Galactic Dynamo Theory

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How was the Universe Magnetized?

- **Top Down:** Early universal process created pervasive magnetic field.
- **Bottom Up:** Magnetic fields were first generated in stars & accretion disks, and then propagated to large scales.

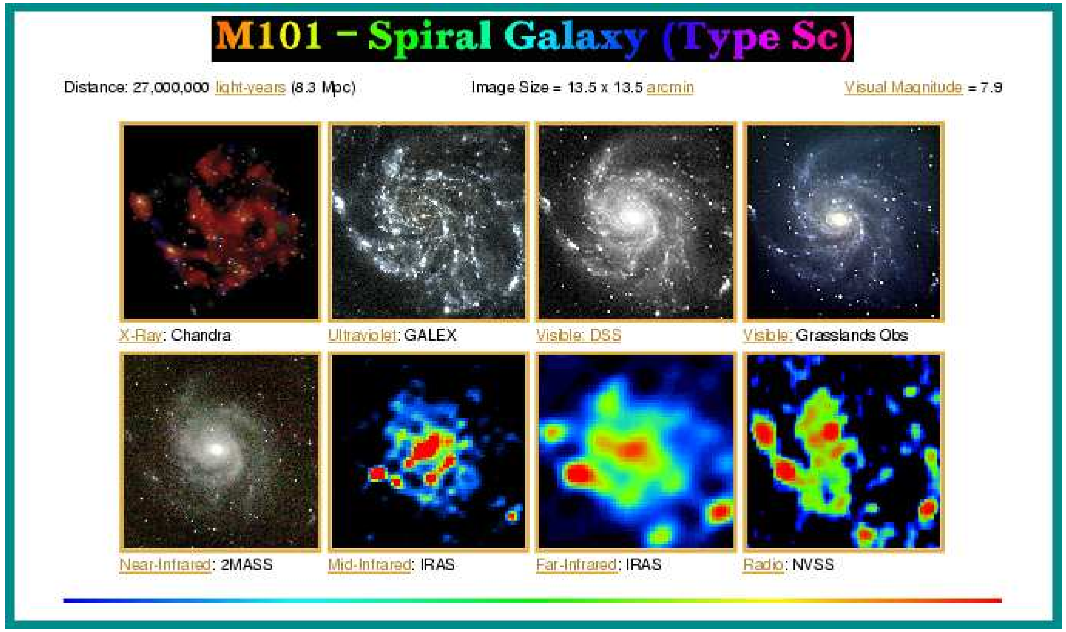
Did magnetic fields play a role in the formation of the first stars, growth of black holes through disk accretion, & gas dynamics in early clusters? Are galactic magnetic fields now sustained by dynamos or is the dynamo era in the distant past?

The Plan of This Talk

Collaborators:*John Everett, Fabian Heitsch*

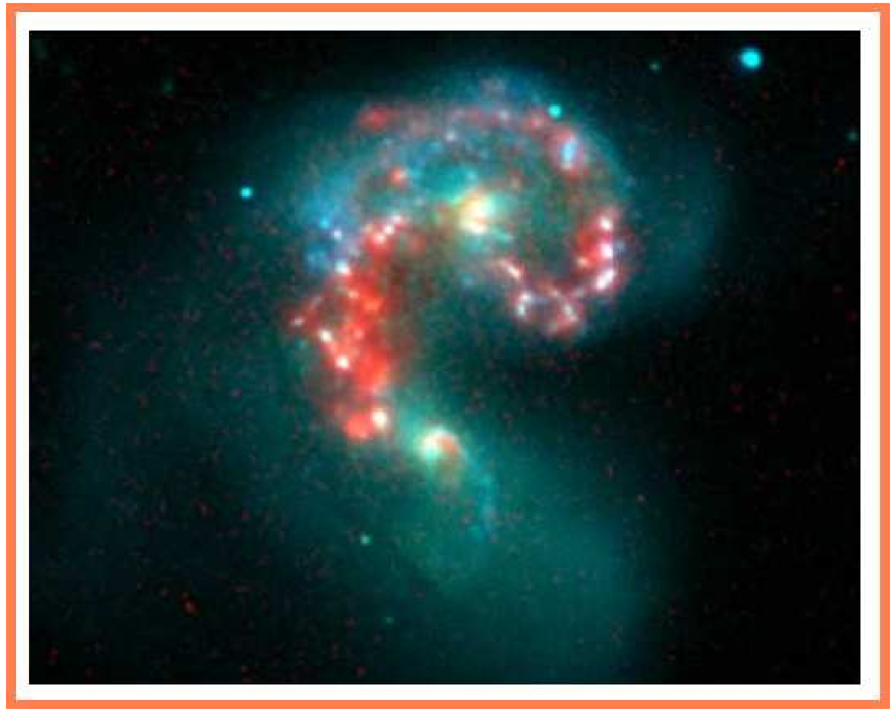
- A short course on galaxies
- Traditional tools & current picture
- What must be explained
- Key processes
- Status of dynamo theory
- Novel ingredients: weak ionization & cosmic rays
- Future prospects

