Cosmic magnetic fields and HE particles

Philipp Kronberg

Los Alamos National Laboratory
and
University of Toronto

Université libre de Bruxelles

26th November 2010
Galaxies with strong starburst-driven outflows

2 examples:
B. Outflow from the M82 starburst galaxy (3 Mpc distant)

M.L. Allen, Ph.D. Thesis 8GHz

Optical image
De-Faraday rotated, projected magnetic field lines From λλ 3.6 & 6.2 cm
Pol’n intensity Ha emission

Massive spiral galaxies more like the Milky Way

an edge-on view:

Example of NGC891 with its projected halo magnetic field structure
a top (plan) view

Projected Magnetic field
In a “grand design” galaxy

M51

R. Beck
in
Sterne und Weltraum,
September 2006.

Question: To an extragalactic observer, does the Milky Way present a clear and beautiful magnetic grand design, like M51 and others?

New results suggest yes
NGC891
Similar to the Milky Way

Edge-on view

of the (projected)
Halo magnetic field structure

So far, difficult to obtain a similar, and 3-D halo magnetic field model for the Milky Way

*Image by M. Krause*
1

A return to the Milky Way

Begin with Simard-Normandin & Kronberg

Inside the plane of the Milky way disk:
a view between $b \pm 4^\circ$

A segment of the Canadian Galactic Plane survey (CGPS) at 1.4 GHz
Faraday Rotation measure studies of the Milky Way

“New Large Scale Magnetic Features of the Milky Way”

Summary of conclusions in 1980:

Simard-Normandin & Kronberg

1. Bisymmetric field pattern
2. Off-plane angular autocorrelation scale of RM sign \( \approx 30^\circ \)
3. Magneto-ionic scale height \( \approx 1.8 \) kpc
4. (Still mysterious) off-plane, high-RM zone at \( l \sim 100^\circ, b \sim -25^\circ \) (region “A”)
5. Spiral with 15° (from tangential) pitch angle
Updated RM probe of the Milky Way disk

New evidence

New smoothed Galactic RM sky from 2250 egrs RM’s

Galactic Latitude

Galactic Longitude

RM (rad m⁻²)

- 0 ≤ RM < 15
- 15 ≤ RM < 30
- 30 ≤ RM < 60
- 60 ≤ RM < 90
- 90 ≤ RM < 120
- 120 ≤ RM < 150
- 150 ≤ RM < 300
- 0 > RM > -15
- -15 ≤ RM > -30
- -30 ≤ RM > -60
- -60 ≤ RM > -90
- -90 ≤ RM > -120
- -120 ≤ RM > -150
- -150 ≤ RM > -300
- RM ≤ -300

Error distribution of individual RM measurements

Kronberg & Newton-McGee 2009
Smoothed RM’s around the Galactic plane at $|b| \leq 10^\circ$  
*New evidence for $\langle B \rangle$ in the disk*

P.P. Kronberg & K. J. Newton-McGee  
arXiv:0909.4753

1. fold about the Galactic center direction ($l=0^\circ$), and reverse sign
Fold RM’s about \( l=0 \), then reverse the sign of RM’s at \( 360^\circ > l > 180^\circ \) (orange points)

Note the clear displacement!

2: shift to match
RM’s after an 11° (± 2°) shift

3. Shift, and optimize
Smoothed RM’s up to $b = |10^\circ|$  
CGPS and SGPS omitted  
RM’s folded and 11°-shifted, as before

Conclusion:  
$\langle RM \rangle$ at $|b| \lesssim 2^\circ$ is coupled to $\langle RM \rangle$ at $(2^\circ \lesssim |b| \lesssim 11^\circ)$, at ~ all $I$  

This pattern deteriorates only at $|b| \gtrsim 12^\circ$ -- see next
Now, migrate further away from the Galactic plane.

$5^\circ < |b| < 20^\circ$
Quick summary of results

1. **Our RM smoothing resolution** is comparable with (1) the galactic z-height (~1.5 kpc), and (2) inter-arm spacing (~ 1 – 2 kpc). It averages over smaller-scale B reversals.

2. Spiral pitch angle is 11± 2°. (This can be confirmed only on our side of MW disk). Similar to recent Han et al RM result, and Heiles (1996) based on interstellar polarization data.

3. Average B aligns closely with the stellar spiral structure –like many other nearby spirals

4. To an extragalactic observer, the magnetic Milky Way is a **highly patterned, “grand design”** spiral galaxy, just like M51, etc.!! – when we look at the forest, not the trees!!

