Cosmic Rays in Clusters of Galaxies and their Non-thermal Imprint

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OUTLINE

• The Latest & Largest Structures: Clusters of Galaxies

• Cosmic Rays and Non-thermal Emission in Clusters

• From Radio to Ultra-high Energies

• Implications & Future Prospects
Non-baryonic Cold Dark Matter is the dominant matter in the Universe and drives the structure formation.

Hierarchical Scenario: structures grow via gravitational instability from initial small density fluctuations → large-scale structures grow through merging and accretion of smaller systems.
CLUSTERS OF GALAXIES

Largest gravitationally bound systems with mass of $10^{14} - 10^{15} \, M_\odot$ and radius of few Mpc

Actively evolving objects

Cosmic energy reservoirs

Contain substantial populations of cosmic rays (CRs) and dark matter

Powerful cosmological tools to test models on the origin and evolution of the Universe

Can generate non-thermal emission from radio to gamma-ray frequencies

Via thermal X-ray emission and Sunyaev-Zel’dovich effect
COSMIC RAYS IN CLUSTERS

adapted from Pfrommer et al. (2008)

energy and particle sources

structure formation

AGNs and supernovae

acceleration processes

turbulence

CR protons

shock waves

CR protons

relativistic populations

re-accelerated CR electrons

IC hard X-ray and gamma-ray

primary CR electrons

secondary CR electrons

expected emission

synchrotron radio

\(\pi^0\)

\(\nu\)

gamma-ray

see also Brunetti & Jones (2014) for a review
OBSERVED NON-THERMAL EMISSION

Radio Relics
• at the cluster periphery
• irregular morphology
• highly polarized
• seem to trace structure formation shocks

Radio Halos
• at the cluster center
• regular morphology
• un-polarized
• similar to thermal X-ray emission

CIZA J2242.8+5301
610 MHz – van Weeren et al. (2010)

Giant Halo
(size is ≈ 2 Mpc)
1.4GHz – Deiss et al. (1997)

see Feretti et al. (2012) for a review
OBSERVED NON-THERMAL EMISSION

Radio Relics
• at the cluster periphery
• irregular morphology

Radio (Mini-)Halos
• at the cluster center
• regular morphology

Key Questions:
• Origin of the radio-emitting electrons?
• Contribution of CR protons?
• Impact on cluster environment?

see Feretti et al. (2012) for a review

CIZA J2242.8+5301
610 MHz – van Weeren et al. (2010)

Giant Halo
(size is ≈ 2 Mpc)
1.4GHz – Deiss et al. (1997)

Coma
Giant Halo
(size is ≈ 2 Mpc)
1.4GHz – Deiss et al. (1997)

thermal X-ray ROSAT/PSPC

Radio (Mini-)Halos
• at the cluster center
• regular morphology

• highly polarized
• seems to trace structure similar to thermal X-ray emission

Radio Relics
• at the cluster periphery
• irregular morphology

• un-polarized
• seems to trace structure similar to thermal X-ray emission

see Feretti et al. (2012) for a review
EXPECTED NON-THERMAL EMISSION FROM PROTON-PROTON INTERACTIONS

Radio Synchrotron & X-ray Inverse Compton

Neutrinos

Gamma-rays
RADIO–TO–X-RAY BIMODALITY

• switch-off mechanism needed

• classical hadronic scenario predict radio emission in all clusters

• turbulent re-acceleration naturally account for switch-off

→ what is going on with the CR protons? do they contribute significantly or not?
RADIO–TO–X-RAY BIMODALITY

Hadronic switch-off through change in CR propagation properties (Enßlin et al. 2011, Wiener, Oh & Guo 2013)

FZ, Pfrommer & Prada (2014b)
RADIO–TO–SZ “REDUCED” BIMODALITY

FZ, Pfrommer & Prada (2014b)
RADIO LUMINOSITY FUNCTION

Low-luminosity (and low-mass) clusters will be crucial in determining the exact role of CR protons.

