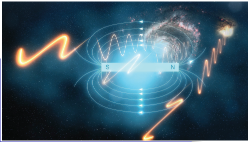

Galactic magnetic fields
II. Theory

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4th Graduate School on Plasma-Astroparticle Physics

Bad Honnef – 29 January - 3 February, 2023

Outline

1. Generation and amplification
   - Magnetogenesis
   - Magnetic field amplification
   - Dynamo theory
2. Impact on the ISM

Outline

Current paradigm

1. Magnetogenesis
   Generation *ab initio* of very weak *seed* magnetic fields

2. Amplification during structure formation
   Contraction of cosmic gas
   $\rightarrow$ Compression of magnetic field lines

3. Amplification & maintenance through a *dynamo*
   Large-scale differential rotation $+$ small-scale helical turbulence
   $\rightarrow$ Stretching & twisting of magnetic field lines

Outline

Exotic processes in primordial Universe

- Universe born with a magnetic field

  Observational constraints

  - Big Bang nucleosynthesis
    ☞ $B \lesssim 10^{-6}$ G
  - CMB anisotropy
    ☞ $B \lesssim 10^{-9}$ G
  - Structure formation
    ☞ $B \lesssim 10^{-9}$ G

Exotic processes in primordial Universe

- Generation during inflation

  ☞ - very speculative
  - important problems & caveats
  - extremely model-dependent

- Generation during phase transition
  - Electro-weak transition ($t \sim 10^{-12}$ sec)
  - Quark-hadron (or QCD) transition ($t \sim 10^{-5}$ sec)

  ☞ Reasonably strong B, but very small coherence scale

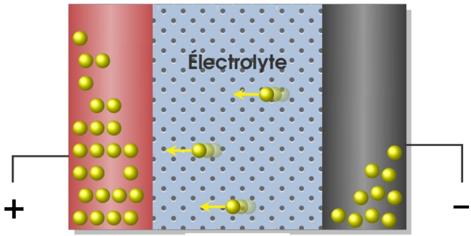
Astrophysical processes

- Thermal (Biermann) battery
  - In the first stars and in AGNs
  - At oblique cosmological shocks (during large-scale structure formation)
    ☞ $B \sim 10^{-20}$ G on protogalactic scales
  - At ionization fronts (during re-ionization)
    ☞ $B \sim (10^{-20} - 10^{-18})$ G on protogalactic scales

- Radiation-driven battery
  - In primordial eddies caught in expansion of Universe
    ☞ $B \sim 10^{-23}$ G on cluster scales ($\sim$ Mpc), at recombinaison
  - Near radiation sources (during re-ionization)
    ☞ $B \sim (10^{-23} - 10^{-19})$ G on scales $\sim$ a few 100 kpc – a few pc
  - In collapsing protogalaxies
    ☞ $B \sim 10^{-20}$ G on protogalactic scales

What is a battery ?

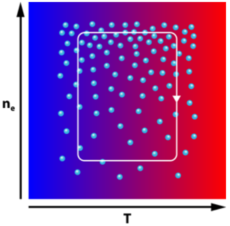
A battery is a device able to separate + & - electric charges and hence to generate an electric tension



Credit: François Bedin

Thermal battery

Inhomogeneous plasma

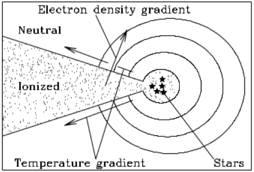


Credit: APS/Alan Stonebraker

$$\vec{\nabla} T \;\&\; \vec{\nabla} n_e \rightarrow \vec{\nabla} P_e \rightarrow \vec{E}$$

$$\vec{\nabla} T \not\parallel \vec{\nabla} n_e \rightarrow \vec{\nabla} \times \vec{E} \rightarrow \frac{\partial \vec{B}}{\partial t} \rightarrow \vec{B}$$

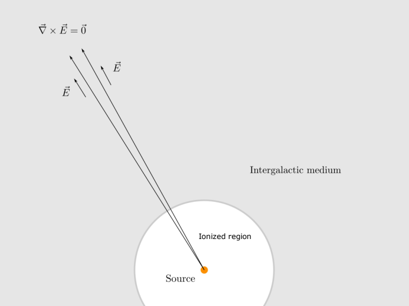
Breakthrough of ionization front from a protogalaxy



Gnedin et al. (2000)