A Course on Galaxies



Interstellar gas is $\sim$ 0.1% by mass. Temperature 10^{1-7}K, ionized by starlight, collisions, cosmic rays. $V_t/V_c \sim$ 0.05. Gas lost to star formation & galactic wind (?), gained by stellar mass loss, intergalactic infall, galaxy mergers. $R_m \sim 10^{15-21}$.

Galaxy Evolution



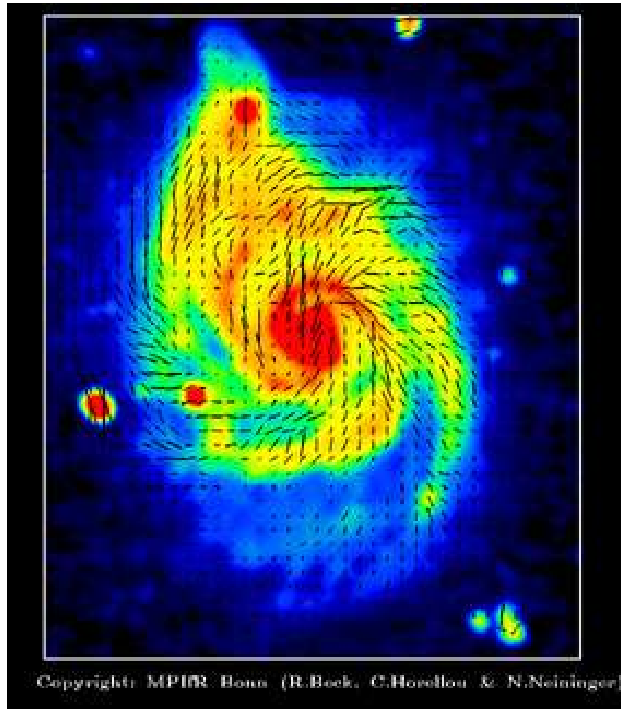
Galaxies form hierarchically from small structures. Galaxy formation is an ongoing processes, with accretion of dwarf galaxies and major mergers continuing today.

Traditional Tools

- Zeeman effect ($B_{||}$; atomic and molecular gas)
- Faraday rotation ($B_{||}$); ionized gas)
- Radio continuum polarization ($B_{\perp}$; relativistic electrons)
- Polarization from aligned dust grains ($B_{\perp}$ orientation only; dense gas and dust)

