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
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. $R_m \sim 10^{15-21}$. 
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 ($B_\parallel$; atomic and molecular gas)
- Faraday rotation ($B_\parallel$); ionized gas)
- Radio continuum polarization ($B_\perp$; relativistic electrons)
- Polarization from aligned dust grains ($B_\perp$ orientation only; dense gas and dust)

$B_\parallel$ 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 is a probe of field direction, and reveals a coherent azimuthal Galactic field, with reversals (Han 2003). $\langle B \rangle \sim 1.5 \mu G$; $B_{rms} \sim 5 \mu G$. 
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 $B_\phi$ with respect to Galactic plane.
- Existence of coherent vertical field.
- Coherence length of $B_\phi$.
- 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?
- Large-scale 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 $n = 1 \text{cm}^{-3}$
- Ionization fraction $x = 0.1$
- Velocity $V = 10 \text{km s}^{-1}$
- Size $L = 300 \text{pc}$
- Kolmogorov scale $\sim 10^{14} \text{cm}$

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

- \( \alpha \) & \( \beta \) 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 \( \alpha \), \( \beta \) dependence on position
  - Variety of saturation models explored

- Subject to the usual criticisms.
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 \( \rho_i / \rho_n \ll 1 \), then on timescales \( \gg \) 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

Dynamos in Weakly Ionized Gases

Left: Field strength in a kinematic “fast dynamo”. Right: Field strength 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).
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.