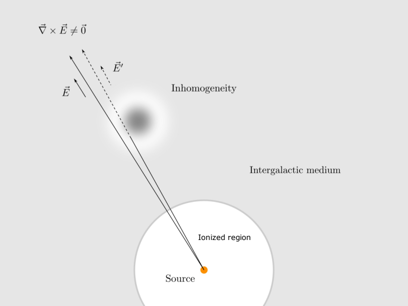
Radiation-driven battery

Homogeneous plasma



Durrive & Langer (2015)

Inhomogeneous plasma



Radiation $\rightarrow$ - Photo-ionization $\rightarrow$ p^+ & e^-
- Momentum transfer $\gamma \rightarrow e^-$
$\rightarrow \vec{E}$

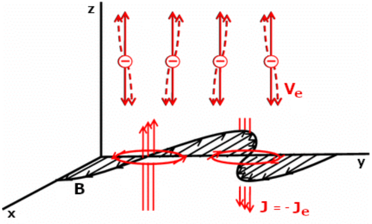
Inhomogeneity $\rightarrow \vec{\nabla} \times \vec{E}$
$\rightarrow \frac{\partial \vec{B}}{\partial t}$
$\rightarrow \vec{B}$

Astrophysical processes

- Plasma instabilities

  - Weibel instability

    ☞ $B \sim 10^{-9}$ G   on scales $\sim \frac{c}{\omega} \sim 10^{-8}$ pc $\lll$



Adapted from Liao & Tsai (2016)

2 electron beams: $\vec{V}_\mathrm{e} = \pm V_\mathrm{e}\ \hat{\mathbf{e}}_z$

Sinusoidal perturbation: $\vec{E} = -\delta E \sin ky\ \hat{\mathbf{e}}_z$

$\vec{\nabla} \times \vec{E} \rightarrow \vec{B} = \delta B \cos ky\ \hat{\mathbf{e}}_x$

$\rightarrow \vec{F}_\mathrm{L} = -e\,\vec{V}_\mathrm{e} \times \vec{B} = \pm\,\delta F \cos ky\ \hat{\mathbf{e}}_y$

Alternating regions where

- $n_\mathrm{e}(\uparrow) > n_\mathrm{e}(\downarrow) \rightarrow \vec{J}_\mathrm{e} \uparrow \rightarrow \vec{J} \downarrow$
- $n_\mathrm{e}(\uparrow) < n_\mathrm{e}(\downarrow) \rightarrow \vec{J}_\mathrm{e} \downarrow \rightarrow \vec{J} \uparrow$

Everywhere $\vec{J} \rightarrow \vec{E} \nearrow \rightarrow \vec{B} \nearrow$

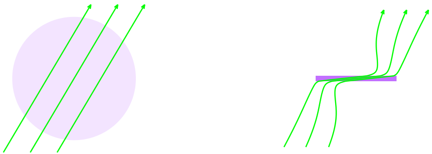
Outline

Amplification in galaxies

- Collapse of a protogalaxy

  Contraction of protogalactic gas
  $\rightarrow$ *Compression* of magnetic field lines

☞ $\vec{B}$ horizontal & B amplified by factor $\sim 10\,000$

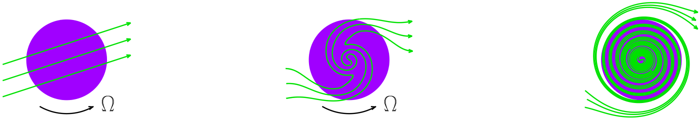


Amplification in galaxies

- Rotation of the galaxy

  Large-scale differential rotation
  → *Stretching* of magnetic field lines

☞ $\vec{B}$ circular & B amplified by factor ~ 100



Amplification in galaxies

- Alpha effect

  Small-scale helical turbulence
  $\rightarrow$ *Twisting* of magnetic field lines

