ABSTRACT

The Sunyaev-Zeldovich (SZ) effect was previously measured in the Coma cluster by the OVRO and MITO experiments, and recently also with the WMAP satellite. We assess the consistency of these results and their implications on the feasibility of high frequency SZ work with ground-based telescopes. The unique dataset from the combined measurements at six frequency bands is jointly analyzed to determine the Hubble constant, $H_0$, towards Coma: $H_0 \simeq (77 \pm 20) \text{ km/(s Mpc)}$, whose error include both $y$ and X-ray data uncertainties.

Subject headings: cosmology: cosmic microwave background – observations – galaxies: clusters: individual (A1656)
The Sunyaev-Zeldovich (SZ) effect (Sunyaev & Zel’dovich 1972) constitutes a unique and powerful cosmological tool (for reviews, see Rephaeli 1995a, Birkinshaw 1999, Carlstrom et al. 2002). Many tens of high quality images of the effect have already been obtained with interferometric arrays operating at low frequencies on the R-J side of the spectrum. Multi-frequency SZ measurements were made of only very few clusters, so the potential power of spectral diagnostics has not yet been sufficiently exploited to reduce signal confusion and other errors. Systematic uncertainties are the main hindrance to the use of the effect as a precise cosmological probe. Our ability to reduce these uncertainties can be optimized by multi-frequency SZ measurements, and high-quality spectral and spatial X-ray measurements of nearby clusters.

Many upcoming multi-frequency bolometric array projects will observe the effect in a large number of clusters. Most will operate from the ground, and will exploit the multi-frequency capability to account for the large confusing atmospheric signals. The availability of both space and ground based measurements of the same cluster can be very helpful for the characterization of atmospheric emission in SZ work.

The S-Z effect was measured in the Coma cluster with the ground-based OVRO (Herbig et al. 1995) and MITO (DePetris et al. 2002) telescopes. The WMAP team has recently reported measurements of the effect in Coma at 61 and 94 GHz (Bennett et al. 2003): the first satellite measurement of the SZ effect. Together these measurements yield the first SZ spectrum with six spectral bands. The relatively wide spectral coverage obtained with ground and space based telescopes allows a much needed gauge of the impact of atmospheric emission on high frequency ground based observations of the SZ effect.

In this paper we briefly discuss the qualitative deductions that can be drawn from the general agreement between the ground based and WMAP results, and use the full database on Coma to derive values of the Hubble constant and the CMB temperature at the redshift of this cluster.

1. **SZ and X-Ray Measurements of the Coma Cluster**

The rich nearby Coma cluster has long been a prime target of SZ observations; the effect was detected towards Coma with the 5.5 m OVRO telescope, with a 7.3’ beam, operating at 32 GHz. A long series of drift scans with the MITO 2.6 m telescope, which had a 17’ beam, led to the detection of the effect at three spectral bands centered on 143, 214, and 272 GHz. Even though the WMAP telescope is not optimized for SZ observations, the effect was detected with the W and V bands radiometers at 61 and 94 GHz, with beam sizes of
20′ and 13′, respectively (Bennett et al. 2003). The predicted SZ size of Coma is more than \(\sim 30′\), so these measurements were not substantially affected by beam dilution. Results of the measurements are listed in Table 1, MITO measurements have recently undergone a new calibration process (Savini et al. 2003) which has slightly corrected the SZ values; the spectrum is shown in Figure 1.

Note that the MITO error bars are about a factor 3 smaller than those of the WMAP data; this is mainly due to the difference in observing time. Given the low signal to noise ratios of the two WMAP data, the main advantage of these satellite observations lies in the capability of relatively precise calibration through measurements of the modulation of the CMB dipole anisotropy. This is estimated to be \(\sim 0.5\%\) by the WMAP team, as compared with \(\sim 10\%\) for MITO and from \(\sim 3\%\) to \(\sim 10\%\) for OVRO.

It is interesting that the respective calibration of MITO and WMAP are in agreement to within \(\sim 10\%\). Basically, this result provides further support for ground based SZ observations, which are known to suffer from an uncertain calibration procedure involving planetary emission and atmospheric corrections. However, because of the poor signal-to-noise ratio of the WMAP data the situation with regard to this calibration method is still unsatisfactory.

