LETTER TO THE EDITOR

First measurement of the cross-correlation of CMB weak lensing and X-ray emission

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Received 10 October 2017 / Accepted 5 March 2019

ABSTRACT

Since the publication of the results of the Planck satellite mission in 2013, the local and early Universes have been considered to be in tension in respect of the determination of amplitude of the matter density spatial fluctuations (σ⁸) and the amount of matter present in the Universe (Ω_m). This tension can be seen as a lack of massive galaxy clusters in the local Universe compared to the prediction inferred from Planck cosmic microwave background (CMB) best-fitting cosmology. In the present analysis we perform the first detection of the cross-correlation between X-rays and CMB weak lensing at 9.1σ. We next combine thermal Sunyaev–Zel’dovich effect, X-rays, and weak-lensing angular auto- and cross-correlation power spectra to determine the galaxy cluster hydrostatic mass bias. We derive (1 − h₈) = 0.71 ± 0.07. Considering these constraints, we observe that estimations of σ⁸ in the local Universe are consistent with Planck CMB best-fitting cosmology. However, these results are in clear tension with the output of hydrodynamical simulations that favor (1 − h₈) > 0.8.

Key words. cosmological parameters – large-scale structure of Universe – galaxies: clusters: general – galaxies: clusters: intracluster medium – cosmic background radiation

1. Introduction

Modern cosmology relies heavily on the observations and analysis of cosmic microwave background (CMB) data. If the standard six parameter Λ cold dark matter (ΛCDM) model provides a satisfying description of the outcome of the main cosmological probes (Planck Collaboration XIII 2016), the determination of its parameters appears to be in tension when separately considering the CMB angular power spectrum on the one hand, and the abundance of galaxy cluster in the local Universe (z < 1) on the other (see, e.g., Salvati et al. 2018, for a recent CMB-galaxy cluster joint analysis).

One current challenge of modern cosmology is thus related to the understanding of the origin of this apparent tension. This could be produced by our lack of knowledge regarding the galaxy cluster mass-observable relations, or by new physics beyond the standard ΛCDM model affecting the structure growth between the CMB last scattering surface and the local Universe (Salvati et al. 2018; Planck Collaboration XX 2014). In this context, several probes can be used to trace the large-scale distribution of matter in the Universe. During their propagation along the line of sight, the CMB photons are affected by several physical processes such as the inverse Compton scattering expressed by the thermal Sunyaev–Zel’dovich effect (Sunyaev & Zeldovich 1969, 1972; hereafter tSZ), and the CMB gravitational lensing (Blanchard & Schneider 1987) accounting for the deflections induced by the gravitational potential integrated along the line of sight, φ. The hot electrons causing the tSZ effect are also emitting in the X-ray domain through Bremsstrahlung radiation in such a way that the tSZ effect, X-ray emission, and gravitational lensing have been powerful sources of cosmological and astrophysical constraints (see, e.g., Planck Collaboration XX 2014; Planck Collaboration XVII 2014).

However, the use of galaxy clusters as cosmological probes often requires the determination of their total mass, a complicated step usually relying on the hydrostatic equilibrium hypothesis. While such mass estimates are known to be biased (M_{hydro}/M_{true} = 1 − b_1), hydrodynamical simulations favor low values for this bias (b_1 < 0.2) (see, e.g., Lau et al. 2013; Biffi et al. 2016). At the same time, on the observational side a significant number of analyses combining X-ray, tSZ, and weak lensing observations have been conducted in the last five years, either based on an object-by-object approach or resorting to stacking algorithms (see, e.g., Hurier & Angulo 2018; Medezinski et al. 2018; Sereno et al. 2017; Jimeno et al. 2018; Parroni et al. 2017; Okabe & Smith 2016; Battaglia et al. 2016; Applegate et al. 2016; Smith et al. 2016; Hoekstra et al. 2015; Simet et al. 2015; Israel et al. 2015; von der Linden et al. 2014; Donahue et al. 2014; Gruen et al. 2014; Mahdavi et al. 2013). These analyses obtain a hydrostatic mass bias b_1 > 0.3, which seem to be compatible with the measurement obtained after combining CMB weak lensing and tSZ measurements towards SDSS DR8 redMaPPer (Rykoff et al. 2014) galaxy clusters: b_1 = 0.26 ± 0.07 (Hurier & Angulo 2018).

