Measuring magnetic fields in the universe

or

Probing plasmas in the lowest possible density régimes

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WHY GIANT RADIO GALAXIES ARE INTERESTING MAGNETO-PLASMA LABORATORIES
Faraday Rotation (RM)

\[ \frac{\Delta \chi}{\Delta \lambda^2} = 8.1 \times 10^5 \cdot \frac{n_{th}}{cm^{-3}} \cdot \frac{B}{\mu G} \cdot \frac{L}{Mpc} \text{ radians / } m^2 \]

Lowest measurable RM \( \approx 1 \text{ radian/m}^2 \)

Galactic foreground RM \( \approx 3 - 500 \text{ radians/m}^2 \)

RM meas’t within a source limited by:

- variable ionospheric RM
- galactic “foreground” removal
- magneto-ionic environment of source
DIAGNOSIS OF AN EXTRAGALACTIC RADIO SOURCE

Galaxy nucleus (black hole)

Zone of “older” radiating electrons (steeper radio spectrum)

Zone of fresher acceleration (flatter synchrotron radio spectrum)

E.L.H. Zukowski and P.P. Kronberg
University of Toronto
How *intergalactic* Cosmic Ray and magnetic energy comes from supermassive black holes

Giant radio galaxies help calibrate this BH – to *intergalactic medium* feedback energy
2147+816 giant radio galaxy

$z=0.146$

2.6 Mpc
GRG 2147+816 at $z=0.146$ (Frame size=1.1x1.1 Mpc $h_{75}^{-1}$)

No evidence for large scale lobe-internal shocks
Faraday Rotation (RM)

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Fig. 8. The distribution of rotation measure over 3C 326 as computed from the 49 cm and 21 cm convolved data superposed upon photograph of the 49 cm total intensity. Note that to produce a simple grid of single digit numbers we have subtracted integrated measures, whose derivation is described in the text, of +25 rad m$^{-2}$ and +20 rad m$^{-2}$ from the values measured at individual sample the east and west components respectively. For reference, these integrated values are displayed under each component
GIANT RADIO SOURCES HAVE:

• Large $\geq 300$ kpc regions of aligned magnetic fields
• Extremely low intra-lobe Faraday rotation/depol’n limits $\lesssim 2$ rad/m$^2$,
• uniquely long intra-lobe path lengths

$\nL_{th} \lesssim 10^{-5}$ cm$^{-3}$ from $\Delta(RM)$

$V_A$, $\sim$ lobe expansion speed, especially if $k \gg 1$
GRG’s

- **low lobe vs. lobe Rotation Measures**

  \[ 1 \lesssim \Delta(RM) \lesssim 10 \text{ rad/m}^2 (\text{lobe1} - \text{lobe2}) \]

  ![ambient nigth] = \[ 10^{-5} - 10^{-6} \text{ cm}^{-3} \]

  - Sometimes even lower **intra-lobe RM’s**

    \[ 0 \lesssim \Delta(RM) \lesssim 5 \text{ rad/m}^2 \]
Alfvén speeds in radio lobes

\[ \nu_A = 696 \times \frac{B_{-6}^L (1 + k)^{2/7}}{\sqrt{\rho_{10^{-5}}^L (1 + k)^{-2/7}}} \text{ kms}^{-1} \]

- \( k = E_p/E_e \)  \textit{In Milky Way, } \( k \approx 100 \)

\( B_{-6}^L \) (G) assumes minimum total energy in field \( \rho + \text{relativistic particles (e}^- + p^+\))

- \( \rho_{10^{-5}}^L \) derived from Faraday rotation limit (\( \propto n_e^L.B^L.L \)) in giant lobes

- \( \nu_A \) depends on (unmeasured) relativistic proton energy \( \propto (1+k)^{3/7} \)
Compare \textbf{rad. Loss time} with \textbf{transport time}

\[
\tau_{\text{rad}} \leq \frac{5.4 \times 10^7 B^{1/2}}{B_{(\text{cmb-equiv})} (1+z)^4 + (3.3 B_{3.3 \mu G})^2} \cdot \left[ \nu_{10.6 \text{GHz}} (1+z)^{1/2} \right] \cdot \left[ \frac{d}{500 \text{pc}} \right] \cdot \left[ \frac{1000 \text{ km s}^{-1}}{v_T} \right] \text{ yr}
\]

in GRG's $\tau_{\text{rad}} \lesssim 0.1 \tau_{\text{transp}}$ !!

- particle transport from outer \textbf{hotspots} (shock acc'n zones) cannot be the energizing mechanism of GRG lobes
- This question was less clear for 10x smaller radio galaxies & quasars
Summary: physical constraints imposed by GRG’s

1. Mpc physical dimensions characteristic of inter-galaxy separations!

2. Outer extremes (hotspots) must advance at $\gtrsim 6000$ km/s, ($\gtrsim 0.02c$), but weak evidence for a supersonic shock at outer interface.