5. Major sign reversal occurs near l = 55° – consistent with a bisymmetric “**BSS**” pattern. ASS outer structure. BUT recall that we “see” only our side of the Milky Way disk

B in the galactic Halo?


In the NGH: median RM = 0 ± 0.5 rad/m²

In the SGH: medium RM = +6.3 ± 0.7 rad/m²

$\sigma = 9 \text{ rad/m}^2$ indep. of angular scale up to 25° $\rightarrow \sigma_B \sim 1\mu G$
Bayesian smoothed RM’s in the Galactic caps $|b|>30^\circ$

M.B. Short, D.M. Higdon & P.P. Kronberg
Bayesian Analysis 2, 665, 2007

Better data and more refined analysis are underway
|B| (R) in the Milky Way disk.

Galactic disk field \( \langle |B| \rangle \) vs R, modelled from all-sky continuum radiation at 0.4 GHz (Haslam et al.) and 1.4 GHz (Reich et al.)

\( B_1(\mu G) \)

MILKY WAY

exponential

\( \sim 10^{-8} \)G? at \( r=100 \)kpc

(E.M Berkhuijsen, W. Reich 2005, 2009)
2. NEARBY EXTRAGALACTIC SPACE

Observations, theory and modelling for extragalactic $B$ – fields in the nearby ($\lesssim 150$ Mpc) universe

-- relevant to UHECR propagation
Faraday rotation at a distant EGRS, and at an intervenor

\[
RM = \frac{\Delta \chi}{\Delta \lambda^2} = 8.12 \times 10^5 \int_0^{z_s} (1 + z)^{-2} n_e(z) B_\parallel(z) dl(z) \quad \text{rad/m}^2
\]

\( B \) in Gauss, \( n_e \) in cm\(^{-3} \), \( l \) in pc
RM of radio sources within, behind, and behind/beside, a sample of (ROSAT X-ray-selected) **galaxy clusters**

Plotted against impact parameter to the cluster center

*Clarke, Kronberg, & Böhringer ApJL 547, 111, 2001*

Cluster redshifts are typically < 0.2
UHECR ANISOTROPIES(?)

2(a).

"Analysis of large scale anisotropy of UHECR’s in HiRes data"

Grey scale steps display

\[ \Phi = \Phi \oplus \mathbb{E} \]

Exposure function

model mass distr. function
(with 9°smearing)
2(b) Case of Centaurus A at 3.8 Mpc
27 events above $6 \times 10^{19}$eV detected by the Auger collaboration


*Cent A image:* N. Junkes et al. *A&A*, 269, 29, 2003/Patricia Reich (priv. comm.)
Faraday Rotation measures around, and behind the Centaurus A radio galaxy (3.8Mpc distance)

Feain, I., J. Ekers, R.D., Murphy, T., Gaensler, B.M., Marquart, J-P, Norris, R.P., Cornwell, T.J., Johnson-Holllitt, M., J. Ott, & Middelberg, E.

Deflection of UHE CR trajectories through the magnetic environment of the local universe

\[ \theta \approx 8^\circ Z \left( \frac{l}{10 \text{ Mpc}} \right)^{0.5} \left( \frac{l_0}{1 \text{ Mpc}} \right)^{0.5} \left( \frac{E}{10^{20} \text{ eV}} \right)^{-1} \left( \frac{B}{10^{-8} \text{ G}} \right) \]

Sample calculation relevant to Centaurus A \((l_0 < l)\):

For protons \((Z = 1)\), \(l = 4\text{Mpc}, l_0 = 1\text{kpc}, E = 10^{20}\text{eV}, B = 10^{-7}\text{G}\)

\[ \theta = 4.8^\circ \]
How do magnetic fields get into the intergalactic medium?
3(a).

The magnetic energy input from central BH’s to the IGM

*Relevant to B in galaxy-overdense cosmic filaments*
Fig. 8. The distribution of rotation measure over 3C 326 as computed from the 49 cm and 21 cm convolved data superposed upon a "photograph" of the 49 cm total intensity. Note that to produce a simple grid of single digit numbers we have subtracted integrated rotation 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 points for the east and west components respectively. For reference, these integrated values are displayed under each component.
Mind the gap!! $R > R_s$

Accumulated energy $(B^2/8\pi + \varepsilon_{CR}) \times \text{(volume)}$ from "mature" BH-powered radio source lobes

