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Clusters of galaxies and variation of the fine structure constant

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Abstract. We propose a new method to probe for variations in the fine structure constant α using clusters of galaxies, opening up a window on a new redshift range for such constraints. Hot clusters shine in the X-ray mainly due to bremsstrahlung, while they leave an imprint on the CMB frequency spectrum through the Sunyaev-Zel'dovich effect. These two physical processes can be characterized by the integrated Comptonization parameter $Y_{SZ}D_A^2$ and its X-ray counterpart, the Y_X parameter. The ratio of these two quantities is expected to be constant from numerical simulations and current observations. We show that this fact can be exploited to constrain α, as the ratio of the two parameters depends on the fine structure constant as $\propto \alpha^{3.5}$. We determine current constraints from a combination of Planck SZ and XMM-Newton data, testing different models of variation of α. When fitting for a constant value of α, we find that current constraints are at the 0.8% level, comparable with current CMB bounds. We discuss strategies for further improving these constraints by at least a factor ~ 3.

Key words. Cosmology: clusters–fine structure constant–variation fundamental constants

1. Introduction

Constraints on the fine structure constant are currently derived from a number of different observations, ranging from laboratory to astrophysical measurements (see e.g. Uzan 2003). E.g. CMB data from the WMAP7 satellite in combination with ACT and SPT data constrain α at $\sim$ 1% level (68% c.l.) at $z \sim 1000$ Menegoni, E., et al. (2012). Tantalizing hints of variation of α have actually been found in atomic absorption lines in quasar spectra at the 5-sigma level (see Webb et al. 2011), although this result was questioned by independent analysis (see e.g. Srianand et al. 2004).

Opening up new redshift ranges is useful as theory is not a reliable guide to the expected nature of variations in fundamental constants, so that variations might be e.g. non-monotonic with z. In Galli (2013), we proposed to constrain the fine structure constant combining measurements of the Sunyaev-Zel'dovich (SZ) effect Sunyaev and Zeldovich (1972) with the measurement of X-ray emission in clusters of galaxies.

CMB experiments such as Planck, SPT or ACT are in fact currently detecting many hundreds of clusters through the SZ effect. Some of these are known clusters, while others are newly discovered, and have been or will soon be observed in follow-up campaigns by other observatories, such as the Chandra or the XMM-Newton telescopes in the X-rays. Thus, measurements of both the SZ effect and of the X-ray emission of hundreds of clusters will soon be available up to a redshift of $z \sim 1$ Chamballu et al. (2012).

The SZ effect is often expressed in terms of the integrated Compton parameter $Y_{SZ}D_A^2$ (see Sect. 2.1 for a detailed definition), while the X-ray emission of hot clusters ($kT \gtrsim 2KeV$), mainly due to bremsstrahlung, can be characterized by the parameter $Y_X = M_g T_X$ (see Sect. ??). Both $Y_{SZ}D_A^2$ and Y_X are approximations of the thermal energy contained in the clusters, and are thus expected to strongly correlate with total mass, weakly depending on its dynamical state Kaiser (1986); Kravtsov et al. (2006). In the limit where gravity completely dominates cluster formation, $Y_{SZ}D_A^2$ and Y_X are expected to scale in the same way with mass and redshift as power-laws. Indeed, numerical simulations suggest they both have equivalent scaling relations that are close to be self-similar. Thus, the $Y_{SZ}D_A^2 - Y_X$ relation is expected to be, on average, constant at all z Kravtsov et al. (2006); Comis et al. (2011); Sembolini, et al. (2012). Furthermore, the same simulations show that the scatter on the relation between $Y_{SZ}D_A^2$ and Y_X is small, at $\lesssim 15\%$ level.

So far, the data are consistent with these predictions, see e.g.Planck Collaboration (2011a).

In Galli (2013), we propose to use the observed linear relation between Y_X and $Y_{SZ}D_A^2$ to constrain the fine structure constant. In fact, the Y_{SZ} and the Y_X parameters have different dependencies on the fine structure constant, so that their ratio strongly depends on α. The fact that no deviation from a constant have yet been observed in the $Y_{SZ}D_A^2 - Y_X$ relation can be used to constrain variations in α.

