Do radio mini-halos and AGN heating in cool-core clusters have a common origin?

Myriam Gitti

DIFA – University of Bologna
INAF – ORA Bologna
Cooling Flow (CF) – standard model

- **cooling time** $t_{\text{cool}}$: characteristic time of energy radiated in X-rays $\approx T^{1/2} / n_e$
- **cooling radius** $r_{\text{cool}}$: radius at which $t_{\text{cool}} = \text{age of the cluster} \sim t_H$
- **cooling region**: within $r_{\text{cool}}$: $t_{\text{cool}} \ll t_H$

Hydrostatic eq. 

- Cooling gas flows inward with mass accretion rate $\dot{M}$ and compressed
- Compression $\Rightarrow$ density increases $\Rightarrow$ **X-ray emissivity** ($\propto n^2 \Lambda$) increases!

(Fabian 1994)
Cooling Flow Problem

BUT.. observed lack of cold gas!

XMM/RGS failed to show strong emission lines expected from Fe XVII as the gas cooled below 0.7 keV

T gas drops only to $T_{\text{min}} \sim 0.3 \, T_{\text{vir}}$ (Chandra spectra consistent)

$\dot{M}_{(<T_{\text{min}})} \sim (0.1-0.2) \, \dot{M}_X$

⇒ CF problem: why, and how, is the cooling of gas below $T_{\text{min}}$ suppressed?

[ new nomenclature $\Rightarrow$ COOL CORE (CC) ]

(Peterson et al. 2001)
Radio-AGN / ICM interaction in cool cores

- in most (~70%) CC clusters the brightest cluster galaxy (BCG) is radio loud
- in most (~70%) CC clusters the central intra-cluster medium (ICM) shows “holes” often coincident with BCG radio lobes

→ radio “bubbles” displace the ICM, creating X-ray “cavities”
(e.g., reviews by McNamara & Nulsen 2007, 2012; Gitti, et al. 2012; Fabian 2012)
Cooling flow regulation in galaxy clusters

Main candidate to solve the CF Problem: **Feedback by AGN**

“The AGN is fueled by a CF that is itself regulated by feedback from the AGN”

**Self-regulated feedback loop**: (recurrent) outbursts from the radio-loud AGN hosted by the BCG at the center of (almost) every CC cluster

\[
\begin{align*}
E &\sim 10^{62} \text{ erg} \\
\text{Age} &= 10^8 \text{ yr} \\
P_{\text{jet}} &= 3 \times 10^{46} \text{ erg s}^{-1} (\sim 100 \times L_\odot)
\end{align*}
\]
Non-thermal emission from CC clusters: (not only) radio-loud AGN

Radio-mode AGN feedback:

- massive subrelativistic bipolar outflows emerging from the BCG core, that
  - inflate large radio bubbles while carving X-ray cavities and driving weak shocks
  - heat the ICM
  - induce a circulation of gas and metals on scales of \( \approx 100 \text{ s kpc} \)

\[ \text{..but many details are still unclear..} \]
Non-thermal emission from CC clusters: 
(not only) radio-loud AGN

RBS 797 (Gitti et al. 2013) 
*Chandra* X-ray 
VLA 4.8 GHz (black)

Radio-mode AGN feedback: 
mechanically-powered AGN 
are also likely to drive 
**turbulence** in the ICM 
which may contribute to heat it

\begin{align*}
Q_{\text{heat}} &= (Zhuravleva et al. 2014, Nature) \\
Q_{\text{cool}} &= \text{(Perseus cluster)} \quad \text{(Virgo cluster)}
\end{align*}
Non-thermal emission from CC clusters: radio-loud AGN + diffuse mini-halos

Radio mini-halos (MH):
- diffuse, faint, amorphous (roundish) in shape
- synchrotron radio emission surrounding
  - the radio-loud BCG in a number of CC clusters

