Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY

Mon. Not. R. Astron. Soc. **404,** 1197–1202 (2010) doi:10.1111/j.1365-2966.2010.16372.x

The Sunyaev–Zel'dovich contribution in CMB analyses

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Accepted 2010 January 18. Received 2009 November 25; in original form 2009 June 17

ABSTRACT

The Sunyaev–Zel'dovich (SZ) effect has long been identified as one of the most important secondary effects of the cosmic microwave background. On the one hand, it is a potentially very powerful cosmological probe providing us with additional constraints and, on the other hand, it represents the major source of secondary fluctuations at small angular scales ($\ell \geq 1000$). We investigate the effects of the SZ modelling in the determination of the cosmological parameters. We explore the consequences of the SZ power spectrum computation by comparing three increasingly complex modelling methods, from a fixed template with an amplitude factor to a calculation including the full cosmological parameter dependency. We study how accurate and unbiased the parameters are when relaxing more and more assumptions on the cosmological model and on the cluster model. A coherent modelling of the SZ power spectrum, including the cosmological dependency, gives better constraints on cosmological parameters, in particular σ_8. Methods assuming an SZ template do not bias strongly the cosmological parameters when the cosmology used in the template deviates (slightly) from the reference one. However, all methods are quite sensitive to the intracluster gas distribution and hence require extra information on the clusters to alleviate the induced biases.

Key words: methods: statistical – galaxies: clusters: general – cosmic microwave background – cosmological parameters – cosmology: theory.

1 INTRODUCTION

Over the last decade, the low multipole observations of the cosmic microwave background (CMB) angular power spectrum, in intensity and polarization, have shown that a Λ cold dark matter (ΛCDM) concordance model describes accurately the Universe (Komatsu et al. 2009) with the basic cosmological parameters constrained (Dunkley et al. 2009) with a precision of the order of a per cent. To obtain even better constraints on 'standard' cosmological parameters and in order to further constrain the cosmological model (dark energy, running of the spectral index etc.), various experiments are collecting data especially at high multipoles (CBI, BIMA, ACBAR, SZA[1]; Holzapfel et al. 2000; Dawson et al. 2001; Padin et al. 2001; Runyan et al. 2003; Muchovej et al. 2007). These experiments discussed the existence of a power excess at large ℓ values that could be accounted for by point sources, Sunyaev–Zel'dovich (SZ) effect or more exotic physics – non-standard inflation, primordial voids, features in the primordial spectrum, primordial non-Gaussianity etc. (Cooray & Melchiorri 2002; Elgarøy, Gramann & Lahav 2002; Griffiths, Kunz & Silk 2003; Bond et al. 2005; Dawson et al. 2006; Douspis, Aghanim & Langer 2006; Reichardt et al. 2009; Sharp et al. 2009; Sievers et al. 2009). This highlights the necessity to carry out a consistent analysis of the CMB signal, based on a model that describes both primary anisotropies and the secondaries arising from the interaction of CMB photons with matter between the last scattering surface and the observer.

In the case of experiments that have access to high multipoles ($\ell \geq 1000$), the contribution of the secondary SZ anisotropies and the point sources will dominate over the primary CMB. A joint analysis of the CMB and SZ power spectra is thus necessary. Different parametrizations of the SZ spectrum have already been used to analyse the data from *Wilkinson Microwave Anisotropy Probe* (*WMAP*), CBI, ACBAR and BIMA (Spergel et al. 2003; Bond et al. 2005; Douspis et al. 2006; Kuo et al. 2007; Spergel et al. 2007; Dunkley et al. 2009; Reichardt et al. 2009; Sievers et al. 2009). In the present analysis, we address the issue of the calculation of the SZ spectrum used to fit the data. We examine the effect each SZ description (power spectrum and intracluster gas model) induces on cosmological parameter estimation in terms of accuracy and possible biases when successive a priori assumptions on the cosmology and on the cluster model are relaxed.

