Galactic& Extragalactic Magnetic Fields

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Magnetogenesis: an Open Problem

- **Top Down:** Early universal process created pervasive magnetic field.
- **Bottom Up:** Magnetic fields 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? How do magnetic fields affect observations of intergalactic cosmic rays and the CMB?

The Plan of This Talk

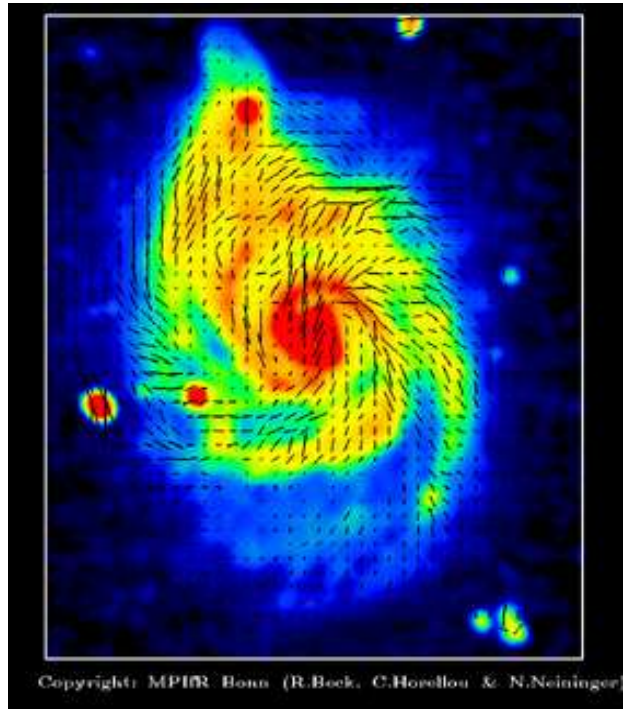
- Galactic magnetic fields: tools, results, & what must be explained
  - Origin of large scale field is key problem
- Magnetic fields in galaxy clusters: likewise
- Bounds on magnetization of the IGM at large
- Mechanisms & scenarios for magnetogenesis
- Detection of magnetic fields
  - Spectrum is key problem

Galactic Magnetic Fields

- 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)
- Morphological evidence

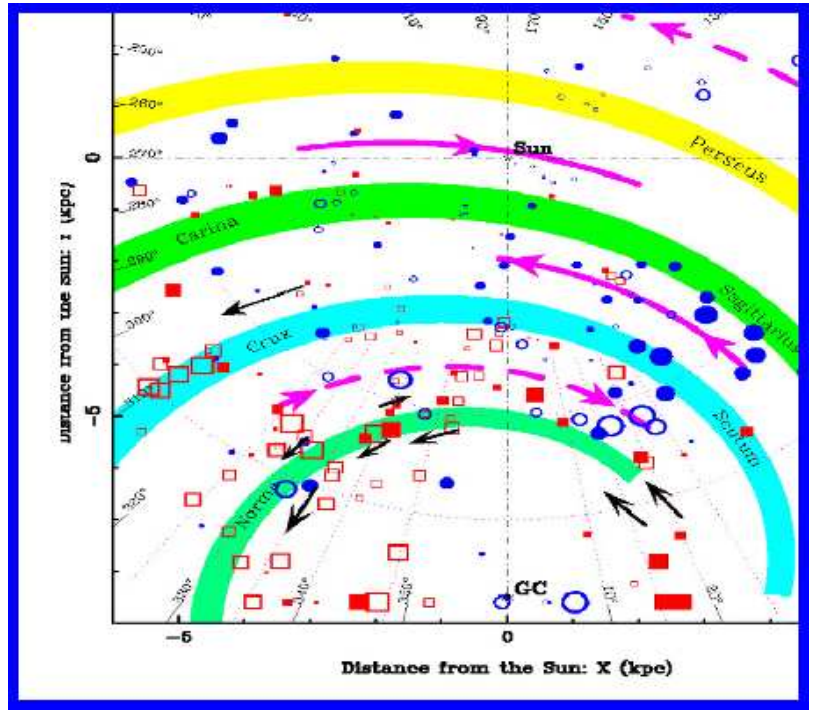
$B_{||}$ means along the line of sight; $B_{\perp}$ means in the plane of the sky. Traditional tools used to great effect in the local Universe and back to a few tenths its present age.

