Mem. S.A.It. Suppl. Vol. 2, 44

Memorie della
Supplementi

Sunyaev-Zel'dovich effect studies with MASTER

A.Tartari[1], G.Boella[1], M.Candotti[3], M.Gervasi[1], V.Natale[3], A.Passerini[1], G.Sironi[1], and M.Zannoni[2,⋆]

[1] Dipartimento di Fisica G.Occhialini, Universitá degli Studi di Milano Bicocca, piazza della Scienza 3, 20126 Milano
[2] I.A.S.F.-C.N.R., Sezione di Milano, via Bassini 15 , 20133 Milano, Italy
[3] I.R.A.-C.N.R., sezione di Firenze, largo Enrico Fermi 5,50125 Firenze, Italy

Abstract. Our three frequencies radiometer MASTER, which allows low noise observations in three frequency intervals around 90, 220 and 345 GHz is being completed. We discuss the possibility of exploiting the MASTER's characteristics for studies of the Sunyaev Zel'dovich effect from the Antartic Plateau and propose an observational program from Dome C.

Key words. cosmic microwave background – cosmology:observations – instrumentation: miscellaneous

1. Introduction

The Sunyaev-Zel'dovich (SZ) effect has been recognized, since the time of its discovery, as a fundamental probe of the physical processes in the *intracluster medium* (ICM), and more and more as a key instrument for the understanding of the evolution of the Universe. It's well known that the SZ effect is also a source of CMB secondary anisotropies and, with respect to this kind of cosmological observations, SZ wide surveys are planned in near future both from space and from ground observatories.

We propose a multifrequency observation based on the employment of three heterodyne SIS receivers, with the aim of characterizing the spectral signature of the thermal SZ. A detailed knowledge of the spectrum, in turn, provides us two different ways to measure the temperature of the CMB at cluster's redshift and it's necessary to obtain a measure of the pure kinematic SZ.

2. Astrophysics around 220 GHz

2.1. The thermal SZ

When CMB photons interact with the thermal electrons of the intracluster medium *via* inverse Compton scattering, a spectral distortion arises in the Rayleigh Jeans and in the Wien region of the 3K black-body spectrum: the brightness temperature in the RJ region decreases, while the Wien tail is characterized by an enhancement. Between these spectral regions there's a pe-

Send offprint requests to: A.Tartari
⋆ e-mail: Andrea.Tartari@mib.infn.it
Correspondence to: Dipartimento di Fisica G.Occhialini, Universitá degli Studi di Milano Bicocca, piazza della Scienza 3, 20126 Milano

culiar frequency (the crossover frequency) in which this effect vanishes and, introducing the non dimensional frequency

$$x = (h\nu/k_B T_{CMB}),$$

this frequency gets the value $x_{0nr} \cong 3.830$ (see Fig.1 left panel).

Statistically, only the 1% of the photons undergo Compton scattering, and this results in a typical spectral distortion of the CMB thermodynamic temperature on the order of $\frac{\Delta T}{T} \sim 10^{-4}$. This effect, derived for the first time by Sunyaev and Zel'dovich (Zel'dovich, Sunyaev 1969) starting from the non relativistic Kompaneets equation, is known as non relativistic thermal SZ effect (thSZ). Analytical descriptions of the relativistic corrections to this effect have been developed in the last decade (Itoh et al. 1998) and, as pointed out by Rephaeli (Rephaeli 1995a), these corrections are no longer negligible when $T_e > 5keV$. In particular, they can affect significantly the spectral signature of the thermal SZ effect shifting x_{0nr} (Rephaeli 1995b) and reducing the amplitude of the spectral distortion. The first order corrected expression for x_0 is

$$x_0 \cong 3.83\big[1 + 1.1674(\frac{k_B T_e}{m_e c^2})\big]. \tag{1}$$

More recently, a deep interest has risen on the non thermal SZ (Blasi et al. 2000), which in principle could give us a new insight on the relativistic electrons in the extended radio halos of clusters of galaxies. Again, this effect should give a contribution to the SZ effect near x_0 (affecting x_0 itself), but it's extremely weak (Shimon and Rephaeli 2002), and its detection seems unlikely in a near future.

