Searching for Shocks in Galaxy Cluster X-ray Temperature Images

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Motivation

Galaxy clusters formed from the hierarchical merging of smaller cluster members. As infalling subclusters merge into the potential well, shocks form with Mach numbers of the order a few and heat the intracluster gas. From galaxy cluster X-ray temperature maps with high spatial resolution and tight temperature constraints, Mach number distributions can be reliably mapped, giving insights into the cluster merging history. We present a new methodology for producing adaptively binned *XMM-Newton*/*Chandra* X-ray temperature maps from joint spectral fitting and apply a shock finding routine to observed and simulated galaxy cluster temperature maps to probe the underlying Mach number distribution.

Galaxy Cluster X-Ray Temperature Maps from Joint Spectral Fitting

- ★ A Voronoi tessellation adaptive binning scheme optimally bins a counts image into regions, each meeting a minimum *S/N* threshold.
- ★ *XMM-Newton*/*Chandra* spectra are extracted from each cell and jointly fitted with an APEC model to determine a temperature for that region (*Figure 1*).
- ★ Temperatures are collected for all regions, producing a temperature map that is then smoothed to remove binning artifacts (*Figure 2*).
- ★ Jointly fitting spectra from both X-ray observatories reduces temperature errors compared to maps created by fitting *XMM-Newton* or *Chandra* data only (*Figure 3*).

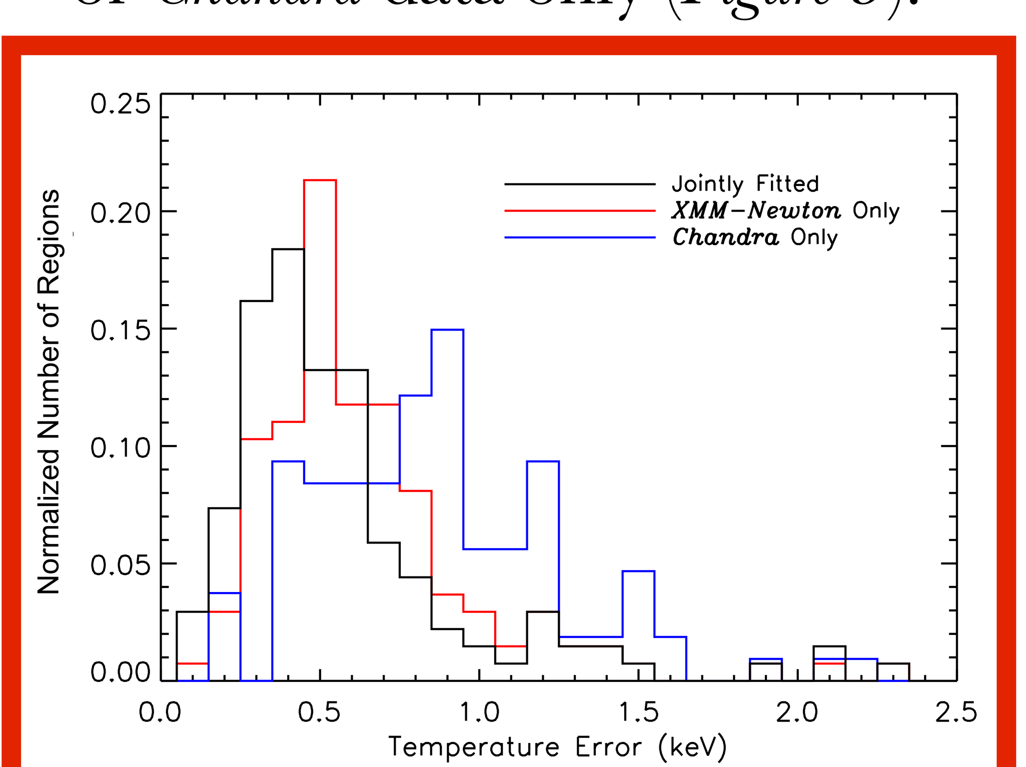


Figure 3: Histogram of temperature errors (90% confidence level) over all Voronoi binned regions within a temperature map. Error distributions are shown for maps of Abell 85 created from spectral fits to *XMM-Newton* only (*red line*), *Chandra* only (*blue line*), and both *XMM-Newton* and *Chandra* jointly fitted (*black line*). High energy channels from EPIC/pn provide a lever arm for improving fits.