☞ Generation of $\vec{B} \perp \vec{B}_{\rm ambient}$

Amplification in galaxies

- Alpha effect

  Small-scale helical turbulence
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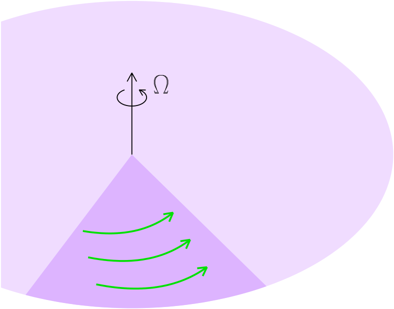
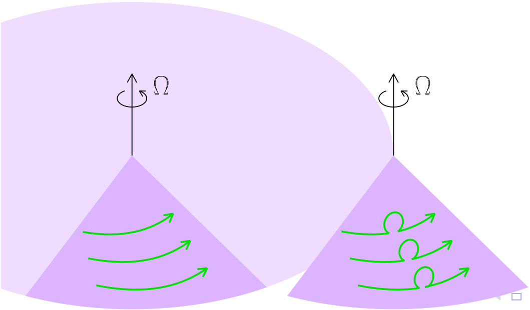


Amplification in galaxies

- Alpha effect

  Small-scale helical turbulence
  → *Twisting* of magnetic field lines

☞ Generation of $\vec{B} \perp \vec{B}_{\rm ambient}$

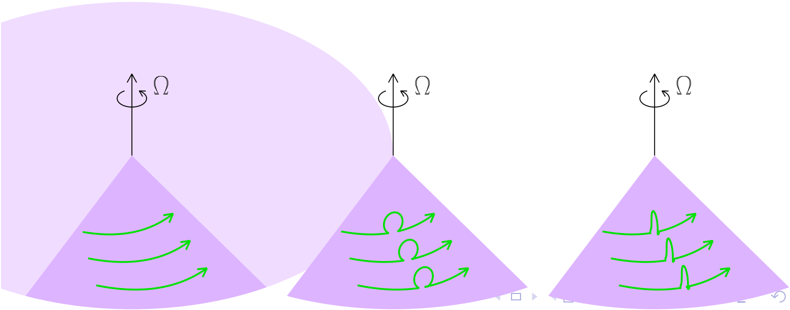


Amplification in galaxies

- Alpha effect

  Small-scale helical turbulence
  → *Twisting* of magnetic field lines

☞ Generation of $\vec{B} \perp \vec{B}_{\mathrm{ambient}}$

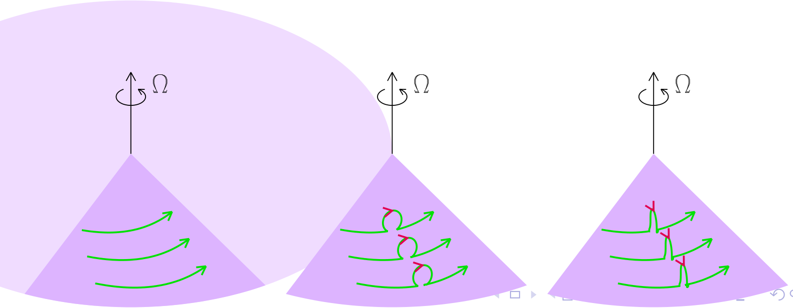


Amplification in galaxies

- Alpha effect

  Small-scale helical turbulence
  → *Twisting* of magnetic field lines

  ☞ Generation of $\vec{B} \perp \vec{B}_{\mathrm{ambient}}$

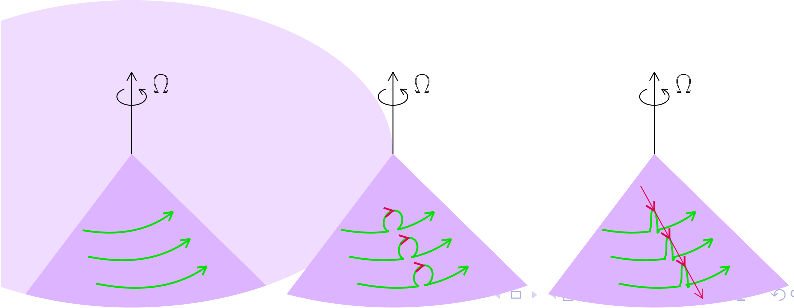


Amplification in galaxies

- **Alpha effect**

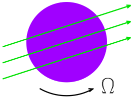
  Small-scale helical turbulence
  → *Twisting* of magnetic field lines

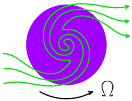
☞ Generation of $\vec{B} \perp \vec{B}_{\rm ambient}$



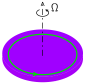
Galactic dynamo

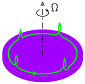
- Large-scale differential rotation
  → *Stretching* of magnetic field lines





