Modeling Galaxy Cluster Outskirts with Cosmological Simulations

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ART simulated cluster

Mock Chandra Image

~1Mpc
Clusters Probe the Growth of Structure

Avestruz

Cluster Outskirts
Clusters Probe the Growth of Structure

Avestruz

Cluster Outskirts

\[ N(M) = 10^{-5} \]

\[ 10^{-6} \]

\[ 10^{-7} \]

\[ 10^{-8} \]

\[ 10^{-9} \]

\[ 10^{14} \]

\[ 10^{15} \]

\[ M_{500c} \]

\[ M_{\text{sun}} \]

<z>=0.1

<z>=0.5

Vikhlinin, et al., 2009
Masses defined with respect to reference densities
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![Diagram of galaxy clusters and observational data](image-url)
Pioneering X-ray observations of cluster outskirts

Suzaku X-ray Key Project

Urban, et al., 2013

Perseus Cluster ~5 Mpc

R200c

Avestruz

Cluster Outskirts
Microwave observations of cluster outskirts
Cluster outskirts ideal for mass measurements
Cluster outskirts ideal for mass measurements
Entropy is expected to scale with radius

Walker et al., 2012
Suzaku entropy profiles flatten in outskirts

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Walker et al., 2012
Simulations necessary to interpret observations

Adaptive Refinement Tree (ART) code: N-body + Gasdynamics
Box size $\sim 100$ Mpc, Spatial resolution $\sim$ few kpc, Region shown $\sim 2$ Mpc

Baryonic physics included (e.g. gas cooling, star formation, heating by SNe/AGN, metal enrichment)
Mock X-ray pipeline allows us to test observations.
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\[
\text{XSB} = \int dV n_e n_p \Lambda(T_X, Z)
\]

Photon counts per second

Emission measure:
\[
\text{EMM} = \int n_e n_p \, dl
\]

Assumed model plasma emissivity
Mock X-ray pipeline allows us to test observations

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Assumed model plasma emissivity
Simulations necessary to interpret observations

\[ z = 0.98 \quad \text{dark matter} \quad \text{stars} \quad \text{gas} \]

\[ \text{temperature} \quad \text{entropy} \quad \text{metallicity} \]
We can test metal abundance with known input.
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We can test metal abundance with known input.
Weak metal contributions are scattered
Stronger metal contributions biased low
Stronger metal contributions biased low
Stronger metal contributions biased low


$T_x \sim 1\text{keV}$
Bias disappears in single temperature medium

![Graph showing the relationship between Abundance [Zsun], f(Z_{Fe}/Z_{Sun}), and R [kpc]. The graph includes data points for x, y, and z with error bars, and the text "Tx(input)=1keV" is overlaid on the graph. The x-axis represents R [kpc] ranging from 10^2 to 10^3 kpc, and the y-axis represents the Abundance [Zsun] and f(Z_{Fe}/Z_{Sun}) ranging from 0 to 1 and 10^-2 to 2, respectively. The graph highlights the data from Avestruz and Cluster Outskirts.]
Non-equilibrium electron temperature biased low

\[ \log_{10} T_{\text{gas}} \quad [K] \quad \text{and} \quad T_e / T_{\text{gas}} \]
Non-equilibrium electron temperature biased low

\[
\log_{10} T_{\text{gas}} \text{ [K]} \quad T_e / T_{\text{gas}}
\]

\[
t_{ei,\text{Spitzer}} = 6.3 \times 10^8 \text{yr} \left( T_e / 10^7 \text{K} \right) \left( 10^{-5} \text{cm}^{-3} / n_i \right) \left( 40 / \ln \Lambda \right)
\]
Non-equilibrium electron temperature biased low

\[ t_{ei, \text{Spitzer}} = 6.3 \times 10^8 \text{yr} \left( \frac{T_e}{10^7 K} \right) \left( 10^{-5} \text{cm}^{-3}/n_i \right) \left( \frac{40}{\ln \Lambda} \right) \]
Non-equilibrium electron temperature biased low

\[ \log_{10} T_{\text{gas}} \ [K] \quad T_{e}/T_{\text{gas}} \]

\[ t_{ei, \text{Spitzer}} \rightarrow \text{Hubble time} \]
Non-equilibrium electron temperature biased low

$\log_{10} T_{\text{gas}} \ [\text{K}]$  \hspace{1cm} $T_e/T_{\text{gas}}$

*$_{t_{ei, Spitzer}}$ sets an upper limit on the temperature bias
Non-equilibrium electrons can affect measured $T_X$.
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$T_X = 5.96\, \text{keV}, \alpha_{200m} = -0.05$

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![Graph showing Te/Tgas vs. R/R200m with annotations for different mass and accretion scenarios.]

- **More massive, fast accreting**
- **Less massive, slow accreting**

**Equations:**
- $T_X = 5.96\text{keV}, \alpha_{200m} = -0.05$
- $T_X = 11.03\text{keV}, \alpha_{200m} = -0.66$

Summary

1. Inhomogeneities in the intracluster medium contribute to observational biases

2. Non-equilibrium electrons are a potential source of systematic uncertainties
End