boldsymbol{\phi}})$$

Where $\widehat{\boldsymbol{b}} = \widehat{\boldsymbol{b}}(R) = cos\omega\mathrm{t}\ \hat{\mathbf{x}} + \sin\ \omega t\ \hat{\mathbf{y}}$

Can the magnetic fields observed be primordial?

- Primordial-field hypothesis[3]
  - $\nabla B \sim \omega t^2/L$

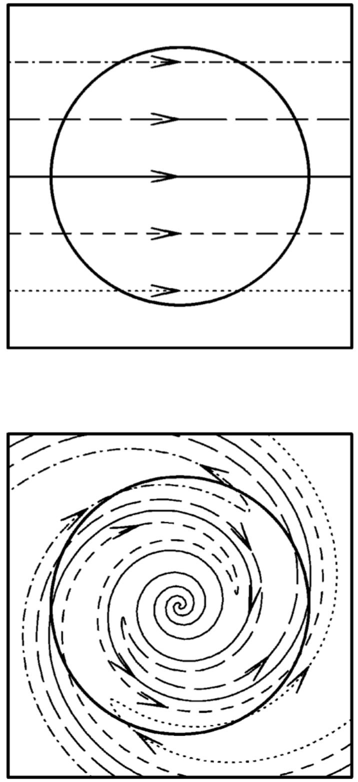
  Where L is the disk scale length and $d\,\omega/d\,r \sim \omega/L$

  - Eventually, magnetic diffusion becomes important with the diffusion time scale(turbulence,random motions driven by random magneticfield,etc.)
  - $\tau_{\mathrm{d}} \equiv B/\eta\nabla^2 B \approx L^2/\eta\omega^2 t^2$

  Where η is the molecular diffusion coefficient

  - $\tau_{\mathrm{d}} = \mathrm{t}$
  - $t \approx \left(\frac{L^2}{\eta\omega^2}\right)^{\frac{1}{3}} \approx 3\times10^8\ yr$
  - The age of the Milky Way: $t_{age} \approx 1.4 \times 10^9\ yr$

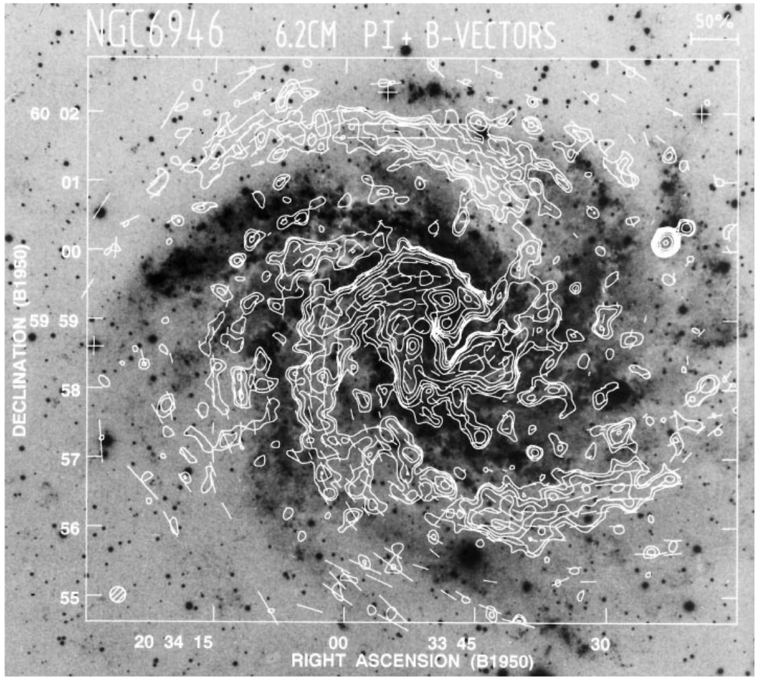
  - t much shorter than the age of a galaxy! The magnetic fields need to be maintained by ongoing dynamo action



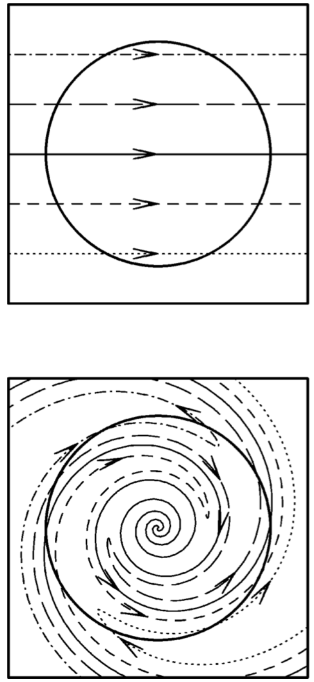
Distortion of magnetic-field lines under the action of differential rotation(Widrow,et al,2002)

Can the magnetic fields observed be primordial?

