Origin & Evolution of Magnetic Fields

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Importance of the Problem

- A cosmological problem.
  - Exotic origin in the early Universe, or standard plasma physics?
  - Top-down or bottom-up process?
  - Role in formation of the first galaxies and stars?
  - Past and present sites of cosmic ray acceleration and propagation?
- Interplay with ISM studies
  - Structure of galactic fields on large & small scales?
  - How do fields affect turbulence?
  - How is field transported, what determines $B - \rho$ relation?
  - What effects do fields have on star formation?

The Plan of This Talk

- Primordial fields
- Intergalactic & intracluster fields
- What must be explained about galactic fields
- Effects of fields on turbulence & vice versa
- The future

Primordial Fields

- Bounds on magnetic energy density from Big Bang nucleosynthesis
- Signatures in CMB
  - polarization
  - effects on oscillations
  - heating by magnetic energy dissipation

Intergalactic & Intracluster Fields

- Only upper limits on a pervasive intergalactic field
- Evidence for turbulent amplification of cluster fields
- Interaction of magnetic fields & cosmic rays with AGN
- Are accretion shocks magnetized & how far back?
- How far back is Faraday rotation in damped Lyα systems detectable?

Galactic Fields I

Reasonable expectations*:

- Azimuthally oriented on large scales
- Turbulent component in rough equipartition with kinetic turbulence down to subviscous scales
- Strong swept up fields in shells
- Randomly directed vertical fields along chimney walls & winds, if present
- Stronger fields in denser gas

$*$ Based on plain vanilla MHD, not dynamo theory

Galactic Fields II

What do we see?

- Azimuthally oriented on large scales? **Yes**
  Large scale *azimuthally directed* field with some reversals
- Turbulent component in rough equipartition with kinetic turbulence? **Yes**
  Detailed small scale structure unknown; $\delta B_{||}$ possibly $> \delta B_{\perp}$.
- Strong swept up fields in shells? **Yes**
- Randomly directed vertical fields along chimney walls & winds? **Some**
- Stronger fields in denser gas? **Not in diffuse ISM, possibly in molecular gas**.

We Also Know...

- Li, Be, B found in oldest halo stars $\Rightarrow$ cosmic ray spallation $\Rightarrow$ magnetic field in parent gas
- Due to infall, outflow(?), birth & death of stars, ISM turns over on $\sim 10^9$ yr timescales.

Best evidence for dynamo as opposed to primordial origin.

What Must be Explained

- Directional coherence of in plane field over at least few kpc scales
  - Is there a coherent vertical field?
- Maintenance of field in steady state in rapidly turning over interstellar gas
- That a field was apparently in place at moderate redshift
  - Light elements $\Rightarrow$ energy density
  - Faraday rotation $\Rightarrow$ coherence

Thumbnails of Theory I

- Magnetogenesis by the Biermann Battery: fastest in small objects - $\frac{r_L}{l} \sim \frac{l}{c_s t}$. Create $\sim 10^{-18} G$ fields in cosmological shocks & ionization fronts, stronger fields in accretion disks & stars.
- Basic ingredients of dynamo theory:
  - Exponentially fast stretching of field by chaotic flow $\Rightarrow$ turbulence
  - Large scale flow or other preferred direction to impose order
  - Fast reconnection of small scale field & provide irreversibility

