MILLIMETER/SUBMILLIMETER SEARCH FOR THE SUNYAEV-ZELDOVICH EFFECT IN THE COMA CLUSTER

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ABSTRACT

Observations from the first flight of the Medium Scale Anisotropy Measurement (MSAM1-92) are analyzed to search for the Sunyaev-Zeldovich (SZ) effect toward the Coma cluster. This balloon-borne instrument uses a 28' FWHM beam and a three-position chopping pattern with a throw of ±40'. With spectral channels at 5.7, 9.3, 16.5, and 22.6 cm⁻¹, the observations simultaneously sample the frequency range where the SZ spectral distortion in the intensity transitions from a decrement to an increment and where the fractional intensity change is substantially larger than in the Rayleigh-Jeans region. We set limits on the Comptonization parameter integrated over our antenna pattern, Δy ≤ 8.0 × 10⁻⁵ (2 σ). For a spherically symmetric isothermal model, this implies a central Comptonization parameter y₀ ≤ 2.0 × 10⁻³ or a central electron density n₀ ≤ 5.8 × 10⁻³ cm⁻³ h₀, a result consistent with central density limits implied by X-ray brightness measurements and central Comptonization estimates from lower frequency observations of the SZ effect.

Subject headings: balloons — cosmic microwave background — cosmology: observations — galaxies: clusters: general — intergalactic medium

1. INTRODUCTION

Compton scattering of the cosmic microwave background (CMB) photons by a hot electron gas results in a characteristic spectral signature, the Sunyaev-Zeldovich (SZ) effect (Sunyaev & Zeldovich 1972). This effect is of cosmological interest because it serves as a probe of intracluster gas and its evolution and, when combined with X-ray observations, can be used to estimate the Hubble constant independent of the distance ladder (Birkinshaw et al. 1992; Birkinshaw & Hughes 1994). Nearby clusters, such as Coma, are particularly interesting because high-quality X-ray measurements exist (Briel, Henry, & Böhringer 1992; White, Briel, & Henry 1993), allowing mapping of the gas distribution in the cluster.

Detection of the small change in the CMB intensity along lines of sight through a hot gas-rich cluster has been a challenging task. The SZ effect has been detected in a number of clusters (see Birkinshaw 1994; Rephaeli 1995a for recent reviews of observations and theory) and even in the Coma cluster (Herbig et al. 1995). At radio frequencies, the presence of weak background sources may lead to significant systematic errors of either sign, canceling or mimicking the real SZ effect. Recent images of the effect (Jones et al. 1993; Carlstrom, Joy, & Grego 1996) have been obtained using radio interferometric arrays. Early attempts to go to higher frequencies (>3 cm⁻¹) using ground-based instrumentation to take advantage of wideband bolometric detectors have encountered problems with the atmosphere (Meyer, Jeffries, & Weiss 1983; Radford et al. 1986; Chase et al. 1987). More recently, high-quality ground-based measurements at millimeter wavelengths have been obtained using difference techniques with an array of detectors (Wilbanks et al. 1994). In the interesting frequency range where the SZ distortion makes its transition from a decrement to an increment, the atmosphere is not very transparent; balloon-borne instruments allow observations at these frequencies and allow detection over wider bandwidths (Page, Cheng, & Meyer 1990; Cheng et al. 1994, hereafter Paper I).

In this paper we describe our attempt to detect the SZ effect in the Coma cluster during the first flight of the Medium Scale Anisotropy Measurement (MSAM1-92). We briefly describe the instrument, observations of the Coma cluster, and the data analysis procedures. Finally, we compare these results with a model based on parameters derived from X-ray observations of the Coma cluster.

2. INSTRUMENT AND OBSERVATIONS

Fixsen et al. (1996) and Paper I provide a detailed description of the instrument and observing method; here we briefly summarize only the essential features. MSAM1 is a balloon-borne, off-axis Cassegrain telescope with a 1.4 m primary mirror, a 0.27 m secondary mirror, and a 28' FWHM beam. The secondary nutates in a four position (left, center, right, center) square wave pattern at a 2 Hz rate with the beams separated by ±40' from the center beam. All of the beams have similar shape and size. The four-frequency bolometric radiometer operates at 0.24 K using a ³He refrigerator and was previously flown in the Far Infrared Survey experiment (Page et al. 1990; Meyer, Cheng, & Page 1991). Table 1 shows the effective frequencies and...
bandwidths of the four channels for a source with an SZ spectrum.

The bolometer output from each of the four channels is sampled synchronously with the secondary chopper and is digitized at 32 Hz for real-time telemetry to the ground. During the flight, MSAM1-92 scanned Jupiter and Saturn to calibrate the instrument (calibration uncertainty is estimated to be 10%), rastered over Jupiter to map the antenna beams, scanned over the center of the Coma cluster X-ray source to search for the SZ effect, and integrated for 4.9 hr on a patch of sky near the north celestial pole to search for CMB anisotropy (Paper I).