3. Internal Alfvén speeds are $\gtrsim 2000$ km/s ($n_{th}^L$ is a lower limit)

4. CR electron radiative lifetimes much less than very long lobe-internal transport times (distances)

5. High acceleration efficiency required: $(E_{min}^{tot})/(BH \text{ infall energy}) \approx 0.1$

6. Classical shock theory (for CR electron acceleration) breaks down

* * *
Important Characteristics of Mpc-scale radio sources.

- relaxed morphologies, no externally caused shape distortion.
- Little evidence for strong shocks around the lobes
- B-field parallel to lobe-igm interface
- Overpressured relative to surroundings
- Low lobe-internal Faraday rotation
- Sizes are of intergalactic dimensions!
  -> over time, can magnetize general igm
The main results from an intercomparison of observations at different wavelengths are the following:

1) The spectral index varies over the outer lobes by, at most, 0.3. This fact implies that in acceleration of relativistic electrons must occur in outer components of 3C 326.

2) Very little depolarization occurs between 21 and 49 cm, indicating that the density of thermal matter in the lobes is \( \sim 2 \) to \( 6 \times 10^{-5} \) cm\(^{-3} \), if equipartition magnetic field strengths are assumed.

3) The magnetic field of 3C 326 has a highly uniform structure over several hundred kpc and is oriented predominantly along the major axis of the source.

4) The density of any intergalactic gas surrounding...
How much **energy** gets out and where does it go?

**Test:** Measure the energy content of egrs in different environments, and with differing **luminosities** (i.e. internal energies)

We have estimated $E_{\text{min}}^{\text{tot}}$ for 3 groups of egrs:

1. All sources with projected size $> 0.6$ Mpc (GRG’s)

2. Sources with the densest ambient environments ($< 150$ kpc of a galaxy cluster core)

3. Other sources with extremes of radio luminosity and distance
Radio lobes (X-ray holes) displacing hot gas (PdV work) in the Perseus cluster

Chandra image (A.C. Fabian et al.)
High energy conversion efficiency ($\eta$) from gravitational to relativistic magneto-plasma energy

\[ \approx 1.8 M_{\text{BH}}^8 c^2 \]

(infall to $R_S$)
Etot (B + rel particles) is close to the maximum reservoir energy (gravitational -> requires very efficient acceleration process for the CR electrons)

BH Energy into the IGM

• Infall energy onto galactic black holes

• Schwarzschild Radius

• GRG’s reveal that $\eta$ is as much as 10%!!

• $E_{\text{released}}$ in magnetic fields and CR’s $\approx$ approximate photon energy release

\[ E_{\text{inf}} = -\frac{GM_{BH}^2}{R_s} \]

\[ R_s = \frac{GM_{BH}}{c^2} \]

\[ E_{\text{released}} = \eta E_{\text{inf}} = \eta M_{BH} c^2 \]

$\eta$ = efficiency factor
3
What’s the missing, efficient acceleration mechanism?

The very high Alfvén speeds, and highly ordered fields suggest acceleration by magnetic reconnection (Li, Nishimura, Barnes, Gary, Colgate 2003)

The scenario:

• Collimated energy flow from BH is electromagnetic. $10^{19}$ amps, energy initially in magnetic fields
• Electron CR’s energized by conversion of magnetic $\rightarrow$ particle energy
• Sheared B-fields evolve to a more relaxed state (Li et al. 2003)
• Magnetic reconnection a natural particle accelerator, esp. if $V_A$ is high
• Other particle acceleration mechanisms possible
• How this happens currently not understood
Magnetic reconnection in radio source lobes?

Standard reconnection models (too slow) seem not to apply in radio lobes.

The (resistive) reconnection layer width $\Delta$ in the Sweet-Parker model is:

$$\Delta_{s-p} \sim 1500 L_{kpc} \bullet n_{3 \times 10^{-6}}^{1/4} \bullet \eta_{4}^{1/2} \bullet B^{-1/2} \bullet 5 \times 10^{-6} km$$

$L$ = length of the reconnection zone, $\eta$ = resistivity (cm$^2$/sec)
Reconnection time scales

\[ \tau_A \sim \frac{L}{v_A} \]

Rate of magnetic energy dissipation

= rate of magnetic flux convection out of reconnection layer

Time scale for this \( = (\tau_A \tau_\eta)^{1/2} \sim 6 \times 10^{26} \) yrs!

