Galactic Dynamos

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Magnetic Field Generation in Experiments,
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Outline

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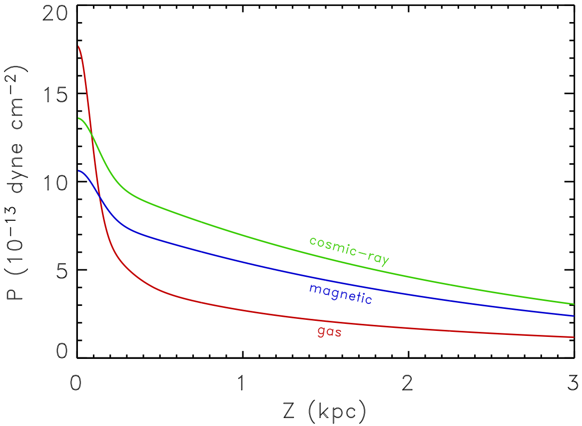
Our Galaxy

- Near the Sun
  Measured polarization of starlight
  $\vec{B}$ is horizontal & nearly azimuthal (angle $\simeq 7^\circ$)
- In neutral regions
  Zeeman splitting measurements
  - In atomic clouds : $B \sim$ a few μG
  - In molecular clouds : $B \sim (10 - 3000)\ \mu$G
- In ionized regions
  Faraday rotation measurements
  - $B_{\rm reg} \simeq 1.5\ \mu$G & $B_{\rm turb} \sim 5\ \mu$G near $\odot$
  - $\vec{B}_{\rm reg}$ is nearly horizontal & predominantly azimuthal away from the GC
  - Reversals in B_Φ in the disk ($\Rightarrow$ spiral structure ?)
- In general ISM
  Synchrotron emission measurements
  - $B_{\rm tot} \sim 5\ \mu$G near $\odot$ $\rightarrow$ $B_{\rm tot} \sim 7\ \mu$G in MR
  - Global spatial distribution

Interstellar pressures near the Sun



Our Galaxy: near the Galactic center

- Non-thermal radio filaments

  ∗ *Morphology & radio (synchrotron) polarization measurements*
  $\vec{B} \parallel$ filaments $\Rightarrow$ $\vec{B} \perp$ GP

  ∗ *Dynamical argument*
  No distortion $\Rightarrow$ $B \gtrsim 1$ mG

  ∗ *Radio (synchrotron) intensity measurements*
  $B_{\mathrm{equip}} \sim (50 - 200)\ \mu$G

- In general ISM
  Diffuse synchrotron intensity measurements
  $B_{\mathrm{equip}} \sim 10\ \mu$G

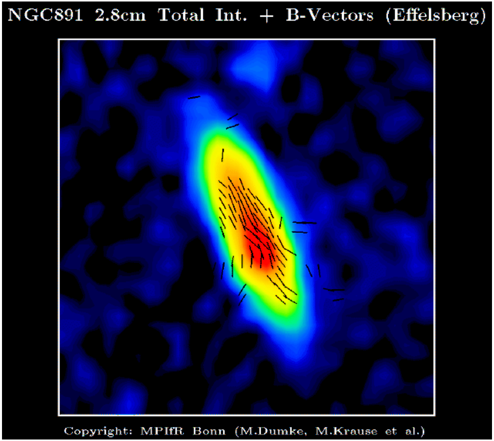
- In dense molecular clouds
  FIR/submm (dust thermal emission) polarization measurements
  $\vec{B}$ is nearly $\parallel$ GP

External galaxies

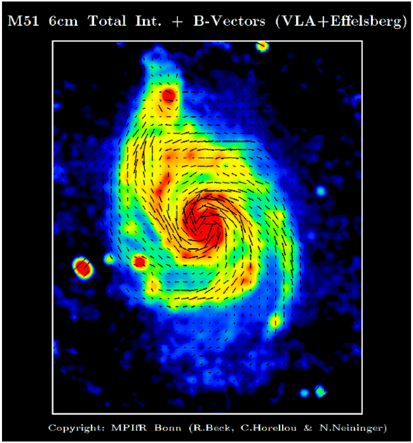
- Spiral galaxies
  Synchrotron (total & polarized) emission & Faraday rotation
  - All spirals have a large-scale, regular $\vec{B}$
  - $B_{\rm tot} \sim$ a few μG
  - Edge-on spirals $\rightarrow$ $\vec{B}_{\rm reg}$ is horizontal in the disk
    has a vertical component in the halo
  Face-on spirals $\rightarrow$ $\vec{B}_{\rm reg}$ follows spiral arms