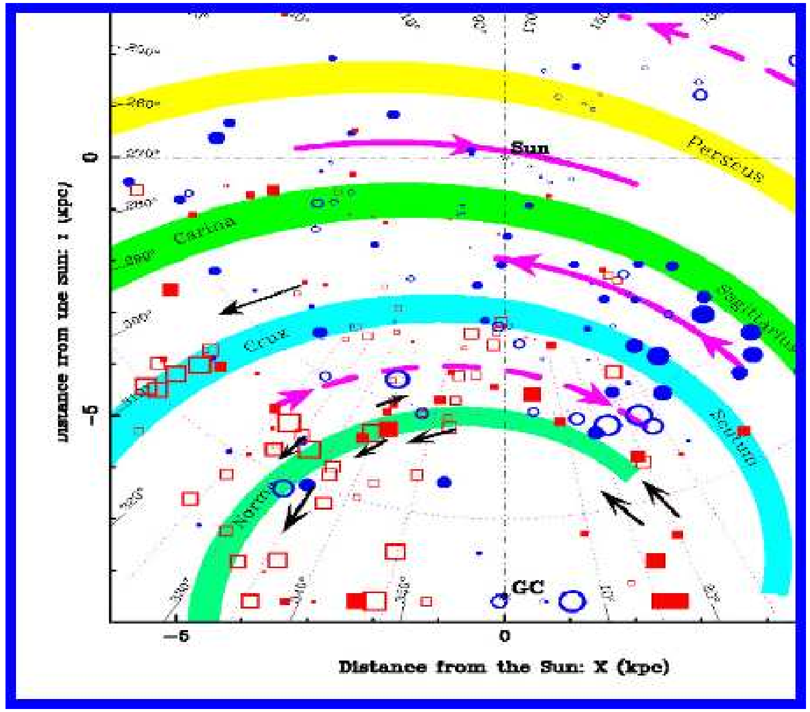
$B_{||}$ means along the line of sight; $B_{\perp}$ means in the plane of the sky. Traditional tools used to great effect in the local Universe and back to a few tenths its present age.

Synchrotron Maps



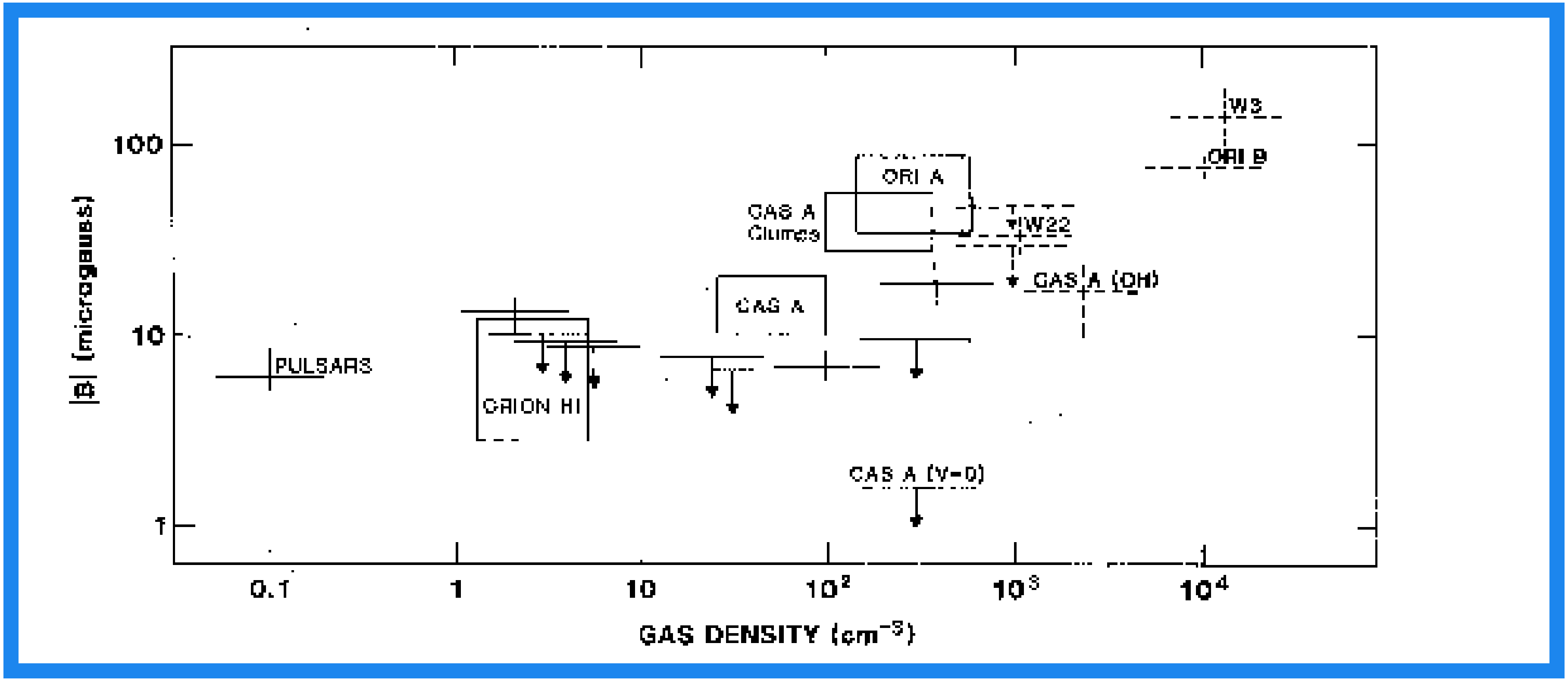
The vectors denote orientation of B projected on the plane of the sky. The degree of polarization is a measure of unresolved magnetic field structure: $p/p_{max} \sim \langle B \rangle^2 / \langle B^2 \rangle$.

