Impact of Chandra calibration uncertainties on cluster temperatures: application to $H_0$ from the Sunyaev-Zel'dovich effect

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Collaborators and references


- **Kawahara et al. (2007)**
  - *Radial Profile and Lognormal Fluctuations of the Intracluster Medium as the Origin of Systematic Bias in Spectroscopic Temperature*

- **Kawahara et al. (2008a)**
  - *Systematic Errors in the Hubble Constant Measurement from the Sunyaev-Zel'dovich effect*

- **Kawahara et al. (2008b)**
  - *Extracting Galaxy Cluster Gas Inhomogeneity from X-ray Surface Brightness: A Statistical Approach and Application to Abell 3667*
Temperature of galaxy clusters is ill-defined; mass-weighted, emission-weighted, and spectroscopic temperatures

\[ \langle T \rangle_w = \frac{\int T W dV}{\int W dV} \]

Clusters have multi-phase temperature structure and substructures/fluctuations

<table>
<thead>
<tr>
<th>name</th>
<th>W</th>
</tr>
</thead>
<tbody>
<tr>
<td>( T_m ) mass-weighted</td>
<td>n</td>
</tr>
<tr>
<td>( T_{ew} ) emission-weighted</td>
<td>( n^2 \Lambda(T) )</td>
</tr>
<tr>
<td>( T_{spec} ) spectroscopic</td>
<td>spectral fit</td>
</tr>
<tr>
<td>( T_{sl} ) spectroscopic-like</td>
<td>( n^2T^{-0.75} )</td>
</tr>
</tbody>
</table>

Mazzotta et al. (2004)
Simulated clusters in the local universe

- **SPH simulations** by Dolag et al. (2005)
- **Local universe distribution** in a sphere of $r=110\text{Mpc}$
- **Initial condition:** smoothing the observed galaxy density field of IRAS 1.2 Jy survey (over $5h^{-1}\text{Mpc}$), linearly evolving back to $z=50$
- with cooling, star formation, SN feedback, and metallicity evolution in $\Lambda\text{CDM}$
Projected views of *simulated clusters*

Coma

Perseus

Virgo

Centaurus

A3627

Hydra

1Mpc/h
$T_{\text{spec}}$ is systematically smaller than $T_{\text{ew}}$

- Spectroscopically more weight (more lines) toward cooler regions

- Mazzotta et al. (2004) & Rasia et al. (2005) found $T_{\text{spec}} \sim 0.7 \, T_{\text{ew}}$ from simulations

- We confirm their results using simulated clusters of Dolag et al. (2005) $T_{\text{spec}} \sim 0.8 \, T_{\text{ew}}$

   (see also Mathiesien & Evrard 2001)

An analytic model for $T_{\text{spec}}/T_{\text{ew}}$

- Spherical polytropic $\beta$-model as global mean radial profiles
- Log-normal density and temperature fluctuations
  - Density and temperature correlations ignored
  - Radius independent dispersion adopted
- $\Rightarrow$ Analytic expressions for the temperature underestimate, $T_{sl}/T_{ew}$
  - Explain numerical simulations well

Origin of $T_{\text{spec}} < T_{\text{ew}}$ (1) mean radial profile

- **Density and temperature radial profiles of simulated clusters**

- **Polytropic $\beta$ model**

\[
\langle n \rangle(r) = n_0 \left[ \frac{1}{1 + (r/r_c)^2} \right]^{\beta/2}
\]

\[
\langle T \rangle(r) = T_0 \left[ \frac{\langle n \rangle(r)}{n_0} \right]^{\gamma-1}
\]

Origin of $T_{\text{spec}} < T_{\text{ew}}$ (2) Local inhomogeneity

- Local inhomogeneities of density and temperature of simulated clusters
  - $\delta_n = n(r, \theta, \phi) / <n>(r)$
  - $\delta_T = T(r, \theta, \phi) / <T>(r)$
- Log-normal PDF provides reasonable approximations

$P_{\text{LN}}(\delta) d\delta = \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(\log \delta + \frac{\sigma^2}{2})^2}{2\sigma^2}\right] \frac{d\delta}{\delta}$