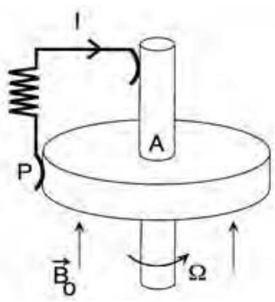
- Small-scale helical turbulence
  → *Twisting* of magnetic field lines (alpha effect)



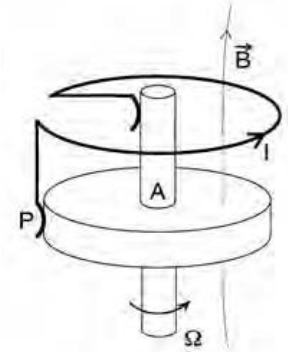


☞ Exponential amplification of $\vec{B}$ ..... until $E_B \simeq E_{\rm turb}$

Link with conventional dynamo



Credit: Stephan Fauve



Conductor + rotation + $\vec{B}_0$
→ electromotive force
→ electric current

Conductor + rotation + $\vec{B}_0$
→ electromotive force
→ electric current
→ $\vec{B}$ amplifying $\vec{B}_0$

Outline

Induction equation

Maxwell-Faraday's equation

$$\frac{\partial \vec{B}}{\partial t} = -\vec{\nabla} \times \vec{E}$$

Ohm's law

$$\vec{j} = \sigma \left(\vec{E} + \vec{v} \times \vec{B} \right)$$

$$\Rightarrow \quad \vec{E} = -\vec{v} \times \vec{B} + \frac{1}{\sigma} \vec{j} = -\vec{v} \times \vec{B} + \frac{1}{\sigma\,\mu_0} \vec{\nabla} \times \vec{B}$$

$\Rightarrow$ Induction equation

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right) + \frac{1}{\sigma\,\mu_0} \Delta \vec{B}$$

Mean-field dynamo equation

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right) + \eta \, \Delta \vec{B}$$

$$\vec{v} = \langle \vec{v} \rangle + \delta \vec{v}$$

$$\vec{B} = \langle \vec{B} \rangle + \delta \vec{B}$$

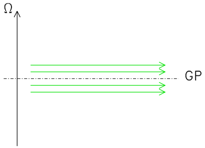
$$\frac{\partial \langle \vec{B} \rangle}{\partial t} = \vec{\nabla} \times \left(\langle \vec{v} \rangle \times \langle \vec{B} \rangle \right) + \vec{\nabla} \times \underbrace{\langle \delta \vec{v} \times \delta \vec{B} \rangle}_{\vec{\mathcal{E}}} + \eta \, \Delta \langle \vec{B} \rangle$$

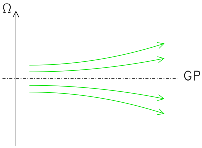
$$\mathcal{E}_i = \alpha_{ij} \, \langle B_j \rangle + \beta_{ijk} \, \frac{\partial \langle B_j \rangle}{\partial x_k}$$ in general

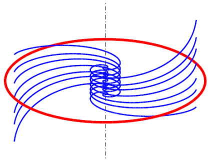
$$\vec{\mathcal{E}} = \alpha \, \langle \vec{B} \rangle - \beta \, \vec{\nabla} \times \langle \vec{B} \rangle$$ for isotropic turbulence

Linear solutions: Overall geometry

- In the disk
  - B_ϕ dominant — strong differential rotation
  - $B_r \sim 0.1\ B_\phi$ — weaker alpha effect
  - $B_z \ll B_r$ — disk geometry $\Rightarrow \partial_r, \partial_\phi \ll \partial_z$
    $\Rightarrow$ weaker alpha effect on B_z

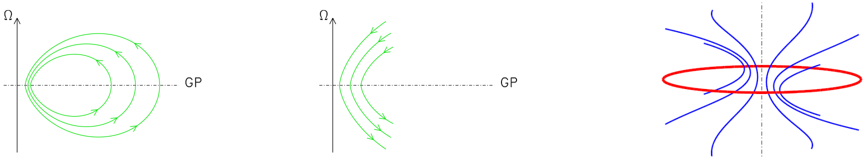






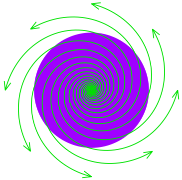
Linear solutions: Overall geometry

- In the halo
  - $B_z \sim B_r$ spherical geometry
  - B_ϕ large *if* strong differential rotation