In Section 2, we briefly introduce the thermal SZ (TSZ) effect and the calculation of its power spectrum. We then present in Section 3 the different methods used to jointly fit the CMB + SZ

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[1] Cosmic Background Image (CBI); Berkeley Illinois Maryland Association Array (BIMA); Arcminute Cosmology Bolometer Array Receiver (ACBAR); Sunyaev–Zel'dovich (SZA)

data. We compare and discuss in Section 4 the accuracy of the parameter estimation for each of these methods and the possible induced biases. We summarize our results in Section 5. Throughout the study, we assume a flat ΛCDM cosmological model and use the *WMAP*5 cosmological parameters (Komatsu et al. 2009): $\sigma_8 = 0.817, n_s = 0.96, \Omega_m = 0.279, \Omega_b = 0.046$ and $h = 0.701$.

2 THE THERMAL SZ ANGULAR POWER SPECTRUM

The SZ effect (Sunyaev & Zel'dovich 1972) is the main secondary anisotropy source at arcminute scales. This consists of two terms: the first is the TSZ due to the inverse Compton scattering of the CMB photons off the hot electrons in the intracluster gas and the second is the kinetic SZ (KSZ), a Doppler shift due to the proper motion of clusters with respect to the CMB. The KSZ power spectrum is approximately two orders of magnitude smaller than the TSZ power spectrum. We thus neglect its contribution in the present analysis. The TSZ effect has a characteristic spectral signature, namely a decrease in the CMB intensity in the Rayleigh–Jeans part of the spectrum and an increase in the Wien part that is due to energy transfer from the hot intracluster electrons to the CMB photons. This characteristic frequency signature is given, in the non-relativistic approximation, by $f(x) = [x\frac{e^x+1}{e^x-1} - 4]$, where $x = \frac{h\nu}{k_B T_e}$.

In the context of the analysis of CMB data, it is necessary to take into account the contribution of the TSZ effect. The most useful tool to account for this contribution as a function of the angular scale on the sky is the TSZ power spectrum. It can be obtained either from hydrodynamical simulations or from analytical calculations. Each of these approaches has its own limitations and drawbacks. In the first case, the amplitude of the SZ spectrum as well as its shape is sensitive to the simulation characteristics. The box-size and resolution, or smoothing length, of the simulation affect the relative amplitudes on large and small scales, respectively. When the box-size is too small, the number of massive clusters is underestimated and so is the SZ power at large scales. The resolution of the simulation, or the smoothing length, artificially decreases the SZ power at small angular scales (see e.g. White, Hernquist & Springel 2002). The physical model used to describe the gas is another important source of alteration of the SZ spectrum. For example, it has been shown that pre-heating (due to energy feedback from supernovae for instance) as well as radiative cooling, which depends on the gas metallicity (Dolag et al. 2005), respectively increases or decreases the amplitude of the TSZ spectrum by a factor of 2 (da Silva et al. 2001). The influence of radiative cooling on the SZ spectrum has also been studied with an analytical treatment by Zhang & Wu (2003) and has been shown to significantly affect the amplitude of the SZ spectrum.

In the second case, the analytical calculation of the TSZ power spectrum is based on two major ingredients: the halo mass function and a model for the intracluster gas distribution within these haloes. Neglecting the correlation between haloes which is much smaller than the Poisson term or the CMB signal (Komatsu & Kitayama 1999), the TSZ angular power spectrum can be calculated as in Komatsu & Seljak (2002):

$$C_\ell^{SZ} = f^2(x) \int_0^{z_{max}} dz \frac{dV_c}{dz\, d\Omega} \int_{M_{min}}^{M_{max}} dM \frac{dn(M,z)}{dM} |\tilde{y}_\ell(M,z)|^2 . \tag{1}$$