The Coma observations are done by pointing the telescope near the X-ray center of the Coma cluster. The telescope is then moved ±45° in cross-elevation with a period of 1 minute, causing the telescope beam to cross within ~1' of the X-ray center of the cluster at closest approach. After scanning across the cluster for 2 minutes, a nearby reference field 1°05 in elevation above (northeast) the X-ray center was scanned in the same manner for a total of 2 minutes. After returning to reproduce the first set of scans across Coma for another 2 minutes, another off-source reference field 1°05 below (southwest) the X-ray center was scanned for 2 minutes, followed by a final set of scans carried out for 4 minutes across the X-ray center. After each set of scans, motion was paused for 40 s to record an image with the on-board star camera to verify pointing. The total elapsed time for these observations was less than 20 minutes, during which 8 minutes of data crossing the Coma cluster X-ray center were obtained.

Figure 1 shows the scan pattern superimposed on the approximate star camera field of view at the time the Coma crossing observations were started. The circles show the positions of (expected) stars that were detected by the star camera at the start of the Coma central scans. The relative location of the telescope beam in the camera frame and the instrument calibration are fixed by the simultaneous observation of Jupiter with the star camera and the radiometer. Both the beam position and the radiometer calibration were confirmed near the end of the flight by a similar observation of Saturn. Between images, the position is interpolated from the gyroscope signals. The resulting final pointing is accurate to 2.5', limited by gyroscope drift.

3. ANALYSIS

3.1. The Signature of Comptonization in Coma

There are extensive X-ray observations of the Coma cluster from numerous space-borne X-ray instruments and satellites. Spectral imaging observations indicate that there is some ellipticity to the cluster and that the core is nearly isothermal out to 30' from the center (Watt et al. 1992). There is some evidence for a decline in temperature at larger radii, although analysis of more recent Advanced Satellite for Cosmology and Astrophysics (ASCA) observations indicate that there may be temperature variations at large (∼40') radii (Honda et al. 1996). We do not account for these details here. We expect to be sensitive only to the high-density core region, and the higher (lower) temperatures reported in low-density regions at large distances from the core would only reduce (enhance) our detection by ~10%.

We therefore estimate the level and spatial characteristics of Comptonization toward Coma in the context of a spherically symmetric, isothermal β-model for the intracluster gas (Cavaliere & Fusco-Femiano 1976; Hughes 1989). The electron density at a radial position, \( r \), is taken to have the form

\[
n_e(r) = n_0 [1 + (r/r_c)^2]^{-3/2}\beta ,
\]

where \( r_c \) is the core radius of the cluster, \( n_0 \) is the central density, and \( \beta \) is a density slope parameter.
The Comptonization parameter is
\[ y = \left( k\sigma_T/mc^2 \right) \int n_e T_e \, dl, \tag{2} \]
where \( k \) is the Boltzmann constant, \( \sigma_T \) is the Thomson cross section, \( m \) is the electron mass, \( c \) is the speed of light, \( T_e \) is the electron temperature, and the integral is along the line of sight. Substituting equation (1) into equation (2), we obtain the Comptonization parameter at an angular distance \( \theta \) from the center of the cluster:
\[ y(\theta) = Yf(\theta), \quad Y = \frac{2kT_e \sigma_T n_e (0)p}{mc^2}, \tag{3} \]
\[ f(\theta) = \left[ 1 + (\theta/\theta_0)^2 \right]^{-\xi/2} \int_0^p \left( 1 + t^2 \right)^{-\xi/2} \, dt, \tag{4} \]
where \( \xi = 3/2\beta, \theta_0 \) is the angular core radius, \( t \) is the distance from the center of the cluster in core radii, and \( p \) is the outer radius of the gaseous sphere in core radii. The ROSAT results trace X-ray emission out to beyond 100'. In contrast to the X-ray emission, which depends quadratically on the electron density, the SZ effect depends linearly on the electron density; we have, therefore, integrated to \( \infty \).

Because the integral converges rapidly, this has little effect on the result. The difference in intensities at a frequency, \( v \), along different (pencil-beam) lines of sight is then (Rephaeli 1995a)
\[ \Delta I = \frac{2kT^3}{hc^2} g(x)\Delta y, \tag{5} \]
where
\[ g(x) = \frac{x^4e^x}{(e^x - 1)^2} \left( x \coth \left( \frac{x}{2} \right) - 4 \right), \tag{6} \]
\[ x = \frac{hv}{kT}. \tag{7} \]

\( h \) is the Planck constant, and \( T \) is the CMB temperature. High-precision observations will have to take relativistic effects into account at high frequencies even for \( kT_0 \sim 5 \) KeV (Rephaeli 1995b).

