Radio Observations of Magnetic fields

in galaxy clusters

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Hot Gas ($10^7 - 10^8$ °K)

Optically-thin bremsstrahlung emission

Soft X

~15% of the Mass

Abell 1689

NASA/CXC/MIT/E.-H Peng et al.
Galaxy Clusters

**Hot Gas** ($10^7 - 10^8$ °K)

**Optically-thin Bremsstrahlung Emission**

**Soft X**

~15% of the Mass

**Dark Matter**

**Revealed by Gravitational Lensing**

~80% of the Mass

Galaxy Clusters

- **Hot Gas** ($10^7 - 10^8$ °K)
- **Optically-thin bremsstrahlung emission**
- **Soft X**
  - ~15% of the Mass
- **Dark Matter**
  - Revealed by gravitational lensing
  - ~80% of the Mass
- **Magnetic fields**
  - Revealed by radio emission

*MacS J0717+3745*

X and Optical: Ma et al. 2008
Radio Halos

Synchrotron emission on Mpc scale

- Low surface brightness
  - $\sim 1\, \mu$Jy/arcsec$^2$ at 1.4 GHz
- Steep spectrum ($\alpha > 1$)
- Usually un-polarized

Origin of the emitting particles?

- Particles generated or accelerated everywhere in the cluster
- Turbulence? (e.g. Petrosian 2001, Brunetti 2001)
- Secondary origin from p–p collisions? (e.g. Dennison 1980, Blasi & Colafrancesco 1999)
  - Difficult to reconcile with present radio and gamma observations
Polarized emission from Radio Halos

Only two clusters so far:

- **A2255**
  - $z = 0.08$
  - Govoni et al. 2005
    - See also Pizzo et al. 2010

![Radio Halos Image](image.png)

- VLA 1.4 GHz, Beam FWHM 25"
- Halo
- Relic
Only two clusters so far:

**A2255**

$z = 0.08$

Govoni et al. 2005

See also Pizzo et al. 2009

**MACS J0717 + 3745**

$z = 0.545$

Bonafede et al. 2009

See also van Weeren et al. 2009

Chandra $[0.1 - 2.4 \text{ keV}]$ ad VLA 1.4 GHz, Beam FWHM 25”
The magnetic field power spectrum: simple model: single power-law

\[ |B_k|^2 \propto k^{-n} \]

\( k \) (kpc\(^{-1}\))

Magnetic Field Scales (kpc)

\[ P_{200\text{kpc}} < 1\% \]

(at 1.4 GHz)
The magnetic field power spectrum: simple model: single power-law

\[ |B_k|^2 \propto k^{-n} \]

\[ P_{200\text{kpc}} \sim 3\% \]

(at 1.4 GHz)
The magnetic field power spectrum:
simple model: single power-law

\[ |B_k|^2 \propto k^{-n} \]

Magnetic Field Scales (kpc)

Murgia et al. 2004

P_{200kpc} \sim 7\%
(At 1.4 GHz)
**Polarized emission from Radio Halos**

\[ |B_k|^2 \propto k^{-n} \]

**A2255**

Govoni et al. 2006

- Power spectrum spectral index:
  - \( n = 2 \) at the cluster center
  - \( n = 4 \) at the cluster periphery

**MACS J0717 + 3745**

Bonafede et al. 2009

- Power spectrum spectral index:
  - \( n > 3 \)
Polarized emission from radio halos

1.4 GHz
15 arcsec resolution for a cluster at z~0.2

Total intensity
Polarized intensity

Intrinsic

Noise added
Noise rms ~ 25 μJy/beam

Vacca et al. 2010
LOFAR: POLARIZED EMISSION FROM RADIO HALOS?

Frequency = 240 MHz  Beam = 3.1''  Sensitivity = 0.076 mJy/beam
Frequency = 15 MHz  Beam = 50''  Sensitivity = 11 mJy/beam

Chance of detecting polarization at level of few % at least at the higher frequencies
Radio Halos: Importance of Low Frequency Observations

LOFAR Abell 2256 (150 MHz)  
VLA Abell 2256 (1.4 GHz)

van Weeren, Shulevski, van der Tol, Pizzo, Orrù, Bonafede, Ferrari, Macario  
and the survey key project team

Clarke & Ensslin 2004

LOFAR \rightarrow \text{spectrum over a wide frequency range -- radio halo statistics}  
\text{test of the formation scenarios}
**Radio Relics:**

Synchrotron emission on Mpc scale in the cluster outskirts

- Low surface brightness $\sim 1\ \mu$Jy/arcsec$^2$ at 1.4 GHz
- Steep radio spectrum ($\alpha > 1$)
- Polarized $\sim 20\%$ at 1.4 GHz

**Origin of the emission?**

different models, they all require shock waves

Bonafede et al. 2009
Radio Relics

- **Radio ghost**: aged radio plasma revived by merger or shock wave through adiabatic compression (Ensslin & Gopal Krishna 2001)

- **“Radio gischt”:**
  Diffusive Shock Acceleration energize cosmic ray electrons that emit synchrotron in magnetic field amplified by shock (Ensslin et al. 98)

- **Curved radio spectrum**
- **Filamentary or toroidal morphology**
- **Polarization vectors perpendicular to the filamentary structure**

- **Straight radio spectrum**
- **Arc-like**
- **Polarization vectors perpendicular to the relic main axis**