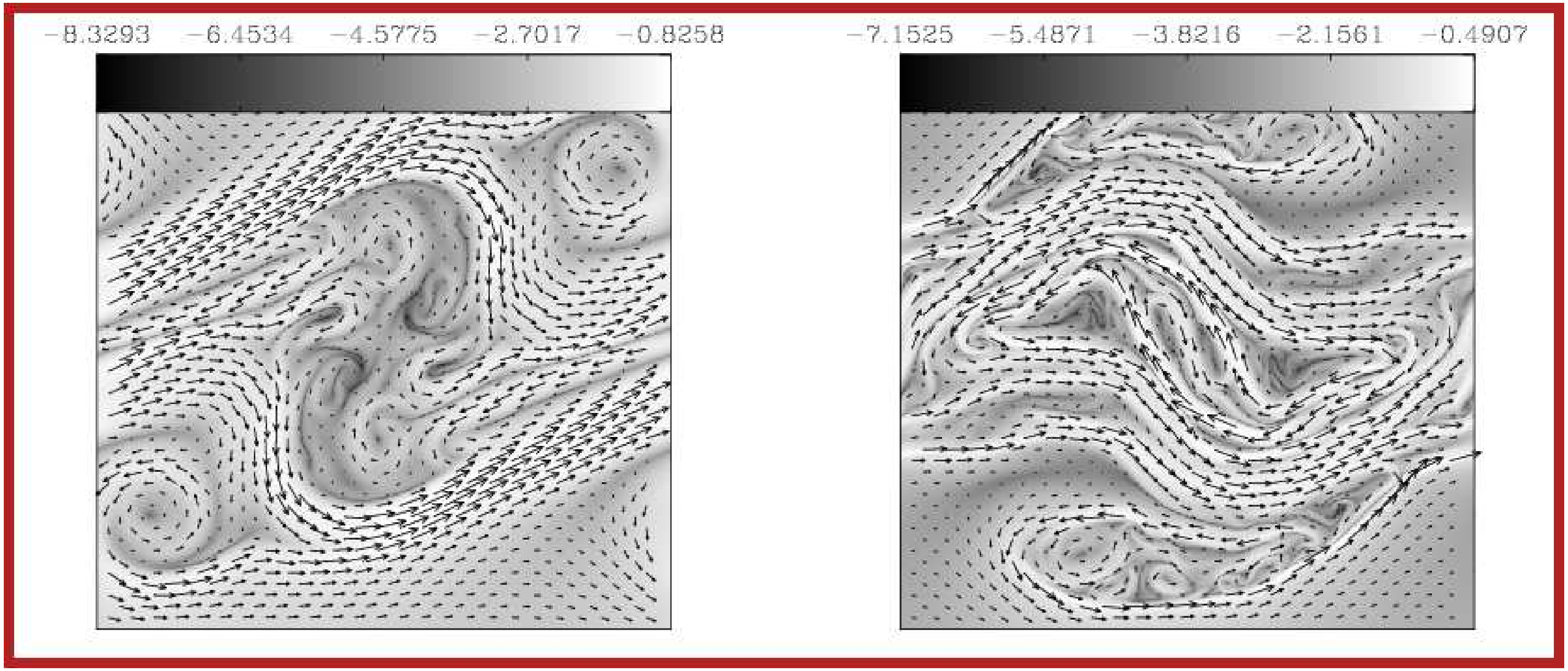
Thumbnails II

- Special features of galactic dynamos:
  - Fast diffusion of field from many small sources
  - Fast incorporation of magnetic field into unmagnetized or undermagnetized material
  - Escape of field, with or without accompanying wind