Brunetti & Jones (2014)
THE HIGH-ENERGY WINDOW

**Hard X-ray IC emission** searched for extensively in the past, with a few claims of detection (e.g., Rephaeli & Gruber 2002; Fusco-Femiano et al., 2004; Rephaeli et al. 2006; Eckert et al. 2008; Rephaeli et al. 2008)


IC emission from clusters remains elusive…

**No detection in gamma-rays so far** (e.g., Reimer et al. 2003; Perkins et al. 2006; HESS 2009; Fermi-LAT 2010, 2014; MAGIC 2010, 2012; VERITAS 2012; Vazza & Brüggen 2014; FZ & Ando 2014)

**Neutrinos**… Well, we have just started looking (IceCube Coll. – e.g., Artsen 2013, 2014)
HARD X-RAY FUTURE – ASTRO-H

To be launched in 2015

Soft X-ray Imager & Hard X-ray Imager (+ SXS, SGD)

Good prospects for IC detection in clusters… How good?

Takahashi et al. (2012)
PREDICTIONS FOR ASTRO-H

Modeling of **ALL** radio halos and relics with spectral index measurement available

Phenomenological approach for radio-emitting electrons
PREDICTIONS FOR ASTRO-H

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intersection point of ASTRO-H sensitivity and dominant background
PREDICTIONS FOR ASTRO-H

Modeling of ALL radio halos and relics with spectral index measurement available

Phenomenological approach for radio-emitting electrons

Intersection point of ASTRO-H sensitivity and dominant background

or

signal-to-noise in the 20-80 keV band $N_s/(N_s + N_b)^{1/2} > 3$
PREDICTIONS FOR ASTRO-H

ASTRO-H (and NuSTAR) can test $> 1 \mu G$ magnetic fields and potentially detect IC emission.

<table>
<thead>
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<th>Cluster</th>
<th>Source</th>
<th>Type</th>
<th>z</th>
<th>Size</th>
<th>$\alpha$</th>
<th>$B_{dt}^{s/n}(100, \text{ks})$</th>
<th>$B_{dt}^{s/n}(1, \text{Ms})$</th>
<th>$B_{dt}(1, \text{Ms})$</th>
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</table>

Bartels, FZ & Ando (2015)
**GAMMA-RAY INSTRUMENTS**

*Fermi*-Large Area Telescope  
**NASA satellite**  
Constantly survey the sky  
(full coverage in 3 hours)  
20 MeV – 300 GeV  
Angular resolution 0.1 deg @ 10 GeV  
Energy resolution 10% @ 10 GeV

*Imaging Atmospheric Cherenkov Telescopes*  
> 50 – 100 GeV  
Angular resolution 0.1 deg  
Energy resolution 15%

*Fermi* 2-year skymap (Nolan et al. 2012)
IMAGING CHERENKOV TECHNIQUE
MAGIC OBSERVATIONS OF PERSEUS

Perseus galaxy cluster

• cool-core $\Rightarrow$ high central gas density
• host the brightest radio mini-halo
$\Rightarrow$ most promising target for gamma-rays!

Deepest cluster observation at very-high energy: 85 hours
MAGIC OBSERVATIONS OF PERSEUS

Perseus galaxy cluster

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Deepest cluster observation at very-high energy: 85 hours

MAGIC Coll. (2012) – FZ as corr. author
MAGIC OBSERVATIONS OF PERSEUS

maximum CR proton acceleration efficiency at shocks is < 40%
(Pinzke & Pfrommer 2010)

OR

CR propagation out of the cluster core

\[
F_{\gamma}(>E) \propto \frac{1}{E^{\alpha}}
\]

\begin{align*}
\alpha & \quad X_{\text{CR,max}} \quad X_{\text{CR,min}} \\
2.1 & \quad 0.77 & \quad 0.42 \\
2.2 & \quad 1.12 & \quad 0.35 \\
2.3 & \quad 2.17 & \quad 0.38 \\
2.5 & \quad 11.6 & \quad 0.67
\end{align*}

MIN = minimum gamma-ray flux in the *hadronic* scenario

MAGIC Coll. (2012) – FZ as corr. author
4-years *Fermi*-LAT OBSERVATIONS

Stacked analysis of 50 HIFLUGCS clusters

maximum acceleration efficiency is $< 25\%$ + CR-to-thermal pressure $< 1.5\%$

Fermi Coll. (2014)
Non-detections do challenge the standard picture of shock acceleration

