Searching for Missing Baryons with the Sunyaev-Zel’dovich effect

José Alberto Rubiño Martín
(IAC-Tenerife)
Outline

- The “missing baryon” problem and the Sunyaev-Zel’dovich effect.
- The Very Small Array (VSA)
- A survey with the VSA in the Corona Borealis Supercluster
  - Observational Data
  - Discussion
  - Follow-up observations
- Conclusions
Cosmic Baryon Budget

BBN:
\[ \Omega_b h^2 = 0.020 \pm 0.001 \]
(Burles, Nollett & Turner 2001)

CMB:
\[ \Omega_b h^2 = 0.0224 \pm 0.0009 \]
(WMAP; Spergel et al. 2003)

Ly\(\alpha\) forest:
\[ \Omega_b h^2 \geq 0.017 \text{ at } z=2 \]
(Weinberg et al 1997; Rauch 1998)

Local Universe:
\[ \Omega_* + \Omega_{HI} + \Omega_{H2} + \Omega_{\text{cluster}} \approx 0.0068 \leq 0.011 \text{ (2\sigma)} \]
(Fukugita et al 1997)
Half of the baryons at present time should have $T$ in the range $10^5 - 10^7$ K

**WHIM:** Warm-Hot Intracluster Medium
How to observe this warm gas?

- **Soft X-ray background** (Wang & McCray 1993 present evidence of a diffuse thermal component in ROSAT deep images with a temperature $2.2 \cdot 10^6$ K; Zappacosta et al. 2004 claim to detect WHIM at Sculptor SC using soft ROSAT data; Soltan, Freyberg & Hasinger 2004 show excess emission of 1.3% consistent with $T_e \sim 0.5$ keV).

- **X-ray absorption forest due to ionized oxigen** (OVII 574 eV) (Hellsten et al. 1998; Nicastro et al. 2004 claim detection of filaments along LOS of two blazars at $z = 0.03$ and $z = 0.361$)

- ...

- **Thermal Sunyaev-Zel'dovich** effect on the CMB photons could trace the presence of hot, ionized gas in cosmological scales.
Thermal Sunyaev-Zel’dovich Effect

\[ \frac{\delta T_{tSZ}}{T_0} = g(\nu) \int d\mathbf{r} \sigma_T n_e(\mathbf{r}) \frac{k_B T_e(\mathbf{r})}{m_e c^2} = g(\nu) \frac{\sigma_T}{m_e c^2} \int d\mathbf{r} \ p_e(\mathbf{r}) \]

Comptonization parameter: \( y \equiv \int d\mathbf{r} \sigma_T n_e(\mathbf{r}) \frac{k_B T_e(\mathbf{r})}{m_e c^2} \)
Observing the WHIM with the SZ effect

Do we expect to detect SZE signal from these baryons in supercluster scales?

- \( T_e \sim 10^5 - 10^7 \) K
- \( L \sim 1-10 \) Mpc
- \( n_e \sim \) few times the cosmological baryonic density

\[
\delta T_{tSZ}\mid_{RJ} \approx -2\mu K \left( \frac{L}{10\, Mpc} \right) \left( \frac{n_e}{10^{-5}\, cm^{-3}} \right) \left( \frac{T_e}{10^7\, K} \right)
\]
• SZ observations are sensitive to lower temperatures than bremmstrahlung
• Most of SZ luminosity from the WHIM (~70%) is generated in regions with $\delta>10$, mostly galaxy groups (Hernández-Monteagudo et al. 2006). SZ surveys should find huge number of these objects.
CMB Experiments at the Teide Observatory
The Very Small Array
**Very Small Array (VSA)**

**Type:** 14-element.

**Scanning:** Tracking by antennas co-mounted on tip-tilt table. Horns rotate E-W.

**Pointing range:** H.A.: ± 3 hrs  Dec.: -6° to +63°

**Antennas:** Corrugated horn feeding 90 degree-offset paraboloidal mirror.

**Receivers:** NRAO design pseudomorphic HEMTs cooled to 15K with Noise temp. of 25K.

**Frequency:** 31 GHz ± 5 GHz  (Compact 34.1 GHz, Extended mostly 33.0 GHz)

**Bandwidth:** 1.5 GHz

**1st LO:** 20-30 GHz

**2nd LO:** 9.0 GHz (fixed)

**Baselines:** 91

**Correlator:** 182 analogue phase-switched channels
The VSA antennas

Compact array

- Primary beam: 4.5°
- Resolution: 30 arcmin
- $\ell$ range: 100 – 800
- Sensitivity: 30 mJy in 300 hrs

