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# The origin of the cold spot in the Corona Borealis supercluster

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## Abstract

The Very Small Array (VSA) detected a cold spot in the Cosmic Microwave Background (CMB) towards the Corona Borealis supercluster of galaxies. The origin of this spot remains unclear as it is not obviously associated to any known cluster of galaxies. We present here recent observational results (GTC, WHT, SDSS) and theoretical (N-body simulations) studies aimed to better understand the origin of this anomalous spot. We carried out a near-IR survey (LIRIS@WHT) complemented with optical data (ACAM@WHT, OSIRIS@GTC and SDSS) in the line of sight of the core of this supercluster to search for new clusters of galaxies at a higher redshift. Using the Mare Nostrum Universe (an N-body SPH cosmological simulation by [18]), we also study the potential of the different physical phases in superclusters to produce similar thermal Sunyaev-Zeldovich signals to the observed in the cold spot.

## 1 Introduction

The temperature fluctuations in the CMB radiation are the imprint of the density perturbations at the moment of the decoupling between matter and radiation, and the signature of several phenomena to which the photons are subjected either during recombination or in their path towards us. One of these phenomena is the Sunyaev-Zeldovich (SZ) effect [17]. It arises when CMB photons go through a region where hot or fast moving gas lies, typically in clusters of galaxies or other strong gravitational potential wells; the high energy electrons of the gas transfer part of their energy to the photons via inverse Compton scattering. This effect is redshift independent and has two components (thermal and kinetic). The thermal component is given by the Comptonization parameter ($y$):

$$y = \int n_{\rm e} \frac{k_{\rm B} T_{\rm e}}{m_{\rm e} c^2} \sigma_{\rm T} \, dl \tag{1}$$

where the integral is computed along the line of sight (*los*), $\sigma_{\rm T}$ is the Thomson cross-section, $n_{\rm e}$ is the electron number density, $T_{\rm e}$ is the electron temperature, $k_{\rm B}$ is the Boltzmann constant and $m_{\rm e}c^2$ is the electron rest mass energy.

A detailed account of the baryons present in all known components of the local Universe gives a value for the baryon density parameter of $\Omega_{\rm B} = (0.010 \pm 0.003)h^{-2}$ [5]. Primordial nucleosynthesis [3], observations of the Lyman-$\alpha$ forest [11] and measurements of the angular power spectrum of the CMB [12, 14] lead to values a factor two times higher for this parameter. It seems that there must exist a baryonic component in the local Universe where half of the baryons would remain hidden. This is usually known as the missing baryons problem.

Theoretical models [4] based on numerical simulations suggest that these missing baryons could be accounted for in a diffuse gas phase with temperatures $10^5 < T < 10^7$ K and moderate overdensities ($\delta \sim 10 - 100$), known as the 'warm/hot intergalactic medium' (WHIM). According to these simulations, the WHIM would be located in filaments connecting clusters of galaxies and in large-scale sheet-like structures. WHIM could be detected via the SZ effect. The basic idea is that since the SZ effect is proportional to the line-of-sight integral of the electron pressure, filamentary structures of superclusters extending over several tens of megaparsecs could overcome the expected low baryon overdensities and produce a measurable signal with present day observing facilities.

Observations of the Corona Borealis (CrB) supercluster (located at $z = 0.074$) carried out with the Very Small Array (VSA) interferometer at 33 GHz [6] showed the existence of two strong and resolved negative features in a region where there are no known clusters of galaxies. We focus here on one of these features, the so-called "H-spot", with a temperature decrement of $\Delta T = -230 \pm 23$ $\mu$K at 33 GHz. A detailed Gaussianity study in the region [13] finds a clear deviation (99.82%) at angular scales of multipole $\ell \sim 500$, which cannot be explained as systematic effects. From the total anisotropy, roughly a 20% of the signal has a thermal SZ spectral behaviour, yielding $y = 7.8^{+4.4}_{-5.3} \times 10^{-6}$ [1].