The statistical correlations of these tracers on the sky have also attracted a lot of attention. For instance, the correlation between tSZ–X and tSZ–φ cross-analyses have been used to set cosmological constraints (see, e.g., Hill & Spergel 2014; Hurier 2015; Hurier et al. 2015). These measurements present different sensitivities to cosmological parameters and mass-observable
relations. Consequently, a coherent statistical analysis of $\phi$, tSZ, and X-ray emission is a powerful tool for identifying the origin of the tension between the CMB and the low redshift Universe.

In the present paper we present the first measurement of the CMB weak lensing and X-ray emission cross-correlation power spectrum. We model this cross-correlation using a halo-model formalism to derive cosmological constraints. Finally, we combine this result with previous studies to derive constraints on the hydrostatic mass bias.

2. Modeling the tSZ, X-ray, and $\phi$ cross-correlations

We refer to Hurier (2015) for a detailed modeling of tSZ and $\phi$ cross-power spectra, and to Hurier et al. (2014) for the modeling of the X-ray emission. We relate cosmological parameters to the dark matter halo number per unit of mass and redshift $dN/dm$ using the mass function from Tinker et al. (2008).

2.1. Poissonian term

Using the Limber approximation, we can write the one-halo term as

$$C_{\ell}^{X\Phi-P} = 4\pi \int dz \frac{dV}{d\Omega} \int dM \frac{d^3N}{dM dV} W^X_b W^P_{\ell}. \quad (1)$$

The tSZ contribution can be written as

$$W^P_{\ell} = Y_{500} \psi_{\ell}, \quad (2)$$

where $Y_{500}$ represents the tSZ flux of the clusters within a radius where the matter density equals 500 times the critical density at the clusters’ redshift, related to the mass contained in the same volume ($M_{500}$) via the scaling law presented in Planck Collaboration XX (2014). In this same expression, $y_\ell$ represents the Fourier transform on the sphere of the cluster pressure profile per unit of tSZ flux from Planck Collaboration XX (2014). We consider a generalized Navarro–Frenk–White (GNFW) Universal pressure profile (Arnaud et al. 2010; Planck Collaboration Int. V 2013).

We model the lensing contribution as

$$W^\phi_{\ell} = -2\psi_{\ell} \frac{(\chi' - \chi)\chi}{\chi'}, \quad (3)$$

with $\chi$ the comoving distance, $\chi'$ the comoving distance to the surface of the last scattering of the CMB, and $\psi_{\ell}$ the 3D lensing potential Fourier transform on the sky. We can express the density contrast $\rho$ as a function of the density contrast, $\Delta \psi = \frac{3}{2} \Omega_m H_0^2 \frac{\delta_{\ell D}}{a}$, with $a$ the Universe scale factor and $\delta$ the density contrast. From this, the lensing contribution reads

$$W^\phi_{\ell} = \frac{3 \Omega_m H_0^2}{c^2} \frac{(1 + \ell)}{\ell + 1} \frac{(\chi' - \chi)\chi}{\chi'}, \quad (4)$$

where $\delta_{\ell}$ is the Fourier transform of the density contrast profile, $\delta_{3D} (a)$, computed as

$$\delta_{\ell} = \frac{4 \pi f_{S500}}{f_{S500}^2} \int_0 \frac{du}{u^2} d3D (u) \frac{\sin(\ell u / f_{S500})}{u / f_{S500}}, \quad (5)$$

where $u = r / f_{S500}$ is the normalized radius of the profile, $f_{S500} = D_A / r_{500}$, $D_A$ is the angular diameter distance, and $r_{500}$ is the radius within which the matter density is 500 times the critical density of the Universe.

Finally, the X-ray contribution can be written as

$$W^X_{\ell} = S^X_{500} \psi_{\ell}, \quad (6)$$

with $S^X_{500} = C L_{S500}$, the X-ray count-rate in the [0.5–2.0] keV energy band of the host halo, $L_{500}$ the unabsorbed X-ray luminosity in the [0.1–2.4] keV energy range, $C$ the average luminosity to count-rate conversion factor described in Hurier et al. (2014), and $x_\ell$ the Fourier transform of the X-ray number count profile. To model the $L_{500} - M_{500}$ relation, we used the relation derived by Arnaud et al. (2010) from the REXCESS sample (Böhringer et al. 2007). We considered a polytropic equation of state with a polytropic index of 1.2 to compute the density and the temperature profiles from the pressure profile.