RBS 797 (Gitti et al. 2012, 2013)
- Chandra X-ray
- VLA 4.8 GHz (black)
- VLA 1.4 GHz (green)
Non-thermal emission from CC clusters:
radio-loud AGN + diffuse mini-halos

Radio mini-halos (MH):
- diffuse, faint, amorphous (roundish) in shape,
- synchrotron radio emission surrounding the radio-loud BCG in a number of CC clusters
- not directly powered by the central AGN, but truly generated from the ICM

MH size ~ 100÷500 kpc
≈ cooling region

RBS 797 (Gitti et al. 2012, 2013)
Chandra X-ray
VLÀ 4.8 GHz (black)
VLÀ 1.4 GHz (green)

Origin of radio mini-halos

Diffusion time $\gg$ Radiative lifetime $\approx 10^8$ yr

MH size $\sim 100s$ kpc
$\approx$ CC region

MHs resemble small-scale versions of giant halos
(see Cassano’s talk)

..but MHs always found in CCs
$\rightarrow$ mergers do not play a major role
**Origin of radio mini-halos**

Diffusion time $\gg$ Radiative lifetime $\rightarrow$ Slow diffusion problem

- **Leptonic models**: Rel. electrons injected by radio BCG are re-accelerated by turbulence in CC region
  
  (Gitti et al. 02, 04, 07; Cassano & Gitti 08; Mazzotta & Giacintucci 08; ZuHone et al. 13)

  and/or (e.g., Brunetti & Jones 2014)

- **Hadronic models**: Secondary electrons generated by p-p collisions in cluster vol.
  
  (Pfrommer & Enßlin 04, Zandanel et al. 13)
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$(\gg 10^9 \text{ yr})$ $(\approx 10^8 \text{ yr})$

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Gitti, Brunetti & Setti (2002) model
$\rightarrow$ CF process powers MHs:

re-acceleration by Fermi II mechanisms associated with MHD turbulence amplified by (frozen-in) magnetic field compression in the CC region

Trend $P_{\text{MH}} - P_{\text{CF}}$ (Gitti et al. 04, 12): connection thermal CCs and non-thermal MHs?

Origin of radio mini-halos

Diffusion time \( \gg \) Radiative lifetime \( \Rightarrow \) Slow diffusion problem
(\( \gg 10^9 \) yr) \( \approx 10^8 \) yr

Gitti, Brunetti & Setti (2002) models:
\( \rightarrow \) CF process

\( \xrightarrow{\text{re-acceleration by magnetic fields}} \)
MHD turbulence
(frozen-in) magnetic field compression

C A V E A T S :
- previous observational studies based on small \( (\approx 5-10 \) MHs), heterogeneous samples
- origin of turbulence, and its connection with CC thermodynamical properties, still unclear

Trend \( P_{\text{MH}} \) vs. \( P_{\text{CF}} \) (Gitti et al. 04, 12):
connection thermal CCs and non-thermal MHs?

(Old student)
A new study of the largest MH sample

We exploit the increased MH statistics \((\text{Giacintucci et al. 2014, van Weeren et al. 2014})\)

Homogeneous analysis of X-ray \textit{Chandra} data of the largest existing sample (~20 objects) of MH cluster candidates

\rightarrow \textbf{Correlation } P_{\text{MH}} - P_{\text{CF}} : connection between thermal CCs and non-thermal MHs

\(\text{(Bravi, Gitti, Brunetti 2015, MNRAS Letter, in press)} \rightarrow \text{see poster by L. Bravi} !!\)
Proposed scenario: turbulence is responsible for both MH origin and CF quenching

• We argue that particle acceleration and gas heating in CCs are due to the dissipation of the same turbulence with power $P_t \gtrsim P_{CF}$

• $P_{CF} \approx$ upper limit to non-thermal luminosity $L_{NT}$ in the MH region:

\[
L_{NT} = L_{Syn} + L_{IC} = L_{Syn} \left[ 1 + \left( \frac{B_{CMB}}{B} \right)^2 \right] \sim 3.2 \mu G
\]

