Diffuse Radio Emission from Galaxy Clusters

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Clusters of galaxies

Largest gravitationally bound objects in the Universe

\[ 10^{13} - 10^{15} \text{ solar masses (} M_{\odot} \text{)} \]

0.5 – 3 million parsecs

~ 1% galaxies
~ 10% intracluster medium gas
~ 90% dark matter

Abell 2218
NASA, A. Fruchter & ERO Team
Clusters in cosmological context

Clusters form through merging and accretion of smaller objects

Filament-void network: matter collects in filaments, then flows toward intersections

Rich clusters lie at the intersections
Observing clusters

Optical/Infrared

- Galaxies
- Intracluster stars
- Dark matter via gravitational lensing

X-Ray

- Thermal hot gas

Radio

- Nonthermal particles
  - Thermal hot gas via Sunyaev-Zel'dovich effect (microwave)
Mpc-scale diffuse radio emission

**Radio halos**
- Round
- Unpolarized
- Covers most of cluster

**Radio relics**
- Elongated
- Polarized
- Outskirts only

**Radio minihalos**
- Round
- Polarized
- Centers of cool-core clusters
Relics – examples

CIZAJ2242.8+5301 ("Sausage")

1RXS 0603.3+4214 ("Toothbrush")

XMM X-ray (blue) + 610 MHz GMRT (red)
(Ogrean et al. 2012)

XMM X-ray image (Ogrean et al. 2013)
1.4 GHz radio contours (van Weeren et al.)
Halos – examples

Abell 2219

Abell 2744

Feretti et al. (2012)
Detections of radio halos

Earliest

- Coma C source detected by Large et al. (1959), identified as diffuse by Willson (1970)
- By 1982 only ~ 4 – 5 radio halos known (Hanisch 1982)
- Coma, A2255, A2256, A2319; Perseus (minihalo)

Recent searches

- NVSS – 13 out of 205 XBACS clusters (Giovannini et al. 1999)
- WENSS – 18 of 1001 ACO clusters (Kempner & Sarazin 2001)
- GMRT – 10 of 50 REFLEX+eBCS clusters (Venturi et al. 2007, 2008)
- Extended GMRT survey: additional 12 clusters w/ no new halo detections (Kale et al. 2013)

~42 clusters with halos known to date
Common features of radio halos

Radio power

- \[ P_{1.4 \, \text{GHz}} \sim 10^{23-26} \, \text{W Hz}^{-1} \]

Spectrum

- \[ P_{\nu} \propto \nu^{-\alpha}, \quad \alpha = 1.2 - 2 \]
- “Normal” and “ultra steep spectrum”

Morphology

- All show distorted X-ray morphology
- No “cool-core” clusters host full-size radio halos

Venturi (2011)
Likelihood of hosting a halo

- ~ 5% of all clusters
- ~ 35% of clusters with $L_X > 10^{45}$ erg s\(^{-1}\) ($M \sim 10^{15} M_\odot$)

Inference: separate “on” and “off” states

Cassano et al. (2008)
For clusters hosting radio halos, 1.4 GHz radio power correlates with (Liang et al. 2000; Feretti 2000)

- X-ray luminosity
- X-ray temperature
- Isophotal size

Kale et al. (2013)
Spatial correlations with X-rays

Some halos show spatial correlations with X-ray surface brightness and temperature ...

... but not all!

Govoni et al. (2004)
Radio spectral index and X-ray emission

**Abell 2744** (Orru et al. 2007)

**VLA (325 MHz – 1.4 GHz)**

**Chandra X-ray**
Radio spectral index and X-ray temperature

Abell 2744 (Orru et al. 2007)
Why do clusters have radio halos?

Mergers clearly matter

- All radio halos are in morphologically distorted clusters
- Radio power increases with amount of distortion
- Clusters are brighter and hotter in X-rays during mergers, and brighter in radio

Mass also matters

- Only the most massive clusters host halos, and only 1/3 of them

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Production of relativistic electrons

**Primary electrons** (Jaffe 1977)
- From intracluster medium or radio galaxies
- Require reacceleration to explain diffuse halos of size $\sim 1$ Mpc

**Hadronic secondaries** (Dennison 1980)
- From interactions of cosmic-ray protons with thermal protons:
  $$p + p \rightarrow p + p + \begin{cases} \pi^\pm \rightarrow e^\pm + \nu \\ \pi^0 \rightarrow \gamma \end{cases}$$
- Do not require reacceleration; relativistic protons last (practically) forever
- Problem: $\gamma$-rays not seen by *Fermi* (Jeltema & Profumo 2011)
(Re-)acceleration mechanisms

First-order Fermi acceleration
- Origin: merger shocks
- Problem: should trace shocks
- Problem: Mach #s too low

Second-order Fermi acceleration
- Origin: merger-induced turbulence
- Needs efficient cascade to resonance scale – fast magnetosonic waves?

Maybe both operate
- Halos: turbulence
- Relics: shocks

\[
\frac{\Delta E}{E} \sim \frac{\nu}{c}
\]

\[
\frac{\Delta E}{E} \sim \left(\frac{\nu}{c}\right)^2
\]
Donnert et al. (2013) – MHD simulation of head-on merger shows transition from “off” to “on” state and back

Mergers can turn on halos
Intermission
What can we learn from radio halo statistics?