2.2. The peculiar motion of clusters

The kinematic SZ (kSZ) is the intensity change due to the peculiar motion of the cluster along the line of sight in the CMB rest frame. The change in temperature is frequency independent, and it is expressed as

$$\Delta T_{kin} = -T_{CMB}\frac{V_p}{c}\tau \tag{2}$$

where τ is the optical depth of the electron plasma and V_p the peculiar velocity, the sign depending on the velocity direction.

The channel where the probability to measure this effect maximizes is the one centered around x_0, simply because the thermal one vanishes there. This means that the residual SZ at the crossover is purely kinematic, allowing us to recover the peculiar velocity of the cluster once we know τ (Sunyaev, Zel'dovich 1980).

Nevertheless this effect is very weak and, from the best fit parameters (T_e,τ and V_p) derived for Abell 2163 by Hansen (Hansen et al. 2002), we deduce a temperature shift of the order of magnitude of $10\mu K$ (see Fig.1 right panel).

Such a weak signal requires a high sensitivity in order to be detected, and we know that the more sensitive receivers nowadays are bolometric arrays cooled down to $300mK$ or less. Nevertheless, if using wide band devices is recommendable in order to reduce the integration time, it's also true that we need frequency resolution around the crossover to disentangle the kinematic from the thermal effect. Another reason which convinced us to pay in sensitivity, with the aim of gaining in spectral accuracy, is the necessity of reconstructing the global spectral signature of thSZ.

2.3. In situ measurement of $T_{CMB}(z)$

A task strictly connected to the determination of the crossover frequency is the measurment of the CMB temperature at cluster's redshift. The key idea is that the non dimensional frequency, in a FLRW Universe, is redshift independent, because ν and T_{CMB} exibit the same $(1 + z)$-scaling. Since x_0 is fixed and supposing that we are able to find ν_0, we can go

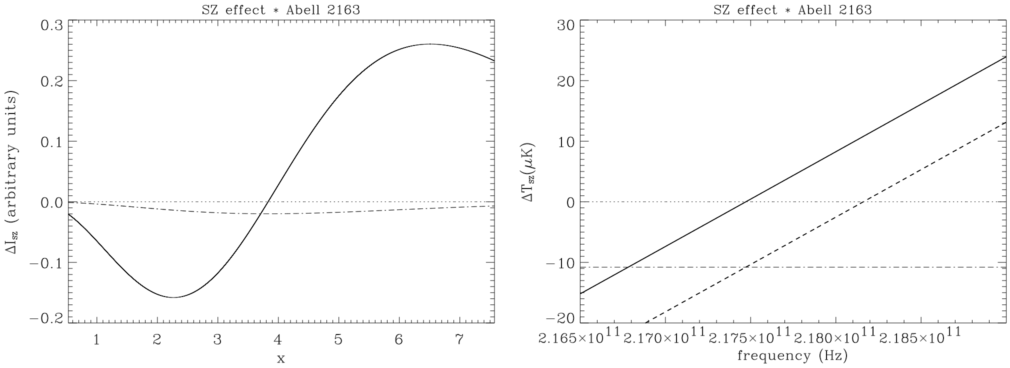

Fig. 1. Left panel: The non relativistic thermal (solid line) and kinematical (dash dot line) SZ effects deduced from best fit parameters derived by Hansen (Hansen et al. 2002) for Abell 2163. This is the spectral shape of intensity fluctuation in arbitrary units, with the kSZ enhanced by a factor 10. Right panel: The temperature change (μK) due to SZ is plotted *versus* frequency (GHz) both for thermal and kinematical SZ effects (respectively solid and dash dot line). The dashed line represent the sum of the two effects. This plot is centered around ν_{0nr}.

