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Searching for the missing baryons with the VSA and WMAP

Ricardo Genova-Santos*
Instituto de Astrofísica de Canarias, Spain
E-mail: rgs@iac.es

The hot diffuse gas in the local Universe which could host the missing baryons, could produce detectable thermal Sunyaev-Zel'dovich effect (tSZE). With this aim, in this work, I present the discussion of the search of this gas, via two different ways. Both takes into account this fact:
Firstly, the search for the imprint of the tSZE in the first year data of the *WMAP* satellite, by applying a pixel to pixel correlation method between this data and a template constructed from the *Two Micron All Sky Survey (2MASS) Extended Source Catalogue*, which it has been assumed that trace the distribution of this hot gas. This analysis has yielded a detection of $-35 \pm 7\ \mu K$ in the $26\ deg^2$ of the sky containing the largest projected galaxy density. Nevertheless, this signal is mostly due to the contribution from galaxy clusters subtending an angular size of $20-30'$. When the regions affected by the clusters are removed from the analysis, it is found a decrement of $-96 \pm 37\ \mu K$ in $0.8\ deg^2$ of the sky. Nevertheless, most of this signal comes from five different cluster candidates in the Zone of Avoidance (ZoA), present in the Clusters in the ZoA catalogue (CIZA). Hence, it is not found any clear evidence of structures larger than clusters, as it would be the case of this hot gas, contributing to the tSZE signal in the *WMAP* data.
Secondly, interferometric imaging at 33 *GHz* of the well known Corona Borealis supercluster with the *Very Small Array* (VSA). The maps built up from these observations, apart from the common Cosmic Microwave Background (CMB) primordial fluctuations, show the presence of two intriguing strong negative features near the centre of the core of the supercluster [1]. It is discussed the possibility of being caused by CMB fluctuations, or by tSZ signals related to either unknown distant galaxy clusters or to diffuse extended warm/hot gas.

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*Speaker.

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1. Introduction

The extended atmospheres of hot gas ($k_B T_e \sim 10 Kev$) located in the potential wells of the richest clusters of galaxies may act as a source of detectable thermal Sunyaev-Zel'dovich effect [2] (tSZE), which is produced by the inverse Compton scattering of the Cosmic Microwave Background (CMB) photons by electrons in the intracluster medium (ICM). Apart from the galaxy clusters, there may be other objects which also contain extended atmospheres of hot gas and may then be sources of detectable tSZE, like superclusters of galaxies, where small enhancements of the baryon density are expected, but where the path lengths may be long so that a signifi cant tSZE could build up, since this effect is proportional to the line of sight integral of the electron density [3]. Also, it is reasonable to look superclusters as optimal regions where the diffuse warm/hot gas could be located, distributed in fi lamentary structures extending over several tens of Mpc, and connecting clusters of galaxies, as simulations suggest [4]. This warm/hot intergalactic medium (WHIM), with temperatures $10^5 < T < 10^7$ not low enough to have condensed into stars or to form cool galactic gas, and neither as high as the hot gas present in galaxy clusters, is actually one of the most important hypothesis related to the hidden baryonic matter of the universe, and hence is what could explain the discrepancy between the observational budget of baryons [5] and the theoretical estimations, through either Big Bang nucleosynthesis [6], or Lyα forest absorption observations [7], or CMB observations [8, 9]. The detection of its radiation could be hidden by the presence of many galactic and extragalactic foregrounds. Up to date, most of the attempts to discover it have been conducted through either correlations between the observed soft X-ray structures and some selected galaxy overdense regions, or by the detection of a soft X-ray excess in clusters of galaxies, or in their proximity. Moreover, as this gas, due to its size, could produce detectable tSZE, there has been also many studies correlating CMB maps where this signal could be present with galaxy or galaxy clusters catalogues (see for example [10] and references therein).