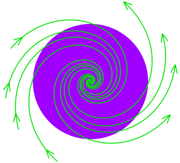


Linear solutions: Azimuthal structure

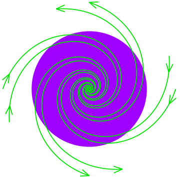
- If underlying galaxy is axisymmetric
  $\Rightarrow$ - ASS $(m = 0)$ is always easiest to amplify
  - Higher-order modes generally decay in time



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



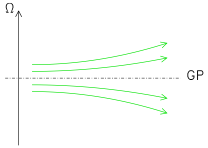
- If underlying spiral or bar
  $\Rightarrow$ Possible to excite QSS $(m = 2)$



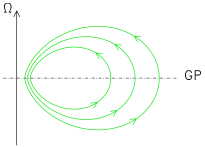
Linear solutions: Vertical symmetry (for ASS)

- Under typical galactic conditions
  ⇒ Both S0 & A0 are amplified

- If the disk dynamo dominates
  ⇒ S0 grows faster



- If the halo dynamo dominates
  ⇒ A0 grows faster



- Possibly mixed S0-A0 configuration
  with S0 dominant in the disk
  A0 dominant in the halo

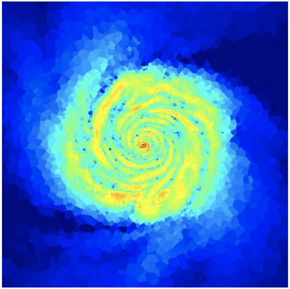
Full dynamo calculations

Solve equations for $\vec{B}$ and $\vec{v}$ simultaneously:

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left(\vec{v} \times \vec{B} \right) + \eta \, \Delta \vec{B}$$

$$\rho \, \frac{D\vec{v}}{Dt} = -\vec{\nabla} P + \rho \, \vec{g} + \frac{1}{\mu_0} \left(\vec{\nabla} \times \vec{B} \right) \times \vec{B}$$

☞ Full numerical simulations



Mocz et al. (2016)

Outline

Dynamic effects

Magnetic fields

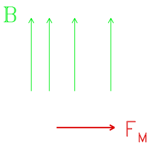
- *Couple* cosmic rays to the gas
- *Channel* gas motions & cosmic-ray trajectories
- *Stiffen* the ISM

Momentum equation

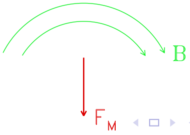
$$\rho \frac{D\vec{v}}{Dt} = -\vec{\nabla} P + \rho \vec{g} + \vec{F}_{\mathrm{M}}$$

$$\begin{aligned} \vec{F}_{\mathrm{M}} &= \vec{j} \times \vec{B} \\ &= \frac{1}{\mu_0} \left(\vec{\nabla} \times \vec{B} \right) \times \vec{B} \\ &= -\vec{\nabla} \frac{B^2}{2\mu_0} + \frac{1}{\mu_0} \vec{B} \cdot \vec{\nabla} \vec{B} \end{aligned}$$

Magnetic pressure force



Magnetic tension force



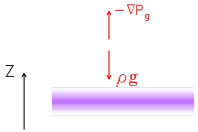
Dynamic effects at large scales

Magnetic fields

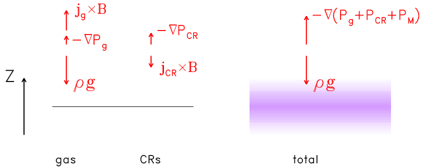
- Partake in the hydrostatic balance
  - *Support* the gas against gravity
  - *Confine* cosmic rays to the Galactic disk
- Give rise to the Parker instability