1 Definition by Kempner et al. (2004)
Cluster with double Radio Relics

A2345

z=0.177
Bonafede et al. 2009

VLA at 1.4 GHz, Beam FWHM = 50"

ROSAT PSPC 0.1 - 2 keV band
Cluster with double Radio Relics

A2345

z = 0.177
Bonafede et al. 2009

Polarized emission at 1.4 GHz, Beam FWHM = 23"

Mean fractional polarization 24%

Arc-like structure of the relic

“Radio gischt” prediction

Magnetic field aligned with the relic main axis
Cluster with double Radio Relics

A2345

$z = 0.177$

Bonafede et al. 2009

Polarized emission at 1.4 GHz, Beam FWHM = 23''

Mean fractional polarization 24%

Mean fractional polarization 20%
Magnetic fields from Faraday RM

**Coma**

$z=0.023$

Bonafede et al. 2010

7 sources observed at 4-5 freq. (from 1.4 to 8.9 GHz)

Resolution = 0.7 kpc
Modeling the magnetic field power spectrum

- The vector potential $A(k)$ with a given power spectrum
  \[ |A_k|^2 \propto k^{-5} \]
  Fourier components $A(k)$
  Rayleigh distribution
  phases random

- The magnetic field $B_k = ik \times \tilde{A}_k$
  FFT $\rightarrow B_z$ in the real space
  \[ \nabla \cdot \vec{B} = 0 \]
  Power spectrum degeneracy (higher $n$, lower $k_{\text{min}}$)

Schuecker et al. 04
from pseudo-pressure map
Kolmogorov power spectrum $n=11/3$
The magnetic field power spectrum

Simulated and observed RM structure function and auto-correlation function

\[ |B_k|^2 \propto k^{-n} \]

\[ n=11/3 \quad \Lambda_{\text{min}}=2 \text{ kpc}, \quad \Lambda_{\text{max}}=34 \text{ kpc} \]

\[ A(\Delta r) \text{ [rad/m]} \]

\[ n=11/3 \quad \Lambda_{\text{min}}=2 \text{ kpc}, \quad \Lambda_{\text{max}}=34 \text{ kpc} \]
Magnetic fields Power spectrum from Faraday RM

**Coma**
Bonafede et al. 2010

\[ n = \frac{11}{3} \text{ Kolmogorov PS} \]
Scales up to 30 kpc

**A2255**
Govoni et al. 2006

\[ n = 2 \text{ (center)} \quad 4 \text{ (periphery)} \]
Scales up to 100s kpc

**A2382**
Guidetti et al. 2008

\[ n = \frac{11}{3} \text{ Kolmogorov PS} \]
Scales up to 35 kpc

**Other works based on different approaches**

**Hydra A**
Kuchar & Ensslin 2009

Consistent with Kolmogorov PS
Single Power law from 0.3 - 8 kpc with no turnover on the large scales

**A400 A2634**
Vogt & Ensslin 2003

Consistent with Kolmogorov PS
Magnetic fields from Faraday RM

RM observations – 3D magnetic field numerical simulations (Faraday code, Murgia et al. 2004)

\[
< B > (r) = B_0 \left( \frac{n_e}{n_0} \right)^\eta
\]

\(X^2\) plane

- Best model: \(B_0=4.7 \mu G, \eta=0.5\)

Coma cluster
Bonafede et al. 2010
Magnetic fields from Faraday RM

RM observations - 3D magnetic field numerical simulations (Faraday code, Murgia et al. 2004)

\[
< B > (r) = B_0 \left( \frac{n_e}{n_0} \right)^\eta
\]

Inside 68% confidence level
\[ \eta = 0.67 \]
Magnetic field frozen into the gas

\[ B_0 > 7 \ \mu G \text{ or } < 3 \mu G \]
\[ \eta > 1 \text{ or } < 0.2 \]
excluded at 99% confidence level

Coma cluster
Bonafede et al. 2010
Magnetic fields from Faraday RM

RM observations – Main limitation: number of EXTENDED sources

**Coma**  
Bonafede et al. 2010

**A2255**  
Govoni et al. 2006
32 clusters
The most luminous from HIFLUGCS catalog
NVSS data

Cluster center
→ higher B and gas density
→ higher RM
→ lower fractional polarization

Bonafede et al. in prep
Magnetic field from Depolarization of radio sources

Radio-halo sub-sample

K S test: P = 0.9

Magnetic field is ubiquitous in galaxy clusters

→ No significant difference from this analysis for clusters with and without radio halo

Bonafede et al. in prep
CONCLUSIONS

Magnetic field in galaxy clusters are revealed by radio emission
Polarization maps + Faraday Rotation allow a reconstruction of the 3D magnetic field

Magnetic field is ubiquitous in galaxy clusters

farthest detection: z=0.55 (Bonafede et al 2009, van Weeren et al. 2009)

Magnetic field strength: 2–5 µG in non cool-core clusters (central regions)

Profile: \( B \sim n_e^\eta \quad \eta \sim 0.5 \) Coma cluster (Bonafede et al. 2010)

Power spectrum: general agreement with Kolmogorov power-law, scales going to few to 10s 100s kpc

In the next Future:
Possibility of studying polarized emission from radio halos (EVLA and possibly LOFAR)

Magnetic field in low density environments will be revealed by LOFAR HB observations