2. A search for the tSZE signature induced by hot gas in the first year *WMAP* data

The signal present in the data of a CMB experiment such as *WMAP* [8] is the sum of different components: a cosmological signal T_{CMB}, the tSZE signal, instrumental noise N, and foreground residuals F. If N is a spatial template which traces the tSZE, then the total signal measured at a given position on the sky is then modelled as $T = T_{CMB} + \alpha M + N + F$, where α measures the amplitude of the induced signal in the template. If all the other components have zero mean and well known correlation functions, and $\mathcal{C}$ denotes the correlation matrix of the CMB and noise components, then the estimate of α and its statistical error are

$$\alpha = \frac{T\mathcal{C}^{-1}M^T}{M\mathcal{C}^{-1}M^T}, \quad \sigma_\alpha = \sqrt{\frac{1}{M\mathcal{C}^{-1}M^T}} \tag{2.1}$$

(see [10] for a detailed description of the method).

Since baryons are distributed on scales comparable to the virial radius of galaxies [12] it is possible to argue that galaxies trace the distribution of hot gas, independently of whether they form clusters, groups, or fi laments. Hence, a template that could trace the tSZ emission from this gas could be made up from a galaxy catalogue. Taking this into account, in this work C.Hernández-Monteagudo, R.Génova-Santos and F.Atrio-Barandela [11] have built the template M by assigning to each pixel a number equal to the projected galaxy density according to the 2MASS Source Extended Catalogue [13]. This template is correlated with the *WMAP* W band, which has the largest angular resolution, after having filtered both by the Kp0 mask in order to remove the foregrounds residuals from the data. The template is convolved with the beam of the *WMAP* W band, so both have the same angular resolution. Since this method requires the inversion of the correlation matrix, it is not possible to apply it in the whole sphere, so it has been sorted the pixels starting from the brightest one, and assembled them in patches of $N_{pix} = 256, 512, 1024$ and 2048.

As expected, it is obtained significant negative values of α (since at 94 *GHz*, the *WMAP* W band frequency, the tSZE is negative) in the densest patches, but this signal vanishes when the projected galaxy density decreases. The strongest tSZE signal comes from the 256 densest pixels, but the highest statistical level of significance is achieved for $N_{pix} = 2048$ ($\sim 26\ deg^2$ on the sky), with a $\sim 5\sigma$ detection: $\alpha = 35 \pm 7\mu K$. By rotating the template and applying correlations in the densest 2048 pixels it has been measured the typical angular extension of the tSZE sources, obtaining $20-30'$, which could imply that most of the signal is coming from galaxy clusters.

In order to study this possibility, it has been removed from the template all those pixels that were associated with known optical and X-ray galaxy clusters. This means that out of the 2048 brightest pixels, 1681 were eliminated. After doing this, it is still found a $\sim 2.6\sigma$ detection of $\alpha = -96 \pm 37\mu K$ in the 64 densest pixels ($\sim 0.8\ deg^2$ on the sky). Out of these 64 pixels, 54 are in the ZoA, and 45 of them coincide with five different cluster candidates in the Clusters in the ZoA (CIZA) [14] catalogue.

3. A search for extended tSZ effect in the Corona Borealis supercluster with VSA

The Very Small Array (VSA) is a 14-element heterodyne interferometer array, tunable between 26 and 36 GHz with a 1.5 GHz bandwidth and a system temperature of ~35 K, sited at 2400 m altitude at the Teide Observatory in Tenerife. For this work, the observing frequency was set to 33 GHz, and it was used the so-called extended configuration, which uses conical corrugated horn antennas of 322 mm diameter aperture with a primary beam of 2.1° FWHM, and a synthesised beam of $\sim 11'$. Next to the main array is located a two element interferometer, which consists of two 3.7-m diameter dishes with a north-south baseline of 9 m, giving a resolution of $4'$ in a $9'$ field. This interferometer is used for source subtraction, monitoring in real-time the known radio-sources in the fields observed by the main array, as it has been described in [15]. This instrument belongs to the consortium: Instituto de Astrofísica de Canarias, Spain; Astrophysics Group, Cavendish Laboratory, Cambridge, UK; Jodrell Bank Observatory, University of Manchester, UK. For a detailed description of the instrument and the data reduction procedure, see [16].