(Bravi, Gitti, Brunetti 2015, MNRAS Letter, in press) → see poster by L. Bravi !!
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$(Bravi, Gitti, Brunetti 2015, MNRAS Letter, in press) \rightarrow$ see poster by L. Bravi!!
Statistics of radio mini-halos

Current sample of confirmed MHs:
16 objects (all at $z < 0.6$)

Observational bias limits our present ability of detecting mini-halos complicated by the need of separating their low surface brightness emission ($\sim \mu$Jy/"") from the bright BCG

→ this requires:
- very good sensitivity to diffuse emission
- high dynamic range
- good spatial resolution

→ SKA
Statistics of radio mini-halos

All known MHs are hosted in clusters with central entropy
\[ K_0 = kT_0 n_0^{-2/3} \leq 25 \text{ keV cm}^2 \rightarrow \text{strong cool cores (SCC)} \]
(Giacintucci et al., in prep.)

Cluster statistics in terms of X-ray properties, available from Chandra and XMM studies, can be exploited to forecast future detections of radio mini-halos, provided an intrinsic relation between the thermal and non-thermal cluster properties exists.
1.4 GHz radio power vs. the CC-excised X-ray bolometric luminosity for the observed MH cluster sample (\(L_{X,bol}\) from the Chandra ACCEPT sample, Cavagnolo et al. 2009)

\[
P_{MH, 1.4} \propto L_X^{1.72}
\]

Our basic assumption: all SCC clusters host a radio MH that follows the \(P_{1.4} - L_X\) correlation
SCC clusters in the Chandra ACCEPT sample

→ candidates to host MHs

(Gitti et al. 2015, AASKA)
SCC clusters in the *Chandra* ACCEPT sample

→ candidates to host MHs

*Indicative* current MH detection limit on the population of SCC clusters

(estimated assuming non-detections by current follow-up observations)

\[
\text{rms} = 25 \ \mu\text{Jy}/\text{bm} \\
\theta_b = 10''
\]

→ at present we are seeing only the *tip of the iceberg* of the SCC cluster population
SCC clusters in the *Chandra* ACCEPT sample
→ candidates to host MHs

**Observed MHs**

SKA All Sky Surveys at Band 2:

- **SKA `early’**
  - (4 μJy rms, 2” res. tapered up to 8”)
  - will follow-up > 70% of the ACCEPT sample

- **SKA1 (2 μJy rms)**
  - will detect all MHs above ~ $10^{23}$ W Hz$^{-1}$ up to redshift 0.6

- **SKA2 (0.2 μJy rms)**
  - will complete the follow-up of the full ACCEPT sample

Typical MH size ~200 kpc
→ 30”@z=0.6

*(Gitti et al. 2015, AASKA)*
How many mini-halos await discovery?

Number of MHs that can be detected from a radio survey:

\[
N_{\text{MH}}^{\Delta z} = \int_{z_1}^{z_2} dV \int_{P_{\text{min}}(z')} dP \frac{dN_{\text{MH}}}{dP dV}
\]

Radio luminosity function of MHs:

\[
\frac{dN_{\text{MH}}}{dP dV} = f_{\text{SCC}} \frac{dN_{\text{cl}}}{dL_X dV} \frac{dL_X}{dP_{1.4}}
\]

Fraction of clusters with SCC \(\sim 0.40\) (Hudson et al. 2010)

Observed MH X-ray power correlation (Gitti et al. 2015)

\[
N_{\text{MH}}(z) = \int_{z_1}^{z_2} dV \int_{P_{\text{min}}(z')} dP \frac{dN_{\text{MH}}}{dP dV}
\]

SKA All Sky Survey at Band 2 (4 \(\mu\)Jy rms, 2’’ res.) will be able to detect \(\geq 300\) new MHs at \(z \leq 0.6\)
Radio mini-halos: open questions

• Do all cool-core clusters host a radio MH? How does the MH/CC fraction evolve with redshift?