The mass function $n(M, z)$ is given by the theoretical expression of Press & Schechter (1974) or by fitting formulae to N-body numerical simulations (Sheth & Tormen 1999; Jenkins et al. 2001; Warren et al. 2006). Different mass functions can lead to different predictions in terms of the predicted numbers of the halo and thus may induce differences in the power spectrum (Komatsu & Seljak 2002). The shape of the TSZ angular power spectrum depends on the intracluster gas distribution and properties through the two-dimensional Fourier transform on the sphere of the three-dimensional radial profile of the Compton y-parameter for individual clusters:

$$\tilde{y}_\ell = \frac{4\pi}{D_A^2} \int_0^\infty y_{3D}(r) \frac{\sin(\ell r/D_A)}{\ell r/D_A} r^2 dr, \tag{2}$$

where $y_{3D}(r) = \sigma_T \frac{k_B T_e(r)}{m_e c^2} n_e(r)$. Several models for the electronic distribution $n_e(r)$ can be used. The most commonly used are the β-profile (Cavaliere & Fusco-Femiano 1976), the polytropic gas distribution (Komatsu & Seljak 2001) and extensions of these two. We used the Komatsu–Seljak (KS) electronic distribution that assumes a gas in hydrostatic equilibrium with dark matter having a Navarro–Frenk–White (NFW) distribution. This KS profile is sharper than the $\beta = 2/3$ profile. In order to account for the contribution of the gas lying outside the virial radius (r_{vir}), following KS we take into account the SZ contribution due to a gas extension to $3\,r_{vir}$. The shape of the TSZ angular power spectrum also depends on the cosmological model through the comoving volume per steradian V_c, the angular diameter distance D_A and the mass function $n(M, z)$.

3 SZ IN CMB ANALYSIS

The estimation of cosmological parameters from the CMB would ideally require a pure primary signal. However the measured CMB data will contain additional contributions, of which the TSZ dominates. The TSZ characteristic frequency signature allows us in principle to remove the secondary contribution of the detected galaxy clusters from the CMB in multifrequency experiments. On one hand the residual SZ signal, if not taken into account in the analysis, biases the cosmological parameters (see Taburet et al. 2009) whereas, on the other hand, taking it into account requires good knowledge of the selection function. An alternative method for extracting the SZ contribution and modelling the residuals is to model the total CMB plus TSZ spectra and to determine the cosmological parameters using both primary and secondary signals. This is the approach used in all the present high-ℓ study.

We can naturally fit the total signal C_ℓ^{tot} with the expression

$$C_\ell^{tot} = C_\ell^{CMB}(\hat{\theta}) + C_\ell^{SZ}(\hat{\theta}) \tag{3}$$

with $C_\ell^{SZ}(\hat{\theta})$ being given by equation (1) as in Douspis et al. (2006), where $\hat{\theta}$ stands for the set of cosmological parameters we want to determine. We refer to this as method 3. The main advantage of method 3 is that it includes the full cosmological parameter dependency of the SZ power spectrum. Parametrizations of the SZ power spectrum are also used to fit the CMB data. They are very efficient from the point of view of computation time since they do not require the full calculation of the SZ spectrum at each step of the Monte Carlo Markov Chains (MCMC). As a result, parametrizations of the SZ spectrum can reduce the chains' convergence time by a factor of the order of 2. However, the drawback is that they do not reflect the full cosmological dependency of the SZ spectrum. Two methods fall in this category. In the first one, method 1, the total CMB power spectrum can be fitted with

$$C_\ell^{tot} = C_\ell^{CMB}(\hat{\theta}) + A_{SZ} C_\ell(\hat{\theta}_0), \tag{4}$$

where A_{SZ} is an amplitude factor multiplying an SZ spectrum template $C_\ell(\hat{\theta}_0)$ calculated analytically for a given cosmology described by the set of cosmological parameters $\hat{\theta}_0$ and intracluster gas distribution or obtained from a given numerical simulation (i.e. for a given cosmology and gas physics).

The last method, method 2, accounts for the main variations in the SZ spectrum amplitude, with the cosmological parameters σ_8 and $\Omega_b h$ following Komatsu & Seljak (2002). In this method, the total CMB spectrum is fitted with

$$C_\ell^{\rm tot} = C_\ell^{\rm CMB}(\hat{\theta}) + \sigma_8^7\,(\Omega_b h)^2\,C'_\ell(\hat{\theta}_0), \qquad (5)$$

where $C'_\ell(\hat{\theta}_0)$ is the SZ spectrum template for a given cosmology and intracluster gas distribution.