Faraday Rotation Maps



Faraday rotation is a probe of field *direction*, and reveals a coherent azimuthal Galactic field, with reversals (Han 2003).$\langle B \rangle \sim 1.5\mu G$; $B_{rms} \sim 5\mu G$.

Fieldstrength - Density Relation



Troland & Heiles (1986) showed that in diffuse gas the fieldstrength-density relation is very weak. Is this evidence of enhanced diffusion?

Beyond Galaxies & Back in Time

- Only upper limits ($10^{-9}G$) for coherent, pervasive intergalactic field.
- Big Bang nucleosynthesis bounds cosmological B at $\sim 0.1\mu G$.
- Galaxy clusters have $\sim 0.1\mu G$ fields.
- The oldest stars in the Galaxy appear to have formed in material irradiated by cosmic rays.

Pending Observational Issues

- Parity of B_ϕ with respect to Galactic plane.
- Existence of coherent vertical field.
- Coherence length of B_ϕ.
- Extension of lookback time to probe earlier evolution.

What Must be Explained

- Fieldstrength near equipartition with gas, consistent with turbulence theory & stability constraints.
- Azimuthal orientation reflects shear by strong differential rotation.
- Is the weak fieldstrength-density relation a signature of turbulent diffusion?
- **Largescale coherence now and 90% of the way back to the Big Bang is the most difficult feature to understand.**

Key Ingredients

- Magnetogenesis (by the Biermann Battery?) & subsequent amplification in *small objects* like stars & accretion disks.
- Propagation to large scales by explosions, winds, jets, & turbulent diffusion.
- Amplification process.
- Process for generating large scale field from small scale incoherent field.
- “Magnetic assimilation" process.

Critical Fieldstrengths

Consider a system with:

- Temperature $T = 10^4$K
- Density $n = 1$cm^{-3}
- Ionization fraction $x = 0.1$
- Velocity $V = 10$km s^{-1}
- Size $L = 300$pc
- Kolmogorov scale $\sim 10^{14}$cm

Then...

Physical Regimes

- $B = 10^{-21}$G: electrons are magnetized
- $B = 10^{-18}$G: protons are magnetized
- $B = 10^{-13.5}$G: GeV cosmic rays are magnetized & couple to gas through collective effects
- $B = 10^{-10}$G: viscosity perpendicular to B is suppressed
- $B = 10^{-7}$G: ions & neutrals decouple above the viscous scale
- $B = 10^{-5.5}$G: field reaches equipartition with the gas

Mean Field Theory

- α & β tensors
  - For magnetic perturbations caused by expanding interstellar bubbles
  - For magnetic buoyancy instabilities
  - In weakly ionized gas
- Solve mean field dynamo equations
  - Monotonic & oscillatory instabilities
  - Sensitive to α, β dependence on position
  - Variety of saturation models explored
- Subject to the usual criticisms.