According to what is explained in section 1, superclusters may be looked as optimal regions where the diffuse warm/hot gas that could host the missing baryons is likely to be detected. It has been chosen the Corona Borealis supercluster (CrB-SC) to be observed by VSA taking into account several factors: the absence of intense radio-sources, the X-ray luminosity of its clusters, the supercluster angular size and the declination range accessible by VSA. In order to survey all the core of the CrB-SC it has been selected 9 pointings. These observations were carried out in the period 2003 May - 2004 March.

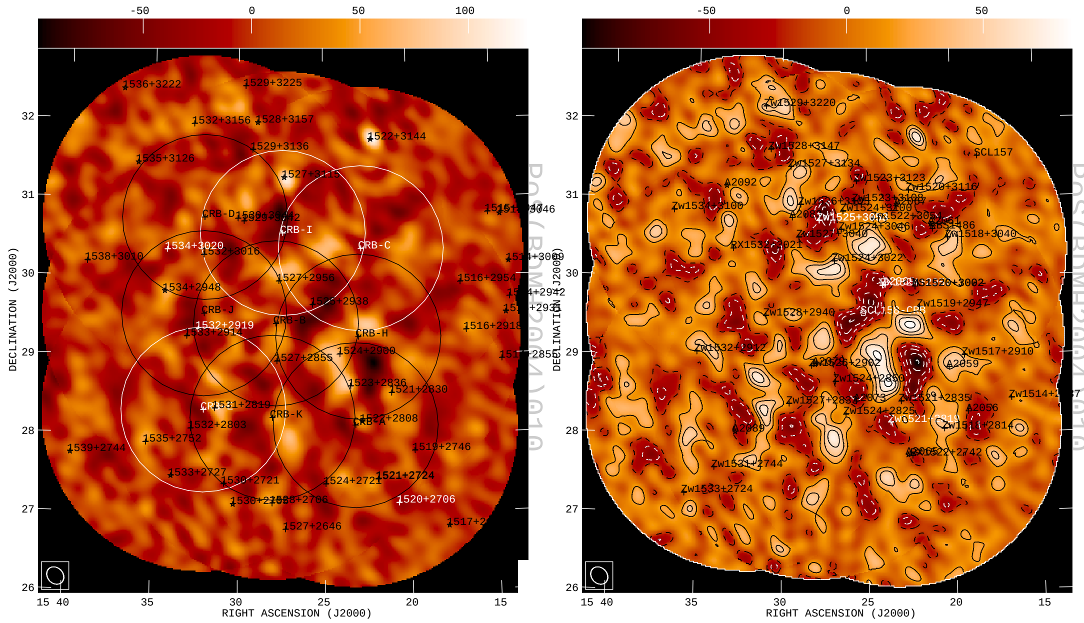

Figure 1: Left: CrB mosaic, before source subtraction. Circumferences indicate the FWHM of the nine primary beams. The positions of the radio-sources are also indicated. Right: source subtracted mosaic, indicating the position of the known clusters in the region (those belonging to the CrB-SC are plotted with a five pointed star, while the centre of the supercluster is plotted with a pentagon). Solid and the dashed contours indicate positive and negative fluxes, respectively. The difference between contours is 1.5σ

Figure 1 shows the final mosaic of the CrB-SC core region, built up from the nine individual pointings. This map shows fluctuations apparently compatible with CMB primordial anisotropies, but it has been detected two prominent negative spots at $\sim 8\sigma$ over noise level, which have been called B and H. They have respectively coordinates 15 25 24.09 +29 33 34.6 (J2000) and 15 22 12.44 +28 55 03.8 (J2000), while their minimum intensities are -72.4 ± 11.9 mJy (-162.2 ± 26.7 μK) and -106.3 ± 12.9 mJy (-238.2 ± 28.9 μK). Both decrements are extended, since they cover an area equivalent to ~ 3 VSA synthesised beams. In principle, these features, given their angular sizes and amplitudes, could be either extraordinary CMB spots, or SZ signals related to either unknown clusters or to diffuse extended warm/hot gas in the supercluster. These three possibilities have been investigated in detail:

- CMB anisotropy. In order to test if a CMB decrement is a suitable explanation for these spots, it has been applied a statistical method in which it has been made Monte Carlo simulations of CMB observations with VSA, adding the noise level of these observations, and analyzing the number of pixels with intensities below those of the spots. This study have yielded that the probability of spot B to be due to CMB is 28.34%, while the probability of the spot H is only 0.16%.