In order to compare the three different methods, we create mock data, at 100 GHz, in the form of temperature and polarization power spectra containing primary CMB anisotropies and SZ contribution from all clusters using equation (1). We computed this SZ spectrum using the Sheth & Tormen (1999) mass function and the Komatsu & Seljak (2001, 2002) intracluster gas description. We did not consider the polarization induced by clusters since it is negligible compared to the primary one (e.g. Liu, da Silva & Aghanim 2005). In this study, we do not analyse the CMB data produced from multifrequency observations after component separation. This would require to monitor precisely the residual signal after component separation which is shown to mix all foregrounds and may differ from one component separation method to another. Such an approach was followed by Rubino-Martin (private communication) and gives similar results to ours. We have rather chosen to use the best channel for the CMB study: the 100 GHz channel. In this channel, galactic foregrounds (free–free, dust emission, synchrotron radiation) will contaminate the CMB minimally as well as extragalactic radio and IR point sources. We also consider a *Planck*-like Gaussian and uncorrelated noise power spectrum with a 9.5 arcmin beam. We ran MCMC analyses, using the COSMOMC code (Lewis & Bridle 2002) with a modified version of the CAMB code (Lewis, Challinor & Lasenby 2000) including a module that calculates the SZ power spectrum with its full cosmological dependency. We followed for this module the computations detailed in Section 2. Given the instrumental beam we considered, we limited the MCMC analysis to multipoles smaller than $\ell_{\rm max} = 3500$. We used a Gaussian likelihood function since the probability distribution function of the SZ spectrum is well approximated by a Gaussian for a *Planck*-like survey (Zhang & Sheth 2007). The MCMC were carried out on the set of parameters $\hat{\theta}: \Omega_b h^2$, $\Omega_{\rm dm} h^2$, the ratio of the sound horizon to the angular diameter distance $100 \times \theta_h$, the optical depth at reionization τ, the spectral index n_s, the CMB normalization A_s and the SZ normalization factor $A_{\rm SZ}$ when method 1 is used. The deduced parameters are Ω_Λ, Ω_m, σ_8, $z_{\rm re}$, H_0 and the age of the universe. To ensure that the MCMC runs have converged, we used the convergence criterion introduced by Dunkley et al. (2005).

4 RESULTS

In the following, we investigate the effects on the cosmological parameter estimation of the three methods introduced above. We first study the ideal case when our knowledge of both the cosmological model and the cluster model is accurate. Then we move to more realistic scenarios by relaxing our assumptions. We study the accuracy and precision of the three methods when the cosmological model is not known perfectly. Finally, we explore the truly realistic case where neither the cosmology nor the cluster model is known.

4.1 Precision on cosmological parameters

As a first step, we compare the three methods in terms of the precision on the cosmological parameters. We use COSMOMC code with an SZ template, for methods 1 and 2, equals to the exact SZ power spectrum used to produce the mock data. The one-dimensional parameter distributions obtained from the different methods are presented in Fig. 1. The black dotted lines represent the parameter