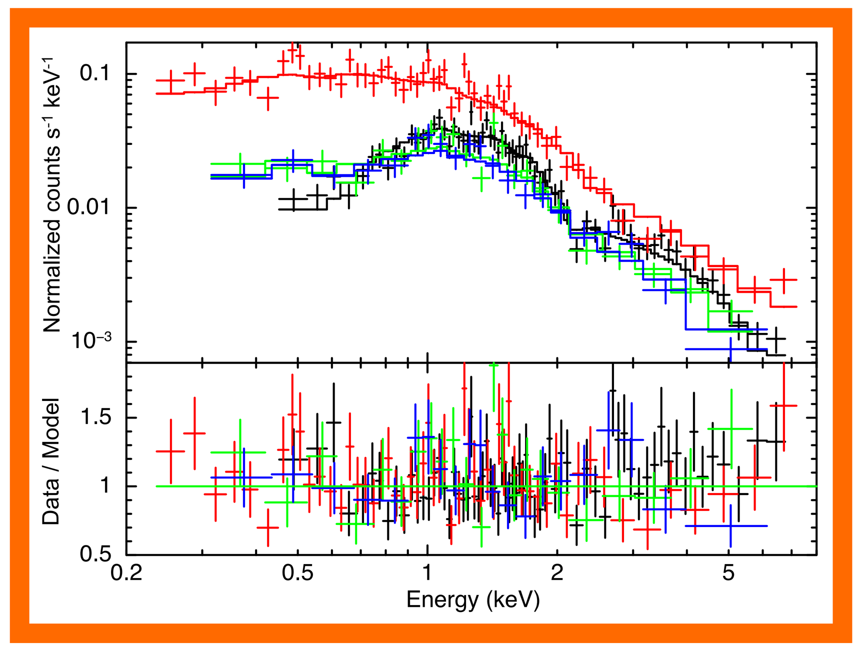


Figure 1: Jointly fitted APEC model to *Chandra* ACIS-I (*black line*) and *XMM-Newton* EPIC/pn, MOS1, MOS2 (*red*, *green*, *blue lines*, *respectively*) spectra for a representative region.

