Results of a blind identification of galaxy clusters in synthetic CMB maps

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Abstract

The Planck satellite was launched in May 2009 by the European Space Agency to study the properties of the Cosmic Microwave Background (CMB). The mission was completed in January 2012 and one of the main results expected from Planck's data analysis is the separation of components that contaminate the CMB. Among these contaminants is the Sunyaev -Zel'dovich (SZ) effect, caused by inverse Compton scattering of CMB photons by the high-energy electrons concentrated in the core of galaxy clusters. This work modifies a public version of the JADE (Joint Approximate Diagonalization of Eigenmatrices) algorithm to deal with noisy data and uses it as a tool to search for SZ clusters in Planck-like simulated CMB maps, composed by CMB, Galaxy emission and instrumental noise. The clusters were produced from SZ temperature profiles corresponding to the generalized Navarro-Frenk-White model for the intra-cluster gas pressure. The SZ map was combined with synthetic maps of the CMB radiation, instrumental noise and Galactic emission generated in HEALPix format, and then run through our pipeline.The process of component separation can be summarized in four main steps: the pre-processing based on Wavelet analysis, which performs an initial cleaning (denoising) of data in order to minimize the noise level, the separation of the components (emissions) by JADE, the calibration of the recovered SZ map and identification of the positions and intensities of the clusters using the SExtractor software. The results show that our JADE-based algorithm is effective in identifying the position and intensity of the SZ clusters, recovering about 87% of inserted objects. The recovery factor changes slightly according to the characteristics of noise and the number of components included in the input maps. The main highlight of our work is the effective recovery rate with no *a priori* assumptions and we consider it to be an interesting complementary approach to the "matched-filter" strategy, more commonly used in the literature.

The Sunyaev Zel'dovich Effect

The thermal SZ effect is caused by inverse Compton scattering of CMB photons during their passage through the core of clusters of galaxies [1, 2]. It produces a small distortion in the spectrum of the CMB radiation, whose temperature variation ΔT_{SZ} can be written, for a given pressure profile, $P_e(r)$, as [3]

$$\Delta T_{SZ}(\theta) = f(x) T_{CMB} \frac{\sigma_T}{m_e c^2} P_e^{2d}(\theta) \tag{1}$$

where $P_e^{2d}(\theta)$ is the electron pressure profile projected in the sky as is given by:

$$P_e^{2d}(\theta) = \int_{-\sqrt{r_{out}^2-\theta^2 D_A^2}}^{\sqrt{r_{out}^2-\theta^2 D_A^2}} P_e\left(\sqrt{l^2+\theta^2 D_A^2}\right) dl, \tag{2}$$

where θ is the angular distance from the cluster center, D_A the angular diameter distance, l the radial coordinate from the center of the cluster along the line of sight and r_{out} the radius where the profile is truncated.

Arnaud et al. [4] defined an electron pressure profile P_e, based in the generalized Navarro-Frenk-White (NFW, [5]) model. This profile fits very well the electron pressure profile obtained from X-ray data, and is given by

$$P_e(r) = 1.65 \times 10^{-3}\, h(z)^{8/3} \left[\frac{M_{500}}{3 \times 10^{14}\, h_{70}^{-1}\, M_\odot}\right]^{2/3+\alpha_p} \times\ p(x)\ h_{70}^2\ keV\ cm^{-3}, \tag{3}$$

where $h(z) = [\Omega_m(1+z)^3 + \Omega_\Lambda]^{1/2}$, $\alpha_p = 0.12$, $x = r/R_{500}$, with R_{500} being the radius within which the mean overdensity is 500 times the critical density of the universe, e M_{500} and M_{500} the mass within the radius R_{500}, given by:

$$M_{500} \equiv \frac{4\pi}{3}[500\rho_c(z)]R_{500}^3. \tag{4}$$

$p(x)$ corresponds to the generalized NFW model,

$$p(x) = \frac{P_0}{(c_{500}x)^\gamma[1+(c_{500}x)^\alpha]^{(\beta-\gamma)/\alpha}}, \tag{5}$$

and the best fit found by Arnaud et al. [4] is given by

$$[P_0, c_{500}, \gamma, \alpha, \beta] = [8.403 h_{70}^{-3/2}, 1.177, 0.3081, 1.0510, 5.4905]. \tag{6}$$

Simulations of the sky

The first step was to generate synthetic maps (1) that try to reproduce, in the best possible way for an outsider of the Planck Collaboration, the observations made by the Planck satellite. These maps were constructed in the frequencies of 100, 143, 217, 353 and 545 GHz, using the HEALPix (Hierarchical Equal Area iso-Latitude Pixelization) pixelization grid, described bellow.