### 3.2. Results

The MSAM1-92 configuration approximately samples the difference
\[ \Delta y = \begin{cases} (y_i - y_s) & \text{(single difference)} \\ \frac{1}{2}(y_i + y_s) & \text{(double difference)} \end{cases}, \]
where \( y_s, y_i, \) and \( y_r \) are the expected Comptonization parameters in the central, left, and right beams, respectively. Equation (5) is integrated over the actual antenna pattern and over the channel bandpasses to estimate the observed intensity difference for a pure SZ spectrum source at each channel.

When the isothermal model described above is convolved with our beam maps, we find that our finite beam size and chopper throw give a response very similar to our point source response (Jupiter scans). The observed Comptonization parameter, \( \Delta y \), is reduced from the central Comptonization of this model by a factor of \( \sim 2.5 \) (2.0) for the double- (single-) difference data compared with a true pencil-beam measurement, \( y_0 \). We correct for this geometric form factor later. We simultaneously fit the Coma scan data to the point-source response and a separate quadratic function of time for each of the three central scans. This permits us to detect and remove any slow drifts from the time series in each channel and to determine the best-fitting surface brightness consistent with a source at the X-ray center of Coma. The simultaneous fit to the model and the baseline drift avoids removal of signal that may result if separate fits were used sequentially.

The results of these fits to the data are summarized in Table 2. The procedure for estimating noise is not the same as we used in Paper I. The majority of those CMB observations were done near transit, while the Coma observations were done as Coma was setting, resulting in a rapidly changing elevation during the observations. Because of the short time under these different observing conditions, we estimate the noise on the Coma observations

### Table 2

| Channel | \( \Delta T_m \) (\( \mu \text{K} \)) | \( \Delta y \) \( \times 10^{-4} \) | Estimated Form Factor* | Central Comptonization \( y_0 = kT/mc^2 \parallel n \, dl \) \( \times 10^{-4} \) |
|---------|----------------|-----------------|------------------|---------------------|
| Single Difference | | | | |
| 1………………… | \(-99 \pm 112\) | 1.0 ± 1.2 | 2.0 | 2.0 ± 2.3 |
| 2………………… | 17 ± 49 | 0.34 ± 1.0 | 2.0 | 0.68 ± 2.0 |
| 3………………… | 7 ± 45 | 0.36 ± 2.2 | 2.0 | 0.74 ± 4.5 |
| 4………………… | \(-7 \pm 108\) | ... | ... | ... |
| Weighted average…… | ... | 0.59 ± 0.71 | ... | 1.2 ± 1.4 |
| Double Difference | | | | |
| 1………………… | 50 ± 43 | \(-0.51 \pm 0.45\) | 2.5 | \(-1.3 \pm 1.1\) |
| 2………………… | 34 ± 21 | 0.69 ± 0.41 | 2.5 | 1.7 ± 1.0 |
| 3………………… | 23 ± 20 | 1.2 ± 1.0 | 2.5 | 2.9 ± 2.5 |
| 4………………… | 1 ± 47 | ... | ... | ... |
| Weighted average…… | ... | 0.22 ± 0.29 | ... | 0.56 ± 0.73 |

* The estimated form factor represents the factor by which the peak signal is reduced after the MSAM1 beam and chopping strategy are applied to a pure SZ source with parameters, \( \theta_c = 10.5, \beta = 0.75 \) (Briel, Henry, & Böhringer 1992). For this model, the MSAM1 chopper throw is not large enough for the off-center beam(s) to be in a region of negligible contribution.
from the dispersion in the data after removal of drifts. Thus, the reduced $\chi^2$ of all fits is unity. No significant detection is found at any frequency, even when the position of the assumed X-ray center along the scan was allowed to vary from the known position. The noise properties of the northeast and southwest scans are consistent with the central scans. Errors derived from the single-difference data are significantly larger than for the double-difference data. This may be due to the greater sensitivity of the single-difference data to contamination from atmospheric gradients. The noise properties of the northeast and southwest scans are consistent with the central density and degree of Comptonization estimated from the ROSAT X-ray data and with the estimate for the central Comptonization of $y_0 = (9.3 \pm 1.7) \times 10^{-5}$ made by Herbig et al. (1995) from measurements with a 7' beam and 22' beam separation at 32 GHz.

Recent observations of the intrinsic CMB anisotropies on angular scales $\~0.5$ (Paper I; Cheng et al. 1996; Devlin et al. 1994; Nettnerfield et al. 1997) show $\Delta T/T \~ 2 \times 10^{-5}$. This intrinsic level represents a potentially significant contaminant to SZ observations at these angular scales because the CMB fluctuations may be comparable to the expected signal from the SZ effect. At higher frequencies (e.g., 16 cm$^{-1}$) the shape of the SZ spectrum will aid in distinguishing SZ fluctuations from intrinsic CMB fluctuations.

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