- Primordial-field hypothesis
  - observation that galactic magnetic fields form, by and large, a loosely wound spiral
  - Simulation of the Primordial-field hypothesis:tightly wound spiral
  - (only appears as a toroidal azimuthal field because of inadequate resolution?)



Polarized synchrotron intensity (contours) and magnetic field orientation of M51(Beck and Hoernes, 1996)



Distortion of magnetic-field lines under the action of differential rotation (Widrow,et al,2002)

Dynamo action: conversion of kinetic energy into magnetic energy

- It seems that there are many problems with Primordial-field hypothesis

- The galactic magnetic field need to be maintained by ongoing dynamo action

- Galactic dynamos:A magnetic dynamo consists of electrically conducting matter moving in a magnetic field in such a way that the induced currents amplify and maintain the original field.

Dynamo action: conversion of kinetic energy into magnetic energy

- Mean-field dynamo theory ($\alpha\omega$ dynamo)
  - In a mean-field analysis:

$$\boldsymbol{B} = \overline{\boldsymbol{B}} + \boldsymbol{b}, \mathbf{V} = \overline{\boldsymbol{V}} + \boldsymbol{v}$$

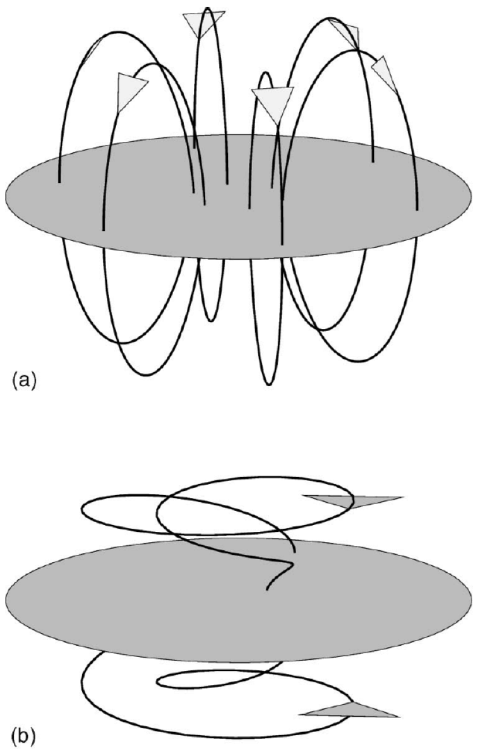
  where $\bar{B}$ and $\bar{V}$ represent ensemble averages of the magnetic and velocity fields and b and v are the corresponding small-scale tangled components.

$$\frac{\partial \overline{\boldsymbol{B}}}{\partial t} = \boldsymbol{\nabla}\times(\overline{\boldsymbol{V}}\times\overline{\boldsymbol{B}}) + \nabla\times\boldsymbol{\varepsilon}$$

  Where $\boldsymbol{\varepsilon}$ is the effective electromotive force due to turbulent motions of the magnetic field as it is carried around by the fluid

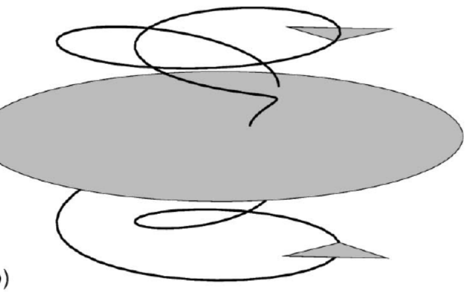
Dynamo action: conversion of kinetic energy into magnetic energy

- **Differential rotation**
  - Begin with a pure poloidal dipolelike field (a)
  - Because of differential rotation,the field lines are stretched (b)

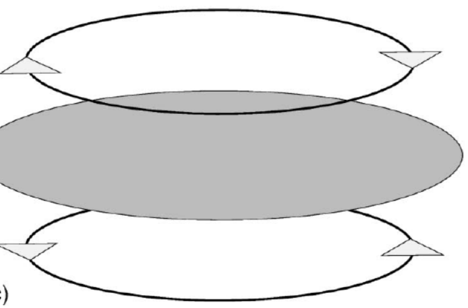


Dynamo action: conversion of kinetic energy into magnetic energy

- **Diffusion**
  - The field in the equatorial plane is characterized by strong gradients and high magnetic tension.
  - This tension can be relieved either by turbulent diffusion, via the β effect, or by some other process(e.g., magnetic reconnection)
  - The net result is to decouple the toroidal field in the upper and lower hemispheres,as shown in Figure(c)