Key Processes - Decay at Small Scales

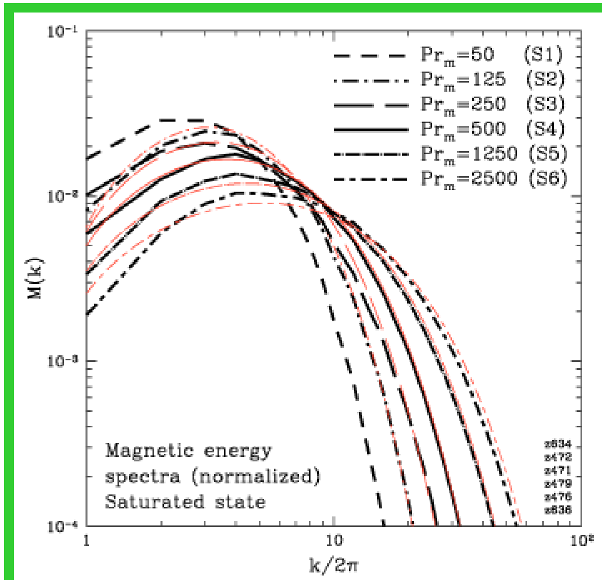


FIG. 20.—Magnetic energy spectra (normalized by the total magnetic energy) in the saturated state. The thin red lines are spectra predicted by our model. For run S1, the model does not give energy growth, but Pr_m in this case is too small for any asymptotic consideration to be applicable.

Magnetic power spectra from a series of simulations with increasing ratio of viscosity/resistivity. Note peak at the resistive scale, expected from previous slide (Schekochihin et al 2002). Anisotropic viscosity is key piece of missing physics.

Novel Ingredient: Partial Ionization

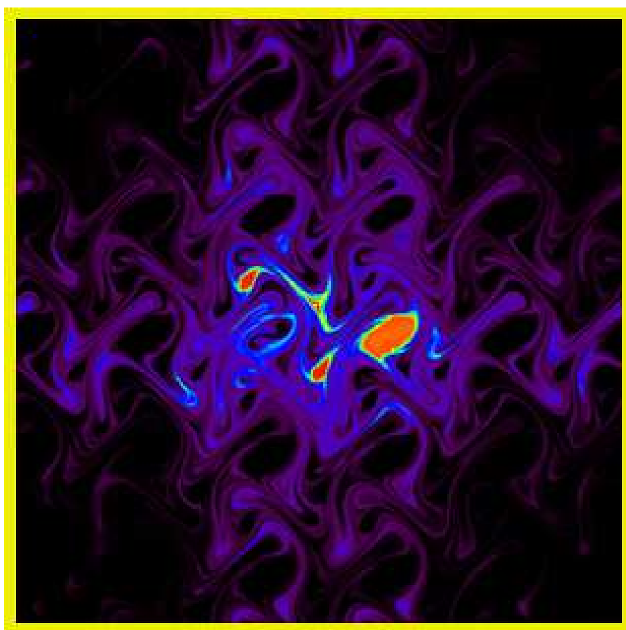
Magnetic field is coupled to the plasma, not the neutrals.

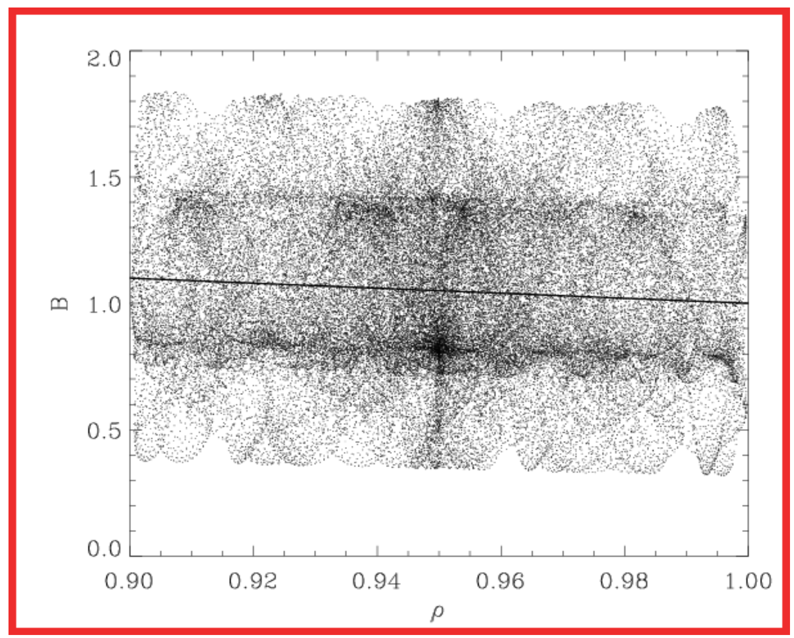
$$\rho_i \frac{d\mathbf{v}_i}{dt} = \mathbf{F_i} + \mathbf{J} \times \mathbf{B} - \rho_i \nu_{in} (\mathbf{v}_i - \mathbf{v}_n)$$

