Baryon Census in Hydrodynamical Simulations of Galaxy Clusters

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Galaxy Clusters as Giant Cosmic Laboratories
XMM-Newton Science Workshop 2012
Madrid, 21st-23rd May 2012
• **Introduction**
  • Galaxy clusters
  • Clusters as cosmological probes

• **Cosmological simulations**
  • DIANOGA cluster set  (S. Borgani’s talk)

• **Preliminary results**
  • Baryon content
  • Cosmological implications

• **Summary and future directions**
• **Largest virialized structures** in the Universe: $M \approx 10^{13} \text{-} 10^{15} M_\odot$, $R \approx 1\text{-}3 \text{ Mpc}$

• Composition: galaxies and stars ($\approx 5\%$), ICM ($\approx 15\%$), DM ($\approx 80\%$)

• **Baryon budget**: stars in galaxies + ICL + ICM

• **Baryonic mass fraction**:

$$ f_b = f_{st} + f_{gas} = f_{gas}(1 + s) \quad s \equiv \frac{f_{st}}{f_{gas}} $$

$$ f_{gas} = \frac{M_{gas}}{M_{tot}} \quad f_{st} = \frac{M_{st}}{M_{tot}} $$

• **Galaxy clusters at X-ray wavelengths**:
  
  • Gravity squeezes gas, heating it to X-ray temperatures
  
  • Clusters only shine in X-rays if they are massive
    
    $\Rightarrow$ clean cluster surveys
  
  • **X-ray observables** $\Leftrightarrow M_{tot} \Rightarrow$ hydro. simulations
Galaxy Clusters

ROLE OF CLUSTERS IN COSMOLOGY

• Cosmological probes:
  • Fair sample of the matter content of the Universe \( \Rightarrow \frac{M_b}{M_{tot}} \sim \frac{\Omega_b}{\Omega_m} \) (White & Frenk 1991)
  • Constraints on cosmological parameters:
    • \( f_b \) (X-ray) + \( \Omega_b h^2 \) (CMB/BBNS) + \( h \) \( \Rightarrow \Omega_m \) (e.g., White & Frenk 1991)
    • Apparent z-evolution of \( f_{gas} \) \( \Rightarrow \) geometry of the Universe (e.g., Allen et al. 2008)

• Challenges:
  • Observed \( f_{gas} \) smaller than expected
  • Intriguing trend with cluster mass

• Possible explanations:
  • Physical processes which lower \( f_b \)
  • Undetected baryon components
  • Systematic underestimate of \( \Omega_m \) by WMAP

\[ f_b (X-ray) + \Omega_b h^2 (CMB/BBNS) + h \Rightarrow \Omega_m \]

Laganá et al. 2011

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Purpose of the Present Work

- Understanding the baryon-mass fraction and its mass and $z$ dependence is crucial to understand astrophysics in galaxy clusters.

- **Our tools**: a set of hydrodynamical re-simulations of galaxy clusters, characterized by different physical processes, including AGN feedback.

- **Main objectives**:
  - **Baryon content**: to study how the fraction and spatial distribution of the baryons are affected by the physical conditions within clusters.
  - **Cosmological implications**: to analyse some implications for the constraints on cosmological parameters over a large redshift range ($z \lesssim 1$).
Cosmological Simulations

DIANOGA CLUSTER SET

• General properties  (S. Borgani’s talk)
  • Parallel Tree-PM SPH code GADGET-3  (Springel 2005)
  • $\Lambda$CDM model: $\Omega_m=0.24$, $\Omega_\Lambda=0.76$, $\Omega_b=0.04$, $h=0.72$, $\sigma_8=0.8$, $n_s=0.96$
  • Re-simulation of 29 Lagrangian regions centred around clusters with $M_{\text{vir}} \geq 10^{15} M_\odot h^{-1}$ (24) and $M_{\text{vir}} \approx (1-7) \times 10^{14} M_\odot h^{-1}$ (5)
  • Parent DM-only simulation: 1024$^3$ DM particles; $L_{\text{box}}=1 \text{ Gpc} h^{-1}$

• Physics included
  • $NR$: non-radiative run
  • $CSF-M-W$: cooling, SF, metals and SN feedback ($v_w=500 \text{ km s}^{-1}$)
  • $CSF-M-W-AGN$: cooling, SF, metals, SN feedback ($v_w=350 \text{ km s}^{-1}$) and AGN feedback