2.2. Large-scale correlation terms

We express the large-scale correlations, the two-halo term, contribution as

$$C_{\ell}^{X\Phi-C} = 4\pi \int dz \frac{dV}{d\Omega} W^X_b W^C_{\ell} P_k, \quad (7)$$

with $P_k$, the matter power-spectrum computed using CLASS (Lesgourgues 2011).

For the tSZ effect, the CMB weak lensing, and the X-ray count rate we can express the window functions as

$$W^C_{X} = \int dM \frac{d^3N}{dM dV} S_{500} \psi_{\ell} b_{\text{lin}}, \quad (8)$$

$$W^C_{\phi} = \frac{3 \Omega_m H_0^2}{c^2} \frac{(1 + \ell)}{\ell + 1} \frac{(\chi' - \chi)\chi}{\chi'}, \quad (9)$$

where $b_{\text{lin}}$ is the linear bias relating the halo distribution to the overdensity distribution. We considered the bias from Mo & White (1996), which is realistic on galaxy cluster scales.

We find that X-ray--lensing cross-correlation power spectra evolves as $\Omega_m^{a_8 b_8^{1.1.8}}$ for $\ell = 200$.

We present in Fig. 1 the power density distribution in the $M_{500} - z$ plane for the X-ray, weak lensing, and tSZ auto- and cross-correlation power spectra at $\ell = 200$. We observe that weak-lensing favors higher redshift objects compared to the tSZ effect and X-ray emission. The X-ray and tSZ are highly correlated (at ≃76%), while the tSZ effect and the weak lensing one-halo terms are moderately correlated (≃46%), and the X-ray emission and the weak lensing one-halo terms show a lower correlation at the level of ≃20%. We refer the reader to Hurier (2015) and Hurier et al. (2015) for a detailed description of the mass and redshift dependence of the CMB weak lensing and X-ray window functions. In the light of Fig. 1, it becomes clear that detecting the X-ray--lensing cross-correlation is particularly challenging, considering the high noise level of Planck CMB weak lensing maps, and the AGN-dominated X-ray sky.

3. First measurement of the cross-correlation between X-rays and weak-lensing

We use the ROSAT all-sky survey (RASS) public data1, which covers 99.8% of the sky, including 97% that has an exposure

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1 http://www.xray.mpe.mpg.de/rosat/archive/
Planck reprojection of the RASS data on the Healpix full-sky map can take longer than 100 s (Voges et al. 1999). A description of the correlation between probes.

The color scale is the same for all panels and represents the total amount of cross-power spectra, from left to right and top to bottom referring to: X-ray–lensing, X-ray–tSZ, and lensing–tSZ cross-power spectra. The scale color is the same for all panels and represents the total amount of correlation between probes.

Fig. 1. Power density for power spectra $d^2 \Xi(\ell)/dM_{\text{peak}} d\ln(z)$ as a function of halo mass $M_{\text{peak}}$ and redshift $z$ at $\ell = 200$. On the diagonal we display power density for the auto-correlation power spectra. From left to right: contribution to X-ray, CMB weak lensing, and tSZ angular power spectrum at $\ell = 200$. Off-diagonal panels represent power density of cross-power spectra, from left to right and top to bottom referring to: X-ray–lensing, X-ray–tSZ, and lensing–tSZ cross-power spectra. The color scale is the same for all panels and represents the total amount of correlation between probes.

The significance smaller than the X-ray–lensing power spectra. We obtained a significance of $9.1 \sigma$ for the angular cross-power spectrum, measured between Planck CMB lensing full-sky map and a RASS data reprojected on the full-sky (black sample); the same cross-spectra when masking NVSS sources is shown as grey samples. The red solid line shows the theoretical prediction assuming $(\sigma_8 = 0.8, \Omega_m = 0.3, b_1 = 0.2)$, the green dashed line shows the two-halo term contributions, and the blue dashed line the one-halo term contribution. The solid cyan line displays the contribution from AGN–φ cross-correlation.