In an attempt to explain the (small) discrepancy between the MITO and OVRO measurements, DePetris et al. (2002) hypothesized that the difference is due to a confusing CMB anisotropy signal. But in light of the WMAP results the contribution of such a signal appears not to be all that significant.

Most recently, the Coma cluster was observed by the XMM satellite. The measurements indicate that the gas temperature is constant in the central 10′ region, \(kT_e = 8.25 \pm 0.10\) (Arnaud et al. 2001). Spatial analysis of the XMM data in the 0.5-2 keV band (Neumann et al. 2003) yields values of the gas (angular) core radius, \(\theta_C\), and the density profile parameter, \(\beta\), that are consistent with those that were previously determined from ROSAT measurements of Briel, Henry, and Bohringer (1992). These results were slightly revised by Mohr et al. (1999) following further analysis; we adopt the values in the latter paper, \(\theta_C = 10.5′ \pm 0.6′\), \(\beta = 0.705 \pm 0.046\), and the X-ray central surface brightness, \(S_0 = (4.65 \pm 0.14) \times 10^{-13} \text{ergs} \text{s}^{-1} \text{cm}^{-2} \text{arcmin}^{-2}\), in our determination of \(H_0\).

2. \(H_0\)

As is well known, the combination of SZ and X-ray measurements can be used to determine an expression for the angular diameter distance, \(d_A\), in terms of observables, from which \(H_0\) can then be deduced by a comparison with the theoretical expression for \(d_A\).
This procedure has been discussed in detail in numerous works (e.g., Holzapfel et al. 1997, Hughes & Birkinshaw 1998, Furuwaza et al. 1998, Reese et al. 2000) and has by now become standard. Mason et al. (2001) and Reese et al. (2002) have obtained $H_0$ employing single frequency measurements obtained from several clusters. Here we employ the mentioned method for the first time to determine $H_0$ from multi-spectral measurements of the Coma cluster.

The Coma measurements are in the frequency range $\sim 32 \div 272$ GHz, namely in the range $x = 0.54 \div 4.56$ of the non-dimensional frequency $h\nu/kT$. Description of the effect at such frequencies must be based on a relativistic calculation (Rephaeli 1995b). We first use the exact relativistic treatment (to first order in $\tau$, the Thomson optical depth) to calculate the spectrum at the gas temperature measured by XMM, $kT_e = 8.25 \pm 0.10$ (Arnaud et al. 2001). Best fitting the six data points in Figure 1 by the calculated spectrum we obtain the central value of the Thomson optical depth of Coma, $\tau \simeq (5.41 \pm 0.62) \times 10^{-3}$.

The final expression used to determine $d_A$ contains (e.g., Reese et al. 2000) $\tau$, the X-ray surface brightness, the angular core radius, and the theoretical expression for the coefficient of the X-ray bremsstrahlung emissivity (integrated over the observed band). A comparison of the deduced value of $d_A$ with the theoretical expression in a cosmological model with a cosmological constant then yields the value of $H_0$, for given values of the cosmological density parameters. However, since Coma is at a low redshift, $z = 0.0231 \pm 0.0017$, the dependence on the density parameters is very weak and can be ignored.

We use the relativistically generalized expression for the X-ray spectral emissivity (Rephaeli & Yankovitch 1997, Hughes & Birkinshaw 1998), and the analytic fit of Itoh et al. (2001) to an exact calculation of the Gaunt factor. Doing so we obtain:

$$H_0 = (77 \pm 18 \pm 9) \text{ km/(sMpc)}$$

where the first error is derived from observed $x$ (at 1$\sigma$), while the second from X-ray data uncertainties; the quadrature combination of the two yields an error of $\pm 20$.