If $\rho_i/\rho_n << 1$, then on timescales » ion-neutral collision time, $\mathbf{v}_i - \mathbf{v}_n \approx \mathbf{J} \times \mathbf{B}/\rho_i \nu_{in} \equiv \mathbf{v}_D$ and $\mathbf{v} \approx \mathbf{v}_n$. The field drifts relative to the neutrals at velocity $\mathbf{v}_D$. This is called ambipolar diffusion.

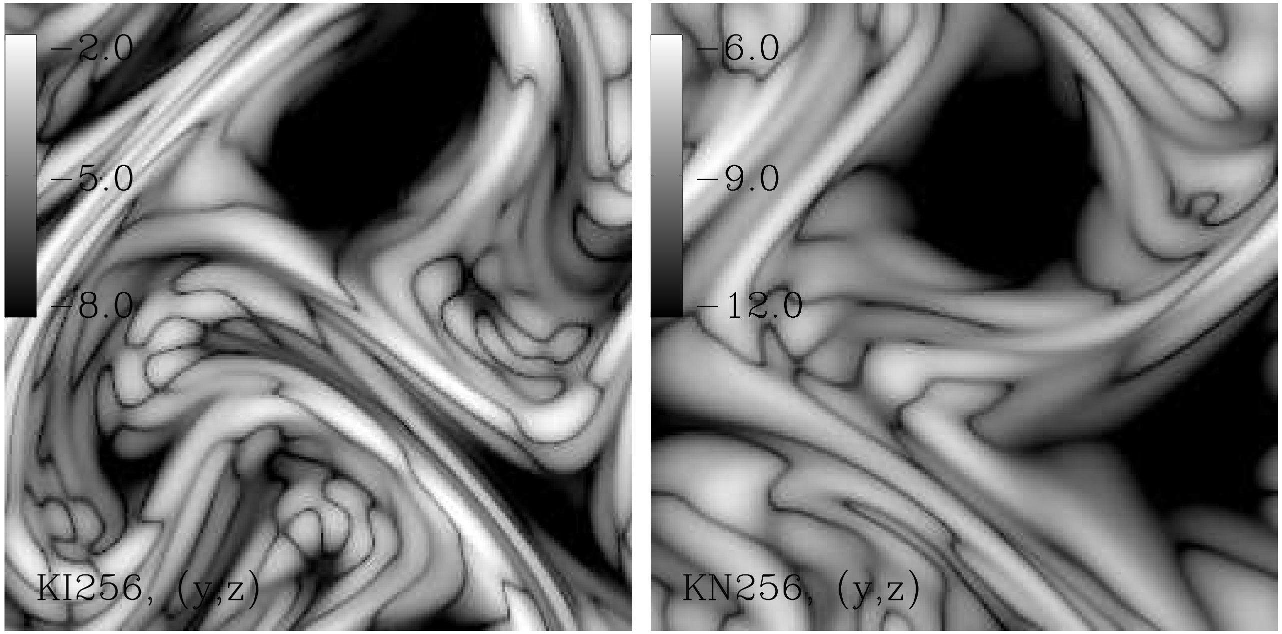
Turbulent Ambipolar Diffusion

Turbulence & ambipolar diffusion combine to give efficient transport, mixing in the field. Gives a large diffusivity but does not change topology. Enhanced rate of ambipolar diffusion in a turbulent medium (EZ2002, Heitsch et al 2004) rapidly destroys fieldstrength-density relation.