Neither the origin of the thermal SZ component of the spot, nor the origin of the remaining 80% have been explained so far. Here we present a twofold study on the possible origin of the thermal SZ signal. On the one hand, we analyse via numerical simulations if the cold spot could have been caused by WHIM within the Corona Borealis Supercluster, as it would mean that CrB-H is the first SZ detection of WHIM (sections 2 and 3). On the other hand, we extend previous searches for unknown clusters in the region of the spot that could be causing the observed SZ anisotropy, out to $z \sim 1$ (sections 4 and 5).

## 2 The Mare Nostrum Universe

The *Mare Nostrum Universe* (MNU) is currently one of the largest cosmological N-body+SPH simulations. It consists of $1024^3$ dark and $1024^3$ baryonic SPH particles in a cubic computational volume of 500 $h^{-1}$ Mpc on a side.[1] This simulation was done at the Mare Nostrum supercomputer, from which it took the name, located at the Barcelona Supercomputer Center,

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[1] http://astro.ft.uam.es/~marenostrum

*Centro Nacional de Supercomputación* (BSC-CNS)[2]. Initial conditions were set according to the so-called "concordance Λ-CDM model" with parameters $\Omega_{\rm m} = 0.3$, $\Omega_\Lambda = 0.7$, $\Omega_{\rm b} = 0.045$, $\sigma_8 = 0.9$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and a slope of $n_s = 1$ for the initial power spectrum [8, 18]. The mass of each dark matter particle is $m_{\rm DM} = 8.239 \times 10^9$ h$^{-1}$ M$_\odot$ and the mass of each gas particle is $m_{\rm gas} = 1.454 \times 10^9$ h$^{-1}$ M$_\odot$, and they are evolved from redshift $z = 40$ using the TREEPM+SPH code GADGET-2 [16, 15].

Using the snapshot at $z = 0$, we selected nine smaller subvolumes of 50 h$^{-1}$ Mpc on a side, that could be assumed to be superclusters of galaxies that resemble the Corona Borealis supercluster. We located them at $z = 0.07$ and generated SZ synthetic maps that accounted for the signal coming from the different physical phases (clusters of galaxies, galaxy groups and WHIM) of these simulated superclusters and compared the numerical predictions with the observations. We took into account possible orientation effects by randomly rotating these subvolumes and re-generating the synthetic SZ maps. In total, we generated 301 thermal and kinetic SZ maps per subvolume and physical phase. Thus, we tested whether or not the MNU simulation is able to explain the detected thermal SZ signal in terms of the WHIM.

## 3 Numerical results

On average, our simulated superclusters show that roughly 73 % of the total thermal SZ flux in the maps comes from clusters of galaxies with $M \geq 5 \times 10^{13}$ h$^{-1}$ M$_\odot$, and the other $\sim 30$ % comes from galaxy groups and WHIM. Of this 30 %, roughly 60% is coming from groups, and 40% is coming from the WHIM. The thermal SZ one-point probability distribution functions (1-PDF) associated with each phase are shown in Fig. 1. As expected from the densities and temperatures of the different gas phases, galaxy clusters are responsible of the high-$y$ tail of the 1-PDF distribution, while groups and WHIM have relevant contributions at the lowest $y$-values.

The maximum values of the Comptonization parameter $y$ we obtain in the synthetic maps when we do not include the cluster contribution are shown in Table 1. We also include the number of maps that yield a $y$ maxima within the $1\sigma$ confidence level of the observations, showing that none of the WHIM maps provide enough thermal SZ signal and only 8 out of 2709 maps that also include galaxy groups are compatible with the observations. We have also computed a crude estimate of the probability distribution function for the expected maximum values of the $y$ parameter. Weighing this probability distribution with the posterior distribution of the observations, gives a probability of $P = 0.9\%$ for the WHIM to cause a thermal SZ signal as high as the observed value. Even if we add the contribution of groups, the probability remains below 5%, supporting our conclusion that neither groups of galaxies, nor WHIM are likely explanations for the thermal SZ component of the spot at a confidence level greater than 95%. The most likely explanation for the thermal SZ signal would then be an unknown background cluster of galaxies.