Large-scale hydrostatic balance

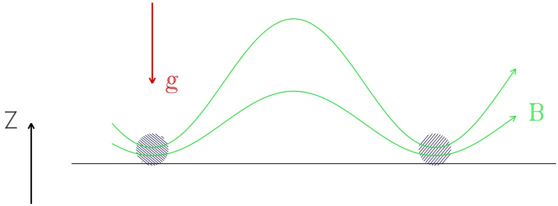
- Thermal gas only



- With magnetic fields and cosmic rays



Parker instability

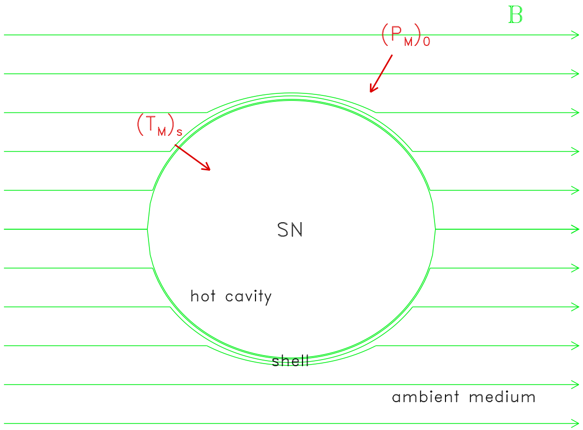


Dynamic effects at small scales

Magnetic fields

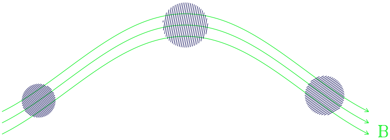
- *Oppose* the expansion of SNRs and SBs
- *Constrain* the motions of interstellar clouds
  - Resist the random translational motions of clouds
  - Brake the rotation of molecular clouds
- *Generate* bipolar jets
- *Control* the star formation process
  - Remove angular momentum $\Rightarrow$ Avoid the centrifugal barrier
  - Provide support against self-gravity $\perp \vec{B}$ $\Rightarrow$ Formation of filaments
  - Lead to ambipolar diffusion

SNR expansion

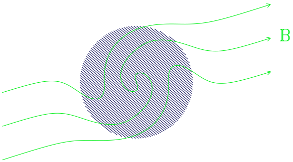


Cloud motions

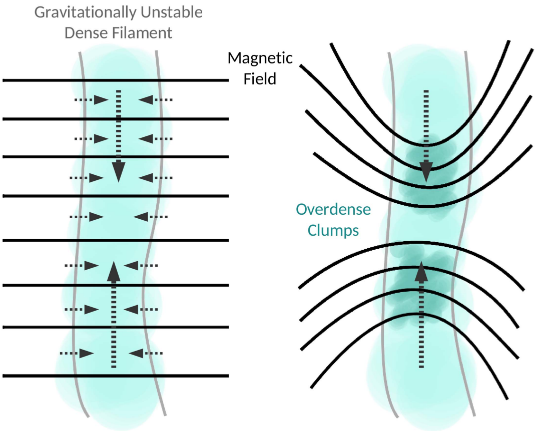
- Translational motions



- Rotational motions



Formation of filaments



Pattle et al. (2017)

Ambipolar diffusion

Neutrals & *ions* have separate momentum equations:

$$\rho_n \frac{D\vec{v}_n}{Dt} = -\vec{\nabla} P_n + \rho_n \vec{g} + \vec{F}_{ni}$$

$$\rho_i \frac{D\vec{v}_i}{Dt} = -\vec{\nabla} P_i + \rho_i \vec{g} + \vec{j} \times \vec{B} + \vec{F}_{in}$$

$$\vec{F}_{ni} = \rho_n \nu_{ni} (\vec{v}_i - \vec{v}_n) = -\rho_i \nu_{in} (\vec{v}_n - \vec{v}_i) = -\vec{F}_{in}$$

When $x_i \ll 1$

$$\Rightarrow \quad \vec{j} \times \vec{B} + \vec{F}_{in} = 0$$

$$\Rightarrow \quad \vec{F}_{ni} = \vec{j} \times \vec{B}$$

$$\Rightarrow \quad \vec{v}_i - \vec{v}_n = \frac{1}{\rho_n \nu_{ni}} \vec{j} \times \vec{B} = \frac{1}{\rho_i \nu_{in}} \vec{j} \times \vec{B}$$

Ambipolar diffusion

Neutrals very gradually slip
through *ions* + *magnetic field lines*
and eventually collapse into new star

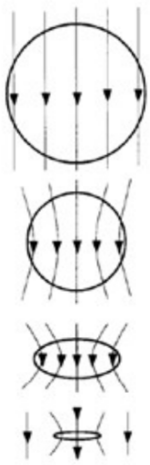


Figure Credit: *Wen-Ping Chen*

Energetic effects

Magnetic fields

- *Suppress* diffusion processes $\perp \vec{B}$
  - thermal conduction
  - viscous friction . . .
- *Heat up* the gas through
  - magnetic reconnection
  - ambipolar diffusion
- *Accelerate* cosmic rays