Mem. S.A.It. Vol. 74, 316

Memorie della

Cosmic microwave background temperature evolution by Sunyaev-Zel'dovich effect observations

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Abstract. Spectral observations of the Sunyaev-Zel'dovich (SZ) effect are now available for a few clusters of galaxies. We have deduced the cosmic microwave background (CMB) temperature using data of the Coma cluster (A1656, $z = 0.0231$) and of A2163 ($z = 0.203$) over four bands at radio and microwave frequencies. The estimated temperatures at these redshifts are $T_{\rm Coma} = 2.789^{+0.080}_{-0.065}$ K and $T_{\rm A2163} = 3.377^{+0.101}_{-0.102}$ K, respectively. These values confirm the expected scaling $T(z) = T_0(1+z)$, where $T_0 = 2.725 \pm 0.002$ K is the value measured by the COBE/FIRAS experiment. At the same time alternative CMB temperature evolutions as foreseen in non-standard cosmologies can be constrained by the data; for example, if $T(z) = T_0(1+z)^{1-a}$ or $T(z) = T_0[1+(1+d)z]$, then $a = -0.16^{+0.34}_{-0.32}$ and $d = 0.17 \pm 0.36$ (at 95% confidence). We briefly discuss future prospects for more precise SZ measurements of $T(z)$ at higher redshifts.

Key words. cosmic microwave background – cosmology: observations – galaxies: clusters: individual: A1656, A2163

1. Introduction

FIRAS, the Far Infrared Absolute Spectrometer on board of the COBE satellite, has precisely measured the (present) CMB temperature in the frequency range 2-20 cm^{-1}: $T_0 = 2.725 \pm 0.002$ K (Mather et al. 1999). These measurements essentially rule out all cosmological models in which the CMB spectrum is non-Planckian at $z = 0$. At the same time those data are not able to constrain models with a purely blackbody spectrum but with a different $T(z)$ dependence than in the standard model. Also unconstrained are models with spectral distortions that are now negligible, but were appreciable in the past. A specific example is the

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relation $T(z) = T_0(1+z)^{1-a}$, where a is a parameter of the theory (see, e.g., Lima et al. 2000). More generally, models in which ratios of some of the fundamental constants vary over cosmological time are also of considerable interest.

So far, $T(z)$ has been determined mainly from measurements of microwave transitions in interstellar clouds which contain atoms and molecules that are excited by the CMB (as reviewed by Lo Secco et al. 2001). The temperature has been determined in the Galaxy, as well as in clouds at redshifts up to $z \sim 3$ (Levshakov et al. 2002). These measurements are affected by substantial systematic uncertainties stemming from the unknown physical conditions in the absorbing clouds (Combes & Wiklind 1999).

The possibility of determining $T(z)$ from measurements of the Sunyaev-Zel'dovich (SZ) effect had been suggested long ago (Fabbri, Melchiorri & Natale 1978; Rephaeli 1980). For general reviews of the effect and its cosmological significance (see Rephaeli 1995a; Birkinshaw 1999). The proposed method is based on the steep frequency dependence of the change in the CMB spectral intensity, ΔI, due to the effect, and the weak dependence of ratios $\Delta I(\nu_i)/\Delta I(\nu_j)$ of intensity changes measured at two frequencies (ν_i, ν_j) on properties of the cluster (Rephaeli 1980). Because of this, and the fact that – in the standard cosmological model – the effect is essentially independent of z, SZ measurements have the potential of yielding much more precise values of $T(z)$ than can be obtained from ratios of atomic and molecular lines. With the improved capability of reasonably precise spectral measurements of the SZ effect, the method can now be used to measure $T(z)$ in nearby and moderately distant clusters. Here we report first results from spectral analysis of SZ measurements in the Coma and A2163 clusters of galaxies.

2. $T(z)$ from SZ

The CMB intensity change due to Compton scattering in a cluster can be written in the form

$$\Delta I = \frac{2k^3T^3}{h^2c^2}\frac{x^4e^x}{(e^x-1)^2} \times \int \left[\theta f_1(x) - \beta + R(x,\theta,\beta)\right] d\tau \qquad (1)$$