- tSZ from clusters of galaxies. To test the possibility of a tSZE decrement caused by a far cluster of galaxies, it has been calculated the mass of a hypothetic cluster which could produce such decrements in our maps, and using the Press-Schechter [17] (PS) mass function it has been determined that the number of clusters massive enough to produce a decrement at least as intense as spots B and H is respectively 0.45 and 0.24. Some authors have claimed that the PS formalism produces an underestimation of the high mass clusters [18]. Hence, it has also been used the Sheth-Tormen [19] (ST) mass function, which yields 0.69 and 0.35. From these results it must be concluded that the possibility of the existence of such a cluster is very low. It is even lower if it is taken into account that these spots, given their angular sizes, should be produced not by a single cluster but by a group of them.

- Diffuse warm/hot gas. It has been checked the ROSAT-R6 soft X-ray ($0.73-1.56$ *keV*) map, but this do not show any excess of emission in the regions of the spots. Moreover, it has been computed the two point correlation function between this and the VSA map, and this shows that there is not any sign of anticorrelation, as it should be expected if it would be the case that the spots are caused by the tSZE from diffuse warm/hot gas. Nevertheless, this could be due to the fact that the low temperature of this hypothetic gas could make it undetectable through X-rays.

4. Conclusions

This work present the discussion of the search for the missing baryons in the local Universe using the tSZE.

In the first part it has been used the *WMAP* data to cross-correlate it with a template built up from the *2MASS* catalogue. The conclusion of this study is that it has been found a significant tSZE detection present in the *WMAP* data, although its angular extension of $20-30'$ and the fact that most of it is associated with clusters of galaxies, dismiss the possibility of being caused by a extended and diffuse phase of hot gas.

In the second part, it has been conducted an observational campaign of the Corona Borealis supercluster with the VSA interferometer. The data show two important decrements, whose angular extensions and intensities make them very unlikely to be due to a primordial fluctuation. Then, it could be possible a tSZE contribution from a phase of warm/hot diffuse gas. In fact our analyzes have shown that the most plausible explanation is a combination of primordial CMB and a tSZE decrement from diffuse gas.

References

[1] Genova-Santos, R., et al. 2004, in preparation

[2] Sunyaev, R. A. & Zeldovich, Y. B. 1970, Ap&SS, 7, 3

[3] Birkinshaw, M., 1999 , Phys Rep , 310 , 97

[4] Cen, R. & Ostriker, J. P. 1999, ApJ, 514, 1

[5] Fukugita, M., Hogan, C. J., & Peebles, P. J. E. 1998, ApJ, 503, 518

[6] Burles, S., Nollett, K. M., & Turner, M. S. 2001, ApJ, 552, L1

[7] Rauch, M., et al. 1997, ApJ, 489, 7

[8] Bennett, C. L., et al. 2003, ApJS, 148, 1

[9] Rebolo, R., et al. 2004, MNRAS, 353, 747

[10] Hernández-Monteagudo, C. & Rubiño-Martín, J. A. 2004, MNRAS, 347, 403

[11] Hernández-Monteagudo, C., Genova-Santos, R., & Atrio-Barandela, F. 2004, ApJ, 613, L89

[12] Fukugita, M. & Peebles, P. J. E. (2004). astro-ph/0406095

[13] Jarrett, T. H., Chester, T., Cutri, R., Schneider, S. E., & Huchra, J. P. 2003, AJ, 125, 525

[14] Ebeling, H., Mullis, C. R., & Tully, R. B. 2002, ApJ, 580, 774

[15] Taylor, A. C., et al. 2003, MNRAS, 341, 1066

[16] Watson, R. A., et al. 2003, MNRAS, 341, 1057

[17] Press, W. H. & Schechter, P. 1974, ApJ, 187, 425 (PS)

[18] Efstathiou, G. & Rees, M. J., 1988, MNRAS, 230, 5

[19] Sheth, R. K. & Tormen, G. 1999, MNRAS, 308, 126 (ST)