Synchrotron Maps



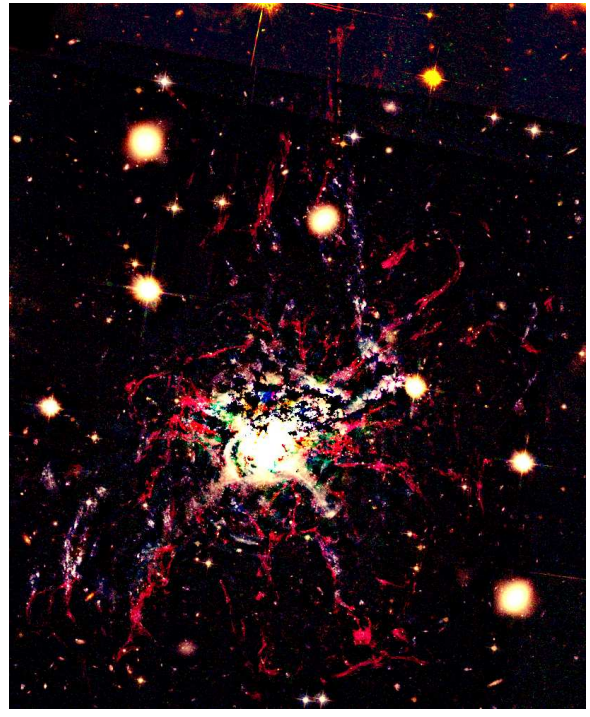
The vectors denote orientation of B projected on the plane of the sky. The degree of polarization is a measure of unresolved magnetic field structure: $p/p_{max} \sim \langle B \rangle^2 / \langle B^2 \rangle$.

Faraday Rotation Maps



Faraday rotation is a probe of field *direction*, and reveals a coherent azimuthal Galactic field, with reversals (Han 2003).

Morphological Evidence: NGC 1275



Extended, massive filaments surround NGC 1275 in the Perseus cluster, imaged by HST. We argued (Fabian et al. 2008) that they are thermally insulated & dynamically supported by strong ($\sim 100\mu G$) magnetic fields.

Galactic Fields in Time

- Faraday rotation
- Zeeman splitting
- Radio continuum
- Light elements in halo stars & ISM

All imply μG magnetic fields with directional coherence were present in galaxies by $z \sim 2 - 3$.

Do we Understand Galactic B?

- Azimuthal orientation reflects shear by strong differential rotation
- Strength near equipartition with gas turbulence, consistent with turbulence theory & stability constraints
- **Largescale coherence now and at $z > 1$ is most challenging feature to explain.**

Turnover of interstellar gas on $\sim 10^9$ yr timescales due to stellar processes, infall, & galaxy mergers implies continuous regeneration of the magnetic field.

Galaxy Clusters

- Weakly polarized nonthermal continuum
- Faraday rotation of AGN & background sources

IGM in clusters is weakly (0.1 - few μG) magnetized. Spectrum of fluctuations from tens to a few kpc. Synchrotron filaments seen at $z \geq 0.5 - 0.7$.

Universal Intergalactic B

- Bound on RMS B from BBN $\sim$ 0.1 μG (nucleosynthesis era)
- Bound on B spectrum from WMAP: $B < 0.7nG$ on 100 Mpc scales; $0.4 - 30nG$ on Mpc scales
- Bound on coherent B from lack of RM - z correlation in quasars ($z < 3$)