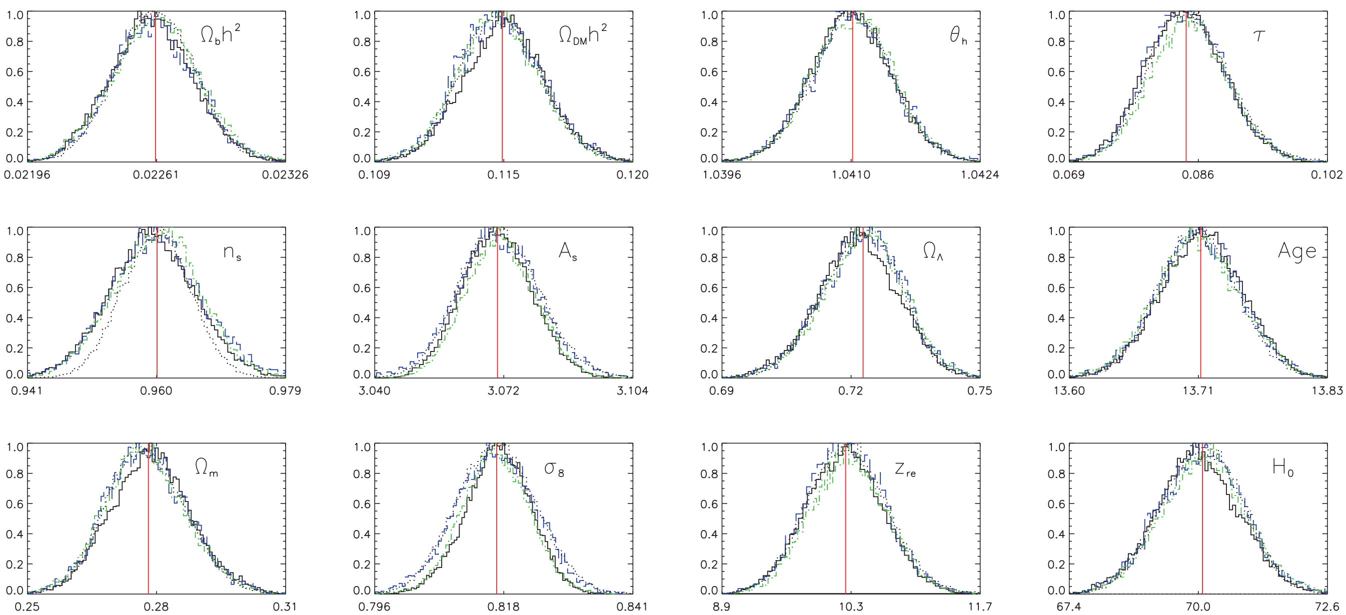

Figure 1. One-dimensional parameter distribution. The coloured curves represent the distribution for the CMB+SZ signal fitted with the three different methods. Long dashed blue line: method 1, dot–dashed green line: method 2, solid black line: method 3. The SZ template used in methods 1 and 2 is the same as that used to create the data. The black dotted line represents the parameter distributions when the signal contains only a pure primary CMB. The vertical red lines represent the input values of the parameters we used to create our mock data.

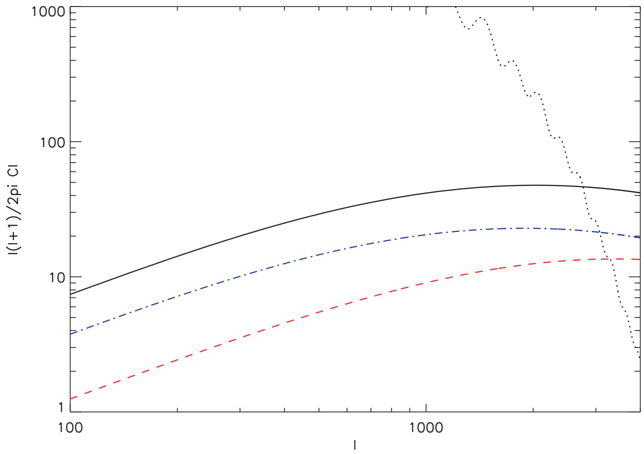

Figure 2. Theoretical SZ reference spectrum [Komatsu & Seljak (2001, 2002) intracluster gas description, solid black line], SZ spectrum calculated for an isothermal β-model ($T = T_{\rm vir}$ and $\beta = 2/3$, red dashed line) and SZ spectrum calculated for the Komatsu–Seljak gas description but with an alternative cosmology $\sigma_8 = 0.9, n_{\rm s} = 1, \Omega_{\rm m} = 0.3, \Omega_{\rm b} = 0.05, h = 0.72$ (dot–dashed blue line).

distribution when we fit, with a pure primary CMB, a signal that contains a primary CMB alone. The coloured curves represent the parameter distribution when fitting the CMB plus SZ signal with the different methods. As expected, all three methods give unbiased parameters since we used in methods 1 and 2 the same SZ template as the one used to create our mock data. The associated error bars (i.e. the accuracy of the parameter determination) do not differ significantly.

We note that methods 3 and 2 (black solid and long dashed blue curves, respectively), which account for cosmological dependence totally or partially, improve the constraints on σ_8 by 20 per cent in comparison to the pure CMB analysis (black dotted line). At the same time, the accuracy on the spectral index $n_{\rm s}$ is deteriorated. As a matter of fact when σ_8 is more constrained, larger and smaller values of $n_{\rm s}$ are needed to reproduce the signal at large scales.