back to $T_{CMB}(z)$(Fabbri et al. 1978), providing a further test to the standard cosmology (LoSecco et al. 2001). Besides, we can exploit the increasing quality of the X-ray cluster surveys (see the observation of the Coma cluster with XMM by Arnaud (Arnaud et al. 2001)) in order to consider possible relativistic corrections to $x_{0nr} \cong 3.830$, which require a detailed knowledge of T_e. It's important to underline that, neglecting the relativistic correction to x_{0nr} for a hot plasma with $T_e \cong 15keV$, the CMB temperature derived in this way will be overestimated by few percent ($\sim 3\%$), since, according to eq.(1), there's a shift in frequency of $\sim$ 6 GHz. A multifrequency approach to the measurment of $T_{CMB}(z)$, similar to that proposed by Rephaeli (Rephaeli 1980) is also a viable chance. This technique relies on the measurement of the thSZ in three frequency bands, which allows one to build two ratios, $\Delta I_{\nu 1}/\Delta I_{\nu 2}$ and $\Delta I_{\nu 3}/\Delta I_{\nu 1}$, completely characterized in the (y, T_{CMB}) parameter space. Recently Battistelli (Battistelli et al. 2002) reported a T_{CMB} measurement in the Coma cluster and in Abell 2163 with the MITO telescope, using this procedure.

2.4. Foregrounds

The main foreground in our frequency bands is dust emission both from Galactic Cirrus and, eventually, from IC dust, since we can not rule it out *a priori.*

The presence of dust in galaxy clusters seems to be likely because of the galactic winds responsible of the enrichment of the ICM (Faber, Gallagher 1976). In this context, the survival of dust grains of galactic origin under sputtering in a hot plasma has been extensively discussed (as reference, Burke and Silk 1974).

In order to achieve an order of magnitude of the brightness temperature (T_{Bd}) of dust grains in clusters, we followed the model of dust emission built by Dwek (Dwek et al. 1990) for the Coma cluster. This model predict a $100\mu m$ brightness $\approx 0.2MJysr^{-1}$ for the cluster center (the region inside $R < 2Mpc$) where $T_d \cong 20K$, T_d being the dust physical temperature. Normalizing a modified black-body spectrum with respect to this value and extrapolating to lower frequencies, we found that this foreground emission is comparable to the kinematic SZ effect around $220GHz$ ($\sim 3\mu K$). On the other hand, we adopted a frequency dependent emissivity $\varepsilon(\nu) \sim \nu^{\alpha}$ with $\alpha = 1.5$, even if a steeper spectrum ($\alpha \simeq 2.0$) seems preferable. This means that we obtained an upper limit for T_{Bd} (since we overestimated the brightness in the low frequency tail), and that we can guess that this foreground won't affect thSZ measurements, even if it could affect significantly kSZ.

The far infrared (FIR) emission of the Galactic Cirrus can be in principle the dominant foreground, even if the observational techniques help us to keep its impact under control, as described in 3.2. Besides, the increasing quality of CMB data is providing us with a detailed description of galactic foregrounds (Masi et al. 2001, Finkbeiner et al. 1999), whose anisotropic components cannot be removed with differential sky-chopping techniques. On the other hand, we could exploit our three-frequency measurements to disentangle the dust emission from the cosmological signal.

3. Observations with MASTER

3.1. The receiver

MASTER is a triple heterodyne receiver operating at three central frequencies corresponding to atmospheric windows: 94, 220, 345 GHz.

The front-end of the system, cooled to 4 K, is characterized by three SIS mixers, which are the only devices allowing coherent detection above 200 GHz, followed by low noise HEMT amplifiers operating in the range $1 \div 10$ GHz, the IF filters being centered at 1.2 GHz with ± 1 GHz bandwidth. The details concerning the receiver and the optical coupling with the MITO telescope at the Testagrigia observatory have been discussed in previous works (Battistelli et al. (2002) and references therein). Now it is useful to recall that the expected noise temperatures of the SIS at 94, 220 and 345 GHz are respectively ~ 120, ~ 140 and ~ 160 K. The tuning bandwidhts are 10 % of the central frequencies, while the instantaneous bandwidth is 0.6 GHz.