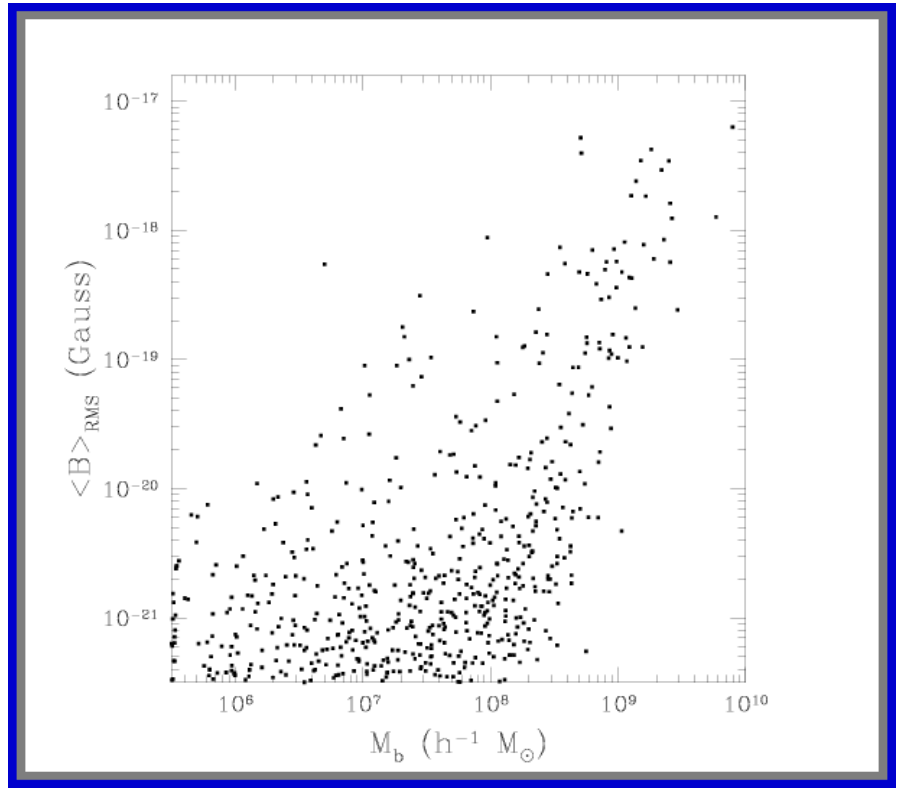
Probe at moderate z with SKA, LOFAR, GRB pair echoes.

Probe within GZK cutoff with UHECR.

Mechanisms for Magnetogenesis

- Exotic
  - Cosmological phase transitions
  - Break conformal invariance of EM fields during inflation
- Plasma based
  - Biermann battery (L is $\nabla\rho$, ∇T scale, τ is dynamical time)
  - Weibel instability (L is electron skindepth c/ω_{pe}, τ is plasma period)

Battery in Cosmological Ionization Fronts

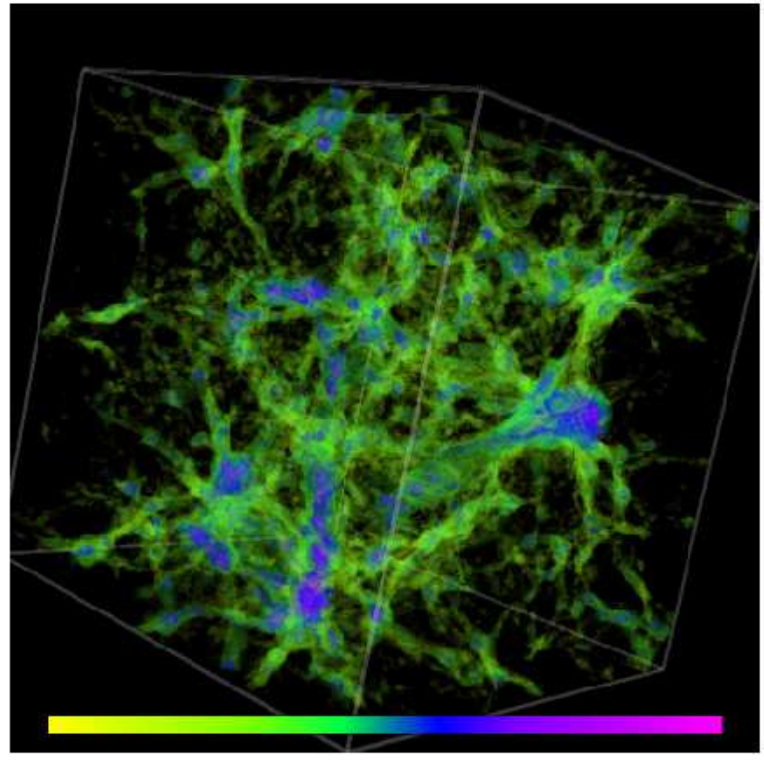


Weak, large scale fields generated by reionization, compression, & stretching (Gnedin, Ferrara, & Zweibel 2000).