We also note that by adding an extra parameter (the SZ amplitude $A_{\rm SZ}$) to the MCMC analysis, method 1 does not significantly enlarge the error bars, even if they are systematically the largest.

4.2 Relaxing the assumption on cosmology

We now consider, in a more realistic case, the fact that we do not know a priori the ‘true’ cosmological parameters. This affects the SZ template chosen for methods 1 and 2. Namely, the template will deviate from the real SZ angular power spectrum (i.e. the one used to produce the mock data). To account for this, the SZ template we use to fit our data is now based on a set of parameters chosen to be inside the 99 per cent confidence level of the *WMAP* results ($\sigma_8 = 0.75, n_{\rm s} = 0.95, \Omega_{\rm m} = 0.25, \Omega_{\rm b} = 0.045, h = 0.70$) – dot–dashed blue curve in Fig. 2.

We show in Fig. 3 the one-dimensional distribution of cosmological parameters obtained with the three methods. Using the SZ parametrization of method 1 (long dashed blue lines) or 2 (dot–dashed green curves) does not bias significantly the determination of cosmological parameters. As expected, method 3, which does not require any SZ template, gives unbiased determination of the cosmological parameters as shown by the black curves in Fig. 3.

4.3 Realistic scenario

As discussed in Section 2, the computation of the TSZ power spectrum also involves assumptions about the gas physics. Either hydrodynamical–numerical simulations are performed with given models for the gas evolution (adiabatic cooling, pre-heating, feedback etc.) or theoretical computations of the power spectrum choose a model for the intracluster gas distribution as well as scaling relations between the total mass and other cluster physical parameters (e.g. temperature). The large diversity of the possible models describing the cluster gas properties reflects the difficulty to summarize in a simple parametrization the complexity of the intracluster gas physics. The cluster physical description will inevitably affect the SZ spectrum and consequently the cosmological parameter estimation.

In the following, we consider that none of the cosmology nor the cluster model is perfectly known. This affects the three methods. We used a cluster model that differs from the KS profile used to create the mock data . Namely, we described the gas profile by an isothermal β-model with $T = T_{\rm vir}, \beta = 2/3$ and a gas extension up to $1\,r_{\rm vir}$. This $\beta = 2/3$ profile is less sharp than the KS one. Moreover, since we only consider the gas to extend to $1\,r_{\rm vir}$, the SZ spectrum computed for this latter gas distribution peaks at a smaller angular scale than the one computed for the KS model (dashed red and solid black curves in Fig. 2, respectively). This illustrates the wide range of amplitudes and shapes for the SZ spectrum.

We present in Fig. 4 the one-dimensional parameter distributions resulting from our MCMC runs with the three methods.

Methods 1 and 2 present quite similar results: $n_{\rm s}$ and $\Omega_{\rm b}h^2$ suffer significant biases. For the gas profile we considered, with method 1 the most biased parameter is the spectral index $n_{\rm s}$ (four times the expected accuracy). $\Omega_{\rm b}h^2, \tau, \Omega_{\rm m}, \sigma_8$ and H_0 are also biased (1.5, 0.8, 1.1, 0.9 and 1.2 times the expected accuracy, respectively). With method 2, these parameters suffer biases of the same order of magnitude: $n_{\rm s}$ suffers a bias equal to 4.4 times the expected accuracy while $\Omega_{\rm b}h^2, \tau, \Omega_{\rm m}, \sigma_8$ and H_0 are biased by, respectively, 1.7, 1.3, 0.9, 1.8 and 0.9 times the expected accuracy. The largest biases on σ_8 and $n_{\rm s}$ compared to those obtained with method 1 are explained by the fact that method 2 does not have an extra parameter that accounts for the SZ amplitude and that can absorb a certain level of the biases. With method 3, on the contrary, $H_0, \Omega_{\rm m}$ and Ω_Λ remain unaffected, but $n_{\rm s}$ and σ_8 are still strongly biased (3.1 and 3.2 times the expected accuracy, respectively).