3.2. The observations

Our aim is to study galaxy clusters, structures which extend in the sky with diameters ranging from few arcminutes to about ten arcminutes. This means that we can achive the suitable resolution for this kind of observations with a 2-m class telescope (like MITO or OASI). The optimal observing technique for SZ measurments is a three-field modulation of the sky signal, obtained by chopping the secondary mirror of the telescope. In this way, we observe alternatively the cluster and two reference patches of sky diametrally opposed with respect to the cluster itself (ON-OFF modulation followed by synchronous detection). Moreover, the beam switching is carried out at constant elevation, in order to cut (on average) the atmospheric emission. It is also important to remind that the angular amplitude of the modulation has to be chosen in such a way to guarantee that the beam in the OFF-position shall be completely outside the cluster. This fact, in turn, sets a minimum value for the amplitude $\Delta\theta$ of sky chopping. This differential technique has the advantage that the foregrounds with multipole index $0 \leq l < (\pi/\Delta\theta)$ are removed, and that gain variations could be kept under control. On the other hand, the sensitivity of the instrument is reduced, because half of the observing time is spent on the reference regions in the sky. It's important to underline that the anisotropic component of the galactic dust emission and the CMB anisotropies (on the angular scale corresponding to $\Delta\theta$) are not cut by the sky signal modulation and, statistically, they will affect SZ detection. In particular, different chopping amplitudes will be associated to different correlated dust signals, because the interstellar dust exhibits an angular power spectrum scaling as a power law $c_l \sim l^{-\beta}$ with $2 \leq \beta \leq 3$, depending on the galactic latitude (Masi et al. 2001). At the same time,

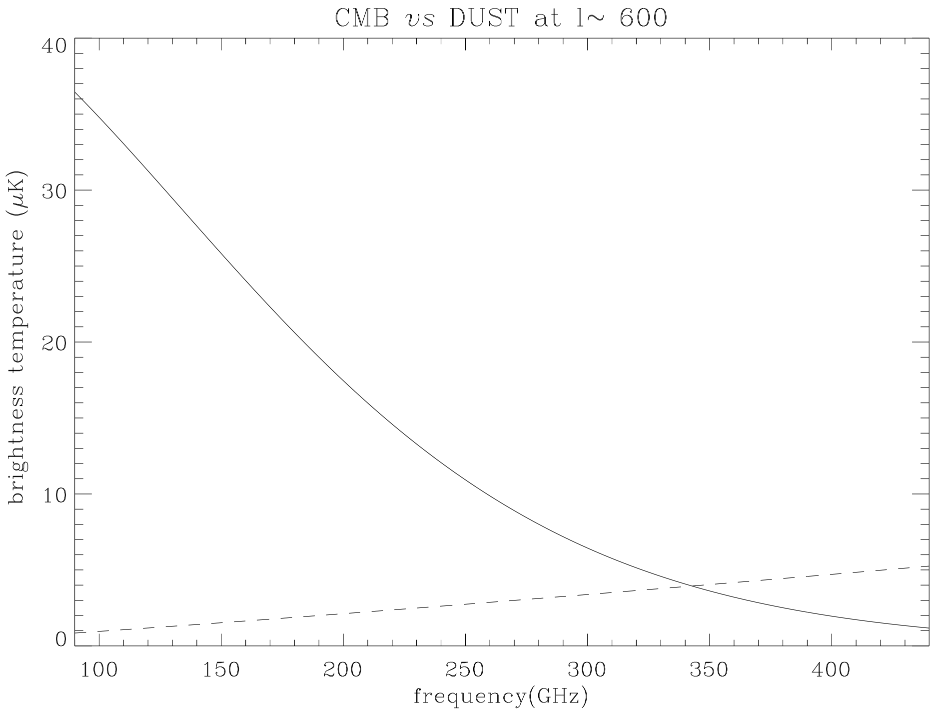

Fig. 2. The brightness temperature of CMB in μK (solid line) compared with the dust anisotropic emission at medium galactic latitudes (dashed line) at the multipole $l \simeq 600$.

our experiment will be liable to the multipole $l \sim 1/\Delta\theta$ of CMB anisotropies. We noted that a beam switching of $\sim 20'$ amplitude introduces an overall $\sim 20\mu K$ noise level around 220 GHz, mainly due to the CMB (see fig.2). Again, this effect overtakes the expected kSZ signal.