where $x = h\nu/kT$ is the non-dimensional frequency, $\theta = kT_e/mc^2$ is the electron temperature in units of the electron rest energy, and β is the line of sight (los) component of the cluster (peculiar) velocity in the CMB frame in units of c. The integral is over the Compton optical depth, τ. Both the thermal (Sunyaev & Zel'dovich 1972) and kinematic (Sunyaev & Zel'dovich 1980) components of the effect are included in equation (1), separately in the first two (additive) terms, and jointly in the function $R(x,\theta,\beta)$. In the non-relativistic limit (which is valid only at low electron temperatures and frequencies) the spectral dependence of ΔI is fully contained in the product of the x-dependent pre-factor times the function $f_1(x) = x(e^x+1)/(e^x-1)-4$. The more exact treatment of Compton scattering in clusters necessitates a relativistic calculation (Rephaeli 1995b) due to the high electron velocities. The function $R(x,\theta,\beta)$ includes the additional spectral, temperature, and (cluster) velocity dependence that is obtained in a relativistic treatment. This function can be approximated by an analytic expression that includes terms to orders θ^5 and $\beta^2\theta$:

$$R(x,\theta,\beta) \simeq \theta^2\left[f_2(x) + \theta f_3(x) + \theta^2 f_4(x) + \theta^3 f_5(x)\right] - \beta\theta\left[g_1(x) + \theta g_2(x)\right] + \beta^2\left[1 + \theta g_3(x)\right] \qquad (2)$$

The spectral functions f_i and g_i were determined by Itoh et al. (1998), Itoh et al. (2002), and Shimon & Rephaeli

(2002). For our purposes here this analytic approximation is sufficiently exact even close to the crossover frequency. The non-relativistic limit, $R \equiv 0$, applies if the sum of all these terms can be ignored at the desired level of accuracy.

The z dependence of ΔI is fully determined by the functions $\nu = \nu(z)$, and $T = T(z)$. The temperature-redshift relation may assume various forms in non-standard cosmologies; here we consider two examples. In the first, $T(z) = T(0)(1+z)^{(1-a)}$, where a is taken to be a free parameter, but with the standard scaling $\nu = \nu_0(1+z)$ unchanged. With these relations the non-dimensional frequency obviously depends on z, $x = x_0(1+z)^a$, if $a \neq 0$; here, $x_0 = h\nu_0/kT(0)$. Another functional form which seems also to be of some theoretical interest is $T(z) = T(0)[1+(1+d)z]$ (Lo Secco et al. 2001), for which $x = x_0(1+z)/[1+(1+d)z]$. Obviously, in the standard model $a = d = 0$.

For a slow moving ($\beta < 10^{-3}$) cluster, the expression for ΔI in the non-relativistic limit depends linearly on the Comptonization parameter, $y = \int \theta d\tau$, which includes all dependence on the cluster properties. A ratio of values of ΔI at two frequencies is then essentially independent of these cluster properties. In the more general case, the first term in the square parentheses in equation (1) still dominates over the other two, except near the crossover frequency (whose value generally depends on T_e, except in the non-relativistic limit where $x_c = 3.83$ (Rephaeli 1995b; Nozawa et al. 1998; Shimon & Rephaeli 2002), where the sum of the temperature dependent terms vanish. For values of x outside some range (roughly, $3.5 < x < 4.5$), the dependence of ΔI, and – particularly, a ratio of values of ΔI – on β is very weak since the observed temperature range in clusters corresponds to $0.006 < \theta < 0.03$, whereas typically $\beta < 0.002$.

3. Data analysis

We have analyzed results of SZ measurements in the Coma cluster (A1656) and A2163. Measurements of Coma, $z = 0.0231 \pm 0.0017$ (Struble & Rood 1999) were made with the MITO (De Petris et al. 2002) telescope in 20 hours of integration. We also use the result of measurements at 32 GHz made with the OVRO 5.5m telescope (Herbig et al. (1995), Mason et al. (2001)). A2163, $z = 0.203 \pm 0.002$ (Arnaud et al. 1992) was observed with the SuZIE array (Holzapfel et al. 1997a) and with both the OVRO and BIMA interferometric arrays (La Roque et al. 2002).

When observing a cluster the SZ part of the measured signal is

$$\Delta S_i = G_i A\Omega|_i \int_0^\infty \Delta I(0)\epsilon_i(\nu)d\nu \,, \qquad (3)$$

where G_i is the responsivity of the i^{th} photometric channel, $A\Omega|_i$ is the corresponding throughput, and $\epsilon_i(\nu)$ is the spectral efficiency. The full measured signal includes also contributions from the atmosphere, CMB anisotropies, and – at very high frequencies – also emission from dust. Multifrequency observations allow us to remove contributions from both the primary CMB anisotropy and the kinematic SZ effect, as has been attempted in the analysis of MITO measurements of the Coma cluster (De Petris et al. 2002).