$b_{1h} = 0.2$). We observe that the two-halo term dominates for $\ell < 100$ and that the one-halo term dominates at higher multipoles. This illustrates how Planck weak lensing map contains a significant signal produced by compact objects like galaxy clusters. Assuming a Gaussian prior of $b_{1h} = 0.20 \pm 0.05$, consistent with hydrodynamical simulations and marginalizing over other cosmological parameters according to Planck CMB best-fitting cosmology (Planck Collaboration XIII 2016), we derive $\Omega_m = (0.3)^{0.22} = 0.80 \pm 0.03$. We verified that masked galaxy clusters only marginally affect (<1%) the constraints on $\sigma_8$, which can thus be safely neglected.

4. Combined analysis of thermal Sunyaev–Zel’dovich effect, X-ray, and weak-lensing signals

We next combine our results with tSZ–φ, tSZ-tSZ, tSZ-X-ray, φ-φ, and CMB–CMB power spectra results. We assume that the CMB angular power spectrum is uncorrelated with all other probes, so we compute the covariance between all large-scale structure tracers following the procedure described in Hurier & Lacasa (2017) accounting for non-Gaussian contributions to the uncertainties. We use the tSZ analysis from Hurier & Lacasa (2017), the tSZ–φ measurement corrected for cosmic infra-red background contamination from Hurier (2015), the tSZ–X-ray results from Hurier et al. (2015), the Planck weak lensing results from Planck Collaboration XVII (2014), and the Planck CMB results from Planck Collaboration XIII (2016).

We performed a join fit of these results to derived cosmological constraints on $\sigma_8$ and $\Omega_m$ on constraints on the hydrostatic mass bias $b_{1h}$. Both weak-lensing and CMB results are not sensitive to the hydrostatic mass bias. Consequently, weak lensing and CMB constraints set the cosmological parameters $\sigma_8$ and $\Omega_m$, whereas the large-scale structure tracers, namely the AGN contribution to the X-ray–lensing cross-correlation.

In Fig. 2, we present the derived angular cross-power spectrum, compared to our modeling for $(\sigma_8 = 0.8, \Omega_m = 0.3)$.
tSZ effect and the X-ray emission, set the hydrostatic mass-bias value. From this combined analysis, we derived \( b_1 = 0.71 \pm 0.07 \). We present the resultant likelihoods for tSZ, tSZ–X, X–\( \phi \), \( \phi \), and CMB analyses for \( b_1 = 0.71 \pm 0.07 \) in Fig. 3. The X-ray auto-correlation power spectrum is not shown in this figure as it is particularly difficult to derive robust constraints from it, considering that the X-ray sky is dominated by AGN contribution. We observe that some tension remains, especially with tSZ derived constraints, but all large-scale structure analyses presented here are consistent within 2\( \sigma \) with the Planck CMB results.

5. Conclusion and discussion

We produced the first detection of the X-ray–\( \phi \) cross-correlation angular power spectrum, with a significance of 9.1\( \sigma \). We established cosmological constraints on \( \sigma_8 \) and \( \Omega_m \) from this cross-correlation, which we find consistent with previous large-scale structure (Hurier et al. 2015; Hurier & Lacasa 2017; Hurier & Angulo 2018) and CMB analyses (Planck Collaboration XIII 2016; Planck Collaboration XVII 2014). Similarly to the tSZ–X cross-correlation, the X–\( \phi \) correlation favors values of the hydrostatic mass bias lower than those suggested in tSZ-CMB combined analyses (Salvati et al. 2018). It also favors a higher value for \( b_1 \) than most of the weak-lensing based analyses of the last four years (see, e.g., Medezinski et al. 2018; Sereno et al. 2017; Jimeno et al. 2018; Parronni et al. 2017; Okabe & Smith 2016; Battaglia et al. 2016; Applegate et al. 2016; Smith et al. 2016; Hoekstra et al. 2015; Simet et al. 2015; Israel et al. 2015; Donahue et al. 2014; Gruen et al. 2014; Mahdavi et al. 2013). These analyses prefer \( b_1 \approx 0.20 \). With the constraint inferred here (\( b_1 = 0.29 \pm 0.07 \)), large-scale structure cosmological constraints from the local Universe on \( \sigma_8 \) and \( \Omega_m \) now surround the CMB-based cosmological constraints. This result favors a high value of \( b \) compared to hydrodynamical simulations that prefer \( b < 0.2 \). Additionally, under the assumption that these measurements are systematic-free, the significant difference between tSZ and X-ray based results may indicate that these two probes select significantly different populations of galaxy clusters in terms of hydrostatic mass bias.

Acknowledgements. We acknowledge the use of HEALPix (Górski et al. 2005).

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