Vazza & Brüggen (2014)
THE CASE OF THE COMA CLUSTER

Analysis of 5.25-year *Fermi* observations

Test different models:

- Point Source
- Disk (Kushnir & Waxman 2009)
- Pinkze & Pfrommer (2010)
- FZ, Pfrommer & Prada (2014)
- Radio Relic template
- Ring-like template (Keshet et al. 2003)

→ NO DETECTION (TS ≤ 2)

FZ & Ando (2014)
THE CASE OF THE COMA CLUSTER

Analysis of 5.25-year *Fermi* observations

CR proton acceleration efficiency < 15%

CR electron acceleration efficiency < 1%

CR-to-thermal pressure < 0.6% – 2.7%

→ Coma giant radio halo cannot be (uniquely) of hadronic origin!

FZ & Ando (2014)
More than 100 telescopes in two sites, south and north, with full sky coverage

Construction begins in ~2015

Aim: one order of magnitude better than current Cherenkov telescopes!
ROUGH PREDICTIONS FOR CTA

Based only on mass-scaling (not considering radio emission)
CTA SIMULATIONS & PROSPECTS

PERSEUS: parameter space accessible by CTA in about 300 hr

Pinzke & Pfrommer (2010), 0.15 deg
Zandanel et al. (2014), 0.15 deg, $\gamma_{tu} = 100$
Zandanel et al. (2014), 0.15 deg, $\gamma_{tu} = 3$

$E_{\gamma, \text{min}}$, $\alpha_p = 2.1$
$E_{\gamma, \text{min}}$, $\alpha_p = 2.2$
$E_{\gamma, \text{min}}$, $\alpha_p = 2.3$

EXCLUDED BY MAGIC

ACCESSIBLE BY CTA

PRELIMINARY

CTA will be able **either** to detect the cluster gamma-ray emission **or** to push a **paradigm shift** for CR proton confinement in galaxy clusters!
WHAT ABOUT NEUTRINOS?

Murase, Ahlers & Lacki (2013)
WHAT ABOUT NEUTRINOS?

Model all galaxy clusters through their mass function

Calculate radio and gamma-ray emissions that respect both observed radio counts and gamma-ray upper limits

Test different spectral indices (-1.5 to -2.4) and magnetic fields

FZ, Tamborra, Gabici & Ando (2014)
WHAT ABOUT NEUTRINOS?

FZ, Tamborra, Gabici & Ando (2014)
COSMIC RAYS IN CLUSTERS – TAKE AWAY

**RADIO → SYNCHROTRON →** relativistic electrons
+ magnetic field

**HARD X-RAYS → INVERSE →** relativistic electrons
+ COMPTON

**GAMMA-RAYS → PION DECAYS →** CR protons
& NEUTRINOS

- ORIGIN OF RADIO EMISSION
- MAGNETIC FIELD distribution
- CR PROTON CONTENT
- CR ACCELERATION and
  CONFINEMENT in clusters
- STRUCTURE FORMATION
- EXTRAGALACTIC CR ORIGIN
SUMMARY

FACTS
More than 50 clusters host diffuse radio emission
No high-energy emission detected so far

CONSTRAINTS
CR-to-thermal pressure $< 1\% \ (\alpha_p = 2.1)$ to $< 10\% \ (\alpha_p = 2.5)$
Maximum CR proton acceleration efficiency $< 15\%$
CR proton / electron efficiency at odds with DSA

→
Giant radio halos cannot be generated only by CRp (at least Coma)
CR protons in clusters contribute $< 1 – 10\%$ to EGRB – $\nu$ fluxes

UNCERTAINITIES
CR acceleration efficiency, transport properties, spectral index + magnetic field
FUTURE PROSPECTS

LOFAR (and other SKA precursors) will improve our knowledge on diffuse radio emission: all-sky surveys, low-mass clusters

SKA will be crucial for magnetic fields in clusters

ASTRO-H and NuSTAR can shed light on the long-sought hard X-ray emission, and probe $>1\ \mu$G magnetic fields

We DO expect CR protons to accumulate in clusters and we DO expect a corresponding high-energy emission

IceCube can test the most optimistic scenarios, but not compete with other constraints

Fermi-10 years and CTA could detect “few” clusters = major breakthrough, or they can significantly improve our constraints!
THANKS!