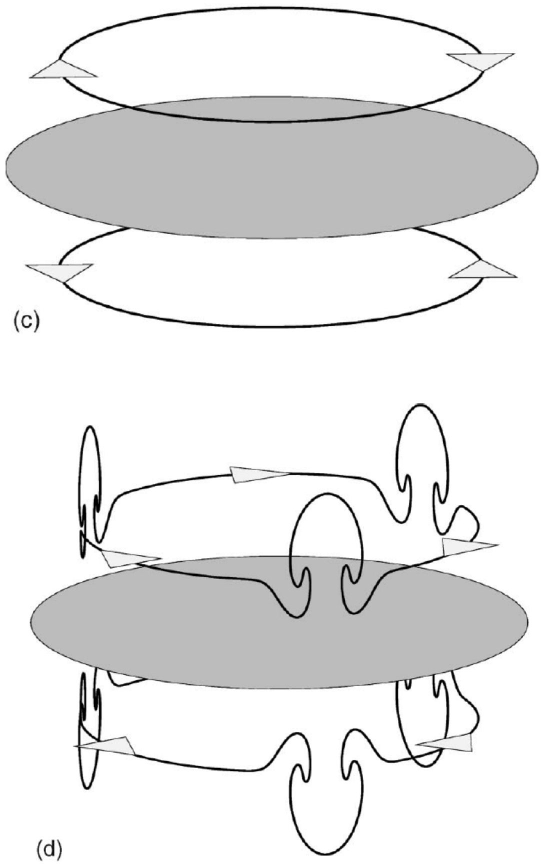
(b)



(c)

Dynamo action: conversion of kinetic energy into magnetic energy

- **Turbulence**
  - we assume that cyclonic events occur throughout the disk.
  - The toroidal field is distorted in the vertical direction

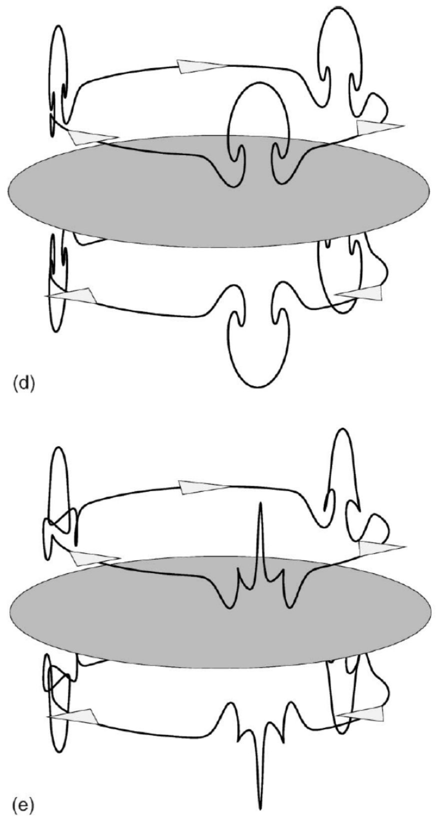


Dynamo action: conversion of kinetic energy into magnetic energy

- **Coriolis effect**
  - The loops of vertical field are then twisted into the poloidal plane by the Coriolis effect