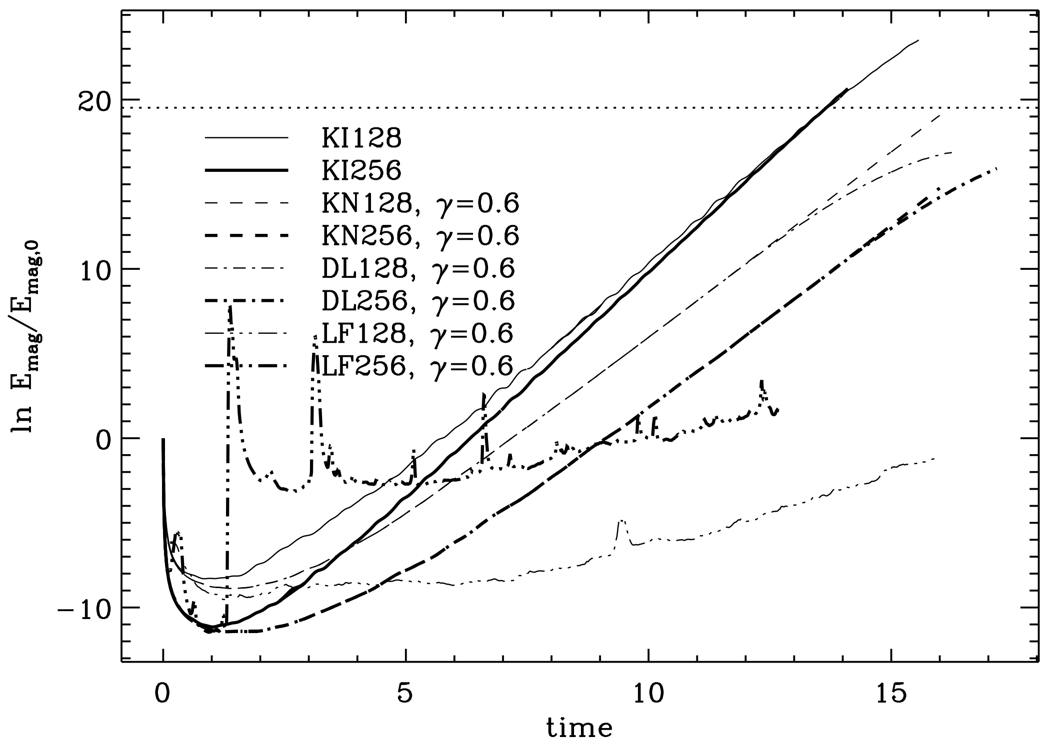


Dynamos in Weakly Ionized Gases



Left: Fieldstrength in a kinematic “fast dynamo". Right: Fieldstrength if the neutrals have the flow pattern in the LHS panel but the ion flow is determined by ion-neutral friction & Lorentz forces (Heitsch & Zweibel 2008).

Dynamo Suppressed at Small Scales



The ion flow acts like a dynamo, but it saturates when B reaches equipartition. Field might therefore be amplified down to ambipolar scale; $\gg$ resistive scale. Reynolds stresses destroy the dynamo.

Novel Ingredient: Cosmic Rays

Relativistic particle component in equipartition with turbulence & magnetic field. Nearly isotropic, $\sim 10^7$ yr confinement time.

- Cosmic rays scatter from gyro-radius scale ($\sim$ AU) turbulence
  - scattering frequency $\nu \sim \omega_{cr} \left(\frac{\delta B}{B}\right)^2$
  - diffusion coefficient $D \sim \frac{c^2}{3\nu}$
- Gyroresonant excitation of Alfven waves by bulk streaming at $v_D > v_A$
  - growth rate $\Gamma \sim \omega_p \frac{n_{cr}}{n_i} \left(\frac{v_D}{v_A} - 1\right)$
- momentum & energy are transferred from the cosmic rays to the waves & from the waves to the background.

Implications

- Add buoyancy to galactic disk.
- Drive galactic winds, injecting magnetic fields into intergalactic medium
- Source of turbulence at gyroscale & below.
  - Preferred helicity
  - Amplify magnetic fields near shock waves

Summary & Outlook

- Origin & evolution of magnetic fields is still very open.
- Key observational data is still missing, but could be acquired.
- Galactic dynamos have unique requirements, extreme parameters & some novel features.
- Dynamo processes must operate today and may have observable signatures.