The XMM Cluster Outskirts Project

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Cluster Outskirts: Introduction

Most current studies focus on the region inside $R_{500}$.
Most current studies focus on the region inside $R_{500}$... But a wide range of interesting phenomena take place beyond that radius...
Cluster Outskirts: Introduction

ICM entropy generation

Lau et al. 2015

Vazza et al. 2010

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Cluster Outskirts: Introduction

ICM entropy generation

Lau et al. 2015

Non-thermal pressure
Turbulence, shocks, cosmic rays, ...

Vazza et al. 2010

Miniati 2014
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Non-thermal pressure
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Eckert et al. 2017
Vazza et al. 2010

Infalling substructures
Bulk motions

Miniati 2014

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ICM entropy generation
Lau et al. 2015

Non-thermal pressure
Turbulence, shocks, cosmic rays, ...
Eckert et al. 2017
Vazza et al. 2010

Infalling substructures
Bulk motions

Filaments and the WHIM
Dolag et al. 2005

Miniati 2014
A universal entropy flattening?

- Thanks to its low background, *Suzaku* measured entropy profiles out to $R_{\text{vir}}$ in a few clusters.
- A deficit of entropy is often observed beyond $R_{500}$.
- Possible interpretations: gas clumping, non-thermal pressure support, non-equilibrium electrons, ...

Walker et al. 2013
Combining X-ray and SZ measurements

With modern SZ data we now get pressure profiles out to large radii

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**Planck Collaboration V 2013**

**Sayers et al. 2016**
Combining X-ray and SZ measurements

With modern SZ data we now get pressure profiles out to large radii

Planck Collaboration V 2013

Combining with X-ray data we can get

\[ kT = \frac{P_{SZ}}{n_{X-ray}}, \quad K = P_{SZ}n_{X-ray}^{-5/3}, \quad \frac{dP_{SZ}}{dr} = -n_{X-ray} \frac{kGM(< r)}{\mu m_H r^2} \]
The X-COP project

X-COP (PI: Eckert) is a very large program on XMM to follow up the most significant Planck clusters
The X-COP strategy

XMM has a large FOV and collecting area... but also a high and variable background
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In the [0.7-1.2] keV band we reach an accuracy of $\sim 3\%$ on the subtraction of the XMM background.
Gas clumping

At large radii the gas distribution is clumpy and inhomogeneous

Zhuravleva et al. 2013
Gas clumping

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Zhuravleva et al. 2013

Eckert et al. 2015

Median
Mean

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Gas density and pressure profiles

XMM gas density profiles reach $2 \times R_{500}$
Planck pressure profiles reach $2.5 \times R_{500}$
We reconstruct $M_{HSE}$ by fitting jointly X-ray and SZ data

Our mass profiles can be used for
- Self-similar scaling
- Testing hydrostatic equilibrium
- Mass distribution
Except for one cluster (A2319) all clusters are consistent with gravitational heating once corrected for clumping.
Entropy profiles

Slope beyond $R_{500}$ of $1.25 \pm 0.23$ fitted over $> 30$ data points

Ghirardini et al. to be subm.
Gas clumping as source of entropy flattening?

The entropy flattens beyond $R_{500}$ when clumps are not excised...

A2142, Tchernin, DE et al. 2016
The entropy flattens beyond $R_{500}$ when clumps are not excised... but not when clumping is taken into account!

A2142, Tchernin, DE et al. 2016
Intrinsic scatter

We measure the dispersion of the profiles out to $R_{200}$
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$\sigma_P > \sigma_n, \sigma_T$ at all radii! Implies $n$ and $T$ are positively correlated.
Median [percentiles] for the full sample:

• $f_{\text{gas},500} = 0.141 \ [0.131, 0.154]$
• $f_{\text{gas},200} = 0.149 \ [0.121, 0.161]$
We used a large set of $\sim 300$ simulated clusters (Rasia et al. in prep.) to determine the baryon depletion.

