Radio emission in clusters of galaxies

An observational perspective

Tiziana Venturi
INAF, IRA, Bologna

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Overview

- What are galaxy clusters
- Radio emission from elliptical galaxies
- Interaction between cluster radio galaxies and external medium
  morphologies and statistical properties
  central radio galaxies
  restarted and dying radio sources

- Diffuse cluster scale radio emission
  morphologies and observational properties of halos and relics
  statistical properties of radio halos
What are galaxy clusters

Largest gravitationally bound systems in the Universe

Galaxy cluster constituents

Galaxies: ~5%
\((\sim 10^{13} - 10^{15} \, M_{\text{Sun}})\)

Dense and hot gas: ~ 15%
\(\rho_0 \sim 10^{-3} \, \text{part/cm}^3\)
\(T \sim 5 - 8 \times 10^7 \, K\)
\(L_x \sim 10^{44} - 10^{45} \, \text{erg/s}\)
\(M_{\text{gas}} \sim 10^{14} - 10^{15} \, M_{\text{Sun}}\)

Dark matter ~80%

Non-thermal radio emission

- radio galaxies
- diffuse cluster sources
Radio emission from elliptical galaxies

Active Galactic Nuclei

**FRI:** $\log P_{1.4\text{GHz}} \leq 24.5 \text{ W/Hz}$

Central core coincident with optical nucleus

Visible straight symmetric jets, which lose collimation and expand to form the lobes

**FRII:** $\log P_{1.4\text{GHz}} \geq 24.5 \text{ W/Hz}$

Central core coincident with optical nucleus

Straight asymmetric jets which culminate in compact high surface brightness regions (hot spots) and extended backflow lobes
Radio Galaxies and Cluster Environment

- Morphology
- Statistical properties
- Confinement of extended emission and steep spectrum sources
- AGN – ICM feedback in the central cluster regions and restarted radio galaxies
Morphologies of radio galaxies in clusters. I.
Morphologies of radio galaxies in clusters. II.

Deviation from jet straightness

**Wide Angle Tail sources**
- Associated with BCG
- Radio power close to the FRI/FRII divide
- Slow galaxy motion + “cluster weather”

**Narrow Angle Tail sources**
- Associated with less massive galaxies
- FRI radio powers
- Optical counterparts with high dispersion velocities
Statistical properties of radio galaxies

Cluster environment:
High galaxy density in clusters compared to the field
galaxy-galaxy interaction
Large scale interaction (cluster merger)

Does this affect the AGN radio luminosity
function in ellipticals?

Auriemma et al. 1977
Ledlow & Owen 1996
Radio galaxies at the cluster centres

A large fraction of brightest cluster members (BCG) is radio loud (~60%) – Their radio morphology can be broadly divided into two classes:

- **WATs and extended**
  - Both in cooling and non-cooling clusters

- **Core-Halo radio galaxies**
  - Only in cooling clusters
Radio emission and ICM at the cluster centres know of each other

Image from Sarazin et al. 2006
Cycles of AGN radio activity

The detection of cavities in the ICM of a number of clusters by Chandra, and the following finding that some of these cavities are filled with old (steep spectrum) radio plasma, has triggered the study of a possible connection between cycles of radio activity in the cluster BCG and substructure in the ICM.

3C338 in A2199

Multiple BCG

VLBI

Giovannini et al. 1998
3C317 in A2052

Steep spectrum dominated by the diffuse emission

VLBI Active nucleus

Venturi et al. 2004
Galaxy cluster environment and late stages in the life of radio galaxies

When the activity in the nucleus stops or decreases to such a low level that the plasma outflow can no longer be sustained, the radio source is expected to undergo a period of fading (the dying phase) before disappearing completely.
In the dying phase, the radio core, the jets and the hot spots quickly fade away. On the other hand, the radio lobes may remain detectable for a long time if they are subject only to radiative losses.

Only few sources in the dying phase are known so far
Steep spectrum: best detected at low frequencies
It has long been known that the radio spectra of radio galaxies in the central regions of galaxy clusters are on average steeper than those in other environments (i.e. Roland 1985; Slee et al. 2001). This has always been interpreted in terms of confinement of the external gas, which prevents adiabatic expansion of the radio lobes and aging of their synchrotron spectrum.

Galaxy clusters seem an appropriate place to search for radio galaxies in the final stages of their evolution.