4. Conclusions

We propose two main targets to be achieved with the MASTER receiver: the *in situ* measurement of the CMB thermodynamic temperature and the detection of the kinematic SZ effect. Both these measurements are linked to the spectral characterization of thSZ in three frequency bands, which could be achieved with a remarkable accuracy exploiting the narrow instantaneous bandwidth of our receiver and the chance of LO tuning (particularly around the expected crossover frequency). Nevertheless, passing from the first task to the second one, a jump of more than a factor 10 in sensitivity is required. We know also that this jump cannot be achieved simply extending the integration time, because long-term instabilities could arise in the electronics.

The electronic instabilities become decisive in limiting the sensitivity when the spectral density of the $1/f^{\alpha}$ noise equals the pure white noise contribution (Wollack 1995). This happens in correspondence of a characteristic frequency, f_{knee}, which depends on the intrinsic properties of the device. The knowledge of the knee frequency is of great practical importance, because it is used to set a lower limit to the chopping frequency. In turn, this value has to be compared with the lower limit set by atmospheric instabilities. In fact, we know that long time integration is also exposed to sky-noise. A first condition to be accomplished to face the latter problem consists in carrying out the observations in a site with a low PWV content and stable atmospheric conditions (with regard to this, Dome C seems to be the ideal site, (Valenziano, Dall'Oglio 1999)). Then, the chopping period should be lower than the typical timescale of atmospheric fluctuations, and the beam switching angle should be smaller than the angular scale of correlated atmospheric emission.

As final remark, particularly thinking to an observational campaign from Dome C, we add that the choice of the telescope's optics will allow us to estimate a realistic value for T_{sys} (and hence for the sensitivity) and it will suggest us also the final optical configuration of MASTER.

References

M.Arnaud et al. 2001, A& A 365,L67

E.S.Battistelli et al. 2002, Ap.J. 580,L101

E.S.Battistelli et al. 2002, P.A.S.A 19,313

P.Blasi, A.V.Olinto and A. Stebbins, 2000, Ap.J. 535,L71

J.R.Burke, J.Silk, 1974, Ap.J. 190,1

E.Dwek,Y.Rephaeli,J.C.Mather, 1990, Ap.J. 350,104

R.Fabbri, F.Melchiorri, V.Natale, 1978, Ap& SS 59,223

S.M.Faber, J.S.Gallagher, 1976, Ap.J. 204,365

D.P.Finkbeiner, M.Davis, D.J.Schlegel, 1999, Ap.J. 524,867

S.H.Hansen,S.Pastor,D.V.Semikoz,2002, Ap.J. 573,L69

N.Itoh, Y.Kohyama, S.Nozawa,1998, Ap.J. 502,7

J.A.S.Lima, A.I.Silva, S.M.Viegas, 2000, M.N.R.A.S. 312,747

J.M.LoSecco,G.J.Mathews,Y.Wang,2001, Phys.Rev.D 64 123002

S.Masi et al.,2001, Ap.J. 553,L93

Rephaeli,1995a, A.R.A&A 33,541

Rephaeli,1995b, Ap.J. 445,33

Rephaeli,1980, Ap.J 241,858

M.Shimon, Y.Rephaeli,2002, Ap.J. 575,12

R.A.Sunyaev, Ya.B.Zel'dovich, 1980, M.N.R.A.S 190,413

L.Valenziano, G.Dall'Oglio 1999, P.A.S.A. 16,167

E.J.Wollack 1995, Rev.Sci.Instrum. 66(8),4305

Ya.B.Zel'dovich, R.A.Sunyaev, 1969, Ap& SS 4,301