X-ray mass analysis of LoCuSS* clusters with Chandra

*Local Cluster Substructure Survey

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X-ray mass analysis overview

1) Deprojection
   ➔ gas temperature & density profiles

2) Mass modelling
   ➔ $M(r)$, $f_{\text{gas}}(r)$, $\rho_{\text{tot}}(r)$ etc.

3) Estimation of parameter errors
   ➔ also need errors on any derived quantities
X-ray analysis stages:

1) Deprojection

- Using XSPEC “projct” model
- Non-parametric deprojection
- Assume spherical geometry
- Ignore spectral bias & PSF blurring

- Exclude “obvious” subclumps
- Fix metallicity and galactic absorption at projected values
- Sometimes also need to fix temperature at projected values (ok if ~isothermal)
- No soft excess bg modelling

3d shells map onto 2d annuli

X-ray spectrum in each annulus

Model parameters for each shell fitted simultaneously
1) Deprojection
   → gas temperature & density profiles

2) Mass modelling
   → \( M(r) \), \( f_{\text{gas}}(r) \), \( \rho_{\text{tot}}(r) \) etc.

3) Estimation of parameter errors
   → also need errors on any derived quantities
The Ascasibar & Diego (2008) cluster model

- Hernquist $M_{\text{tot}}(r)$
- Polytropic gas with variable cool-core component: specifies $T(r)$ & $\rho_{\text{gas}}(r)$ in full
- 5 parameters, each with a clear physical meaning:
  - $T_0 = \text{central gas temperature of non-cool core polytropic profile}$
  - $t = \text{actual central gas temperature normalized to } T_0$
  - $a = \text{dark matter scale radius} \ [\text{NB } \sim 2 \times \text{NFW } r_s ]$
  - $\alpha = \text{cooling radius normalized to scale radius, } a$
  - $f = \text{scaling factor to define gas density normalization wrt cosmic baryon fraction} \ (f = 1)$

Examples of model fits

Examples of a cool-core and non-cool core cluster with relatively few bins; errorbars are the deprojected data & line is best-fit Ascasibar & Diego model + $1\sigma$ error envelope (in both cases the model determines $r_{500}$ to ~5% accuracy)
Ascasibar & Diego cluster model pros & cons

**Strengths**

- Physically-motivated and well behaved: e.g. no negative $T(r)$
- Simple (won't overfit the data), yet reasonably flexible
- Mass is modelled directly
- Stable & easy to fit, even with sparse & noisy data
  - no need for gradient estimates to get $M(r)$
  - will yield fairly sensible results even for “problem” clusters

**Limitations**

- Fixed (Hernquist) $M(r)$ – e.g. can't investigate inner slope
- Potential lack of flexibility
  - use bootstrap resampling to determine errors
  - need to monitor residuals & ignore innermost data (< 5-10 kpc)
Model residuals vs. scaled radius (coolest clusters)

- Only 21 coolest clusters shown (half the sample)
- No significant radial trends in residuals
Model residuals vs. scaled radius (hottest clusters)

- Only 21 hottest clusters shown (half the sample)
- No significant radial trends in residuals
No bias in density residuals; but some (symmetric) outliers – intrinsic scatter due to density substructure, non-equilibrium etc.

- Temperature residuals slightly biased high (i.e. model underpredicts data), but fewer outliers
X-ray mass analysis overview

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   - gas temperature & density profiles

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   - $M(r)$, $f_{gas}(r)$, $\rho_{tot}(r)$ etc.

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Model fitting procedure

- Joint chi-squared fit to (independently binned) $T(r)$ & $\rho_{\text{gas}}(r)$ with asymmetric errors

Error estimates

- Separate bootstrap resampling of temperature and density profiles – 200 Monte Carlo realizations of the original data
  - model fitted to each MC realization
- Use median absolute deviation to estimate $\sigma$, as robust to outliers – equivalent to median vs. mean
  - can use any quantile or other statistic as necessary
- A MC realization of every derived quantity can be obtained
  - no error propagation $=>$ fully allows for parameter correlations
Example case of the cluster A586.

- Black curve is kernel-smoothed density plot;
- Dashed blue line is best-fit value
- Red lines are +/- 1 sigma errors (200 Monte Carlo realizations in total).
Testing the model: $R_{500}$ comparison

- Weighted orthogonal regression (BCES: Akritas & Bershady, 1996)
- Good agreement between $r_{500}$ estimated from spectrum and $r_{500}$ determined by mass modelling

Graph showing the BCES orthogonal slope is 0.937 +/- 0.172 with data points for Cool Core and Non-Cool Core.
Comparison of mass analysis methods: $r_{500}$ & $M_{500}$

- Same Chandra data, analysed differently by Pasquale Mazzotta (y axis) & me (x axis)
- 6 LoCuSS clusters observed in 2008 (all 20ks, so fairly shallow)
Some preliminary scaling results: $c_{500}$ & $M_{500}$

- 42 LoCuSS clusters with Chandra data (NB $c_{500} \sim 0.5 \times \text{NFW value for Hernquist model}$)
- Fairly narrow dynamic range & large scatter $\Rightarrow$ large errors on slopes
Bootstrap error diagnostics: parameter correlations

- Matrix of scatterplots of parameters (for cluster A586)
- Many correlations evident (red numbers highlight strongest correlations)
Parameter correlations: \( M_{500} - c_{200} \) relation

- Parameters are not independent!
- Intrinsic correlation highly variable
- Hot core clusters show strong correlation
- Cool core clusters show anti-correlation
- Need to deal with these correlations in fitting global scaling relations
Parameter correlations: $M_{500} - T_0$ relation

- Parameters very highly correlated
- Hot core clusters flatten the relation
- Bootstrap realizations sample probability space & capture the correlation
- Dashed line is unweighted fit to all Monte Carlo points
  - steeper => internal correlation flattens
  - automatically handles intrinsic scatter
- Orthogonal regression needed...

\[
y = (1.44^{+0.043/-0.043}) \times x + (13.3^{+0.035/-0.035})
\]
\[
(MC) \ y = (1.51^{+0.0059/-0.0059}) \times x + (13.2^{+0.0049/-0.0049})
\]
Summary

- XSPEC project is a simple & effective scheme for non-parametric X-ray deprojection
  - Some issues with instabilities in recovered $T(r)$, especially for hotter clusters
- Ascasibar & Diego (2008) model effective at determining $M(r)$, especially with sparse/noisy data
  - Less suitable for detailed studies with v. high quality data
- Bootstrap resampling of mass models is ideal for error estimation and handling of parameter correlations
- Need detailed comparison of methods (inc. lensing) for 10's of clusters to establish best approach