Extended array

- Primary beam: 2.0°
- Resolution: 12 arcmin
- $\ell$ range: 250 – 1500
- Sensitivity: 6 mJy in 300 hrs
VSA Source subtraction system

**Type:** 2-element (double side-band) 3.7 m Cassegrain parabolic dishes

**Baseline:** 9 m separation N-S

**Primary beam:** 12’ Resolution: 3’

**Correlator:** 4 analogue phase-switched channels

**Sensitivity:** 5 mJy in 1 hour

*Source substraction strategy:* we use the Ryle Telescope at 15GHz (5 ant., 13m, σ~4 mJy) to identify sources. Simultaneous observation of radiosources.
The Receivers

The amplifiers are based on the 26-36 GHz Pospieszalski NRAO design. Built and modified by Eddie Blackhurst at the Jodrell Bank Observatory, using unpassivated InP HEMTs from Hughes and Fujitsu.

The bias supplies are fed from a battery pack to give a low noise protected voltage free from switch transients which can cause damage to the HEMTs.

Each antenna has a 4-stage (Hughes) and a 2-stage (Fujitsu) amps. Bias conditions can be set individually for each transistor to optimize sensitivity.

Noise temperatures of 25 K (including horn) are achieved across the band which is flat to 1dB.
The Very Small Array
VSA extended configuration (Feb 2004)

(Dickinson et al. 2004)
**VSA extended configuration (Feb 2004)**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Omega_b h^2$</td>
<td>$0.023 \pm 0.0012$</td>
<td></td>
</tr>
<tr>
<td>$n$</td>
<td>$0.97 \pm 0.03$</td>
<td></td>
</tr>
<tr>
<td>$h$</td>
<td>$0.73 \pm 0.05$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_{cdm} h^2$</td>
<td>$0.113 \pm 0.013$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_m$</td>
<td>$0.32 \pm 0.06$</td>
<td></td>
</tr>
<tr>
<td>$\Omega_{\Lambda}$</td>
<td>$0.66 \pm 0.05$</td>
<td></td>
</tr>
<tr>
<td>Age</td>
<td>$13.8 \pm 0.4$ Gyr</td>
<td></td>
</tr>
</tbody>
</table>

(Rebolo et al. 2004)
SZ observations of galaxy clusters (Lancaster et al. 2005)
X-ray flux limited sample of 7 clusters with $z<1$.

Using only the SZ cluster measurements, we can infer constraints on the gas fraction:

$$f_{\text{gas}} h = 0.08 \pm 0.06$$

$$-0.04$$
A Survey with the VSA in the Corona Borealis Supercluster

The “missing baryons” problem: are half of the baryons in the local Universe in a Warm-Hot phase?

A total area of 24 deg$^2$ was imaged using a mosaic of 9 pointings, with 11´ resolution.

The total integration time was approx. 300 hrs.

(Génova-Santos, Rubiño-Martín et al. 2005)
Summary of Observations (33 GHz)

A total area of 24 deg$^2$ was imaged, with 11′ resolution.