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[2] http://www.bsc.es

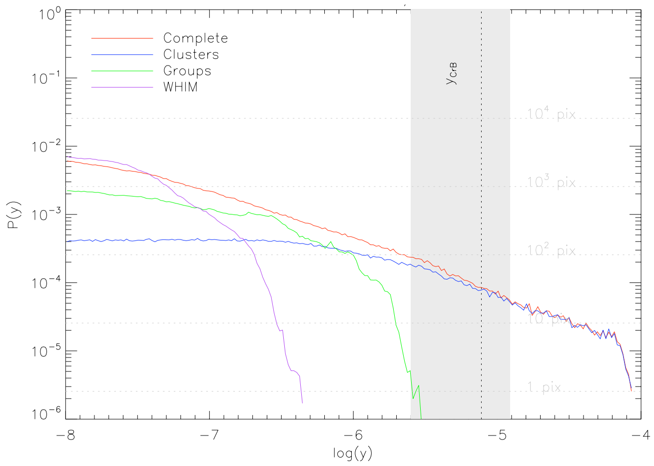

Figure 1: 1-PDF of the Comptonization parameter $y$. Different colours correspond to the different phases as noted in the legend. The shaded area corresponds to the $1\sigma$ interval of the observations [1], showing that the WHIM fails to build up enough tSZ signal to be responsible for the cold spot.

## 4 Optical and nIR observations

The physical distribution and colours of SDSS galaxies showed an excess of red galaxies in the region of the cold spot, which could be the signature of an unknown background cluster of galaxies [10]. Using a sample of SDSS DR7 spectroscopically characterized galaxies, [7] detected a possible cluster of galaxies at $z = 0.11$, which could only account $\sim 60\%$ of the claimed SZ signal. In this context, a deeper study of the galaxy population beyond SDSS data was the natural route to follow.

Using LIRIS and ACAM (WHT) and OSIRIS (GTC), we have obtained deep nIR ($J$ and $K_s$ bands) and optical ($gri$ filters) images of the central region of the spot to search for unknown background galaxy clusters. With these images and complementary data from SDSS DR7, we have used several indicators that trace the location of galaxy clusters. We have searched for red-sequences of galaxies at different colour cuts, analysed the abundance of Extremely Red Objects (EROs) and studied the distribution of the galaxies in photometric redshift bins (determined using the BPZ algorithm [2]).

## 5 Observational results

All three methods seem to indicate that there are two cluster candidates (which we designate as GCL 152223+285454 and GCL 152234+285606, according to the location of the maxima in the galaxy spatial number density in the color cut $1.1 < r' - i' < 1.3$), within $8'$ of the center of the cold spot (Fig. 2). These two cluster candidates would be located at an estimated redshift of $z \simeq 0.7$, beyond previous studies and current cluster catalogues such as MaxBCG [9]. They are very close to one another (at less than $4'$), and we have roughly estimated their

Table 1: Maximum values of the Comptonization parameter obtained in the synthetic maps of the diffuse phase after considering orientation effects. The last two columns indicate the number of orientations (out of 301 maps per subvolume) that yield maxima of $y$ within the $1\sigma$ interval of the observations.

| Subvolume | $y_{\rm max}^{\rm Groups}$ | $y_{\rm max}^{\rm WHIM}$ | $N_{1\sigma}^{\rm Groups}$ | $N_{1\sigma}^{\rm WHIM}$ |
|---|---|---|---|---|
| 001 | $1.39 \times 10^{-6}$ | $0.51 \times 10^{-6}$ | 0 | 0 |
| 002 | $1.30 \times 10^{-6}$ | $0.53 \times 10^{-6}$ | 0 | 0 |
| 003 | $1.08 \times 10^{-6}$ | $0.50 \times 10^{-6}$ | 0 | 0 |
| 004 | $1.04 \times 10^{-6}$ | $0.55 \times 10^{-6}$ | 0 | 0 |
| 005 | $1.07 \times 10^{-6}$ | $0.49 \times 10^{-6}$ | 0 | 0 |
| 006 | $2.62 \times 10^{-6}$ | $0.42 \times 10^{-6}$ | 5 | 0 |
| 007 | $1.01 \times 10^{-6}$ | $0.36 \times 10^{-6}$ | 0 | 0 |
| 008 | $2.84 \times 10^{-6}$ | $0.46 \times 10^{-6}$ | 3 | 0 |
| 009 | $1.05 \times 10^{-6}$ | $0.48 \times 10^{-6}$ | 0 | 0 |