• What is the role of the central AGN in powering MHs? What is the fraction of MH clusters showing evidence of radio-mode AGN feedback?

• Are MH intrinsically different from giant halos (GH), or just a different evolutionary stage? If non-CCs $\rightarrow$ CCs, also GHs $\rightarrow$ MHs?
Radio mini-halos: open questions

• Do all cool-core clusters host a radio MH? How does the MH/CC fraction evolve with redshift? *(power-limited sample with wider redshift distribution, synergy with eROSITA and ATHENA X-ray satellites)*

• What is the role of the central AGN in powering MHs? What is the fraction of MH clusters showing evidence of radio-mode AGN feedback? *(spectral studies, radio bubbles filling the X-ray cavities)*

• Are MH intrinsically different from giant halos (GH), or just a different evolutionary stage? If non-CCs → CCs, also GHs → MHs? *(polarimetric studies, evolutive models and synergy with ATHENA)*

➤ Surveys with SKA will address these key points
Conclusions

Non-thermal emission from cool-core (CC) clusters: radio-loud AGN + diffuse radio mini-halos (MH)

• Homogeneous analysis of X-ray Chandra data of the largest existing sample (~ 20 objects) of MH clusters [Bravi+15, MNRAS]:
  ✓ Correlation MH power vs. CF power: \[ \nu P_{\nu}^{1.4 \text{GHz}} \propto P_{\text{CF}}^{0.8} \]
  ✓ Turbulent re-acceleration scenario: rel. electron acceleration (\( \rightarrow \) MHs) and gas heating (\( \rightarrow \) CF quenching) are due to the dissipation of the same turbulence, provided \( B \gg 0.5 \mu \text{G} \)

• Large MH samples necessary to unveil MH origin and connection with CC thermodynamics (synergy SKA-ATHENA) [Gitti+15, AASKA]:
  ✓ SKA All Sky Survey at Band 2 (4 \( \mu \text{Jy} \) rms, 2’’ res.) will be able to detect \( \gtrsim 300 \) new MHs at \( z \leq 0.6 \)
Thank you

Myriam Gitti
DIFA – University of Bologna
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Observed $P_{1.4} - L_X$ correlation for MH clusters

1.4 GHz radio power vs. the CC-excised X-ray bolometric luminosity for the observed MH cluster sample

$P_{1.4, \text{MH}} \propto L_X^{1.72}$

Is this valid for the whole population of SCC clusters?

$\log P_{1.4} = 1.72 (\pm 0.28) \log L_X - 2.20 (\pm 0.46)$

(bisector BCES regression)

$L_{X,\text{bol}}$ from the Chandra ACCEPT sample, Cavagnolo et al. 2009

**Observed $P_{1.4} - L_X$ correlation for MH clusters**

- observed MHs
- GMRT upper limits (Kale et al. 13)
  \[ \text{rms} = 0.05 \div 0.1 \text{ mJy} \]
  \[ \theta_b = 18'' \div 25'' \]
- estimated upper limits for the ACCEPT SCC clusters assuming they are undetected by current follow-up obs.
  \[ \text{rms} = 25 \mu\text{Jy} \]
  \[ \theta_b = 10'' \]

*(Gitti et al. 2015, AASKA)*
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Conclusions

Non-thermal emission from cool-core clusters:
radio-loud BCGs + diffuse radio mini-halos

• **SKA1-MID** surveys with rms = 2 μJy at confusion limit will be able to detect all sources above $10^{23}$ W Hz$^{-1}$ up to $z \sim 0.6$ for mini-halos and up to $z \sim 1.7$ for radio-loud BCGs

• **SKA2** will perform the radio follow-up of cool cores up to the highest-$z$ where virialized clusters are currently detected

→ **SKA** will open an unprecedented window on the exploration of mini-halos and radio-mode AGN feedback

*Work in progress...*

Comparison with eROSITA and extension to SKA-LOW