• The set of simulated clusters
  • Final sample: 140 clusters with $M_{500} \geq 5 \times 10^{13} M_\odot h^{-1}$ ($\approx 30$ with $M_{\text{vir}} \geq 10^{15} M_\odot h^{-1}$)
  • Cluster identification: minimum potential + SO method

\[
M_\Delta = \Delta \rho_c(z) \left( 4 \pi / 3 \right) R_\Delta^3 \quad (\Delta=2500, 500, 200)
\]
Baryon content

BARYON MASS FRACTION

- **NR & CSF-M-W runs:**
  - $f_b$ appears flat as a function of $M_{500}$
  - $f_b$ differs by $\leq 10\%$ from the assumed cosmic fraction
    (e.g., Kravstov et al. 2005, Ettori et al., 2006)

- **CSF-M-AGN run:**
  - Significant baryon depletion for $M_{500} \leq 10^{14} M_\odot h^{-1}$
  - $f_b$ is closer to the cosmic value for the most massive clusters
  - Better agreement with observations when including AGN feedback

\[ f_b = f_{st} + f_{gas} \]
**Baryon content**

**GAS MASS FRACTION**

- **NR run:**
  - \( f_g \) appears flat as a function of \( M_{500} \)
  - \( f_g \) is larger than in the radiative runs

- **Radiative runs:**
  - \( f_g \) increases as a function of mass
  - AGN feedback significantly reduces:
    - \( f_g \) in poor clusters and groups
    - overcooling in the richest clusters
  - \( f_g \) is still smaller than the observed value
• General behaviour:
  • $f_{st}$ decreases smoothly with increasing mass and flattens for $M_{500} \leq 10^{14} M_{\odot} h^{-1}$

• CSF-M-W:
  • $f_{st}$ is quite large: $\sim (30\%-50\%) f_b$

• CSF-M-AGN:
  • $f_{st}$ is lowered by $\sim 1/3$ but still larger than observations by a factor 2-3
  • None of our simulations reproduce the observed strong trend of $f_{st}$ with mass
INTRODUCTION

- **Basic idea**: galaxy clusters are so large that their matter content should provide a \(~\) fair sample of matter content of the Universe \(\) (White & Frenk 1991)

- **Constraining \(\Omega_{m}\)**: \(\) (e.g., Allen at al. 2008)

\[
\begin{align*}
  f_b &= Y_b \frac{\Omega_b}{\Omega_{m}} \\
  s &= \frac{f_{st}}{f_{gas}}
\end{align*}
\]

\[
\Rightarrow \quad \Omega_{m} = \frac{Y_b \Omega_b}{f_{gas}(1 + s)}
\]

- **Main assumptions**: 1) \(Y_b\) does not evolve with \(z\)  
  2) The ratio \(s=f_{st}/f_{gas}\) holds constant at any radius and \(z\)

- **Main advantages**:  
  - This test can be performed with a small statistics  
  - Relative insensitivity to cluster selection
**Cosmological implications**

**BARYONIC BIAS**

- **Reduced sample**: the hottest \((T_{sl} \geq 4\) keV) and most X-ray luminous galaxy clusters

- **Results on \(Y_b\):**
  
  - **Within \(R_{500}\):**
    - \(Y_b \approx (0.86 \pm 0.03)\)
    - \(Y_b \approx (0.85 \pm 0.02)\)
    - \(Y_b \approx (0.85 \pm 0.03)\)
  
  - **Within \(R_{2500}\):**
    - \(Y_b \approx (0.84 \pm 0.06)\)
    - \(Y_b \approx (0.85 \pm 0.07)\)
    - \(Y_b \approx (0.79 \pm 0.09)\)

- Roughly constant up to \(z=1\) (e.g., Eke et al. 1998, Kravstov et al. 2005)

- Dependence on physics within \(R_{2500}\)
Cosmological implications

• Main assumptions: 1) $Y_b$ does not evolve with $z$
  2) The ratio $s = f_{st}/f_{gas}$ holds constant at any radius and $z$