GRG’s capture the highest fraction of the magnetic energy released to the IGM

$E_{\text{tot}} = M_{BH}c^2$

Expectation of the average intergalactic field seeded by supermassive black holes:
A global calculation

Average galactic BH density
\( M_{BH} \gtrsim 10^{6.5} M_\odot \)

Gravitational energy reservoir per BH
(scaled to infall to \( R_S \))

\[
\langle \rho_{BH} \rangle \approx 2 \times 10^5 \frac{M_\odot}{Mpc^3}
\]

\[
M_{BH} c^2 = 1.8 \times 10^{62} \frac{M_{BH}}{10^8 M_\odot} \text{ ergs}
\]

\[
\varepsilon_B = 1.36 \times 10^{-15} \left( \frac{\eta_B}{0.1} \right) \times \left( \frac{f_{RG}}{0.1} \right) \times \left( \frac{f_{VOL \text{ FILAMENTS}}}{0.1} \right)^{-1} \times \left( \frac{M_{BH}}{10^8 M_\odot} \right) \text{ erg cm}^{-3}
\]

Gives
\[
B_{IG}^{BH} = \sqrt{8 \pi \varepsilon_B} = 1.8 \times 10^{-7} \text{ G}
\]

- Initially captured within galaxy filaments
- Intergalactic medium near galaxies should contain significant magnetic energy, originating in central BH’s
3 (b)

- First test for $|B_{\text{IGM}}|$ in nearby galaxy supercluster filaments --
- If $|B_{\text{IGM}}| \approx 10^{-7} \text{G}$ on scales of few $\times 100$ kpc, it has a chance of being detectable in RM

\( B_{\text{IGM}} \) in the local Universe and UHECR propagation

\textit{K. Dolag, D. Grasso, V. Springel \\ & I. Tkachev}

\textit{J. Cosm. \\ & Astroph. Phys. 1:009, 2005}

- Seed field at high redshift
- \( |B| \) growth driven by LSS formation (gravity)
- MHD field amplification
- \( \approx 10^{-12} \) G (voids) – few \( \times 10^{-6} \) G (Clusters)

Fig. 14. — Full sky maps of expected deflection angles for protons with the arrival energy \( E \approx 4 \times 10^{19} \) eV. The upper panel is restricted to the 25 Mpc propagation distance, while in the lower panel the whole simulation volume within a radius of 110 Mpc around the position of the Galaxy was used.
SMOOTHED FARADAY ROTATION

Region containing the Perseus-Pisces supercluster

GALAXY COLUMN DENSITY
(Method #2: 2MASS survey, HEALPix algorithm)

galaxies per pixel ($\propto$ column density)

Optical galaxy counts vs. RM plots for the Perseus-Pisces supercluster chain
Two types of investigation


Galaxy column density vs RM from 7°-smoothed data
(used the 2MASS galaxy survey)

Weighted path length vs RM from 3-D Voronoi-tessilated IGM filament volumes (~3-D spectroscopic z’s known).
also from 7°-smoothed data
(Used the CfA2 galaxy survey)
2 methods of IGM $B$ analysis for the Perseus-Pisces supercluster

Results of RM + optical galaxy survey data (CfA2, 2MASS)


*For the Perseus-Pisces supercluster:*

HEALpix algorithm
Col. density 2MASS
Weighted path $l$. Voronoi diagrams. CfA2

2 independ. measures of pathlength through the intergalactic filament

Result: $<B>_{IGM} \approx 10^{-7} G$ within the Perseus-Pisces IGM `filament``
The *Xu et al. 2006* (RM)- (2MASS/CfA) results of $\sim 10^{-7}G$ are roughly consistent with:

1. Calculated, space –averaged, supermassive ($\gtrsim 10^7M_\odot$) BH magnetic energy ($B^2/8\pi \times Vol.$) output (shown above)

2. Models/Predictions of LSS filament fields amplified by LSS gravitational infall. 
   

   **Most recent:** *J. Cho & D.Ryu, ApJL, 705, 90, 2009 predict:*

$$\sigma_{RM} \sim 15 \left( \frac{n_e}{10^{-4} \text{ cm}^{-3}} \right) \left( \frac{\langle B \rangle}{3 \times 10^{-7} \text{ G}} \right) \left( \frac{l}{300 \text{kpc}} \right) \left( \frac{L}{5 \text{Mpc}} \right)^{0.5} \text{ rad m}^{-2}$$
A recent $B_{IG}$ probe, using synchrotron radiation

- Search for intergalactic, diffuse synchrotron radiation,

- Until recently, difficult to isolate from foreground Galactic diffuse emission

- New method combines world’s largest single dish (Arecibo) telescope with the precision imaging DRAO Interferometer.