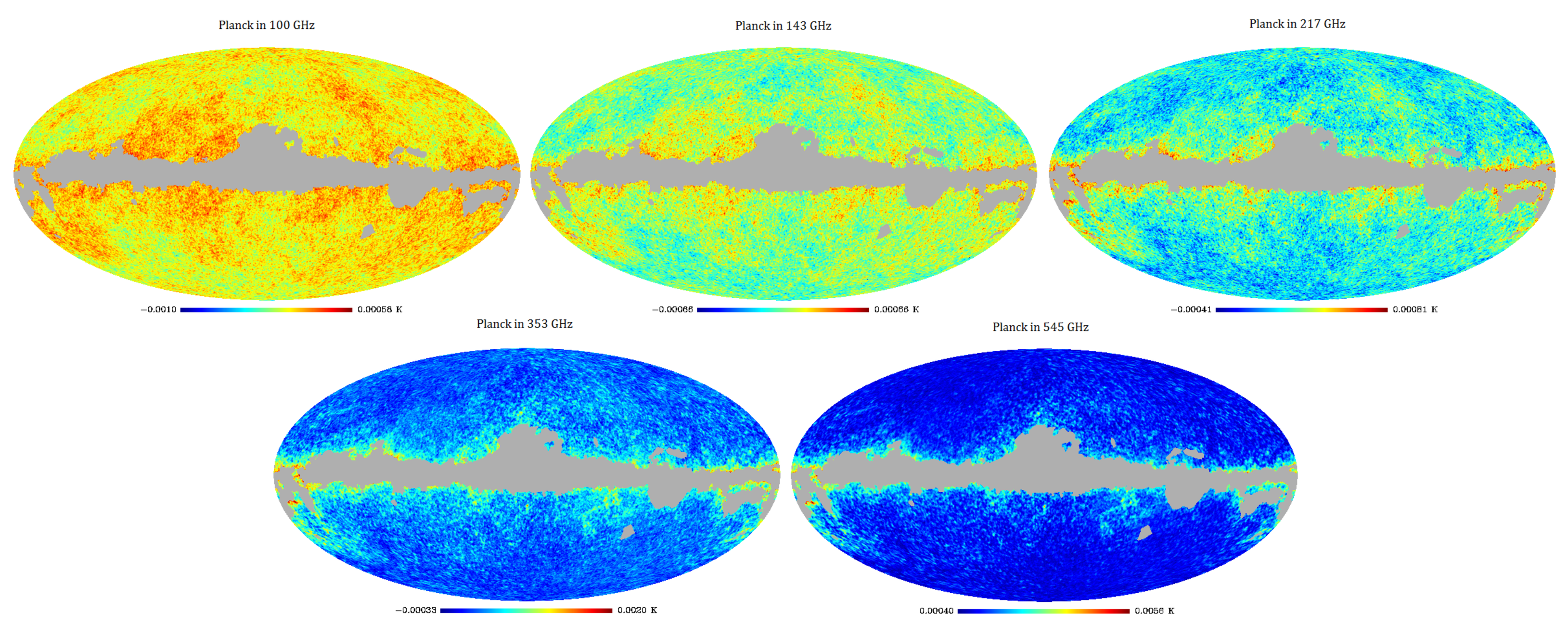

Figure 1: Simulated maps of the Planck satelite observations.

CMB Anisotropy: the synthetic map was generated from C_l coefficients created using the online interface of CMBFAST code and the SYNFAST routine of the HEALPix package, considering ΛCDM standard model with $\Omega_M \sim 0,27$, $\Omega_\Lambda \sim 0,73$, $\Omega_b h^2 \sim 0,024$ and $h = 0,72$.

The SZ Effect: 1000 clusters were positioned throughout the sky outside the Galactic region, with random orientation and following a uniform distribution. The SZ temperature profiles are corresponding to the generalized Navarro-Frenk-White model for the pressure profile of the intracluster gas, considering $r_{out} = R_{500}$, mass values in range $5 \times 10^{13} M_\odot < M_{500} < 1 \times 10^{15} M_\odot$ and a redshift interval $3 \times 10^{-4} < z < 1.5$.