Dynamo Processes & ISM Studies

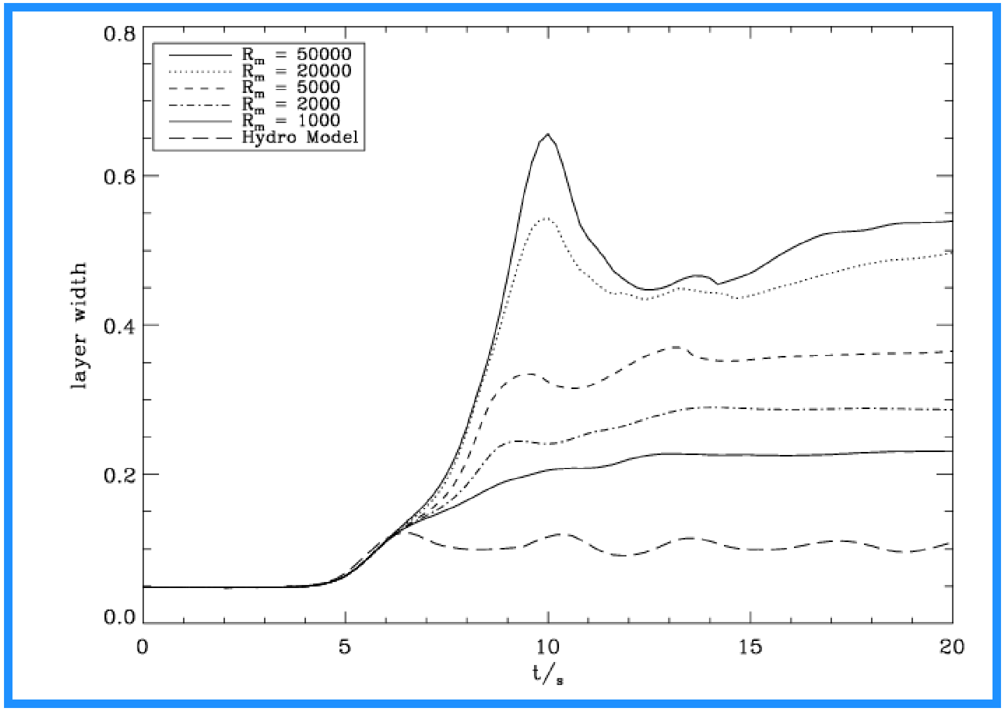
- Mapping
  - large scale component
  - characterize field fluctuations: spectrum, isotropy
  - vertical structure, halo fields, fields in HVCs
  - fieldstrength - density relation
- Is there a Galactic wind?
- Is the ISM chemically well mixed?
- Is there evidence for magnetic reconnection?

Example: Shear Layers



The magnetized Kelvin-Helmholtz instability generates rich magnetic structure which depends on resistivity; the left panel is 10$\times$ more resistive than the right panel & $10^{12}\times$ more resistive than the ISM (Palotti et al. submitted to ApJ).

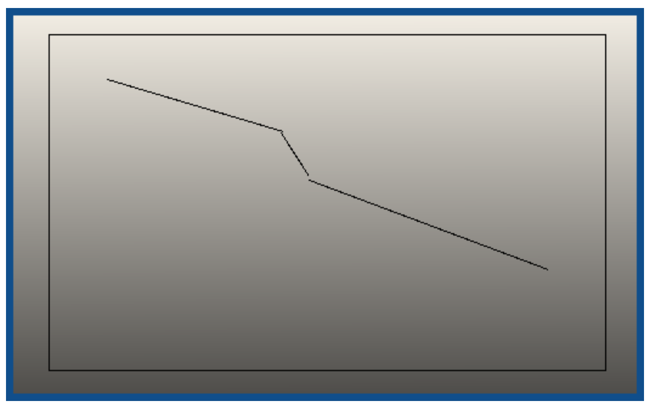
Velocity Diffusion



Small scale turbulence causes a shear layer to broaden and relax, but in a resistivity dependent way (Palotti et al. submitted to ApJ).

Magnetized Turbulence I

- Is there a direct cascade?
  - Energy injection at large scales, nonlinear transfer to intermediate scales, dissipation at smallest scales?
  - Energy sources: supernovae, instabilities, infall
  - Dissipation sources: viscosity, ion-neutral friction, radiative losses, resistivity, collisionless processes.



Magnetized Turbulence II

- Is there a direct cascade in molecular clouds and if so, what drives it?
- Is there an inverse cascade which creates flows and/or magnetic field on larger scales?
- Is there strong spatial intermittency $\Rightarrow$ strong localized dissipation?
- Is the power spectrum anisotropic?

The Future

- Observations:
  - Mapping in-plane and vertical structure of B
  - Zeeman mapping of more molecular clouds
  - Faraday rotation at moderate redshift
  - Spectroscopic probes of a Galactic wind
- Theory:
  - Grapple with diffusivity/resolution dependence; develop scalings
  - Improve subgrid modelling
  - Better post-processing of ISM simulations; include chemistry, radiative transfer, predict line profiles & dissipation scales