$R_s = 6h^{-1}\text{Mpc}/512$
Both the density and temperature fluctuations can be approximated by lognormal distribution:

\[
P(\delta_x; \sigma_{LN,x}) \, d\delta_x = \frac{1}{\sqrt{2\pi} \sigma_{LN,x}} \exp\left[-\frac{(\log \delta_x + \sigma_{LN,x}^2/2)^2}{2\sigma_{LN,x}^2}\right] \frac{d\delta_x}{\delta_x}
\]

\[
\delta_x \equiv \frac{x(r)}{\langle x \rangle} \quad (x = n \text{ or } T)
\]
Each radial bin
Fluctuation (data)
Lognormal function

$$\delta_T \equiv \frac{T(r)}{\overline{T}(r)}^2$$

Other 6 + 2 clusters

$$\delta_n \equiv \frac{n(r)}{\overline{n}(r)}^2$$
Application to a real cluster: A3667

Good agreement with the Lognormal distribution

Estimated value of the density fluctuation:
\[ \sigma_{\text{LN},n} = \left[ 0.75 + \frac{50}{(\alpha_{\text{Sx}} - 0.2)^4} \right] \sigma_{\text{LN},\text{Sx}} \sim 0.4 \]

The Hubble constant measurement using galaxy clusters

- SZ: primary distance indicator
- Assumption: the spherical isothermal $\beta$ model

\[ d_A = \frac{L}{\theta} \]

\[ H_0 = \frac{cz}{d_A(z)} \left[ 1 + \frac{2\lambda_0 - \Omega_0 - 6}{4}z + \mathcal{O}(z^2) \right] \]

\[ \frac{\Delta I}{I} \propto y \approx nT L \]

+ X-ray brightness

\[ S_x \propto n^2 \Lambda_x(T) L \]

+ spectroscopic $T$

\[ T = T_{\text{spec}} \rightarrow \text{length } L \]
Isothermal $\beta$ -model fit by force

- Isothermal $\beta$ -model fit to polytropic density and temperature profiles
  \[
  < n >(r) = n_0 \left[ \frac{1}{1 + (r / r_c)^2} \right]^{3\beta/2}
  \]
  \[
  < T >(r) = T_0 \left[ \frac{< n >(r) / n_0}{n_0} \right]^{\gamma-1}
  \]
- Core radius estimated from X-ray + SZ
  \[
  r_{c,iso\beta}(T_{spec}) = \frac{y(0)^2}{S_X(0)} \frac{m_e^2 c^4 \Lambda(T_{spec})}{4\pi (\sigma_T k T_{spec})^2 (1 + z)^4} \frac{G(\beta_{fit})}{G(\beta_{fit} / 2)^2}
  \]
  \[
  \beta_{fit} = \beta \frac{\gamma + 3}{4}
  \]
Analytic modeling of $H_0$ measurement

- Spherical polytropic $\beta$-model as mean radial profiles
- Log-normal density and temperature fluctuations
- Still fit to the isothermal $\beta$-model by force, and the estimated $H_0$ is biased as

\[
\int_{H_0,\text{polyLN|iso}\beta} H_0,\text{est} \equiv \frac{H_0,\text{est}}{H_0,\text{true}} = \chi_\sigma \frac{\chi_T(T_{\text{ew}})}{\chi_T(T_{\text{spec}})}
\]

inhomogeneity \quad $\chi_\sigma = \exp\left(\sigma_{\text{LN},n}^2 - \sigma_{\text{LN},T}^2 / 8\right) \approx (1.1 - 1.3)$

non-isothermality \quad $\chi_T(T_{\text{ew}}) = \frac{J(\beta, \gamma, r_c / r_{\text{vir}})^{1.5}}{G(\beta (\gamma + 3)/8)} \approx (0.8 - 1)$

temperature bias \quad $\frac{\chi_T(T_{\text{spec}})}{\chi_T(T_{\text{ew}})} \approx \left(\frac{T_{\text{spec}}}{T_{\text{ew}}}\right)^{1.5} \approx (0.8 - 0.9)$