Standard Sweet-Parker doesn’t work here!!
Recent insights on FAST reconnection

- GRG Radio lobe plasmas are collisionless

- Analogous conditions in the Earth’s magnetotail

- A key parameter is the ion skin depth, $d_i$

- $d_i = \frac{c}{\omega_{pi}} \sim 1.3 \times 10^{10} n^{-1/2} \times 3.10^{-6} \text{ cm}$

  ($\omega_{pi} = \text{ion plasma frequency}$)

- $d_i >> \Delta_{s-p}$ in radio lobes;

- This breaks the frozen-in flux condition
Application to force-free fields in radio lobes

- in a collisionless, and force free magnetoplasma reconnection rate $\rightarrow x\%$ of $v_A$. (indep. of plasma resistivity $\eta$)
- i.e. in GRG’s $v_{\text{reconn}}$ a fraction of $c$!


- A significant first step in facilitating particle acc’n by reconnection.
Reconnection acceleration?

- Reconnection acceleration not yet fully understood (C. Nodes et al Phys Plas. 10, 835, 2003), but can efficiently produce relativistic particles.

- Reconnection acceleration probably highly efficient – consistent with GRG lobe energy content.

- Converts magnetic to particle energy

- High $V_A$ in GRG radio lobes is satisfied-- a key prerequisite to understanding the systems.
\[ \int_{0}^{10^{21}} N_0 E^{-2.7} dE = 0.07 \text{ eV cm}^{-3} \]

\[ = 1.12 \times 10^{-13} \text{ erg cm}^{-3} \]

E^{-2.6} \rightarrow 5 \times 10^{59} \text{ ergs per “galaxy spacing” volume} (10^{74} \text{ cm}^{-3})

\[ B_{eq} = 3.5 \times 10^{-7} \text{ G!} \]

Where radio astronomy meets cosmic ray physics

Credit:
Stirling Colgate
2005
Astrophysical implications

*If* CR particles are accelerated by reconnection in GRG’s, then:

- It is a universal mechanism in *all* e.g.r.s.,
- Including radio lobes in galaxy clusters.
- Space – filling particle acceleration
- Candidate to explain UHECR’s (*S. Colgate*).
- Might explain optical/x-ray synchrotron radiation in diffuse radio lobes.
Recent experimental searches for intergalactic magnetic fields, and CR’s and tests for Intergalactic CR acceleration
A recent low-level search for magneto-plasmas on intergalactic dimensions

410/430 MHz 8°x8° field in Coma supercluster

Philipp Kronberg (LANL)
Roland Kothes (DRAO – Penticton BC)
Chris Salter (Cornell-Arecibo)
Phil Perillat (Cornell-Arecibo)

• Arecibo images at 430 MHz (305m aperture) combined with:
• DRAO interferometer images (2x full synthesis) (resolution equivalent to a 1600m single dish)
Dominion Radio Astrophysical Observatory
Penticton BC, Canada
Search for faint Galactic and extragalactic diffuse emission on arcminute scales at 0.4 GHz


8° dia. Field containing combined Arecibo + DRAO data, at a resolution of 2.8’ x 6.7’

2.7K CMB background and galactic foregrounds (≈ 18K) are included
A 16 – 22K linear $T_B$ plane has been subtracted out (= CMB + smooth gal. foreground)

Resolution: 2.8’ x 6.7’, elongated N-S (= the beam of the DRAO interferometer)

Note the new temperature scale!
Diffuse emission

+ 

Locations of brightest discrete radio sources

0.4 GHz
8°x 8° Field
10’ resolution

Arecibo
+ DRAO

P.P. Kronberg,
R. Kothes,
C.J. Salter,
P. Perillat
ApJ (submitted)
2006
First attempt to detect magnetic fields in galaxy filaments

SMOOTHED
RM – associated with the WHIM in LSS filaments?

GALAXY COLUMN DENSITY from 2MASS (Method #2)

galaxies per pixel
TENTATIVE CONCLUSIONS

• “Energy feedback” into the IGM happens via conversion of $\eta E_{\text{infall}}$ into a magnetized plasma.

• Faint intergalactic synchrotron emission traces intergalactic magnetic fields.

• Faraday rotation a complementary tracer

• Primary energy source probably comes from galactic black holes.
Major unanswered questions

1. How is the energy transferred from the galactic black hole into extragalactic space?
   • e+e- pairs generated near the BH accretion disk?
   • hadron acceleration close to the black hole?
   • electromagnetic energy coupled directly out of the BH? Colgate et al.

2. How is angular momentum transferred outward, to permit collapse? Colgate, Li, Warren, Currier 2004

3. Location of energy/ang momentum transfer?
   • Close to the BH ergosphere? (Kerr metric space-time)
   • From the BH’s accretion disk? (100 AU scale)
High energy conversion efficiency ($\eta$) from gravitational to relativistic magneto-plasma energy.

$10^8 M_\odot$ black hole infall energy $\approx 10^{62}$ ergs

$\approx 1.8 M_\odot^8 c^2$

(assuming infall to Schwarzschild Radius, $R_S$)