2. Method

2.1. Sunyaev-Zel'dovich effect

Over 80% of the baryonic content of clusters of galaxies is expected to be under the form of intergalactic hot gas at temperatures of order $T \sim 10^7 - 10^8 K$ Borgani & Kravtsov (2009). The ionized gas can inverse Compton scatter CMB photons, leaving a signature, the Sunyaev-Zel'dovich effect, in the CMB spectrum Sunyaev and Zeldovich (1972). From this spectral distortion, one can calculate the so called spherical integrated Compton parameter, defined as:

$$Y_{SZ}(R)D_A^2 = \frac{\sigma_T}{m_e c^2} \int_0^R n(r)T(r)4\pi r^2 dr \quad (1)$$

$$(2)$$

where m_e is the electron mass, n is the electron number density at distance r from the center of the cluster, T is the temperature of the gas, D_A is the angular diameter distance and σ_T is the Thompson cross section, which depends on the fine structure constant as

$$\sigma_T = \frac{8\pi}{3} \frac{\hbar^2}{m_e^2 c^2} \alpha^2. \quad (3)$$

The Y_{SZ} parameter thus depends on the fine structure constant via the Thompson cross section in Eq. 3 as

$$Y_{SZ} \propto \alpha^2 \quad (4)$$

The magnitude of the X-ray emission is often quantified through the Y_X parameter Kravtsov et al. (2006); Arnaud et al. (2010), which is analogous to the SZ parameter Y_{SZ}. It is defined as

$$Y_X = M_g(R)T_X \quad (5)$$

Here, $M_g(R)$ is the X-ray determined gas mass within a certain cluster radius R, and T_X is the spectroscopically determined X-ray temperature of the cluster, determined within a cylindrical annulus that excludes the core. The gas mass is defined as

$$M_g(R) = \mu_e m_p \int n_e dV \quad (6)$$

$$\propto n_e R^3 \quad (7)$$

with μ the mean molecular weight of eletrons. The gas mass can be determined from X-ray data as the density profile of the cluster can be inferred from the emissivity, which is in turn obtained from the observed surface brightness. This assumes that the temperature can be spectroscopically determined and that the angular diameter distance is known.

We can then link the inferred gas mass to the fine structure constant (see Galli (2013) for details)

$$M_g(R) \propto \sqrt{\epsilon_\nu T^{1/2} e^{h\nu/kT} \alpha^{-3}} R^3 \quad (8)$$
$$\propto \sqrt{\alpha^{-3} I_\nu D_A^{-1}} D_A^3 \quad (9)$$
$$\propto \sqrt{\alpha^{-3} I_\nu} D_A^{5/2} \quad (10)$$

The Y_X parameter thus depends on the fine structure constant as

$$Y_X \propto \alpha^{-1.5} \quad (11)$$

2.2. $Y_{SZ} - Y_X$ relation and α

From Eq. 5, 2 and 7, the ratio between Y_{SZ} and Y_X depends on the structure of a cluster as

$$\frac{Y_{SZ} D_A^2}{Y_X} = C_{XSZ} \frac{\int n_e(r) T(r) dV}{T_X(R) \int n_e(r) dV} \quad (12)$$
$$C_{XSZ} = \frac{\sigma_T}{m_e c^2} \frac{1}{\mu_e m_p} \quad (13)$$

The Y_{SZ} parameter depends on the gas mass weighted temperature, while Y_X depends on the X-ray temperature. Both are approximations of the same physical quantity, i.e. the thermal energy of the cluster. It is then clear that if clusters were isothermal, the ratio between the two would exactely be equal to a constant. However, the ratio can still be expected to be constant if the temperature profile of the clusters is universal. This condition is fullfilled if the evolution of clusters is completely dominated by gravity, weakly depending on gas physics. In this case, both Y_{SZ} and Y_X are expected to strongly correlate with the mass of the cluster via the virial theorem, both with the same dependence on mass and redshift Kaiser (1986); Borgani & Kravtsov (2009)

Numerical simulations have shown that indeed the two parameters have scaling relations with the total mass of the cluster that are very close to be self-similar, i.e. that $Y_X, Y_{SZ} \propto M^{5/3} E(z)^{2/3}$, with $E(z) = (H(z)/H_0)$. Furthermore, they have shown that the scaling relation between Y_X and $Y_{SZ} D_A^2$ has very small scatter, at the level of $\sim 15\%$Stanek, et al. (2010); Kay et al. (2012); Fabjan et al. (2011). The relation between the two is also expected to be independent of redshift, as their scaling relation with mass have the same dependence on cosmology. Finally, the relation seems not to crucially depend on the dynamical state of the clusters Arnaud et al. (2010).