We consider now the ratio of signals in two different photometric channels i and j as $\Delta S_i/\Delta S_j$ with ΔS defined as in equation (3). The main dependence on the cluster properties in y cancels out when β is negligible. Multi-frequency observations that include measurements at the crossover frequency (e.g., MITO) afford effective separation of the thermal and kinematic components, exploiting their very different spectral shapes. This was demonstrated in the analysis of MITO measurements of the Coma cluster (De Petris et al. 2002). Since the above ratio depends weakly on the cluster velocity, the residual uncertainty due to velocities of even ± 500 km/s can be ignored in comparison with other errors. The ratio is also weakly dependent on the gas temperature at a level which we found to correspond to $\sim 1\%$ uncertainty in the estimation of the CMB temperature (for a typical observational error in T_e). Moreover, the uncertainty associated with the absolute calibration, G_i, is largely removed once we fit data from several photometric channels, as long as they are calibrated with a source with a known spectrum (e.g., a planet) even if its absolute calibration is uncertain. Only relative uncertainties among the various spectral channels are important; these include differences in angular response and in atmospheric transmittance. A standard blackbody source with a precisely calibrated temperature is therefore not required. We expect these considerations to imply that the precision of CMB temperature measurements via the SZ effect will not be appreciably affected by most of the known systematic errors. The level of precision in the measurement of $T(z)$ is limited largely by other observational uncertainties, as discussed below.

The responsivity G_i of each channel is usually determined from detailed observations of very well measured sources such as planets (mostly Jupiter or Saturn) and the Moon. While the temperature uncertainty of these sources can be as large as 10%, their spectra are relatively well known. For a source at a temperature of T_S and with a throughput Ω_S, the signal in the Rayleigh-Jeans part of the spectrum is

$$\Delta S_i = G_i A_i \Omega_S T_S \frac{2k}{c^2} \int_0^\infty \nu^2 \epsilon_i(\nu)\eta(\nu) d\nu \,. \quad (4)$$

Since we are interested in the ratio of the signals in two channels, T_S drops out from the final expression, and the uncertainty in the ratio of values of the brightness temperature in the two channels depends only on the emissivity of the planet, $\eta(\nu)$, convolved with the spectral efficiencies of the channels, $\epsilon_i(\nu)$. Note that the throughputs of individual channels, $A\Omega|_i$, are usually made almost equal by an appropriate choice of the optical layout.

The main uncertainty in the MITO measurements is due to imprecise knowledge of the bandwidth and transmittance of the filters. Therefore, we have precisely measured the total efficiency of our photometer by means of a lamellar grating interferometer. The response of the photometer is measured when it is illuminated with a laboratory blackbody at different temperatures ranging from liquid N_2 to room temperature. The effect of the uncertainty in our bandwidths has two main consequences. The first is the error in the ratio of responsivities of channel i and channel j, G_i/G_j. We estimate this error by computing the ratio of expected signals evaluated by convolving Moon and Jupiter spectra with the spectra of our filters, and taking into account spectroscopic uncertainties; we obtain a final error estimate which is less than 1%. The second consequence of bandwidth uncertainty enters in the integrations over the SZ spectral functions as defined in equation (3). However, this latter error is smaller than the former and is practically negligible.

The angular responses of the telescope and the photometer in the four channels were measured quite precisely. We have studied differences in the response of the four channels to both a point source, such as Jupiter ($\simeq 30''$), and an extended source, such as the Moon ($\simeq 30'$), as they cross the field of view ($17'$ FWHM). The optical layout of our photometer is such that the four detectors observe simultaneously the same sky region. The discrepancies among channels are less than 1% in the case of extended sources: this was the situation for Coma observations. Finally, we have also studied the change in relative efficiency of our observations under different atmospheric conditions. The simulations show a change of $\sim$ 1 mK in the estimated CMB temperature if the water vapor content changes from 0.5 mm to 1.5 mm, as determined by convolving theoretical atmospheric spectra with our filters. The uncertainties in determining the water vapor content, related to our procedure of measuring the atmospheric transmittance through a sky-dip technique, are at a level of 30%. However, when the effect of this error is propagated through our procedure and analysis we estimate that it amounts to a negligible error in the final result for the CMB temperature.

In conclusion, systematic errors contribute less than 3% to the observed MITO signals, and are quite negligible with respect to the 10% contribution associated with the residual noise of the four detectors. For the OVRO measurement, we use the total error as specified by Mason et al. (2001); the statistical weight of this low frequency measurement is such that it only contributes $\simeq$12% to the final results.