masses ($2.1\times10^{14}$ M$_\odot$ and $3.7\times10^{14}$ M$_\odot$) and the thermal SZ signal they could cause, adding to a total of 52 $\mu$K, which would be compatible with the observations. If both candidates were spectroscopically confirmed as clusters at the estimated redshift, we could be looking at a high redshift supercluster of galaxies aligned along the line of sight with the Corona Borealis supercluster but not physically connected with it.

## 6 Conclusions

Our theoretical study seems to favour the conclusion that the thermal SZ component of the cold spot CrB-H is most likely caused by a background cluster of galaxies rather than by WHIM. From the optical study, we have identified two galaxy cluster candidates that could be part of a supercluster at $z \simeq 0.7$. Given our estimations of mass and thermal SZ signal of these cluster candidates, they could account for the detected SZ signal. However, they have yet to be spectroscopically confirmed. Still, the remaining $\sim 80\%$ of the observed CMB temperature decrement is a significant deviation from Gaussianity that requires explanation.

## Acknowledgments

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## References

[1] Battistelli, E. S., et al. 2006, ApJ, 645, 826

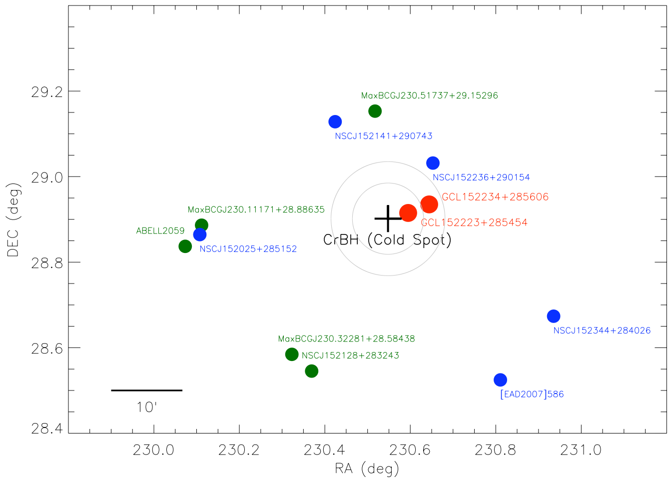

Figure 2: Known galaxy clusters around the location of the cold spot CrB-H. Marked in red, we show our two cluster candidates at $z \simeq 0.7$; in blue, the clusters at $z < 0.1$, which are typically members of the CrB supercluster; and in green, the clusters at $0.1 < z < 0.3$. The coordinates of the centre of the spot is marked by the plus sign, and the two concentric circles around this location, have radii of $5'$ and $8'$, respectively.

[2] Benítez, N. 2000, ApJ, 536, 571

[3] Burles, S., Nollett, K. M., & Turner, M. S. 2001, ApJL, 552, L1

[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] Génova-Santos, R., et al. 2005, MNRAS, 363, 79

[7] Génova-Santos, R., et al. 2010, MNRAS, 403, 1531

[8] Gottlöber, S., & Yepes, G. 2007, ApJ, 664, 117

[9] Koester, B. P., et al. 2007, ApJ, 660, 239

[10] Padilla-Torres, C. P., et al. 2009, MNRAS, 396, 53

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

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

[13] Rubiño-Martín, et al. 2006, MNRAS, 369, 909

[14] Spergel, D. N., et al. 2007, ApJS, 170, 377

[15] Springel, V. 2005, MNRAS, 364, 1105

[16] Springel, V., Yoshida, N., & White, S. D. M., 2001, New Astronomy, 6, 79

[17] Sunyaev, R. A., & Zeldovich, Y. B., 1972, Comments on Astrophysics and Space Physics, 4, 173

[18] Yepes, G., Sevilla, R., Gottlöber, S., & Silk, J. 2007, ApJ, 666, L61