Based on all these considerations, the ratio between Y_{SZ} and Y_X is expected to be constant

$$\frac{Y_{SZ} D_A^2}{Y_X} \sim const$$

for clusters at different redshifts or space positions.

This fact can be exploited to constrain the variation of the fine structure constant at different time/space positions i, as

$$\left(\frac{Y_{SZ} D_A^2}{Y_X}\right)_i = \left(\frac{\alpha_i}{\alpha_0}\right)^{3.5} \left(\frac{Y_{SZ} D_A^2}{Y_X}\right)_0 \quad (14)$$

where $\left(\frac{Y_{SZ} D_A^2}{Y_X}\right)_0$ is a reference value of the ratio that assumes a reference value of the fine structure constant α_0. The method enables us to measure the relative variation of α with respect to α_0 as a function of redshift and space position. Alternatevely, if one could reliably estimate a reference value of $\left(\frac{Y_{SZ} D_A^2}{Y_X}\right)_0$ knowing the value of α_0, e.g. from simulations, it would also be possible to have an absolute measure of α for each cluster.

In any case, if a variation is detected, it could be clearly either due to an uncorrected astrophysical or instrumental systematic error or due to an actual change in α. But if no variation is detected a limit on the variation of α can be extracted. We cannot logically exclude the possibility that intrisic changes of the ratio $\left(\frac{Y_{SZ} D_A^2}{Y_X}\right)$ or uncorrected systematics might provoke a variation in the $Y_{SZ} - Y_X$ relation that conspires to precisely cancel a true variation in α resulting in no apparent variation.This case would lead to a false rejection of the variation hypothesis.

3. Constraints from current data

3.1. Data

We present in this section constraints on α from current data. For the analysis, we use SZ and X-ray data from a subsample of the Planck Early Sunyaev-Zel'dovich cluster sample (Planck Collaboration 2011b), as reported in Planck Collaboration (2011a). The clusters of the ESZ sample are detected in the Planck all-sky maps through their thermal SZ imprint on the CMB. They are characterized by a S/N higher than 6, and are required to have a X-ray counterpart in the MCXC catalog Piffaretti et al. (2011). The subsample then reported in Planck Collaboration (2011a) is composed by 62 clusters that had been observed by the XMM-Newton telescope, that are not contaminated by flares and whose morphology is regular enough that spherical symmetry can be assumed. We additionally exclude from the analysis cluster A2034, whose redshift estimate is discordant in Planck Collaboration (2011a) and Mantz et al. (2010), as noted by Rozo et al. (2012). We thus use 61 clusters, in the redshift range $0.044 < z < 0.44$. The Y_{SZ} and Y_X parameters we use here are measured within a radius R_{500}, i.e. the radius at which the mean matter density of the cluster is 500 times larger than the critical density at the redshift of the cluster. Furthermore, X-ray temperatures are defined within a cylindrical annulus of radius $[0.15 - 0.75]R_{500}$.

Fig. 1 shows the space and redshift distribution of the clusters used.

These data are neither a complete nor a representative sample of clusters, and the observation of a larger sample of clusters in the X-ray will be required to properly characterize the Planck clusters, in particular to study the intrisic scatter and Malmquist bias, as well as possible systematics Planck Collaboration (2012) However, we use this dataset to provide a first estimate of the constraints on α that one can derive from this dataset.

3.2. Analysis and constraints: Constant α

We first analyze the data in order to find constraints on α under the simple assumption that no evolution in time or space is present, i.e. that the $Y_{SZ}D_A^2/Y_X$ ratio is a constant. Any deviation exceeding statistical error is attributed to intrinsic scatter.