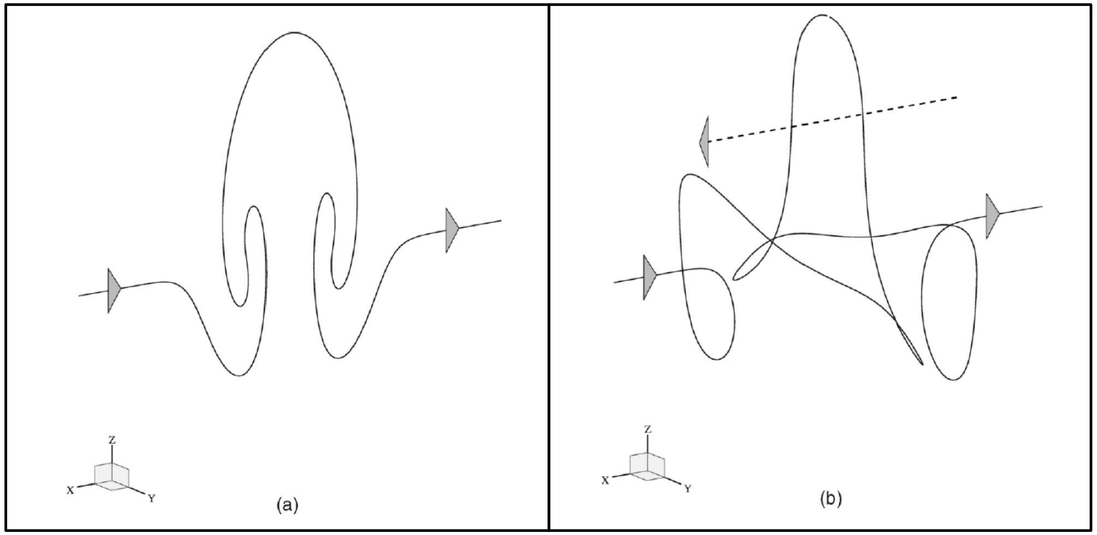
$$\frac{d\mathbf{u}}{dt} = (\mathbf{v_p} \cdot \boldsymbol{\nabla})\mathbf{v_p} - 2\boldsymbol{\omega}_0 \times \mathbf{u} + \cdots$$

Coriolis effect



Dynamo action: conversion of kinetic energy into magnetic energy

- The classic example of the α effect is the distortion of a magnetic-field line by a localized helical disturbance or cyclonic event
- (a) is the field line after it has been distorted by the plume velocity field
- inclusion of the Coriolis effect, the field line will be (b)
- the current associated with this loop is antiparallel to the initial magnetic-field line.

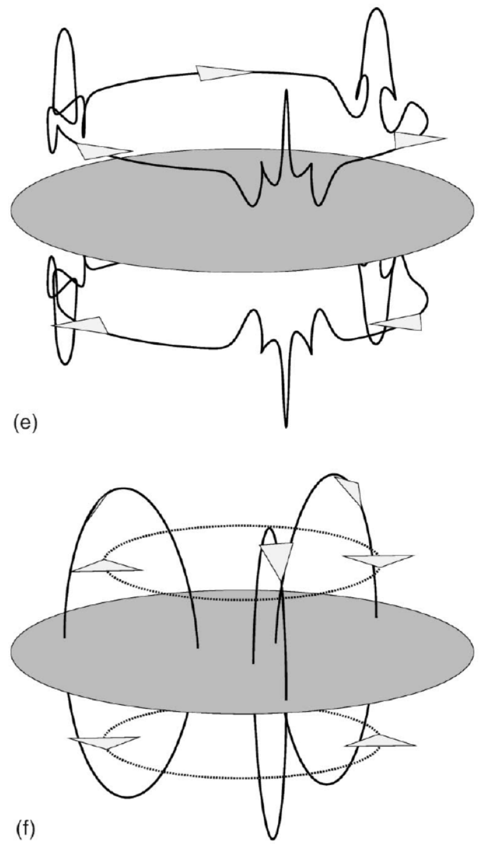


Cyclonic event as an illustration of the α effect(Widrow,et al,2002)