<table>
<thead>
<tr>
<th>Pointing</th>
<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>$T_{\text{obs}}$ (hrs)</th>
<th>$T_{\text{int}}$ (hrs)</th>
<th>Thermal noise (mJy/beam)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CrB-A</td>
<td>15 23 12.00</td>
<td>+28 06 00.0</td>
<td>54</td>
<td>50</td>
<td>12.4</td>
</tr>
<tr>
<td>CrB-B</td>
<td>15 27 48.00</td>
<td>+29 24 00.0</td>
<td>70</td>
<td>70</td>
<td>10.8</td>
</tr>
<tr>
<td>CrB-C</td>
<td>15 22 48.00</td>
<td>+30 21 00.0</td>
<td>33</td>
<td>33</td>
<td>18.9</td>
</tr>
<tr>
<td>CrB-D</td>
<td>15 32 00.00</td>
<td>+30 45 00.0</td>
<td>19</td>
<td>19</td>
<td>20.5</td>
</tr>
<tr>
<td>CrB-E</td>
<td>15 32 00.00</td>
<td>+28 18 00.0</td>
<td>22</td>
<td>22</td>
<td>19.7</td>
</tr>
<tr>
<td>CrB-F</td>
<td>15 02 57.20</td>
<td>+27 11 17.3</td>
<td>47</td>
<td>43</td>
<td>14.4</td>
</tr>
<tr>
<td>CrB-G</td>
<td>15 45 00.00</td>
<td>+36 03 57.6</td>
<td>19</td>
<td>19</td>
<td>21.4</td>
</tr>
<tr>
<td>CrB-H</td>
<td>15 23 00.00</td>
<td>+29 13 30.0</td>
<td>167</td>
<td>130</td>
<td>10.2</td>
</tr>
<tr>
<td>CrB-I</td>
<td>15 27 24.00</td>
<td>+30 33 00.0</td>
<td>56</td>
<td>41</td>
<td>18.6</td>
</tr>
<tr>
<td>CrB-J</td>
<td>15 32 00.00</td>
<td>+29 31 30.0</td>
<td>55</td>
<td>39</td>
<td>18.9</td>
</tr>
<tr>
<td>CrB-K</td>
<td>15 28 00.00</td>
<td>+28 12 00.0</td>
<td>41</td>
<td>33</td>
<td>20.3</td>
</tr>
</tbody>
</table>
CrB SC
seen by VSA
CrB SC seen by VSA

The H spot is detected with a significance greater than 10-sigma (4-sigma with respect to the CMB+noise).

No known cluster of galaxies is associated to these spots.

(Génova-Santos, Rubiño-Martín et al. 2005)
Origin of the spot (I): primordial CMB?

The deviation in the power spectrum at $l=550$ is due to the presence of decrement $H$. Using MC simulations (CMB+noise), we find that the probability for $H$ spot is 0.16%.
Origin of the spot (I): primordial CMB?

A fluctuation analysis (as proposed in Rubiño-Martín & Sunyaev 2003) shows the deviation from Gaussianity as well.
Primordial CMB origin? Gaussianity analysis

• We carried out a complete Gaussianity analysis of all the VSA fields, using a new statistical technique called the “**Smooth Tests of Goodness of Fit**”, developed by Rayner & Best (1989).

• The technique has been adapted to deal with data from interferometers (see details in Aliaga et al. 2005). We follow to steps:

• First, data are transformed into signal-to-noise eigenmodes (Bond 1995), and then normalised.

• The following statistics test smooth deviations of the actual distribution from a Gaussian one:

\[
S_k = \sum_{i=1}^{k} U_i^2
\]

with

\[
\begin{align*}
U_1^2 &= n(\hat{\mu}_1)^2 \\
U_2^2 &= n(\hat{\mu}_2 - 1)^2 / 2 \\
U_3^2 &= n(\hat{\mu}_3 - 3\hat{\mu}_1)^2 / 6 \\
U_4^2 &= n[(\hat{\mu}_4 - 3) - 6(\hat{\mu}_2 - 1)]^2 / 24
\end{align*}
\]
Results of the STGOF analysis
(Rubiño-Martín et al. 2006)

- We analyse the Corona Borealis region, and all the 41 pointings dedicated to primordial observations.

- We find a strong non-Gaussianity deviation (99.8% C.L.) in the Corona Borealis mosaic analysis, for the statistic $U_2^2$.

- This is the strongest non-Gaussian deviation found in any of the fields observed with the VSA.

- This deviation from Gaussianity can NOT be explained as drawn from a Gaussian field with the local power spectrum (i.e. when the data are decorrelated with the local power spectrum, the NG signal remains).
Origin of the spot (II): unknown cluster?

SZ effect from (unknown) clusters of galaxies.

We can estimate the number of expected clusters in the region following Holder et al. (2000).

We used two different prescriptions for mass function, PS (solid) and ST (dashed).