- Searched in part of the Coma supercluster (100Mpc away), near the Galactic pole
0.4 GHz extragalactic diffuse synchrotron emission

P.P. Kronberg (LANL/Toronto), R. Kothes (DRAO), C.J. Salter, P. Perillat (Arecibo)
Arecibo 305m Telescope, PR

- 2 mm rms optics
- illuminated area ≈ 225m
- uv overlap with DRAO ≈ 200m
Dominion Radio Astrophysical Observatory
Penticton BC, Canada

7 x 9m dishes

Max. separation = 617m
Min. projected separation ≈ 18m

In 12 days, 1 full image within 9° circle at 408 MHz
8° dia. Field containing combined Arecibo + DRAO data, at a resolution of 2.5’ x 6.5’ 0.4 GHz

2.7K CMB background and galactic foregrounds (≈ 18K) are included
COMBINED Arecibo-DRAO image, smoothed to 10’ (Arecibo) resolution


Collective energization of several galactic central black holes? (Nos. 1 – 7)

REMOVED:
- Discrete sources
- CMB + linear plane Milky Way foreground

Strongest discrete sources re-overlaid as yellow ellipses
- Black contours at 1.4, 1.9, 2.4, 2.9, 3.4, 3.9, 4.4, 10, 40K
- $\sigma \approx 250\text{mK at 430 MHz}$

Region A (2 – 3 Mpc in extent) requires a distributed “fresh” energy source – plausibly provided by the ~ 7 embedded, radio galaxies.

RESULT:
$\langle |B| \rangle \approx 10^{-7}\text{G over 2 – 3 Mpc}$
Possible UHECR acceleration sites in jets and lobes

- Nearby candidate: Cen A
- Diagnosable “test” jet: 3C303 at $z = 0.14$
Jets as UHECR accelerators?

\[ E = \frac{B}{3 \text{ mG}} \times \frac{L}{1 \text{ kpc}} \Rightarrow 10^{19} \text{ eV} \]
Plasma parameters in the 3C303 jet

• Given $B$ and $n_{th}$ measured in the 3C303 jet, (and scaling to $T=10^8$K)

\[
\beta = \frac{n k T}{B^2/8\pi} \approx 10^{-5} T_8, \text{confirms very little thermal plasma}
\]

• $|B| \sim 3$ mG in the (synch. radiating) jet knots, over $\sim 1$ kpc

• Consistent with a magnetically confined, Poynting flux-dominated jet.
Hillas plot (*A.M. Hillas ARAA 1984*)
(adapted from *M Ostrowski* astro-ph/0101053)

Conditions required for acceleration to an energy **above** the required Line.

3C303’s knot parameters make them potential acceleration sites for CR nuclei up to ~ $10^{19-20}$ eV
Transverse RM gradient in the jet

- For knot “C”, the RM image of 3C303 enables a measurement of the transverse $\nabla RM$ (radians/m²/m) over a knot. i.e. $\nabla RM$ is perpendicular to the jet!

- $B$ (RM) reverses sign on the jet axis. $|B| \approx 3\text{mG}$ estimated from measured synchrotron emissivity ($\gtrsim 1\text{mG}$)

- a galaxy-scale, current-carrying “wire”

- result for 3C303: $I = 7.5 \times 10^{17} (B^{G}_{-3}) \ [r= 0.5\text{kpc}]$ ampères

- $I$ is directed AWAY from the galaxy AGN nucleus in this knot

- Intrinsic knot polarization consistent with low-$\phi$ jet helical field

Magnetism in the widespread IGM to the largest measurable redshifts

1. Optimally remove the galactic foreground $RM \rightarrow$ evaluate residual $RM$ ($RRM$)

2. Test for $\sigma^2(RRM)$ vs. $z$
**RM search at high z for a widespread $B_{\text{IGM}}$**

- Began in 1970's
  
  *M. Rees, M. Reinhardt, P. Kronberg
  M. Simard-Normandin, A. Nelson, J.P. Vallée*

- **Why was it of interest?**
  
  - Then $\Omega_B \approx 1$
    
    $\therefore n_e(z) \text{ is high enough to }$
    
    “illuminate” $B_{\text{IG}}$ to high $z$!
  