Scenarios for Magnetization

- Colgate, Kronberg, Loeb...
  - Biermann battery in accretion disks, accretion disk dynamos, propagate field to ambient medium by jets, winds, bubbles.
- Ryu et al., Li
  - Weibel instability in shocks, amplification by shear & turbulence, leads to magnetized cosmic web.

Magnetized Cosmic Web



Magnetic energy density in cosmological simulations by Ryu et al. (2008). Typical intergalactic fieldstrengths in nG range. Smallest resolved scale is 100 Mpc.

Hydromagnetic Amplification

- Field strength grows in proportion to fieldline length
- When $P_m \equiv$ viscosity/resistivity $\gg 1$, magnetic spectrum extends below velocity spectrum.

Stretching

Stretching a bundle of fieldlines at constant volume reduces its cross section, strengthening the field. $B/B^{'} = L/L^{'}$.

Small Scales Dominate

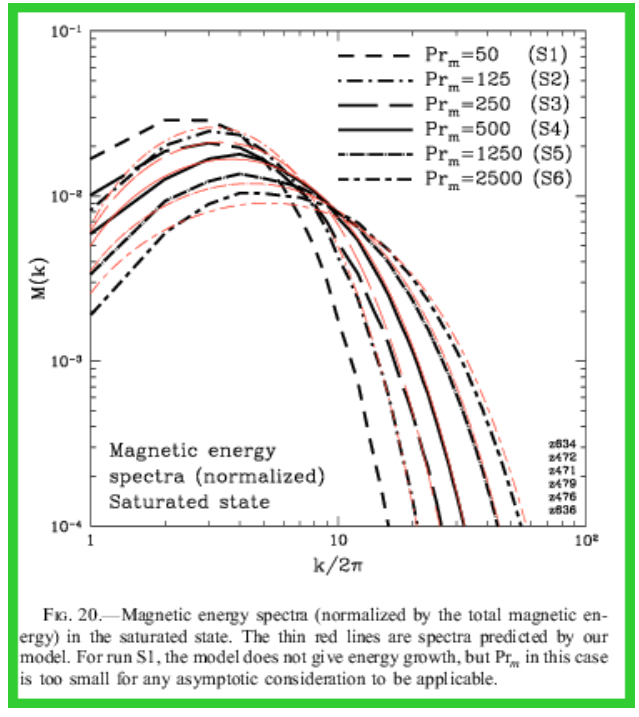


FIG. 20.—Magnetic energy spectra (normalized by the total magnetic energy) in the saturated state. The thin red lines are spectra predicted by our model. For run S1, the model does not give energy growth, but Pr_m in this case is too small for any asymptotic consideration to be applicable.

Magnetic power spectrum extends to resistive scale; fast reconnection required to suppress it.

Diagnosing B

- Pair echoes from GRB
  - TeV GRB γ + CIB $\gamma \rightarrow e^{\pm} \rightarrow$ IC GeV γ. Measure time delay, affected by gyromotion in B field.
- UHECR arrival directions
  - Spread due to gyromotion, energy dependent.