Our assessment of the errors in the SuZIE and OVRO & BIMA measurements of A2163 (La Roque et al. 2002) is far less certain than those in the MITO measurements, since we do not know the exact spectral responses of their filters and the atmospheric conditions during each of these observations. We have used Gaussian profiles for the SuZIE filters, with peak frequencies and FWHM values as given by Holzapfel et al. (1997a). For the OVRO & BIMA data point, we also take a Gaussian profile with a peak frequency at 30 GHz and a 1 GHz bandwidth. We have employed data provided by SuZIE, for which a correction due to thermal dust emission has been taken into account. The Coma and A2163 data are collected in Table 1. Finally, the value we used for the electron temperature is (8.25±0.10) keV, as measured with XMM in the central region of Coma (Arnaud et al. 2001); the value for A2163 is $12.4^{+2.8}_{-1.9}$ keV (Holzapfel et al. 1997b).

In both sets of cluster observations, we have minimized the difference between theoretical and experimental ratios (properly weighted by statistical errors) with T as a free parameter. The results are $T_{\rm Coma}(0) = 2.726^{+0.078}_{-0.064}$ K which, when multiplied by $(1+z)$ with $z = 0.0231 \pm 0.0017$, yields

$$T_{\rm Coma} = 2.789^{+0.080}_{-0.065}\ \mathrm{K}.$$

Exp	ν [GHz]	$\Delta\nu$ [GHz]	ΔT [μK]
COMA			
OVRO	32.0	13.0	-520 ± 93
MITO1	143	30	-179.3 ± 37.8
MITO2	214	30	-33.4 ± 81.2
MITO3	272	32	169.8 ± 35.1
A2163			
OVRO/ BIMA	30	1	-1777 ± 222
SuZIE1	141.59	12.67	-1011.3 ± 98.0
SuZIE2	216.71	14.96	-213.0 ± 159.3
SuZIE3	268.54	25.66	662.2 ± 235.7

Table 1. SZ measurements used in the present analysis.

The main uncertainty is in the SZ observations, with only a small error (7×10^{-4} K) due to the uncertainty (0.1 keV) in the electron temperature. For A2163 we obtain $T_{\rm A2163}(0) = 2.807^{+0.084}_{-0.085}$ K, and when multiplied by $(1+z)$ with $z = 0.203 \pm 0.002$, yields

$$T_{\rm A2163} = 3.377^{+0.101}_{-0.102}\ \mathrm{K}.$$

The larger error in T_e (~ 2 keV) translates to an uncertainty of 1.5×10^{-2} K in the deduced CMB temperature at the redshift of A2163. The mean of the above two values for $T(0)$ is $\langle T \rangle = 2.766^{+0.058}_{-0.053}$ K, in good agreement with the COBE value.

Using the COBE value of the temperature and the two values deduced here for $T(z)$ at the redshifts of Coma and A2163, we fit the three data points by the relation $T(z) = T(0)(1+z)^{1-a}$; the best fit is shown by the dashed line in Fig. 1. It corresponds to $a = -0.16^{+0.34}_{-0.32}$ at 95% confidence level (CL). With the alternative scaling $T(z) = T(0)[1 + (1+d)z]$, we obtain a best fit value of $d = 0.17 \pm 0.36$ at the 95% CL.

These first SZ results for $T(z)$ are clearly consistent with the standard relation, although the most probable values of both a and d indicate a slightly stronger