5 CONCLUSIONS

In this study, we investigate three different methods to jointly fit the primary CMB and SZ signals. We study how accurate and unbiased they are when relaxing more and more assumptions on our knowledge of the cosmological model and the cluster model.

We point out that method 2 (and 3), which depends partially (and completely) on the cosmological model, gives slightly better constraints on σ_8 than method 1, which does not depend on the cosmological model. By adding an extra parameter, the amplitude of the SZ template used in the fit, method 1 ‘decouples’ the cosmological information within the CMB from the SZ signal. Nevertheless, this does not enlarge drastically the error bars. In the case of fitting data with an SZ template computed independently from the true cosmological model, methods 1 and 2 induce no strong biases on the cosmological parameters. As long as the SZ signal amplitude is low, and the assumed cosmological model is not too far from the true one, a fixed shape of the SZ spectrum template does not

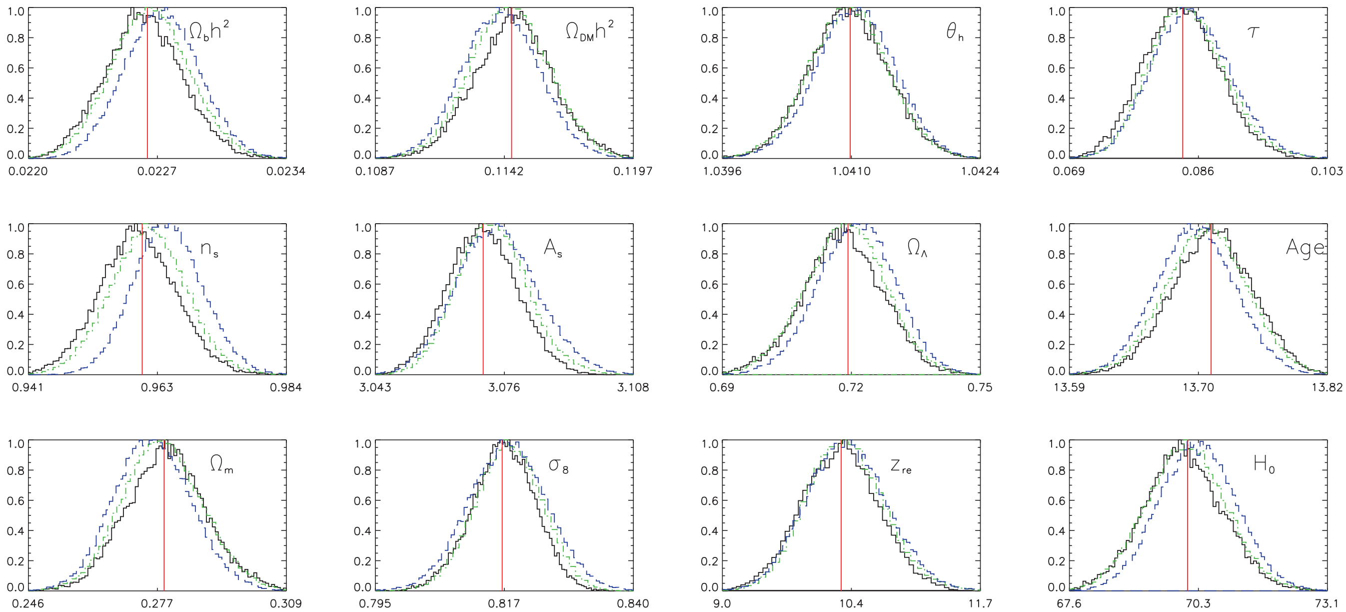

Figure 3. One-dimensional parameter distribution. The curves represent the distributions for the CMB+SZ signal fitted with the three different methods. Long dashed blue line: method 1, dot–dashed green line: method 2, solid black line: method 3. The SZ template used in methods 1 and 2 (blue dotted line in Fig. 2) differs from that used to create the data (black line in Fig. 2). The vertical red lines represent the input values of the parameters we used to create our mock data. Note the substantial biases that can affect the estimation of σ_8 when using method 1 or 2.

