Modelling mass profiles in galaxy groups and clusters using X-rays

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Outline

- Why (X-ray) mass?
- Ascasibar & Diego (2008) cluster model
  - application & validation in galaxy clusters
- Baryon fractions in galaxy groups

Thanks to: Ewan O'Sullivan, Trevor Ponman & Graham Smith (Birmingham), Anthony Gonzalez (Florida), Suresh Sivanadam (Toronto), Ann Zabludoff & Dennis Zaritsky (Arizona)
Why measure mass?

- Cluster scaling
  - Mass provides a normalizing factor and scaling (e.g. virial) radius
  - Similarity breaking is a powerful tool for studying cosmic feedback
X-ray mass measurements

If X-ray emitting gas in hydrostatic equilibrium

\[
\frac{dP}{dr} = -\frac{GM}{r^2}\rho
\]

measure \( T_{\text{gas}}(r) \) & \( \rho_{\text{gas}}(r) \) → \( P(r) \) → measure mass

\[
\frac{M_{\text{est}} - M_{\text{true}}}{M_{\text{true}}}
\]

16 simulated clusters at \( z = 0 \); 3 orthogonal projections

- Small (5 – 20%) bias low in X-ray mass estimates (less for relaxed clusters) due to non-thermal pressure support; *geometry-dependent*

Nagai et al., 2007

(open) solid points = (un)relaxed morphology

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The Ascasibar & Diego (2008) cluster model

- Assumes polytropic ICM in Hernquist (1990) potential, with additional component to describe (cool) core
  - yields convergent projected mass (unlike NFW profile): ideal for comparing X-ray masses with those from gravitational lensing

- 5 parameters, each with a clear physical meaning:
  - \( T_0 \) = central gas temperature of baseline (non-cooling) polytropic profile
  - \( t \) = actual central gas temperature normalized to \( T_0 \) \((0 \leq t \leq 1)\)
  - \( a \) = dark matter scale radius (typically larger than corresponding NFW \( r_s \))
  - \( \alpha \) = cooling radius normalized to scale radius, \( a \)
  - \( f \) = factor to define gas density normalization \( \text{wrt} \) cosmic baryon fraction \((f = 1)\)

Fitting the model to X-ray data

- Model (solid line) jointly ($\chi^2$) fitted to gas $T(r)$ & $\rho(r)$ data (purple error bars)
- Errors on parameters and all derived quantities from (N = 200) bootstrap resamplings of original data (→ grey 1σ error envelope)
- **Good fit with tight constraints, even with few radial bins**
Testing the model

- Residuals (in $\sigma$) from model (i.e. normalized by errors) for density and $T$ profiles from a statistical sample of 20 clusters (Sanderson, O'Sullivan & Ponman, 2009)

- Marginal distribution shown as kernel smoothed density estimate, compared to a Gaussian of zero mean & unit variance

- *No substantial systematic biases → model is a good representation of the data*
Assumptions & implications

- Spherical symmetry & hydrostatic equilibrium → (inevitable) small underestimate of true mass
- Single potential
  - no subhalos or BCG contribution → typically need to mask out inner ~ 5 – 10 kpc (subclumps excluded from X-ray analysis)
- Hernquist potential
  - $\rho_{\text{tot}} \propto r^{-4}$ vs. $r^{-3}$ (NFW) for large $r$
  - *but, total mass converges* → projected mass vs. lensing
- *Only 5 free parameters for $T(r) \& \rho(r)$* → can fit to radial profile with only $\geq 3$ bins
Cluster cooling & dynamical status

- Offset between brightest central galaxy (BCG) & X-ray centroid is a disturbance indicator

- **Clusters without strong central cooling are more dynamically disturbed**

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![Graph showing relationship between projected X-ray centroid/BCG offset and log slope of ρ_{gas}(r) at 0.04r_{500}.](image)

- Hα line emitting BCGs (star forming) all have strong cooling & very small X-ray / BCG offsets
- Cusper ρ(r) (at ~50 kpc) → stronger cooling (Vikhlinin et al, 2007)

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More dynamically disturbed

Sanderson, Edge & Smith, 2009

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Strong lensing vs. X-ray mass comparison

20 clusters with strong gravitational lensing mass analysis + X-ray mass analysis (Richard et al, 2010)

Projected masses measured near cluster core (250 kpc), using projected X-ray mass from Hernquist (1990) profile in cluster model

- Generally good agreement between lensing & X-ray masses, especially for cool core clusters (less disturbed)
- Many non-CC clusters have discrepant masses → consistent with non-equilibrium due to recent disruption
3 groups observed with XMM, from sample of Gonzalez+07, with optical mapping of intracluster stars → full baryon census, with reliable scaling mass and aperture.
Variation in stellar mass fraction

- Solid coloured lines show new data from X-ray model → optical total mass estimates were biased low, but (steep) trend only slightly flattened

- Implies \( \leq 50\% \) of group optical luminosity in intracluster light...

Sanderson, O'Sullivan, Ponman, Gonzalez, +..., in prep.
Summary

- Measuring cluster masses (→ virial radii) using X-ray data is very effective.

- Ascasibar & Diego cluster model is a parsimonious, flexible and effective description of real clusters (& purely analytic)

  - fast & easy to fit for even sparse (≥ 3 bins) & noisy data → ideal for use with very large cluster samples

- Scaling with / by cluster mass is a powerful tool for studying cosmology & cosmic feedback → baryon fraction, scaling relations etc.