Known systematic uncertainties due to simplified modeling of the gas – spherical symmetry, isothermality, unclumped gas distribution – and negligible contribution from CMB anisotropy, the kinematic SZ component, and other confusing signals – have been discussed and assessed (see, e.g., Rephaeli 1995a, Holzapfel et al. 1997, Birkinshaw 1999). We adopt previous estimate of an overall level of $\sim 30\%$ which should be added to the above value of observational error.
3. Discussion

Our deduced value for $H_0$ is about $\sim 30\%$ higher than the current mean value from 33 individual results from the full dataset currently available (Carlstrom et al. 2002). Given the (relatively) large error, it is fully consistent with the recent value derived by Spergel et al. (2003) from the first year WMAP measurements. Clearly, the interest in using the SZ/X-ray method to determine $H_0$ is not diminished by the high quality WMAP result. In addition to the need for alternative independent methods to CMB sky maps, measurement of this basic parameter at many redshifts and directions on the sky yields important additional information on its variation over cosmological time, and test of its predicted isotropy.

The full potential of the SZ/X-ray method to determine $H_0$ has not yet been realized. As has often been stated by Rephaeli (e.g., Rephaeli 1999), results from this method will be optimized when a large sample of nearby clusters will be measured by multi-frequency bolometric arrays, and with the availability of high quality X-ray results from the XMM and Chandra satellites. Many ground-based and stratospheric SZ projects will soon collect sensitive data on a large number of clusters. The overall impact of these projects is likely to be larger than a single – even if multi-year – satellite project: the main advantages offered by space observations are those relative to the highest sensitivity of the low-background detectors (at least for Planck Surveyor), the more precise calibration based on CMB dipole modulation, and safest results in absence of atmospheric corrections. On the other hand, ground based observations, carried out from appropriate dry sites, offer the possibility of longer integration times and the possibility of using larger telescopes allowing better angular resolution and overall more optimal control of systematics, if a dedicated instrument is employed. Thus, even though future SZ all-sky surveys from space experiments will sample a large quantity of clusters, best results on individual clusters are expected from ground-based, dedicated telescopes. When the sensitivity of space observations will reach $S/N \sim 100$, it will be possible to calibrate ground based observations with the same accuracy of space instruments. Under these conditions the uncertainty in determining $H_0$ will be comparable to that recently claimed by the key project of the Hubble space telescope. An alternative of waiting for the more sensitive PLANCK-Surveyor mission is to carry out observations of nearby clusters during a few dedicated balloon flights (e.g., OLIMPO, Masi et al. 2003).

Contributions to the success of the MITO program were made by many scientists. In particular, we are grateful to: S. Masi, P. Lubin, T. Encrenaz, P. de Bernardis and all the people that worked on MITO project during all its phases. This work has been supported by CNR (Testa Grigia Laboratory is a facility of Sezione IFSI in Turin), COFIN-MIUR 1998, & 2000, by ASI contract BAR, and by a NATO Grant.
REFERENCES


Fig. 1.— SZ spectrum of the Coma cluster. The solid line shows the best fit spectrum (assuming isothermal gas with $kT = 8.25$ keV) to the combined MITO (diamonds), OVRO (square), and WMAP (triangles) measurements, corresponding to $\tau \simeq (5.41 \pm 0.62) \times 10^{-3}$. 
Table 1. SZE experiment parameters

<table>
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<tr>
<th>Channel</th>
<th>$\nu$ (GHz)</th>
<th>$\Delta \nu$ (GHz)</th>
<th>f.o.v. (FWHM) (arcmin)</th>
<th>Sensitivity ($mKs^{1/2}$)</th>
<th>$\Delta T$ ($\mu K$)</th>
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<tr>
<td>OVRO</td>
<td>32.0</td>
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<td>7.35</td>
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<td>WMAP(V)</td>
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<td>20</td>
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<td>WMAP(W)</td>
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<td>19</td>
<td>13</td>
<td>1.48</td>
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<td>17</td>
<td>1.21</td>
<td>-184±39</td>
</tr>
<tr>
<td>MITO(2)</td>
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<td>30</td>
<td>17</td>
<td>1.14</td>
<td>-32±79</td>
</tr>
<tr>
<td>MITO(3)</td>
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<td>32</td>
<td>17</td>
<td>0.896</td>
<td>172±36</td>
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