Sunyaev Zel’dovich effect studies with MASTER

A.Tartari¹, G.Boella¹, M.Candotti³, M.Gervasi¹, V.Natale³, A.Passerini¹, G.Sironi¹, M.Zannoni²

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

e-mail: Andrea.Tartari@mib.infn.it

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 Antarctic Plateau and propose an observational program from Dome C.

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

\[ x = \frac{h\nu}{k_BT_{CMB}}, \]

this frequency gets the value \( x_{0nr} \approx 3.830 \) (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 \( \Delta T \sim 10^{-4} \). 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

\[ x_0 \approx 3.83[1 + 1.1674\left(\frac{k_BT_e}{m_ec^2}\right)]. \]  

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

\[ \Delta T_{kin} = -T_{CMB}\frac{V_p\tau}{c} \]

where \( \tau \) 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 $\tau$ [Sunyaev, Zel’dovich(1980)].

Nevertheless this effect is very weak and, from the best fit parameters ($T_e, \tau$ 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 measurement 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 $\nu$ and $T_{CMB}$ exhibit the same $(1+z)$-scaling. Since $x_0$ is fixed and supposing
that we are able to find $\nu_0$, we can go 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 $x_{0nr} \approx 3.830$, 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 $T_e \approx 15\text{keV}$, 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 $\sim 6\text{GHz}$. A multifrequency approach to the measurement 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 $T_d \approx 20K$, $T_d$ 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 ($\alpha \approx 2.0$) 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 ÷ 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 bandwidths 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 achieve the suitable resolution for this kind of observations with a 2-
m class telescope (like MITO or OASI). The optimal observing technique for SZ
measurements 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 diametrically 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 Δθ of sky
chopping. This differential technique has the advantage that the foregrounds
with multipole index 0 ≤ l < (π/Δθ) 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
Δθ) are not cut by the sky signal modulation and, statistically, they will affect
Figure 2: The brightness temperature of CMB in $\mu$K (solid line) compared with the dust anisotropic emission at medium galactic latitudes (dashed line) at the multipole $l \simeq 600$. 
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, 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 the SZ 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, $f_{\text{knee}}$, 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 $T_{\text{sys}}$ (and hence for the sensitivity) and it will suggest us also the final optical configuration of MASTER.
References

[Arnaud et al.(2001)] M.Arnaud et al. 2001, A& A 365:L67:L73
[Battistelli et al.(2002)] E.S.Battistelli et al. 2002, Ap.J. 580:L101-L104
[Battistelli et al.(2002)] E.S.Battistelli et al. 2002, P.A.S.A 19:313-317
[Blasi et al.(2000)] P.Blasi, A.V.Olinto and A. Stebbins, 2000, Ap.J. 535:L71-L74
[Burke and Silk(1974)] J.R.Burke, J.Silk, 1974, Ap.J. 190:1-10
[Dwek et al.(1990)] E.Dwek, Y.Rephaeli, J.C.Mather, 1990, Ap.J. 350:104-109
[Fabbri et al.(1978)] R.Fabbri, F.Melchiorri, V.Natale, 1978, Ap& SS 59:223-236
[Faber, Gallagher(1976)] S.M.Faber, J.S.Gallagher, 1976, Ap.J. 204:365-378
[Finkbeiner et al.(1999)] D.P.Finkbeiner, M.Davis, D.J.Schlegel, 1999, Ap.J. 524:867-886
[Hansen et al.(2002)] S.H.Hansen, S.Pastor, D.V.Semikoz, 2002, Ap.J. 573:L69-L71
[Itoh et al.(1998)] N.Itoh, Y.Kohyama, S.Noza9a, 1998, Ap.J. 502:7-15
[Lima et al.(2000)] J.A.S.Lima, A.I.Silva, S.M.Viegas, 2000, M.N.R.A.S. 312:747-752
[LoSecco et al.(2001)] J.M.LoSecco, G.J.Mathews, Y.Wang, 2001, Phys.Rev.D 64 123002
[Masi et al.(2001)] S.Masi et al., 2001, Ap.J. 553:L93-L96
[Rephaeli(1995a)] Rephaeli, 1995a, A.R.A&A 33:541-79
[Rephaeli(1995b)] Rephaeli, 1995b, Ap.J. 445:33-36
[Rephaeli(1980)] Rephaeli, 1980, Ap.J 241:858-863
[Shimon and Rephaeli(2002)] M.Shimon, Y.Rephaeli, 2002, Ap.J. 575:12-17
[Sunyaev, Zel’dovich(1980)] R.A.Sunyaev, Ya.B.Zel’dovich, 1980, M.N.R.A.S 190:413-420
[Valenziano, Dall’Oglio(1999)] L.Valenziano, G.Dall’Oglio, 1999, P.A.S.A. 16:167-174
[Wollack(1995)] E.J.Wollack, 1995, Rev.Sci.Instrum. 66(8):4305-4311
[Zel’dovich, Sunyaev(1969)] Ya.B.Zel’dovich, R.A.Sunyaev, 1969, Ap& SS 4:301-316