We calculate the mean of $Y_{SZ}D_A^2/Y_X$ through a modified weighted least square method (MWLS). This method differs from a simple weighted least square because it takes into account the fact that statistical uncertainties on $Y_{SZ}D_A^2/Y_X$, calculated by propagating the statistical errors on $Y_{SZ}D_A^2$ and Y_X, can be underestimated or can neglect intrinsic scatter. A weighted least square method provides in fact a simple weighted mean of $\log{(Y_{SZ}D_A/C_{XSZ}Y_X)} = -0.050 \pm 0.014$, with a χ^2 per degrees of freedom of $\chi^2/dof = 223/60$. Clearly, such a high reduced χ^2 might indicate either that a constant is a poor description of the $Y_{SZ}D_A^2/Y_X$ data, or the presence of e.g. additional intrinsic scatter. Under this second assumption, we can account for a possible wider dispersion of the data by quadratically adding to the statistical error of each data point a constant term $\sigma_{\rm intr}$ (see e.g. Pratt et al. 2006) for the unknown intrinsic scatter. The weighted mean and the intrinsic scatter are then jointly determined so that the reduced χ^2 equals 1. Following this method, we obtain $\log{(Y_{SZ}D_A/C_{XSZ}Y_X)_i} = -0.031 \pm 0.028$, which corresponds to $(Y_{SZ}D_A/C_{XSZ}Y_X)_i = 0.969 \pm 0.027$. This result is in perfect agreement with the results found by Planck Collaboration (2011a) and Rozo et al. (2012). We find that the intrinsic scatter term for each data point is equal to $\sigma_{\rm intr}^{\rm log} = 0.17$. We note here that we do not correct the data for Malmquist bias, which for this set of data is not expected to modify the best fit Planck Collaboration (2011a), but might provide a slightly higher estimate of the intrinsic scatter compared to corrected data. We also underline that the magnitude of the scatter, at the level of $\sim 18\%$, is in good agreement with the expectations from numerical simulations mentioned in Sections 1 and 2.2.

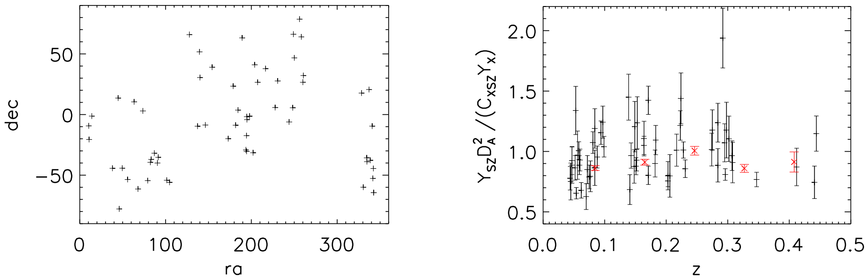

Fig. 1. Left: Right ascenscion and declination (in degrees) of the Planck ESZ cluster subsample used for the analysis. Right: $Y_{SZ}D_A^2/C_{XSZ}Y_X$ of the clusters in function of redshift. The error bars shown are calculated from error propagation of the errors on Y_{SZ} and Y_X as published in Planck Collaboration (2011a). For comparison, we also show the data binned in five uniform redshift intervals (red crosses). Throughout the paper we used the full sample and not the binned data to calculate results. Taken from Galli (2013)

In order to check the results from the MWLS method, we also calculate the mean as a simple arithmetic average and estimate its uncertainty by bootstrap resampling. In this case we obtain $(Y_{SZ}D_A/C_{XSZ}Y_X) = 0.969 \pm 0.021$, in agreement with what previously found. The scatter in this case is calculated following Planck Collaboration (2011a): we calculate $\sigma'_{\rm intr}$ as the quadratic difference between the raw scatter σ_{raw} and the statistical uncertainty

$$\chi_r^2 = \sum_i \frac{(x_i - < x_i >)^2}{\sigma^2(x_i)} \frac{1}{dof} \quad (15)$$

$$\sigma_{stat}^2 = \frac{1}{N} \sum_i \sigma^2(x_i) \quad (16)$$

$$\sigma_{raw}^2 = \chi_r^2 \frac{N}{\sum_i 1/\sigma^2(x_i)} \quad (17)$$

$$\sigma_i'^2 = \sigma_{raw}^2 - \sigma_{stat}^2 \quad (18)$$

where χ_r^2 is the reduced χ^2, dof is the number of degrees of freedom, in this case equal to $dof = 60$, and N is the number of clusters, in this case equal to $N = 61$. The recovered scatter is $\sigma'_{intr} = 0.17 \pm 0.026$, in perfect agreement with what found with the first method. The uncertainty on the scatter is calculated as in Planck Collaboration (2011c), $\Delta(\sigma'_{\rm intr}) = \sigma^2_{\rm intr}(2N(N-1))^{-1} \sum (1 + \sigma(x_i)/\sigma_{\rm intr^2})^2$.