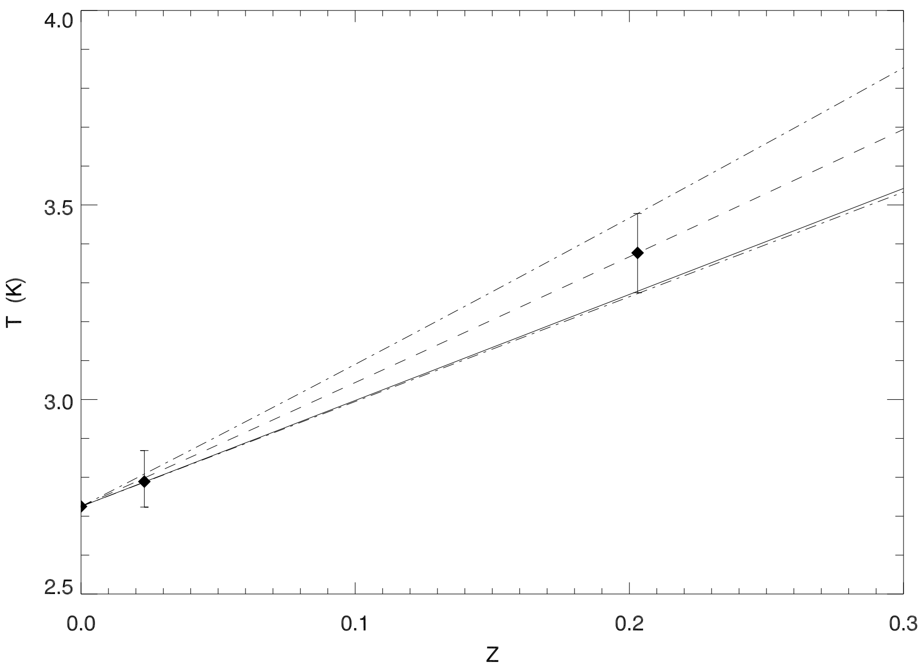

Fig. 1. Black diamonds mark values of the CMB temperature obtained by COBE/FIRAS and SZ measurements. The solid line is $(1 + z)$ scaling law as predicted in the standard model. The dashed line shows the best fit to the alternative scaling law with a determined by the COBE/FIRAS and SZ measurements, whereas dot-dashed lines are the $\pm 1\sigma$ values of a.

z dependence. Our values for these two parameters are quite similar to those deduced by Lo Secco et al. (2001) from measurements of microwave transitions. Their results – based on two firm detections at redshifts 2.338 and 3.025 – are $a = -0.05 \pm 0.13$ and $d = 0.10 \pm 0.28$ (at 95% CL). Thus, our SZ-based values already provide the same level of precision even though the two clusters are at much lower redshifts ($z \leq 0.2$). SZ measurements of higher redshift clusters will clearly provide a preferred alternative to the atomic and molecular lines method. If we fit the above relations to the combined data sets (consisting of all five temperatures), we obtain $a = -0.09 \pm 0.20$ and $d = 0.14 \pm 0.28$ (at 95% CL). Finally, Molaro et al. (2002) have recently questioned the validity of the temperature measurement at $z = 2.338$ by Lo Secco et al. (2001), and have revised the value at $z = 3.025$ to $12.1^{+1.7}_{-3.2}$K. We have thus repeated the fit excluding the fourth data point and using the latter value for the fifth; the results from this fit are essentially unchanged: $a = -0.11 \pm 0.22$, and $d = 0.16 \pm 0.32$.

4. Discussion

The method employed here to measure $T(z)$ can potentially yield very precise values which will tightly constrain alternative models for the functional scaling of the CMB temperature with redshift, and thereby provide a strong test of non-standard cosmological models. In order to improve the results reported here, multi-frequency measurements of the SZ effect in a significantly larger number (~ 20) of clusters are needed. The clusters should include nearby ones in order to better understand and control systematic errors. Exactly such observations are planned for the next 2-3 years with the upgraded MITO project (Lamagna et al. 2002), and the stratospheric BOOST experiment (Lubin P., private communication) and OLIMPO experiment (Masi et al. 2003). These experiments will employ sensitive bolometric arrays at four frequency bands with high spatial resolution.

As detector noise is reduced, the uncertainty in the electron temperature may contribute the dominant relative error. For example, an uncertainty of ~ 2 keV – as in the case of A2163 – becomes dominant when detector noise is reduced to a level ten times lower than the values used here. Therefore, it will be necessary to select clusters for which the gas temperature is precisely (to a level of ~ 0.1 keV) known. With the large number of clusters that have already been – or will be – sensitively observed by the XMM and Chandra satellites, it should be possible to optimally select the SZ cluster sample.

With the currently achievable level of precision in intracluster gas temperature measurements, the present technique makes it possible to determine a and d with an uncertainty that is not less than 0.03 on both parameters, even with ideal (i.e., extremely high sensitivity) SZ measurements. The projected sensitivities of the future Planck and Herschel satellites will enable reduction of the overall error in the values of these two parameters by more than an order of magnitude. In addition to limits on alternative CMB temperature evolution models, such a level of precision will open new possibilities of testing the time variability of physical constants. For example, it will be feasible to measure a possible variation of the fine structure constant, thereby providing an alternative to the current principal method which is based on spectroscopic measurements of fine structure lines in quasar absorption spectra.

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