Galactic emission: the Galactic contribution (synchrotron, dust and free-free emissions in 94 GHz) and spectral indices ($\beta_s = -3.0$, $\beta_d = 2.0$ e $\beta_{ff} = -2.16$, respectively) from WMAP 7-year products applied to

$$I_e(\nu_1) = I_e(\nu_2)\left(\frac{\nu_1}{\nu_2}\right)^{\beta_e}. \tag{7}$$

Instrumental noise: it was simulated using the sensitivities of each chosen Planck channel, estimated for the Planck mission, and in order to obtain a map of white noise.

Table 1: Thermo. temperature sensitivity per channel for the full Planck mission [6].

Frequency (GHz)	100	143	217	353	545
Sensitivity (μK)	11	17	37	111	801

Independent Component Analysis (ICA / JADE)

Many methods developed for signal separation are based on ICA (Independent Component Analysis) [7], and can be considered as a class known as *Blind Source Separation (BSS)* problems. A typical example of BSS is the processing of multidimensional data with no *"a priori"* information [7]. This problem consists primarily on estimate the matrix of the sources (independent components), S, from X, the matrix of linear combinations of individual sources.

The method chosen for this work is known as JADE (*Joint Approximate Diagonalization of Eigenmatrices*) [7, 8] based on ICA and effective in extracting non-gaussian components in the CMB data, such as SZ clusters. Besides, it does not use any "prior" information about the input components, which is a desirable feature and sets JADE apart from other methods used in this type of analysis. This mixture model is described by Eq. 8.

$$X = AS, \tag{8}$$

X: Input matrix where each row is a map in a different frequency.

A: Mixing matrix.

S: Output matrix where each row corresponds to a source.

The whole separation process is outlined in Fig. 2 [9].

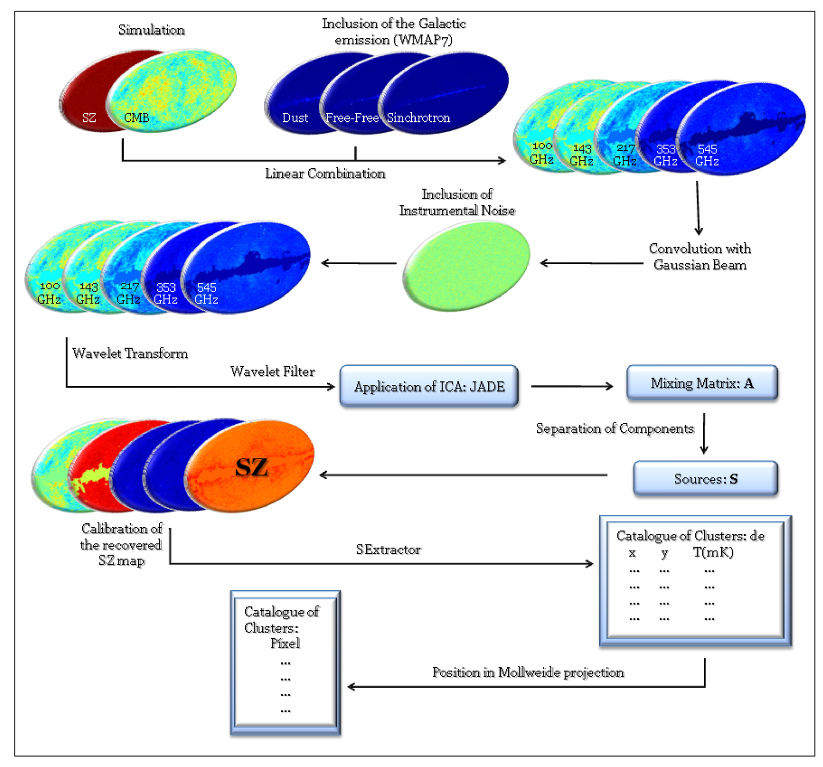

Figure 2: Flowchart of the total process of identifying clusters via the SZ effect.

Results

Comparing the positions of the calibrated clusters found by SExtractor with those of the 1000 clusters included in the input sky map, we found that, 868 were identified as "real" (input) clusters, and there were 20 false detections in the 888 clusters identified by SExtractor. The overall percentage of recovering is 86.8 %, and this result indicates a purity of $p = true\ detections/total\ detection \simeq 0.98$, and a completeness of $c = true\ detections/simulated\ clusters \simeq 0.87$. As should be expected, undetected clusters have a very low y value (5).