It is expected that dense gas is surrounding dying radio galaxies.
A recent study of the radio properties of cD galaxies in a sample of poor clusters led to the unexpected finding of a number of radio galaxies in their final evolutionary stage (Giacintucci et al. 2007)
A study of the environment around dying radio galaxies selected from the WENSS shows that they are all located in high gas density regions (Parma et al. 2007; Murgia et al. 2008)
Diffuse cluster sources

Radio halos and relics

Very large radio sources, not associated with individual galaxies, not a blend of radio sources either, but rather “connected” with the intracluster gas
Cluster radio halos

Very extended radio sources (up and beyond Mpc size)
Low surface brightness
Located at the centres of a fraction of rich clusters
Synchrotron steep radio spectrum: $\alpha \sim 1.2 - 1.4$
“Regular” morphology, similar to the X-ray brightness
Unpolarized, except A2255 (Govoni et al. 2005)

Coma C

Thierbach et al. 2003

Govoni et al. 2004
Cluster relics

Large linear size (Mpc)
Low surface brightness
Steep synchrotron spectrum: $\alpha \approx 1.2 - 1.4$
Range of morphologies (elongated, arcs, toroids)
Located in peripheral cluster regions
Highly polarized (up and beyond 30%)
Double relics in 5 clusters

Giacintucci et al. 2008
Mini-halos

Extended (few hundred kpc) emission at the centres of cool core clusters, surrounding the BCG, which is radio loud

Perseus, prototypical mini halo
Radio halos and relics probe the existence of magnetic fields and relativistic particles spread over volumes as large as the extent of galaxy clusters.

Magnetic field strengths of the order of the $\mu$G from equipartition arguments.

Clarke et al. (2004)

Giant halo

Relic

Polarised 20-40% ordered B on large scale
And large regions with uniform B

Magnetic fields exist in all galaxy clusters – RM in radio galaxies
Problem of the origin of halos and relics

Their Mpc size imply that \( t_{\text{diff}} \gg t_{\text{synchr}} \). Some form of re-acceleration is needed.

Primary electron models: in situ reacceleration, first proposed by Jaffe (1977)

Secondary electron models: in situ production of relativistic electrons via proton-proton collisions, first proposed by Dennison (1980)

Next presentation by Brunetti
~25 radio halos and ~20 relics known to date

Candidates from the NVSS (VLA-D, 1.4 GHz) (Giovannini, Feretti, Tordi, 1999) and pointed follow up studies (Govoni et al. 2001, 2004, ...; Bacchi et al. 2003)

Studies of individual objects

Candidates from WENSS (WSRT, 327 MHz) (Kempner & Sarazin, 2001)

GMRT Radio Halo Survey (GMRT, 610 MHz) (Venturi et al. 2007 & 2008)

Radio halos are found in ~ 5% to ~ 30% of galaxy clusters, depending on the X-ray luminosity
Radio halos are more frequently found in clusters with high X-ray luminosity (i.e. more massive)

More massive clusters host larger radio halos

The radio power of radio halos correlates with the cluster X-ray luminosity
More on radio halos and cluster X-ray properties 

(0 < z < 0.4)

Bimodal distribution of clusters with and without radio halos

Fraction of clusters with radio halos as function of cluster mass


Cassano et al., 2008, A&A, 480, 327
Radio halos relics and major cluster mergers

Relaxed clusters: never host diffuse cluster galaxies
Merging clusters: sometimes do, sometimes don’t

Cluster dynamical state and presence of halos and relics, or lack thereof

Venturi et al., 2007 & 2008
Classical and ultra steep radio halos

235 MHz - GMRT - 610 MHz

VLA 1.4 GHz

Brunetti et al. 2008

Expected in the re-acceleration model: less energetic merger events

RXCJ2003.5-2323

1.4 GHZ VLA overlaid on 610 MHz GMRT

Giacintucci et al. To be submitted

240 MHz - GMRT

Expected in the re-acceleration model: less energetic merger events
Cluster relics: connection with merger shocks?

A521

Electron acceleration by a shock with Mach number ~ 2.2

Giacintucci et al. 2008

Relic in the Coma cluster

No indication of shock at the relic location

Feretti et al. 2005
The radio emission in galaxy clusters takes a variety of forms, which can be broadly divided into two main flavours:

1) Radio emission associated with individual galaxies
2) Diffuse extended emission on the cluster scale, in the form of halos and relics

1) The interaction between the intergalactic medium and the cluster radio galaxies allows us to study the late stages in the radio galaxy evolution and the cycles of activity in AGNs
2) Halos and relics witness the existence of magnetic fields and relativistic particles over cluster scale volumes. The origin of such sources may be related to the formation of clusters (and large scale structures) in the Universe