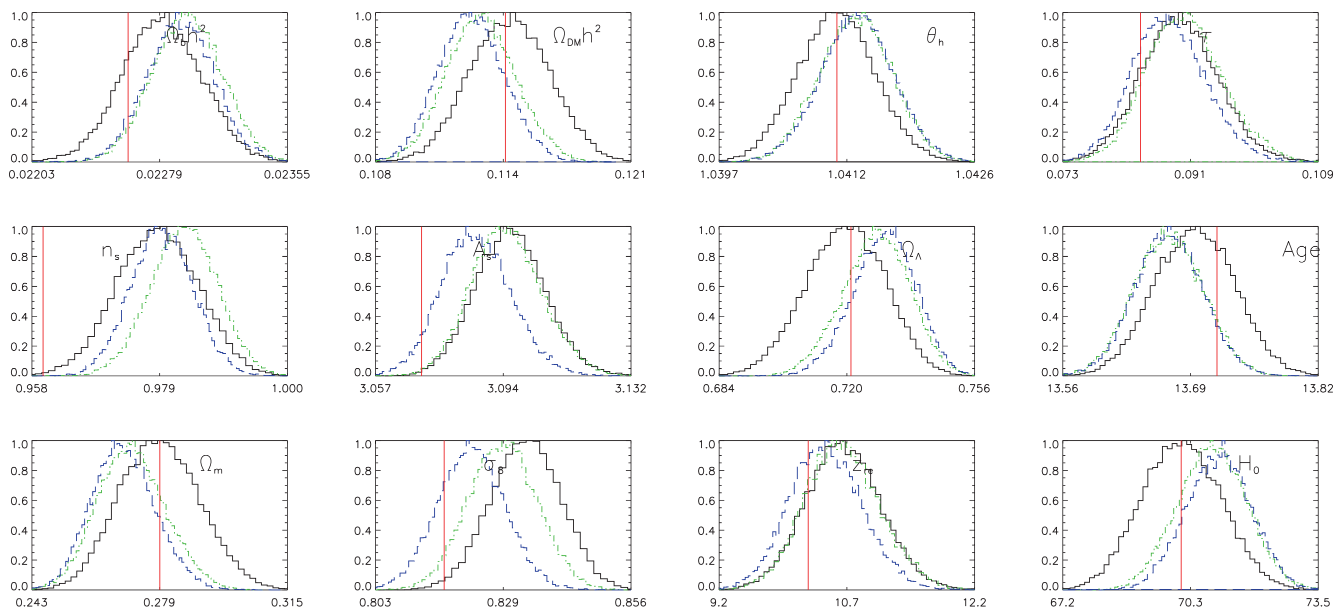

Figure 4. One-dimensional parameter distribution. The coloured curves represent the distribution for the CMB+SZ signal fitted with the three different methods. Long dashed blue line: method 1, dot–dashed green line: method 2, solid black line: method 3. The SZ template used in methods 1 and 2 differs from that used to create the data (β profile versus KS profile; see the text for details). Method 3 also uses a β profile when computing the SZ spectrum. The vertical red lines represent the input values of the parameters we used to create our mock data.

introduce large biases. Obviously, a coherent cosmological analysis as that done with method 3 is totally unbiased.

We show in our study that an incomplete understanding of the intracluster gas distribution and properties translates into a wrong modelling of the cluster SZ signal and consequently of the SZ angular power spectrum. This, in turn, results in important biases on the cosmological parameters. In the particular case we considered here, we found that methods 1 and 2 introduce large biases, in particular on n_s. To a lower extent, $\Omega_b h^2$, τ, Ω_m, σ_8 and H_0 are also biased. Method 3 seems less affected even if large biases are seen on σ_8 and n_s. This last result reinforces the need for better constraints on the description of the galaxy cluster gas properties.

ACKNOWLEDGMENTS

The authors thank the referee and they particularly thank M. Langer for enthusiastic and useful discussions. They acknowledge the use of the CAMB and COSMOMC packages. They also thank G. Efstathiou for pointing us an error in the amplitude of our calculated SZ spectrum.

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