If $T = T_{ew}$, our results are consistent with the previous numerical studies (Inagaki et al. 1995, Yoshikawa et al. 1998)
Analytic model vs Simulation

\( T = T_{\text{spec}} \)

Symbols with error bar: mock observation of simulated clusters

Green: theoretical prediction \( \chi_\sigma \chi_T(T_{\text{spec}}) \)

\( H_{0,\text{est}} / H_{0,\text{true}} \)

Underestimate

Overestimate

\( f_H \)

\( T_{\text{cl}} = T_{\text{spec}} \)

- ■ SZ+X clusters should underestimate the value of \( H_0 \) by 10-20\%
Mean values are in good agreement with the analytic model.

Additional small bias expected due to non-sphericity of clusters even after averaging over l.o.s. angles.

Skewed distribution due to the prolateness

Previous studies did not find the large bias because we set $T_{cl}=T_{ew}$ instead of $T_{spec}$ (Inagaki, Suginohara & YS 1995, Yoshikawa, Itoh & YS 1998), consistent with our results of the isothermal fit with $T_{ew}$
Summary of theoretical predictions

- \( \frac{H_{0,\text{est}}}{H_{0,\text{true}}} = 0.8-0.9 \) from simulated clusters
- Analytic modeling of \( H_0 \) from the SZ effect
- \( \frac{H_{0,\text{est}}}{H_{0,\text{true}}} = 0.8-0.9 \) from simulated clusters is well explained by the combination of inhomogeneity and non-isothermality of ICM
- Is this consistent with the existing SZ observations?
H$_0$ estimated from the SZ effect

- **ROSAT+SZ:**
  - $60 \pm 3$ km/s/Mpc
    (Reese et al. 02)

- **Chandra+SZ**
  - $76.9^{+3.9}_{-3.4}^{+10.0}_{-8.0}$ km/s/Mpc
    (Bonamente et al. 06)

- **WMAP:**
  - $73 \pm 3$ km/s/Mpc
    (Spergel et al. 07)

- Which is believable
  (if any at all !) ?
The same SZ but different X-ray data

- Reese et al. (2002)
  - 60 km/s/Mpc with ROSAT
- Bonamente et al. (2006)
  - 77 km/s/Mpc with Chandra
  - calibration data ver.3.1
- Chandra calibration data revision (2009)
  - Jan. 2009 ver.4.1: effective area of mirror
  - Dec. 2009 ver.4.2: ACIS (AXAF CCD Imaging Spectrometer) contamination model
Majority of clusters are observed with ACIS-I (front illuminated chips).

Ver. 3.1 overestimates A, and thus T as well.
Spectroscopic temperatures

Relative to the latest calibration data (ver. 4.2)

- Ver. 3.1 overestimates $T$ by 6%
- Ver. 4.1 underestimates $T$ by 7%
X-ray emissivity
The Hubble constant of each SZ cluster

\[ \frac{H_{0,2}}{H_{0,1}} = \left( \frac{T_2}{T_1} \right)^2 \frac{\Lambda_{\text{eff}}(T_1)}{\Lambda_{\text{eff}}(T_2)} \frac{\Lambda_{\text{eff}}(T_1)}{\Lambda_{\text{eff}}(T_1)} \frac{A_1(E_{\text{fid}})}{A_2(E_{\text{fid}})} \]

\[ \Omega_{\Lambda} = 0.73, \quad \Omega_m = 0.27 \text{ assumed} \]
Angular diameter distances

$\Omega_\Lambda = 0.73, \ \Omega_m = 0.27$ assumed
Abundances

[Graphs showing data points and trends related to abundances, with annotations for 3.1, 4.1, and ASCA.]
Summary of comparison