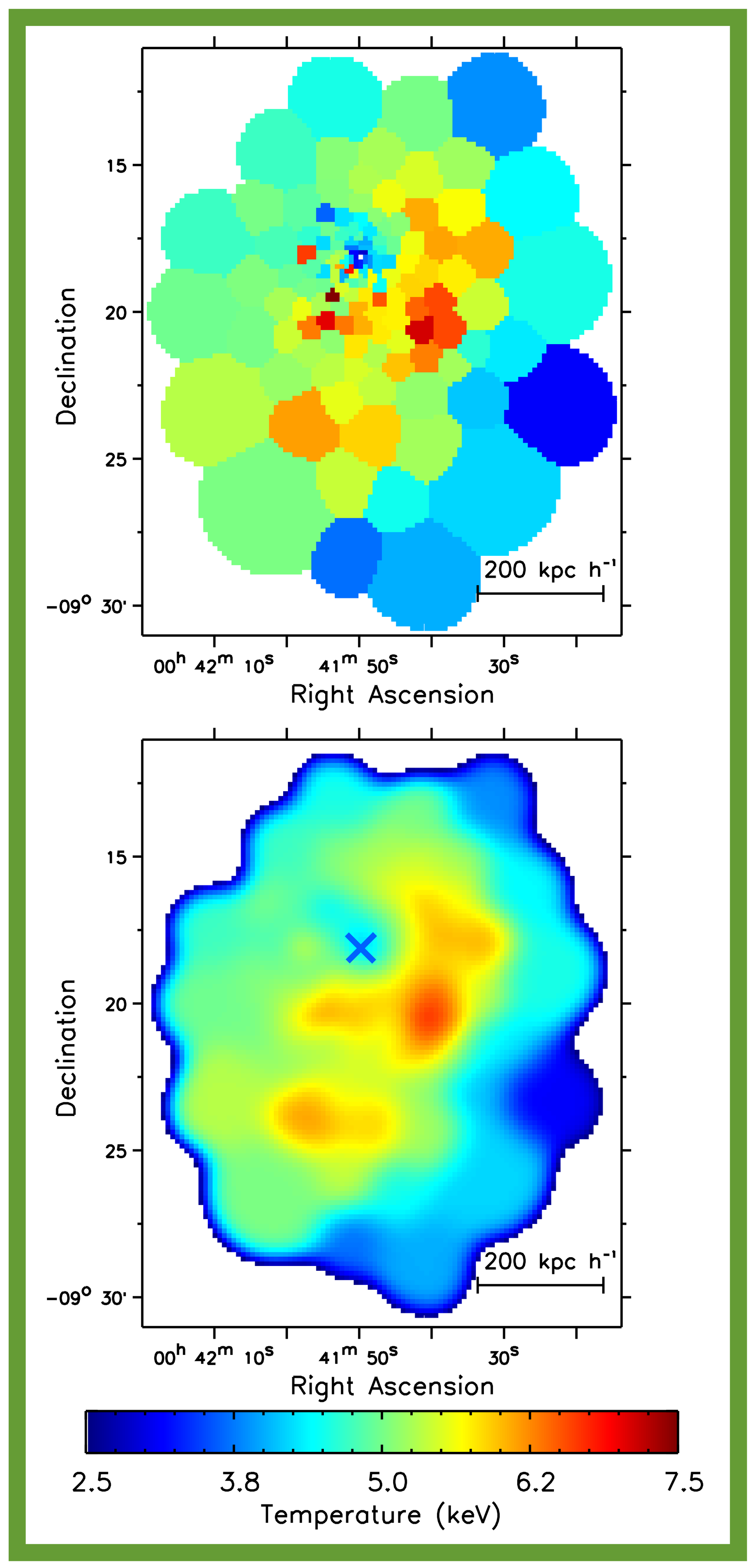


Figure 2: Adaptively binned temperature map of the galaxy cluster Abell 85 ($z \sim 0.055$, $T \sim 6.5$ keV). The binning was determined by a weighted Voronoi tessellation algorithm requiring a $S/N > 5$ per cell. Temperatures were determined from joint fits to *Chandra* and *XMM-Newton* spectra (*top*). Voronoi binned temperature map of Abell 85 smoothed with a Gaussian filter of FWHM ~50 kpc h^{-1} (7.0 pixels). The shock finding algorithm is applied to this smoothed temperature map (*bottom*). The color bar applies to both images. The blue X marks the location of the cool core.

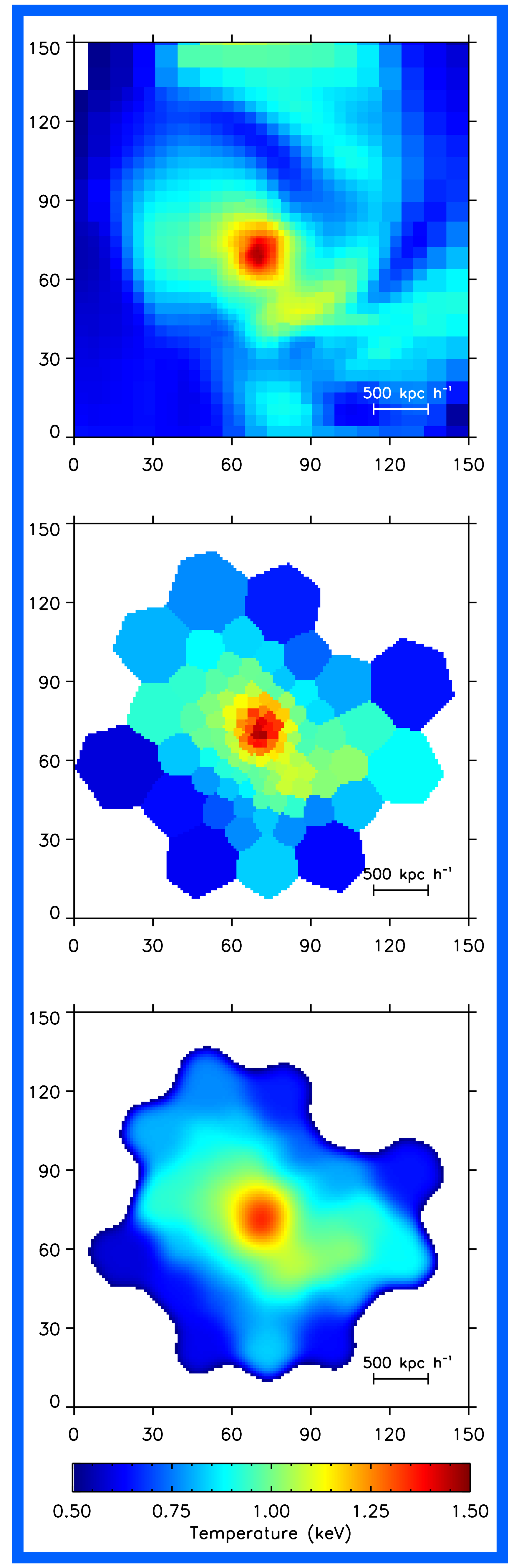
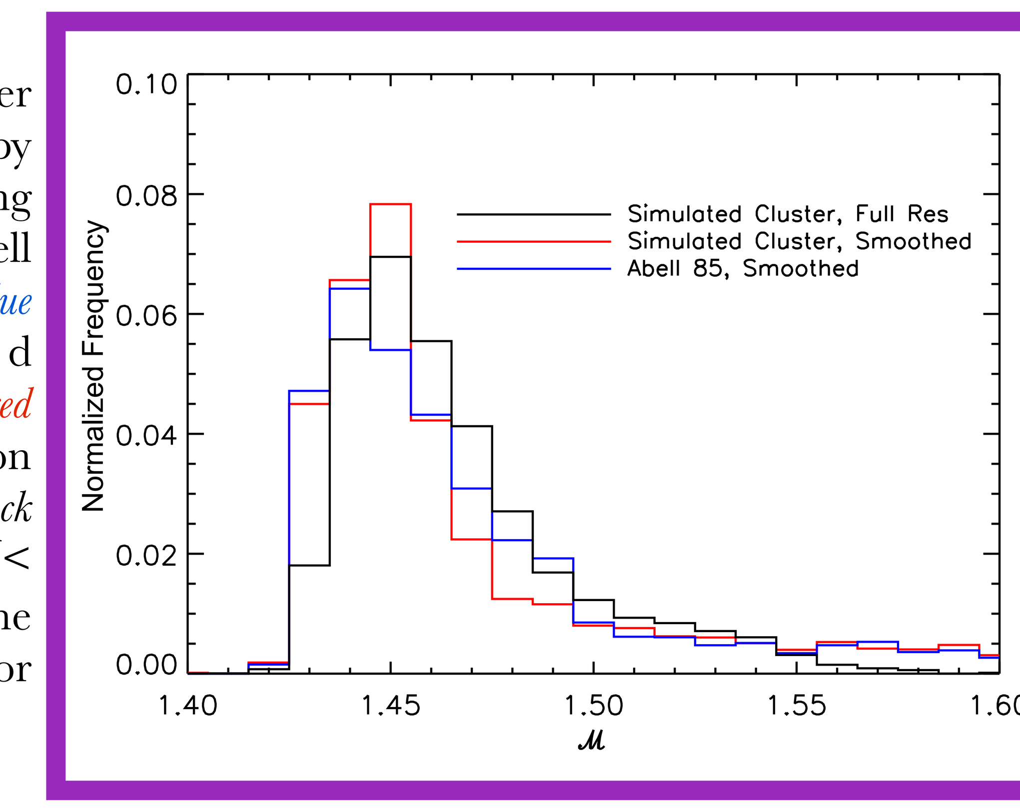