- Magnetic field scaling with cluster mass
- Cluster merger rate as a function of redshift
- Relative contributions of hadronic and turbulent sources
- Cosmological parameters?
Observations

- Power-law radio halo luminosity function (RHLF) sensitive to sample completeness

- “On” and “off” states

- Spectral index $\sim 1.2 – 1.3$ at 1.4 GHz, possibly steeper at lower frequencies

Zandanel et al. (2013)
Theoretical expectations for the RHLF

- Purely from observed scalings
  - Enßlin & Röttgering (2002)
    - Press-Schechter mass function \( \times \)
    - \( L_X - M \times P_{1.4} - L_X \times 0.3 \)

- Turbulent reacceleration
  - Cassano et al. (2006, 2012)
    - PS \( \times \) B(M) scaling \( \times \) acceleration efficiency \( \times \) spectral cutoff
    - Merger tree + Fokker-Planck model of turbulence decay

- Hadronic secondaries
  - Zandanel et al. (2013)
    - (N-body halos + gas model) \( \times \)
    - B(M) scaling \( \times \) (turbulent advection, streaming)

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  Press-Schechter mass function $\propto L_x - M \propto P_{1.4} - L_x \propto 0.3$

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FLASH 3.3 simulation (Sutter & Ricker 2012)

- $\Lambda$CDM
  - $\Omega_m = 0.262$, $\Omega_b = 0.0437$
  - $h = 0.719$, $\sigma_8 = 0.74$
- DM + preheated hydro
- Volume 1024 $h^{-1}$ Mpc
- Particles $6.7 \times 10^{10} \ h^{-1} \ M_\odot$
- AMR within 100 regions to $\Delta x = 32 \ h^{-1} \ \text{kpc}$
- Jaguar (ORNL), 16K cores, 450K hours
Cluster samples

- High-resolution (131) clusters found in the 100 refined regions
- Low-resolution (3900) clusters outside refined regions; assign radio power using mean scalings from high-resolution sample
Modeling radio halo emission

- Allow for dependence of radio power on mass $M_{\text{vir}}$ and turbulent pressure $\Gamma_{\text{vir}}$

\[ P_{1.4 \ \text{GHz}} = C_s B_S(M_{\text{vir}}) M_{\text{vir}}^{a} \Gamma_{\text{vir}}^{c} \]

\[ \Gamma_{\text{vir}} \equiv \sum_{\text{cells}} \rho \Delta x^3 \mid \mathbf{v} - \bar{\mathbf{v}}_{300 \ \text{kpc}} \mid^2 \]

- Magnetic field dependence on mass

\[ B_S(M_{\text{vir}}) = \frac{B(M_{\text{vir}})^2}{(B(M_{\text{vir}})^2 + B_{\text{CMB}}^2)^2} \ , \ B(M_{\text{vir}}) \equiv \langle B \rangle (M_{\text{vir}}/\langle M \rangle)^b \]

- Calibration using observed X-ray/radio correlation and X-ray luminosity/mass correlation for most massive cluster

- Two states assuming fixed radio halo probability of 5%
Parameter constraints

\( \langle B \rangle \) limits

Upper: 6.0 \( \mu \)G from Faraday rotation measurements

Lower: 0.2 \( \mu \)G from limits on hard X-rays

Limits on scaling exponents

Compare fit to our \( P^{1.4} - M \) relation to observed one

\[ \langle B \rangle = 2 \, \mu \text{G}, \ a = 0, \ b = 1, \ c = 0.7 \]
Parameter constraints from observed $P-M$ relation

- Large $\langle B \rangle$ requires steep emissivity dependence on $M_{\text{vir}}$ and $\Gamma_{\text{vir}}$

- Steep $B(M_{\text{vir}})$ essentially requires emissivity depend only on mass, or else high $\langle B \rangle$

Max allowed $a+c$

Dolag et al. (2002)
Scaling of turbulent energy with mass

- Scaling of mean turbulence-mass relation comparable to Vazza et al. (2006) result
- Large scatter due to mergers
Radio halo luminosity function at $z = 0$

Solid: 1.4 GHz
Dashed: 150 MHz
(assuming spectral slope -1.2)

Missing ~ 12 high-luminosity clusters because of limited volume
Sky maps

- Light cones with replicated box using simulated observations of individual clusters
- Pixel size 2'
- 200 MHz
- FITS

http://sipapu.astro.illinois.edu/foswiki/bin/view/Main/RadioHaloMaps
Conclusions

- Parameters allowed by observed $P-M$ relation
  
  Large $\langle B \rangle$ requires steep emissivity dependence on $M_{\text{vir}}$ and $\Gamma_{\text{vir}}$

  Steep $B(M_{\text{vir}})$ requires weak turbulence dependence or large $\langle B \rangle$

- Wide range of RHLFs allowed at present

  Need better constraints on $P-M$ relation

  Shape of RHLF at low luminosities and frequencies is an important discriminator between models

  Need better understanding of survey completeness

- Next steps for our simulations

  Larger/more boxes – RHs are rare!

  MHD, physical cosmic ray injection and transport