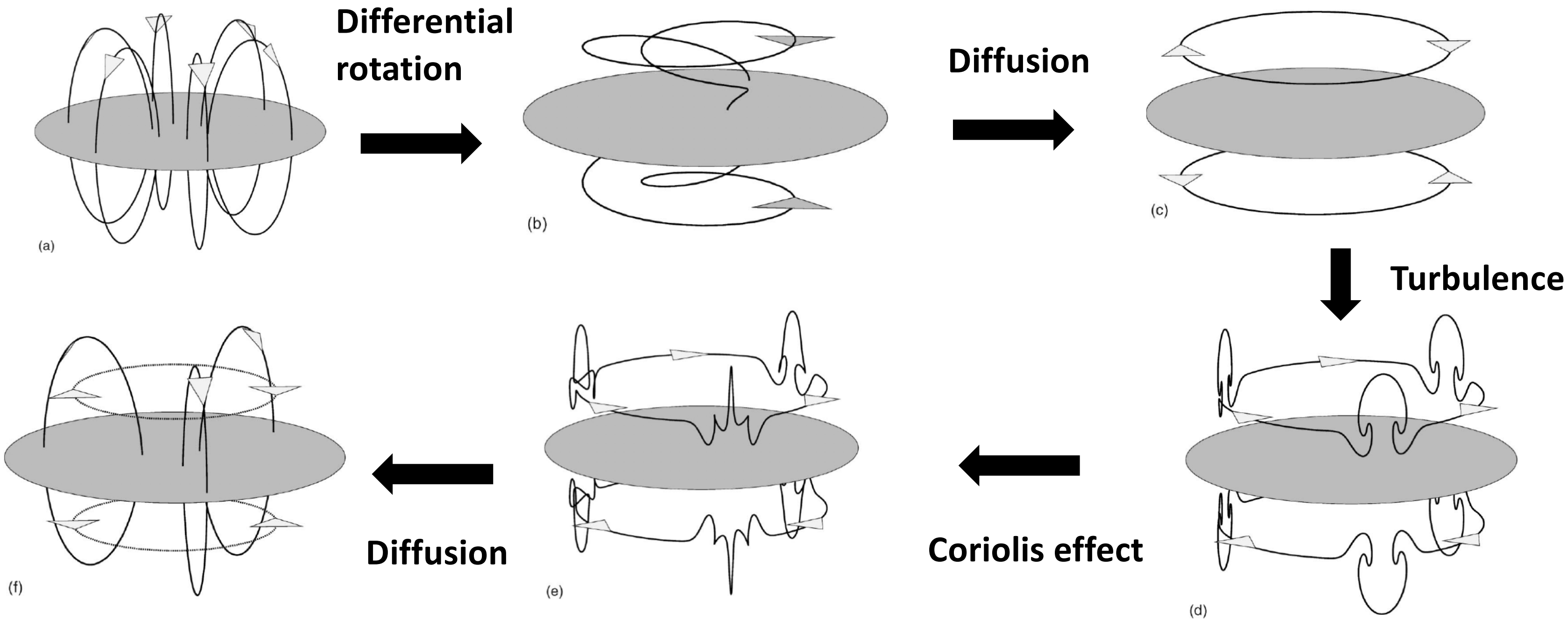
Dynamo action: conversion of kinetic energy into magnetic energy

- **Diffusion**
  - Once again, some form of diffusion or dissipation is needed to eliminate magnetic field near the equatorial plane.

  - Provided that this occurs, poloidal loops in upper and lower hemispheres can combine to yield a dipolelike field which reinforces the original field



Dynamo action: conversion of kinetic energy into magnetic energy



Sequence of events illustrating galactic dynamo(Widrow,et al,2002)

- **Galactic dynamo is an effective way to maintain the galactic magnetic field!**

The importance of diffusion

- The α and ω effects twist, shear, and stretch magnetic-field lines but do not create new ones.

- While they can increase the magnetic-field energy in the system, they cannot change the net flux through a surface that encloses it.

- Diffusion eliminates unwanted flux.

- Flux expulsion can occur by a number of mechanisms, including magnetic buoyancy and supernovae or superbubble explosions.

Criticisms of mean-field dynamo theory

- amplification of the regular field takes place on a time scale much longer than the eddy diffusion time associated with the turbulence.

- Lorentz forces on small scales can react back on the fluid, altering the turbulent motions, turbulent motions are suppressed and finally shutting off the dynamo

Criticisms of mean-field dynamo theory

$$\alpha \sim \alpha_T / [1 + (\bar{B}/B_{eq})^2 R_M^p]$$

- α_T[2]: the standard result calculated in the absence of backreaction
  - $\alpha_T \sim \min(\Omega l^2/h, v)$($l$: correlation length of the turbulence, h: the scale height, v: the rms turbulent velocity)
- R_M: the magnetic Reynolds number based on the microscopic diffusivity
- p: a constant of order unity
- In present-day galaxies, $\bar{B} \approx B_{eq}$ and $R_M \approx 10^{20}$, implying that α is reduced by enormous factors.

Other Criticisms

- mean-field dynamo contain fundamental flaws?
  - boundary conditions
  - backreaction
  - …
- The dynamo is not caused by turbulence and differential rotation?
  - a dynamo based on buoyancy of magnetic flux tubes and neutral point reconnection.
  - …

Reference

- [1] Shukurov A. Introduction to galactic dynamos[J]. Newcastle University, 2004.
- [2] Beck R , Brandenburg A , Moss D , et al. GALACTIC MAGNETISM: Recent Developments and Perspectives[J]. Annual Review of Astronomy and Astrophysics, 1996, 34(1):155-206.
- [3] Widrow, Lawrence M . Origin of galactic and extragalactic magnetic fields[J]. Reviews of Modern Physics, 2002, 74(3):775-823.

Summary

- Galactic dynamos is a way that can induced currents amplify and maintain the original field.
- differential rotation, turbulence and diffusion are most important in this theory
- There are still many problems:The seed field, feedback, small-scale dynamo action vs large-scale fields…