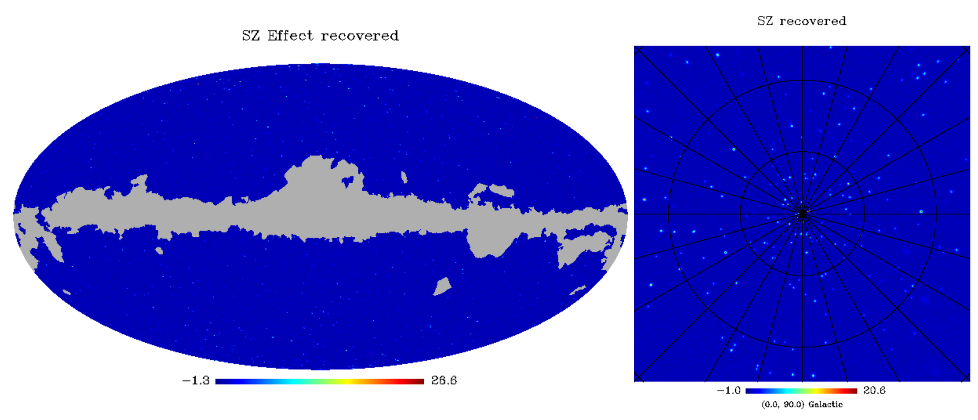

Figure 3: SZ map recovered with JADE algorithm before calibration. Left: Mollweide projection of all sky. Righ: Gnomonic projection centered around the North Galactic pole.

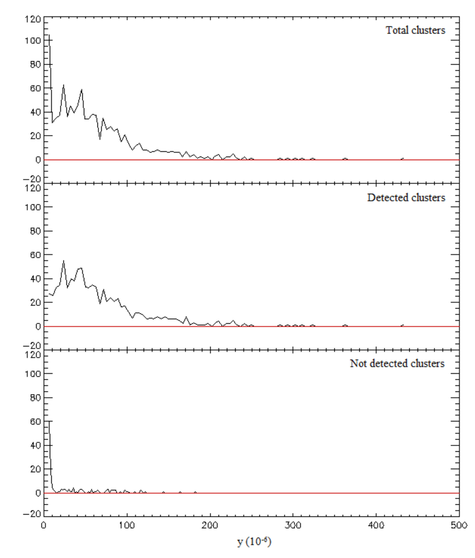

Figure 4: Histogram of Comptonization parameter y of total number of the clusters included in the maps (above), the detected (middle) and undetected clusters (below).

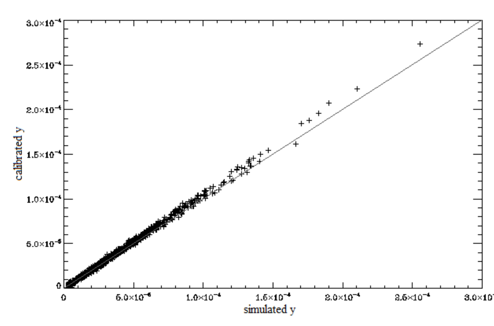

Figure 5: Graph of the values of simulated and calibrated y parameter. The diagonal straight of each graph is the line of equality.

Table 2: Results obtained from other applications of the method.

Linear combination	Found clusters	Confirmed clusters
CMB + SZ + Synchr. + Dust + Free-Free + Instr. noise (10%)	888	868
CMB + SZ + Synchr. + Dust + Free-Free + Instr. noise (20%)	820	819
CMB + SZ + Synchr. + Dust + Instr. noise (10%)	861	848
CMB + SZ + Synchr. + Instr. noise (10%)	862	856

Conclusions

One of the most attractive features of this method is that it is based on a blind search process, i.e., its application does not require any *a priori* information about the clusters, considering them completely unknown. The essential contribution of this work was the preparation of a tool based on wavelet analysis for the initial cleaning of the input data. Our method is a complementary approach to the popular "Matched Filter" approach, currently used by the Planck team [10].

The full procedure adopted in the recovery of a CMB map containing SZ clusters can be considered very efficient for the case to which it was applied. The method identifies about 87% of the 1000 clusters included in the simulations, this fraction varying slightly according to the number of input components and noise level included in the simulated maps.

Bibliography

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