  - Now, $\Omega_B \approx 0.04$; too little to detect an $RM_{\text{IGM}}$

  BUT

  - High energy extragalactic events can probe/limit $|B|$ to
    
    $\sim 10$ orders of magnitude fainter.

---

**Fig. 1.** The calculated variation of $V(z)$ for models 1 (solid lines) and 2 (dashed line) over the redshift range $0 < z < 3.6$. The following values were assumed: $B_0 = 1.8 \times 10^{-8}$ Gauss, $\eta = 1$, $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $l_0 = 1 \text{ Mpc}$, and $f = 1/64$ for model 2. Model 1 is shown for $g_0 = -\Omega/2$ values of 0.5, 0.1 and 0.01.
Magnetic fields in cosmic voids? from where? how to detect them?

- Diffusion out of the walls and filaments? (galaxy-supplied)
- Relic of a pre-galactic, or primordial field?
- B measurements still mainly *Gedanken-Experimente*,
- Most involve high energy particle & photon propagation
- Time of arrival, deflection, energy and composition

At $E \gtrsim 10^{18}$ eV, all of ``empty” i.g. space becomes a (passive) particle physics laboratory!!
Energy cascade cartoon of a broadband $\gamma$-ray burst could probe a very weak IGM field

(Left) The received CR energy distribution on Earth for a monoenergetically injected proton energy of $10^{21.5}$ eV for a randomly orientated $B_{IG} = 10^{-9}$ G at progressively larger distances, up to 512 Mpc. The energy is reduced by the GZK effect (most severe), B-H pair production losses, and adiabatic losses.

(Right) The relative time delay for protons injected at the same distance when propagated through a randomly oriented magnetic field of $10^{-9}$ G, where $l_0 = 1$Mpc.
Discrete magnetized *intervenors* in the universe

Note: galaxy clusters barely count here!

→ $\rho(z) \cdot \sigma(z)$ is too small relative to that of galaxies
Detections of magnetized optical absorption line systems

G.L. Welter, J.J. Perry, & P.P. Kronberg
(119 RM sample, 40 had spectra with strong optical absorption lines)

P.P. Kronberg & J.J. Perry,
(37 RM + Abs. spectrum QSO’s)
Cumulative plots of RM for 3 different MgII absorption line groups


Observed RM increase through a population of intrinsically similar Faraday intervenors (galaxy systems) out to $z = 2.5$

\[
\sum (RM_i) \text{ for a population of discrete magnetized } L^* \text{ galaxy intervenors}
\]

RM$_0$ of a 37 rad m$^{-2}$ intrinsic Faraday rotation at $z_{qso}$ -- illustrates $(1 + z)^{-2}$ decrease of RM with $z$. 

M. L. Bernet and P. P. Kronberg
\( N(RRM, z) \) is a complex, multivariate distribution!

It contains:

- a strong \((1+z)^2\) factor \((0.06 \times RRM_0 \text{ at } z = 3!)\)
- varying fraction of real RRM< “outliers”
- RM outliers have different causes
- multiple populations of galaxy and halo intervenors
- galaxy groups and (fewer) galaxy clusters
- small subset of high intrinsic (& evolving?) RM’s
- Cross-section evolution
- etc.

Philipp Kronberg
Galaxy-corrected ``residual'' RM (RRM) for ~ 800 RM sources to z ≈ 3.4

Katherine Newton-McGee and Philipp Kronberg 2009

For a typical intervening ``galaxy system'' at z = 2.5; and adopting optical dN/dz statistics (N_e = ionized H column)

\[ \langle B_{||} \rangle \geq 5.5 \times 10^{-7} G \left( \frac{1 + z_C}{3.5} \right)^2 \times \left( \frac{\sigma_{RRM}}{20 \text{ rad m}^{-2}} \right) \times \left( \frac{N_e}{1.7 \times 10^{21} \text{ cm}^{-2}} \right) \]

1. smallest RRM bin declines with z, then reappears as z → 3
2. strongest RRM perturbations are at ≈ 20 – 100 rad m^{-2}

Principal new result: The Universe begins to get “Faraday RM – opaque” at ~1.4 GHz to sources beyond z ~ 2.5

Newton-McGee & Kronberg, 2009
Faraday rotations of extragalactic radio galaxies and quasars

Including the RM “outliers” --to be “filtered out” data:epoch ~1995
Bayesian smoothed RM’s in the Galactic caps $|b|>30^\circ$

M.B. Short, D.M. Higdon & P.P. Kronberg
*Bayesian Analysis 2*, 665, 2007

Better data and more refined analysis are underway