- Elliptical galaxies
  Synchrotron (total & polarized) emission & Faraday rotation
  - No large-scale, regular $\vec{B}$
  Only small-scale, turbulent $\vec{B}$
  - $B_{\rm tot} \sim$ a few μG

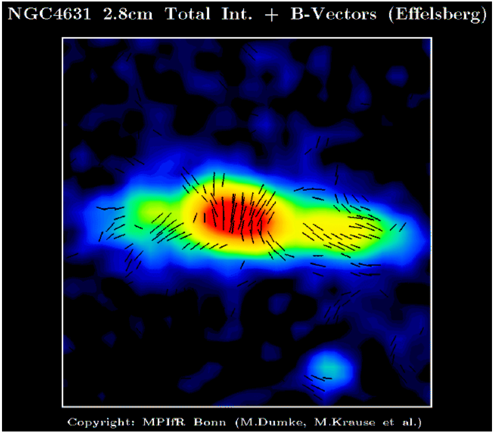
Edge-on spiral galaxy: NGC 891



Face-on spiral galaxy: M 51



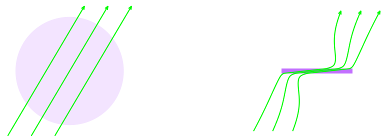
Edge-on spiral galaxy: NGC 4631



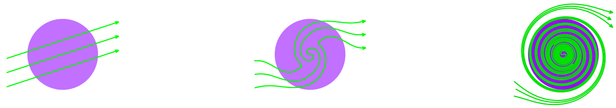
Outline

Primordial origin

1. Compression of field lines *upon protogalaxy collapse*

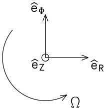


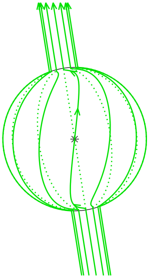
2. Winding up of field lines *by galactic differential rotation*



Alpha effect

Magnetic field generation in the direction $\perp \vec{B}_0$
due to small-scale cyclonic turbulence





Dynamo process

1. Azimuthal stretching of field lines *by galactic differential rotation*

2. Alpha effect *due to small-scale cyclonic turbulence*

Seed magnetic field

- Universe born with a magnetic field
  ☞ $B_0 \lesssim \text{a few } 10^{-9}$ G
- Exotic processes during a phase transition in the early Universe
  ☞ $B_0 \lll$
- Harrison's cosmic battery
  ☞ $B_0 \sim 10^{-20} - 10^{-18}$ G
- Biermann battery
  ☞ $B_0 \sim 10^{-20} - 10^{-18}$ G
- Creation inside the first stars
  ☞ $B_0 \sim 10^{-9}$ G (?)
- Creation inside Active Galactic Nuclei
  ☞ $B_0 \sim 10^{-6}$ G (?)

Outline

Mean-field dynamo

$$\frac{\partial \vec{\mathbf{B}}}{\partial t} = \vec{\nabla} \times \big(\underbrace{\vec{\mathbf{v}} \times}_{\langle \vec{\mathbf{v}} \rangle + \delta \vec{\mathbf{v}}} \vec{\mathbf{B}} \big) + \eta \, \Delta \vec{\mathbf{B}}$$

$$\frac{\partial \langle \vec{\mathbf{B}} \rangle}{\partial t} = \vec{\nabla} \times \left(\langle \vec{\mathbf{v}} \rangle \times \langle \vec{\mathbf{B}} \rangle \right) + \vec{\nabla} \times \underbrace{\langle \delta \vec{\mathbf{v}} \times \delta \vec{\mathbf{B}} \rangle}_{\vec{\mathcal{E}}} + \eta \, \Delta \langle \vec{\mathbf{B}} \rangle$$

$$\mathcal{E}_i = \alpha_{ij} \, \langle B_j \rangle + \beta_{ijk} \, \frac{\partial \langle B_j \rangle}{\partial x_k}$$