- The value of $Y_{\text{bar}}$ is nearly independent of the adopted baryonic physics (Planelles et al. 2014).
- Considering the (well-measured) stellar fraction, we set $f_{\text{gas}} = Y_b \frac{\Omega_b}{\Omega_m} - f_*$.
In the presence of non-thermal pressure the HSE equation becomes

\[ \frac{d}{dr}(P_T + P_{NT}) = -\rho \frac{GM}{r^2} \]

We assume a parametric form for \( P_{NT}/P_T(r) \) and solve for the parameters assuming universal \( f_{gas} \)

Scatter and uncertainties in universal \( f_{gas} \) are propagated to NT pressure

\[ P_{rand}/P_{tot} \]

Nelson et al. 2014
With one exception (A2319) the level of NT pressure is lower than predicted.
Median $P_{NT,500} = 6\%$, $P_{NT,200} = 10\%$
The case of A2319

A2319 is a head-on merger with 3:1 mass ratio

Ghirardini, Ettori, DE et al. 2018
The case of A2319

A2319 is a head-on merger with 3:1 mass ratio

Ghirardini, Ettori, DE et al. 2018

A2319 is probably in a transient phase of high NT pressure (~ 40%)
We compared our masses corrected for NT pressure with hydrostatic masses

- On average we measure $M_{HSE}/M_{tot} = 0.94 \pm 0.04$
- Planck masses are slightly biased low, $M_{SZ}/M_{tot} = 0.85 \pm 0.05$
- $1 - b = 0.58 \pm 0.04$ would imply a very low $f_{gas} = 10.5\%$
Our mass estimates agree with results obtained with other techniques.

We measure \( \frac{M_{HSE}}{M_{WL}} = 1.02 \pm 0.13 \) at \( R_{500} \).

_Ettori et al. to be subm._
Our mass estimates agree with results obtained with other techniques.

We measure a scatter $\sigma_{\ln c} = 0.22$ in the $c - M$ relation.
We fitted the data with 5 different mass models (NFW, Einasto, Isothermal, Burkert, Hernquist).

![Graph showing Bayes factor of the mass models with respect to the one with the highest evidence. Shaded regions identify values of the Bayes factor where the tension between the models is either weak (<2.5) or strong (>5) according to the Jeffreys's scale (Jeffreys 1961).]

In Fig. 2, we present the Bayes factor estimated for each object as the ratio between the Bayesian Evidence, i.e. the integral of the likelihood multiplied by the priors on the parameters, of the mass model with the highest Evidence with respect to the others. Nine, out of 13, objects prefer a NFW model fit and have data that are significantly inconsistent (Bayes factor >5) with an isothermal/Burkert mass model. The remaining four objects prefer different mass models (ISO for A2255 and A2319, HER for A1644, and BUR for A644) but do not show any statistically significant (Bayes factor <5) tension with NFW.

3.2. Reference mass model: backward method with NFW mass model

We present the results of our analysis with a backward method and a NFW mass model in Table 1. We measure mean relative (statistical only) errors lower than 8% (mean and dispersion at = 1000, 500, and 200, respectively: 4 ± 2%, 5 ± 3%, and 7 ± 4%; see Fig. 3).

In Fig. 3, we show the distribution of the best-fit results on the NFW concentration and $R_{200}$. The agreement with the predicted values from numerical simulations is remarkable. The overall distribution presents a scatter log$c$ equal to 0.12 (0.14 and 0.10, when we split the data in two bins accordingly to the mass), that is in well agreement with the values estimated in numerical simulations (e.g. 0.09 in the Millennium Simulation).

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We fitted the data with 5 different mass models (NFW, Einasto, Isothermal, Burkert, Hernquist).

NFW is the best fit model in 9/13 cases; models with central core (ISO, Burkert) strongly disfavored.
Regular outskirts when clumping is taken into account.

The gas fraction of X-COP clusters implies a mild HSE bias $M_{\text{HSE}}/M_{\text{tot}} = 0.94$.

The scatter in density and temperature is positively correlated.

All X-COP clusters but one follow gravitational collapse predictions.

The level of NT pressure is just 6% at $R_{500}$.

The gas fraction of X-COP clusters implies a mild HSE bias $M_{\text{HSE}}/M_{\text{tot}} = 0.94$.

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