Table 3. Compilation of Mean Ratios: Updated A2163 $N_H$

<table>
<thead>
<tr>
<th>parameter</th>
<th>3.1/4.2</th>
<th>4.1/4.2</th>
<th>3.1/B06</th>
<th>4.1/B06</th>
<th>4.2/B06</th>
<th>ASCA/4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_e$</td>
<td>1.06 ± 0.05</td>
<td>0.93 ± 0.03</td>
<td>1.05 ± 0.11</td>
<td>0.92 ± 0.10</td>
<td>0.99 ± 0.11</td>
<td>0.98 ± 0.12</td>
</tr>
<tr>
<td>$Z$</td>
<td>1.08 ± 0.21</td>
<td>0.96 ± 0.04</td>
<td>1.16 ± 0.43</td>
<td>1.03 ± 0.31</td>
<td>1.08 ± 0.34</td>
<td>0.66 ± 0.28</td>
</tr>
<tr>
<td>$A_{\text{eff}}$</td>
<td>1.01 ± 0.01</td>
<td>1.01 ± 0.01</td>
<td>1.03 ± 0.07</td>
<td>1.03 ± 0.07</td>
<td>1.02 ± 0.07</td>
<td>0.66 ± 0.28</td>
</tr>
<tr>
<td>$f_{(\nu,T_e)}$</td>
<td>0.998 ± 0.002</td>
<td>1.002 ± 0.001</td>
<td>0.999 ± 0.003</td>
<td>1.003 ± 0.004</td>
<td>1.001 ± 0.003</td>
<td>0.66 ± 0.28</td>
</tr>
<tr>
<td>$A(1\text{kev})^a$</td>
<td>1.01 ± 0.02</td>
<td>0.95 ± 0.01</td>
<td>0.96 ± 0.10</td>
<td>0.91 ± 0.10</td>
<td>0.95 ± 0.10</td>
<td>0.66 ± 0.28</td>
</tr>
<tr>
<td>$d_A^b$</td>
<td>0.93 ± 0.08</td>
<td>1.13 ± 0.06</td>
<td>1.06 ± 0.24</td>
<td>1.29 ± 0.29</td>
<td>1.15 ± 0.25</td>
<td>1.07 ± 0.37</td>
</tr>
</tbody>
</table>

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- $^a$B06 are the effective areas from the 3.1 calibration using only those data sets that appear in Bonamente et al. 2006.
- $^b$B06 are the published distances from Bonamente et al. 2006.

- Systematic difference between different calibration data of Chandra
Compilation of $H_0$ results