Field geometry

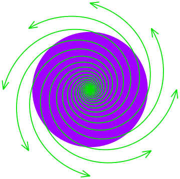
- In the disk
  - B_Φ dominant *because strong differential rotation*
  - $B_R \sim 0.1\ B_\Phi$
  - $B_Z < B_R,\ B_\Phi$ *because disk geometry*
  - Reversals in B_Φ if non AS $\vec{\mathbf{B}}$ or if AS $\vec{\mathbf{B}}$ & strong $\partial\Omega/\partial Z$

- In the halo
  - $B_Z \sim B_R$ *because spherical geometry*
  - B_Φ large if strong differential rotation
  - $B_R,\ B_Z$ large if Galactic wind

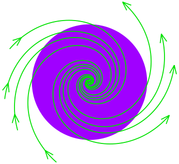
- Near the GC
  - $B_Z \sim B_R$ *because spherical geometry*
  - $B_R,\ B_\Phi$ large *because strongly sheared noncircular motions*
  - B_Z large if horizontal inflow or vertical outflow

Azimuthal structure

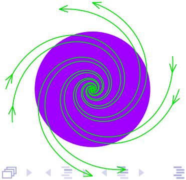
- If underlying galaxy is axisymmetric
  $\Rightarrow$ - ASS $(m = 0)$ is always easiest to amplify
  - Higher-order modes generally decay in time



- If external disturbance
  $\Rightarrow$ Possible to excite BSS $(m = 1)$



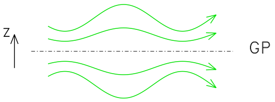
- If underlying spiral or bar
  $\Rightarrow$ Possible to excite QSS $(m = 2)$



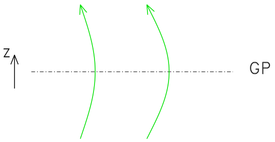
Vertical symmetry (for ASS)

- Under typical galactic conditions
  $\Rightarrow$ Both S0 & A0 are amplified

- If the disk dominates
  $\Rightarrow$ S0 grows faster



- If the halo and/or the GC region dominates
  $\Rightarrow$ A0 grows faster



- At early times & in the nonlinear regime
  $\Rightarrow$ Possibly mixed S0-A0 configuration
  with S0 dominant in the disk
  A0 dominant near the GC & in the halo

Temporal behavior (for ASS)

- Under typical galactic conditions
  - S0 & A0 grow *monotonically* with time
  - S0 grows faster ($\gamma \sim 1$ Gyr^{-1})
  - A0 gets more easily *oscillatory* ($\omega \sim 1$ Gyr^{-1})
- Factors favoring oscillatory behavior :
  - Spherical geometry (halo, GC)
  - Weak differential rotation
  - α strongly anisotropic
  - Vanishing or weak Galactic wind
  - Ω decreasing away from the midplane

Nonlinear solutions

- Field growth saturates when $B \longrightarrow B_{\rm equip}$
  - $B_{\rm final} \lesssim 2\,B_{\rm equip}$
  - $t_{\rm sat} \sim$ several Gyrs
- Final spatial configuration is smoother than in linear regime
- Nonlinear interactions occur between different modes
  $\Rightarrow$ Possible to amplify modes that would decay in linear regime
  $\Rightarrow$ Possible to maintain a mixed S0-A0 configuration

Direct numerical simulations

Elstner et al. 2008; Hanasz et al. 2008

- Present ingredients
  - Resistive MHD
  - Large-scale shear & vertical gravity
  - Random supernova explosions
  - Small box (size ~ 1 kpc) with shearing-periodic BCs

- Limitations
  - Local simulations
  - Small dynamic range

- Results
  - Large-scale magnetic field is amplified
  - Monotonic growth
  - $\gamma \sim 4$ Gyr^{-1}