We can then convert these results to a measurement on α. The current assumption is that $(Y_{SZ}D_A^2/C_{XSZ}Y_X)$ ratio is constant, and thus that the fine structure constant has the same value for all the clusters considered, $\alpha = \alpha_0$. The uncertainty on α is then:

$$\frac{\sigma(\alpha)}{\alpha_0} = \frac{1}{3.5} \frac{\sigma(Y_{SZ}D_A^2/C_{XSZ}Y_X)}{(Y_{SZ}D_A^2/C_{XSZ}Y_X)_0} = 0.0078,$$

i.e. a constraint on α at $\sim 0.8\%$ level at 68% c.l. This uncertainty includes both statistical error and intrinsic scatter, but does not include uncertainties on the cosmological parameters used to determine the angular diameter distance, here chosen for our reference cosmology, i. e. flat ΛCDM with $H_0 = 70$Km/s/Mpc, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

The cosmological parameters are not perfectly known, and degeneracies with α could limit the constraining power of clusters. We now analyze the impact of these uncertainties.

The dependence of the $(Y_{SZ}D_A^2/C_{XSZ}Y_X)$ ratio on the angular diameter distance is

$$\left(\frac{Y_{SZ}D_A^2}{C_{XSZ}Y_X}\right)_{ref} \sim \left(\frac{Y_{SZ}D_A^2}{C_{XSZ}Y_X}\right)_{true} \left(\frac{(D_A)_{ref}}{(D_A)_{true}}\right)^{-0.5} \quad (19)$$

where ref indicates the angular diameter distance calculated with the reference cosmology, and $true$ indicates the unknown true cosmology.

First, a wrong estimate of the angular diameter distance could generate a "fake" evolution with redshift of the $(Y_{SZ}D_A^2/C_{XSZ}Y_X)$ ratio. Second, the uncertainties on the knowledge of D_A can affect the errors on α. Still, the dependence is weak and current constraints on the angular diameter distance are at the level of a few percent Larson et al. (2011). We thus expect that, at least for current data, the uncertainty on cosmological parameters should not affect constraints on α. We indeed verified that marginalizing over cosmological parameters do not significantly affect the preented constraints (see Galli 2013).

As more and more clusters are found, this might become a limiting factor for constraints on α from clusters. We estimate that with 2000 clusters, the constraint obtainable would be $\sigma(\alpha)/\alpha_0 = 0.0052$, while in the limit of an infinitely large sample of clusters, the best constraint, limited only by cosmological uncertainties, would be $\sigma(\alpha)/\alpha_0 = 0.0032$. Upcoming data from on-going experiments such as Planck are expected to improve the constraints on cosmological parameters. In particular, Martinelli et al. (2012) calculated forecasts for a combination of future CMB and weak lensing data for a Planck-satellite like and a Euclid-satellite like experiments, for a model where α is also allowed to vary. Using the priors on cosmological parameters from these experiments, with 2000 clusters the constraint on α would improve to $\sigma(\alpha)/\alpha_0 = 0.0034$, while in the limit of an extremely large number of clusters, the ultimate constraint, limited only by cosmological uncertainties, would be $\sigma(\alpha)/\alpha_0 = 0.00061$.

4. Conclusions

We propose a new method to constrain the fine structure constant by using SZ and X-ray observations, opening a complementary redshift window on α. With 61 clusters in our data set, no evolution has been detected in the scaling relation between the integrated Compton parameter $Y_{SZ}D_A^2$ and the X-ray analogous parameter Y_X so far. We can take advantage of this fact to put a constraint on the fine structure constant in the redshift range $0 \lesssim z \lesssim 0.5$ at the 0.8% level. The ratio between the two parameters have in fact a strong dependence on the fine structure constant, namely $(Y_{SZ}D_A^2/Y_X) \propto \alpha^{3.5}$.

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