<table>
<thead>
<tr>
<th></th>
<th>DL A2163 $N_H$</th>
<th>Updated A2163 $N_H$</th>
<th>No A2163</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\chi^2$ Full sample</td>
<td>38</td>
<td>38</td>
<td>37</td>
</tr>
<tr>
<td>$H_0^{3.1}$</td>
<td>$82.8 \pm 4.6 (75.9)$</td>
<td>$70.0 \pm 3.7 (40.6)$</td>
<td>$69.7 \pm 3.7 (40.5)$</td>
</tr>
<tr>
<td>$H_0^{4.1}$</td>
<td>$58.4 \pm 3.1 (42.4)$</td>
<td>$55.4 \pm 2.9 (34.3)$</td>
<td>$55.5 \pm 2.9 (34.3)$</td>
</tr>
<tr>
<td>$H_0^{4.2}$</td>
<td>$68.8 \pm 3.7 (52.2)$</td>
<td>$63.7 \pm 3.3 (38.8)$</td>
<td>$63.7 \pm 3.4 (38.8)$</td>
</tr>
<tr>
<td>$\chi^2$ R02 overlap</td>
<td>17</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>$H_0^{3.1}$</td>
<td>$90.1 \pm 7.0 (48.5)$</td>
<td>$66.9 \pm 4.7 (15.8)$</td>
<td>$66.1 \pm 4.8 (15.5)$</td>
</tr>
<tr>
<td>$H_0^{4.1}$</td>
<td>$58.2 \pm 4.1 (21.2)$</td>
<td>$52.3 \pm 3.6 (11.8)$</td>
<td>$52.2 \pm 3.8 (11.8)$</td>
</tr>
<tr>
<td>$H_0^{4.2}$</td>
<td>$70.1 \pm 5.1 (28.7)$</td>
<td>$60.5 \pm 4.3 (14.4)$</td>
<td>$60.2 \pm 4.4 (14.3)$</td>
</tr>
<tr>
<td>Avg Full sample</td>
<td>38</td>
<td>38</td>
<td>37</td>
</tr>
<tr>
<td>$H_0^{3.1}$</td>
<td>$66.1 \pm 30.3$</td>
<td>$62.9 \pm 21.7$</td>
<td>$62.6 \pm 21.9$</td>
</tr>
<tr>
<td>$H_0^{4.1}$</td>
<td>$52.5 \pm 17.2$</td>
<td>$51.3 \pm 15.4$</td>
<td>$51.2 \pm 15.6$</td>
</tr>
<tr>
<td>$H_0^{4.2}$</td>
<td>$59.7 \pm 22.1$</td>
<td>$58.0 \pm 18.9$</td>
<td>$57.8 \pm 19.1$</td>
</tr>
<tr>
<td>Avg R02 overlap</td>
<td>17</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>$H_0^{3.1}$</td>
<td>$68.3 \pm 36.1$</td>
<td>$61.2 \pm 17.6$</td>
<td>$60.4 \pm 17.7$</td>
</tr>
<tr>
<td>$H_0^{4.1}$</td>
<td>$51.8 \pm 16.9$</td>
<td>$49.2 \pm 12.0$</td>
<td>$48.9 \pm 12.3$</td>
</tr>
<tr>
<td>$H_0^{4.2}$</td>
<td>$60.0 \pm 23.3$</td>
<td>$56.1 \pm 15.5$</td>
<td>$55.6 \pm 15.9$</td>
</tr>
<tr>
<td>$\chi^2$ B06 refit</td>
<td>38</td>
<td></td>
<td>37</td>
</tr>
<tr>
<td>$H_0^{B06}$</td>
<td>$76.2 \pm 4.1 (55.9)$</td>
<td>$\ldots$</td>
<td>$73.5 \pm 4.1 (51.7)$</td>
</tr>
<tr>
<td>$\chi^2$ R02 refit</td>
<td>18</td>
<td>17</td>
<td>16</td>
</tr>
<tr>
<td>$H_0^{R02}$</td>
<td>$60.8 \pm 4.0 (16.5)$</td>
<td>$60.5 \pm 4.1 (16.4)$</td>
<td>$60.7 \pm 4.3 (16.4)$</td>
</tr>
</tbody>
</table>

DL: Dickey & Lockman (1990)

R02: Reese et al. (2002)

B06: Bonamente et al. (2006)

$\Omega$ $\Lambda = 0.73$

$\Omega$ $m = 0.27$

assumed
### Ups and downs of $H_0$ from SZ+Xray

<table>
<thead>
<tr>
<th>X-ray data</th>
<th>$H_0$ [km/s/Mpc]</th>
<th>reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>ROSAT+ASCA</td>
<td>60±3</td>
<td>Reese et al. (2002)</td>
</tr>
<tr>
<td>Chandra: ver. 3.1</td>
<td>$77^{+3.9}_{-3.4}$</td>
<td>Bonamente et al. (2006)</td>
</tr>
<tr>
<td>WMAP</td>
<td>73±3</td>
<td>Spergel et al. (2007)</td>
</tr>
<tr>
<td>Chandra: ver. 3.1</td>
<td>70.0±3.7</td>
<td>this work</td>
</tr>
<tr>
<td>Chandra: ver. 4.1</td>
<td>55.4±2.9</td>
<td>this work</td>
</tr>
<tr>
<td>Chandra: ver. 4.2</td>
<td>63.7±3.3</td>
<td>this work</td>
</tr>
</tbody>
</table>
Conclusions

- X-ray calibration is not robust as believed before
  - Cluster temperature may vary $\pm 7\%$
  - $H_0$ combined with SZ may vary $\pm 12\%$
- If the latest Chandra calibration data (ver.4.2) is the most reliable, $H_0(SZ) \sim 0.9H_0(WMAP)$
  - This might indicate the presence of the inhomogeneities in intra-cluster medium (Kawahara et al. 2008a)
- Possible systematics for cluster cosmology in general
  - Previous results based old Chandra calibration need to be re-examined
  - Mass-temperature relation of clusters
  - Cluster abundances and $\sigma_8$