On average, we expect 0.38 clusters of galaxies in the region which are able to produce such a decrement.
Origin of the spot (III): WHIM?

SZ effect from diffuse gas could be extracted from cross-correlations with X-ray maps. We use the ROSAT R6 band (0.73-1.56 keV)
Origin of the spot (III): WHIM?

No clear excess in the ROSAT-R6 band (0.73 - 1.56 keV). A correlation analysis yields:

$$\alpha = -0.28 \pm 0.74 \, \mu K/X$$
Origin of the spot (III)

We can infer the parameters allowed by the observations if the signal is produced by diffuse gas.

If the case of a filament is pointing towards us: 
\[ \frac{\delta \rho_B}{\rho_B} = 450, \text{ and } 2 \times 2 \times 40 \text{ Mpc}, \text{ then} \]

\[ M_{\text{gas}} \approx 5 \times 10^{14} \, M_\odot \]

This is 10% of the total baryonic mass of the SC!
Multifrequency Observations in CrB

**MITO** (Millimeter and Infrared Testa Grigia Observatory)

- Collaboration between IAC and Univ. Roma (F. Melchiorri, M. De Petris).
- Observations during one campaign in the CrB H spot at 143, 214, 272 and 353 GHz, with angular resolution of 16'.
MITO observations:

- 105 scans across H spot.
- High frequency channel used for atmospheric decorrelation.
- Calibration using scans on Jupiter.
- Maximum Entropy method is used to reconstruct the signal of the three remaining channels plus the VSA data.
- Multi-pixel Maximum Likelihood code is used to look for common (CMB) and frequency dependent (SZ) signals.

Fig. 2.— Strip of thermodynamic temperature maps derived from the MEM for VSA and the 3 MITO channels.

(Battistelli et al. 2006)
MITO results

- A Maximum-Likelihood derived maps for the primary and SZ-like (in RJ units) components.
- There is a detection of a SZ component with amplitude:
  \[ y = (7.8 \pm 4.9) \cdot 10^{-6} \]
- This implies that 25% of the VSA detection is due to SZ.
- If we assume temperatures of 0.5-0.8 keV, then \( \delta \sim 400-600 \) to be consistent with X-ray constraints.
Is this signature produced by WHIM in simulations?

• We have used high-resolution adiabatic SPH cosmological simulation (Yepes et al. 2004) to study the probability of finding such an structure produced by the WHIM.

• Details of the simulation: $500h^{-1}$ Mpc a side; resolution of $15/h$ kpc with $2 \times 512^3$ particles. Almost 200,000 objects with masses above $2 \times 10^{12}$ Msun are identified. The cosmology adopted is $\Lambda$CDM model with $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, $\Omega_b = 0.045$ and reduced Hubble constant $h = 0.70$.

• We identified 6 sub-volumes of $50 \times 50 \times 50$ Mpc$^3$ containing a supercluster which mimic the physical properties of CrB: the total mass in each region is higher than $10^{15}$ Msun, and more than 6 clusters with masses higher than $5 \times 10^{13}$ Msun are found.
Could this signature be due to WHIM?

- Clusters are identified and subtracted from the simulations, and y-parameter maps are obtained from the remaining particles.

*How often do we find a signal like the one measured by MITO?*

- Superclusters with **high elongation** along l.o.s. give higher probabilities.
- This signal is generally associated to **groups**, and usually lie between two clusters which are well-separated in z-space.
- The spot H is placed between clusters A2069 and A2073, which are separated by \( \Delta z=0.06 \). This is exactly the largest separation found between two members of the Corona Borealis SC.
- Probability of finding an spot like H is 13% for PLANCK.

(Coratella et al. 2006, in prep.)
Conclusions

• We report the detection with the VSA of a negative extended feature inside the Cr-B supercluster, which is not associated to known clusters of galaxies, and is not detected in ROSAT SXRB maps.

• A multifrequency analysis with the MITO telescope confirms that the signal is a combination of primordial CMB and a SZ component.

• If produced by extended gas, it would contribute with a significant fraction of the missing baryonic mass.

• This is the first detection of a SZ signature in a “blind observation”. In the coming years, many SZ experiments (ACT, SPT, AMI, APEX) will be doing these kind of studies.