Cosmic Rays from Clusters of Galaxies: Where are the Secondaries?

Fabio Zandanel
(Grappa Institute – University of Amsterdam)
f.zandanel@uva.nl

Radboud University Nijmegen – Department of Astrophysics
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OUTLINE

• The Latest & Largest Structures: Clusters of Galaxies

• Cosmic Rays and Non-thermal Emission in Clusters

• High-energy Observations

• Implications, Predictions & 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 in the Universe with mass of $10^{14} - 10^{15} \, M_\odot$ and radius of few Mpc

Actively evolving objects

Cosmic energy reservoirs

Expected to contain substantial populations of cosmic rays (CRs) and dark matter (DM)

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

Brunetti & Jones (2014)

Gelmini (2009)
The original: Hillas (1984)
SHOCKS & COSMIC RAYS IN CLUSTERS

Pfrommer et al. (2008)

Brunetti & Jones (2014)
COSMIC RAYS IN CLUSTERS

adapted from Pfrommer et al. (2008)

energy and particle sources
structure formation
AGNs and supernovae
shock waves
CR protons
acceleration processes
turbulence
CR protons
relativistic populations
re-accelerated CR electrons
primary CR electrons
expected emission
synchrotron radio
IC hard X-ray and gamma-ray
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 (Mini-)Halos
• at the cluster center
• regular morphology
• un-polarized
• similar to thermal X-ray emission

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?

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
THE HIGH-ENERGY WINDOW

Radio Synchrotron & X-ray Inverse Compton (IC)

Neutrinos

Gamma-rays
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)

More recent observations do not confirm most of the earlier claims (Ajello et al., 2009, 2010; Wik et al., 2012; Ota, 2012; Ota et al., 2013; Wik et al., 2014; Gastaldello et al., 2014)

IC emission from clusters remains elusive…

No detection in gamma-rays so far… (e.g., Reimer et al. 2003; Perkins et al. 2006; HESS Coll. 2009; Fermi-LAT Coll. 2010, 2014; MAGIC Coll. 2010, 2012; VERITAS Coll. 2012; 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

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HALOS
Bartels, FZ & Ando (2015)

03/02/2015
Fabio Zandanel (GRAPPA)
### PREDICTIONS FOR ASTRO-H

ASTRO-H 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>
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Bartels, FZ & Ando (2015)
GAMMA-RAY INSTRUMENTS

**Fermi**-Large Area Telescope
NASA satellite

- Constantly survey the sky (full coverage in 3 hours)
- 100 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)
MAGIC OBSERVATIONS OF PERSEUS

Perseus galaxy cluster

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

85 hours of data: deepest cluster observation at very-high energy

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

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

OR

CR propagation out of the cluster core

\[
F_{\gamma}(>E) \text{ [photons s}^{-1}\text{ cm}^{-2}] = \alpha X_{\text{CR, max}} \% \text{ or } X_{\text{CR, min}} \%
\]

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(min = minimum gamma-ray flux in the hadronic scenario)

MAGIC Coll. (2012) – FZ as corr. author
HADRONIC MODEL

Assuming the hadronic model valid, constraints on the magnetic field can be obtained

Radio Mini-Halo
Pedlar et al. (1990)

\[
B(R) = B_0 \left( \frac{\rho_{\text{gas}}(R)}{\rho_{\text{gas,0}}} \right)^{\alpha_B}
\]

**Minimum magnetic field, \(B_{0,\text{min}}\) [\(\mu\text{G}\)]**:

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MAGIC OBSERVATIONS OF PERSEUS

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)
4-years *Fermi*-LAT OBSERVATIONS

Significant excess found in 3 objects

Explained as point-like emission or unmodeled background

see also Huber et al. (2013) and Prokhorov & Churazov (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 protons acceleration efficiency < 15%
[< 5% to respect radio + B]
(Pinkze & Pfrommer 2010)

CR electrons acceleration efficiency < 1%
(Keshet et al. 2003, Kushnir & Waxman 2009)

CR-to-thermal pressure < 0.6% - 2.7%

FZ & Ando (2014)
CHERENKOV TELESCOPE ARRAY

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)

Pinzke et al. (2011) - HIGFLUGCS - $\xi_p = 50\%$
Pinzke et al. (2011) - HIGFLUGCS - $\xi_p = 20\%$

point-source sensitivity

$\log_{10} N(F_{>100 \text{ GeV}})$

$\log_{10} F_{>100 \text{ GeV}}$ [ph cm$^{-2}$ s$^{-1}$]

CTA 100 hr

500 hr
CTA SIMULATIONS & PROSPECTS

PERSEUS: parameter space accessible by CTA in about 300 hr

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

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

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 $\Rightarrow$ SYNCHROTRON $\Rightarrow$ relativistic electrons magnetic field

+

HARD X-RAYS $\Rightarrow$ INVERSE $\Rightarrow$ relativistic electrons COMPTON

+ 

GAMMA-RAYS $\Rightarrow$ PION DECAYS $\Rightarrow$ CR protons & NEUTRINOS

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

DISENTANGLE electrons and magnetic field
ARE WE DETECTING SECONDARIES?

FACTS
More then 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%

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

UNCERTAINTIES
CR acceleration efficiency, transport properties, spectral index
+ need to match/respect radio data where
the magnetic field enters the game
WILL WE DETECT SECONDARIES?

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!