Figure 4: Representative simulated galaxy cluster temperature map created with the *Enzo* *N*-body + hydrodynamic AMR cosmological code with 5 levels of refinement and a maximum resolution of 24.4 kpc h^{-1} (*top*). Voronoi adaptively binned temperature map of the simulated cluster (*middle*). Voronoi binned temperature map smoothed with a Gaussian filter of FWHM ~200 kpc h^{-1} (8.2 pixels). The shock finding algorithm is applied to this smoothed temperature map (*bottom*). The color bar applies to all 3 images and the axes labelings are arbitrary.

Mach Number Distributions for Shocks

- ★ Shock finding algorithm uses temperature gradients in a galaxy cluster temperature map to calculate the distribution of Mach numbers within the cluster (Skillman et al. 2008).
- ★ We generated simulated clusters and temperature maps with the *Enzo* code to test the shock finder.
- ★ The shock finding algorithm was applied to the smoothed temperature map of Abell 85 (*Figure 2, bottom*), the smoothed simulated temperature map (*Figure 4, bottom*), and the highest resolution simulated temperature map (*Figure 4, top*).
- ★ Mach number distributions are shown in *Figure 5*.

Figure 5: Mach number distributions determined by applying our shock finding code to the smoothed Abell 85 temperature map (*blue line*), the smoothed simulated cluster map (*red line*), and the full resolution simulated cluster map (*black line*). Distributions for $\mathcal{M} < 1.4$ are unreliable, as the algorithm breaks down for weakly supersonic shocks.



Conclusions and Future Work

- ★ Temperature maps of Abell 85 produced from joint spectral fitting improve constraints on temperature by 15% and 40% compared to maps generated from *XMM-Newton* or *Chandra* data alone, respectively.
- ★ Systematic offsets in temperature as measured by each observatory individually must be explored.
- ★ Mach number distributions from simulated temperature maps and adaptively binned, smoothed temperature maps show promising agreement for $\mathcal{M} > 1.4$.
- ★ Extend methods to a large sample of clusters.
- ★ Incorporate temperature errors into calculating Mach number distributions and apply robust statistical tests to the shock finding algorithm.

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