• However, these assumptions are not completely valid in our simulated dataset!
  $\Rightarrow$ we evaluate how $\Omega_m$ changes due to the variation of $Y_b$ ($\equiv D_b$) and $s$ ($\equiv D_{st}$) as a function of $R_\Delta$, $z$, and physics:

\[
D_b \equiv \frac{\Omega'_m - \Omega_m}{\Omega_m} = \frac{\Delta \Omega_m}{\Omega_m} = \frac{Y_b(< R_\Delta, z = z_0)}{Y_b(< R_\Delta, z = 0)} - 1
\]

\[
D_{st} \equiv \frac{\Omega'_m - \Omega_m}{\Omega_m} = \frac{\Delta \Omega_m}{\Omega_m} = \frac{1 + s(< R_\Delta, z = 0)}{1 + s(< R_\Delta, z = z_0)} - 1
\]  

(Ettori et al. 2006)

\[
R_\Delta = (R_{vir}, R_{200}, R_{500}, R_{2500}) \quad z_0 = (0.3, 0.5, 0.8, 1)
\]
Cosmological implications

**DEVIATIONS FROM THE MODEL**

- **NR runs**
  - Correction to $\Omega_m$ due to the variation of $Y_b$ with $z$ and overdensity

- **Radiative runs**
  - $\Delta \Omega_m/\Omega_m$ has two contributions due to the variation with $z$ of $Y_b$ and $s$

- Different physical models $\Rightarrow$ different $z$-dependent corrections to $\Omega_m$
Main conclusions

• Consistency with observations in $f_b=f(M_{500})$ and $f_g=f(M_{500})$.
• None of our simulations is able to reproduce the observed $f_{st}=f(M_{500})$.
  However, better agreement with observations when AGN feedback is included.
• $Y_b \approx$ constant with $z$ but shows some dependence on physics within $R_{2500}$

Future directions

• Analyse in detail the different stellar components (ICL+BCG+satellites)
• Constraints on $\Omega_m-\Omega_\Lambda$ using $f_{\text{gas}}(z) \propto d_{\text{ang}}(z, \Omega_m, \Omega_\Lambda, w)$
"I think you should be more explicit here in step two."

Thank you!
## Baryon content

### Observational Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lin et al. (2003)</td>
<td>$f_{b,500} = 0.148^{+0.005}<em>{-0.004}(M</em>{500}/[3 \times 10^{14} M_\odot])^{(0.148\pm0.040)}$</td>
</tr>
<tr>
<td>Giodini et al. (2009)</td>
<td>$f_{b,500} = (0.123 \pm 0.003)(M_{500}/[2 \times 10^{14} M_\odot])^{(0.09\pm0.03)}$</td>
</tr>
<tr>
<td>Laganá et al. (2011)</td>
<td>$f_{b,500} = 10^{-0.930\pm0.018}(M_{500}/10^{14} M_\odot)^{(0.136\pm0.028)}$</td>
</tr>
<tr>
<td>Z11+S09</td>
<td>$f_{g,500} = 10^{-(1.07\pm0.02)}(M_{500}/[10^{14} M_\odot])^{(0.30\pm0.07)}$</td>
</tr>
<tr>
<td>V06+APP07+S09</td>
<td>$f_{g,500}(h/0.7)^{3/2} = (0.093 \pm 0.002)(M_{500}/[2 \times 10^{14} M_\odot])^{(0.21\pm0.03)}$</td>
</tr>
<tr>
<td>Lin et al. (2003)</td>
<td>$f_{s,500} = 0.0164^{+0.0010}<em>{-0.0090}(M</em>{500}/[3 \times 10^{14} M_\odot])^{-(0.26\pm0.09)}$</td>
</tr>
<tr>
<td>Gonzalez et al. (2007)</td>
<td>$f_{s,500} = 10^{7.57\pm0.08}M_{500}^{-(0.64\pm0.13)}$</td>
</tr>
<tr>
<td>Giodini et al. (2009)</td>
<td>$f_{s,500} = (0.050 \pm 0.001)(M_{500}/[5 \times 10^{13} M_\odot])^{(-0.26\pm0.09)}$</td>
</tr>
<tr>
<td>Laganá et al. (2011)</td>
<td>$f_{s,500} = 10^{-1.54\pm0.10}(M_{500}/[10^{14.5} M_\odot])^{(-0.36\pm0.17)}$</td>
</tr>
</tbody>
</table>
Baryon content

INTRA CLUSTER LIGHT

Gonzalez et al. 2007
CSF-M-W

Gonzalez et al. 2007
CSF-M-W-AGN