Motion in Random B

Gyroradius ($\beta = 1$)

$$r_g = \frac{E}{ZeB} = 1 \frac{E_{EeV}}{ZB_{nG}} \mathrm{Mpc}.$$

If $r_g/L \gg 1$,

$$\delta\theta \sim \frac{L}{r_g}$$

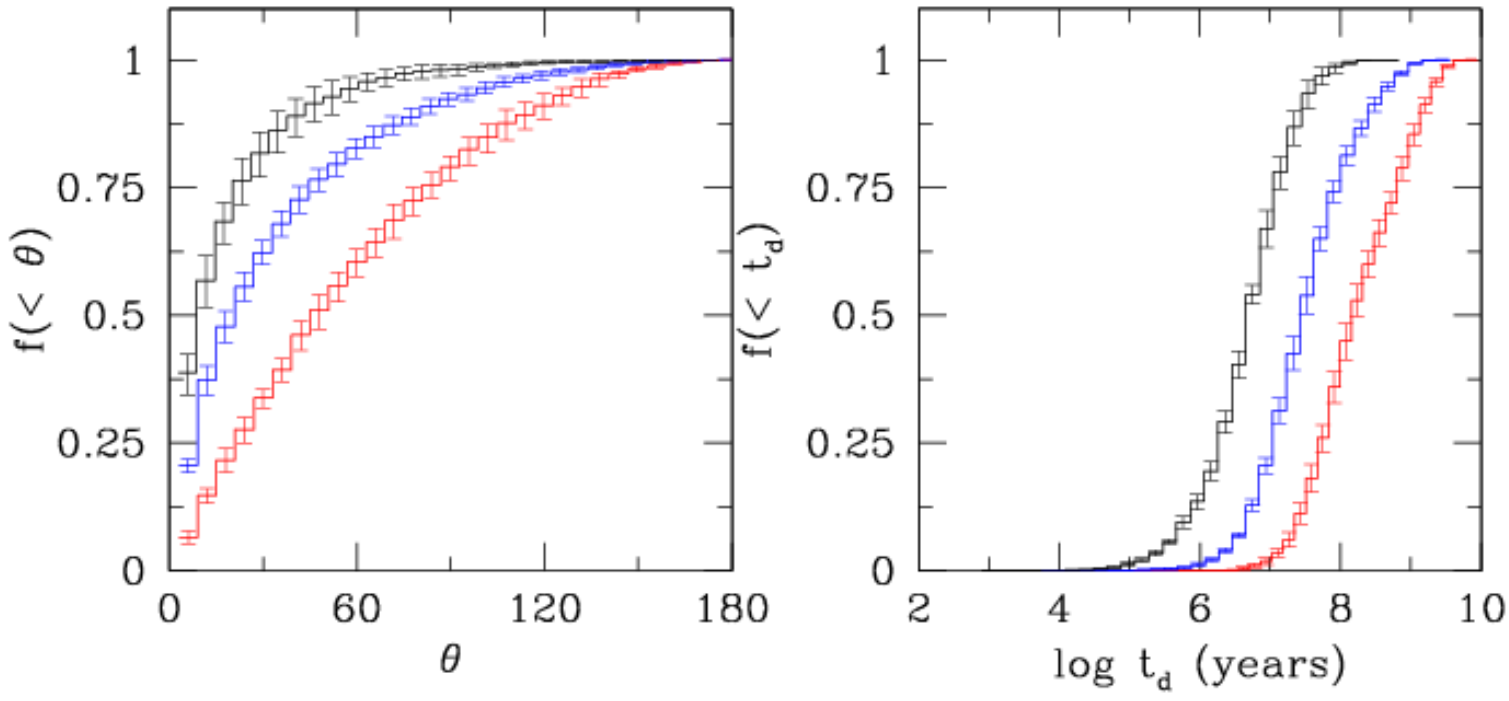
Angular Diffusion

For a source at distance D

$$\langle (\delta\theta)^2 \rangle^{1/2} \sim \frac{(DL)^{1/2}}{r_g}$$

The angular dispersion depends on the magnetic length-scale L; we must calculate the small scale spectrum!

Computed Diffusion



Angular spreading vs energy for Ryu et al. magnetic fields (Das et al. 2008).

Summary & Outlook

- Origin & evolution of magnetic fields is still very open.
- Fields may affect growth of cosmological structure & interpretation of CMB measurements
- GRB & UHECR can probe intergalactic fields
- B spectrum, especially contribution of small scales, is critical to understanding GRB & UHECR response & signatures.